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**Multi-Criteria Decision Making Approach to
Optimization of Fuel-Mix Choice for Electric Power
Generation under Environmental Impact Constraints**

by

Aimée Smith

A thesis
submitted under the supervision of
Dr. Sampat Sridhar

Department of Civil and Environmental Engineering
Carleton University
Ottawa, Ontario

**Presented to Ottawa-Carleton Institute for Civil Engineering
In partial fulfillment of the requirements for the degree of
Master of Engineering in Civil Engineering**

August, 2000

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Department of Civil and Environmental Engineering

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acceptance of the thesis

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A handwritten signature in black ink, appearing to read "Wade Parker", written over a horizontal line.

Chair, Department of Civil and Environmental Engineering

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Abstract

Selection of a proper mix of primary fuels is imperative in the deployment of centralized electric power generation systems that are required to satisfy the electricity demands of a region under environmental, economic, safety and reliability constraints. A Multi-Criteria Decision Making (MCDM) approach is employed under which a Weighted Goal Programming (WGP) Model has been developed as the decision making tool to aid in fuel choice decisions.

Impacts of power generation on the global environment are of significant concern and in this study an emphasis has been placed on the minimization of these impacts through the use of environmental externalities. The Model includes coal, oil, natural gas, nuclear and hydroelectric power as well as purchased power contributions to the centralized electrical grid as decision variables and considers multiple objectives over a twenty year analysis period, beginning in the year 2000.

Different fuel mix scenarios are modeled and the results are compared to recent NRCAN demand projections. Through this evaluation, various relationships and trade-offs between power generation systems are identified and discussed. As well, the implications of Canadian compliance to the Kyoto Protocol on carbon dioxide emissions are analyzed for each of the scenarios.

The modeling exercise revealed the complex interplay of competing constraints in achieving goals and objectives in the different scenarios. More importantly, the model formulation is such that it is flexible enough to allow the user to tailor and prioritize the nature and magnitude of the constraints. Based on the results, recommendations are made on the research and technology needs of the power generation industry for future application of some of the strategies suggested by the model results. The need for a more rigorous compilation and assessment of the environmental externalization database employed in the model is recognized and suggestions are made for further development and improvement of the WGP model.

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Nomenclature and Acronyms

a	risk per unit of coal power (\$/GWh)
AHP	Analytic Hierarchy Process
A_{MZ}	affected area in the mixing zone
Annual Deaths	annual number of deaths
Annual ΔC	annual number of morbidity cases
AT	average daily intake
A_{WB}	total area of water body
b	estimated coefficient
b	risk per unit of natural gas power (\$/GWh)
b_{ext}	total light extinction coefficient (Mm^{-1})
b_{Ray}	Rayleigh light scattering coefficient ($11.6 Mm^{-1}$)
BTEX	benzene, toluene, ethylbenzene and xylene compounds
Btu	British thermal unit
BW	body weight (Kg)
BWR	Boiling water reactor
c	risk per unit of oil power (\$/GWh)
Cancer Slope Factor	oral cancer slope factor for chemical j ($mg/Kg/d$) ⁻¹
CANDU	CANadian Deuterium and Uranium reactor
CAPP	Canadian Association of Petroleum Producers
CC_{jp}	chemical concentration of chemical j in pathway p
CEA	Canadian Electricity Association
CF	Capacity factor
CFCs	chlorofluorocarbons
cfs	design flow of desired station (cfs)
CH ₄	methane
C_i	atmospheric concentration for species i ($\mu g/m^3$)
cm	centimeters
CO	carbon monoxide
CO ₂	carbon dioxide
CP	Compromise Programming
CPI	consumer price index
CR ₃₀	capital recovery factor for a plant lifetime of thirty years
CV	contingent valuation
CVM	contingent valuation method
d	risk per unit of nuclear power (\$/GWh)
D	total annual damages to commercial and recreational fishing for a specific plant (\$1992)
D/cfs	damages per unit flow from Hudson River case study (\$1992/cfs)
D/cfs	total annual damages at site j per unit flow (\$1992/cfs)
DAD _j	damage per affected angler-day at site j
Di	0 for metals (central and low estimates), 1 for metals (high estimate)

D _{LF}	present value of damages due to landfill aesthetics (\$1992)
DNA	deoxyribonucleic acid
D _{PV}	present value of total damages due to contamination of groundwater summed over ten years of WTP starting at time of initial leachate contamination (\$1992)
d _s	inside stack diameter (m)
DSM	demand side management
D _{TR}	present value of damages due to aesthetics associated with new truck miles to support landfill
e	risk per unit of hydro power (\$/GWh)
ED _{jp}	exposure duration to chemical j through pathway p (years)
EF _{jp}	exposure frequency to chemical j through pathway p (days or events/yr)
ET _{jp}	exposure time to chemical j through pathway p (hrs/event)
Ex/V	exposure levels (person-rem/yr/m ³ of waste)
Flow _j	design flow of discharge at site j
GHG	greenhouse gas
GP	Goal Programming
GWh	Gigawatt-hour
h	the metric defining the family of distance functions and
H ₂ S	hydrogen sulfide
HEAST	Health Effects Assessment Summary Tables
HH _i	households in the affected area i
H _L	number of local households
H _N	number of national households
HQ	hazard index
h _s	stack height (m)
Intake _j	Intake of chemical j (mg/Kg/d)
Intake _{jp}	Intake of chemical j through pathway p (mg/Kg/d)
IRIS	Integrated Risk Information System
IR _{jp}	ingestion rate of chemical j through pathway p
kW	kilowatt
kWh	kilowatt-hour
lb	pound
L _h	family of distance functions
Lifetime	lifetime (years)
M	merged stack parameter
m ³	cubic meters
m ³ /d	volumetric rate of supply
MCDM	Multiple Criteria Decision Making
MCLP	maximum coverage location model
MOP	Multiple Objective Programming
MSW	Municipal Solid Waste
Mt	Megatonnes
MW	Megawatt
N ₂ O	nitrous oxide

NYSEE	New York State Electricity Externality Study
NH ₃	ammonia
n _i	negative deviation variable for goal i
NO	nitrogen oxide
NO ₂	nitrogen dioxide
NO _x	nitrogen oxides
NRCAN	Natural Resources Canada
O ₃	ozone
p	pathway (drinking water or surface water ingestion)
PbB	annual blood lead levels
pH	measure of acidity or alkalinity
p _i	positive deviation variable for goal i
PJ	Petajoule
PM	particulate matter
PM ₁₀	particulate matter smaller than 10 µm diameter
PoP	affected population
Pop _p	population exposed through pathway p
PWR	pressurized water reactor
Q	pollutant emission rate (g/s)
R	annual death risk factor (effect/µg/m ³ or ppm)
R	annual dose-response coefficient (effect/µg/m ³ or ppm)
r	discount rate (%)
Ra-226	Radium
rad	measure of the absorbed radiation dose
rem	Roentgen Equivalent Man (measure of biological dose from radiation)
RfD _j	oral reference dose for chemical j (mg/Kg/d)
R _{Fi}	cancer risk factor for inhalation of chemical i (µg/m ³)
RHS	right hand side (bound) of constraint equation
R _i	total ingestion/inhalation ratio for chemical i
Rn-222	Radon
rpm	rotations per minute
RTED	Real time economic dispatch
share	share of landfill volume utilized by an electricity generating facility
S _N	number of national sites expected to leak
SO ₂	sulfur dioxide
t	time when initial leachate contamination is discovered
TAD _j	total annual recreation angler days in water body j
Th-230	Thorium
tons	net tons of ash landfilled per year
T _s	stack gas exit temperature (K)
TWh	Terawatt-hour
U.S. EPA	United States Environmental Protection Agency
V	stack gas volumetric flow rate (m ³ /s)
V _L	local groundwater use value (\$WTP/HH/month)

V_N	national groundwater use value (\$WTP/HH/month)
VOCs	volatile organic compounds
V_r	visual range (common visibility)
$VR1_i$	starting annual average visual range (Mm)
$VR2_i$	annual average visual range after the change in emissions (Mm)
v_s	stack gas exit velocity (m/s)
V_T	total volume of radioactive waste produced (m^3)
WAC	willingness to accept compensation
WGP	Weighted Goal Programming
W_j	measures the relative importance of the discrepancy between the jth attribute and its anchor value
WTP	willingness to pay
WTP_i	total annual WTP for visibility changes in area i for residents of area i (\$1992)
x_1	coal power contribution (GWh)
x_2	natural gas power contribution (GWh)
x_3	oil power contribution (GWh)
x_4	nuclear power contribution (GWh)
x_5	hydro power contribution (GWh)
x_6	purchased power contribution (GWh).
Δc	change in annual average concentration ($\mu g/m^3$ or ppm)
ΔC_{air}	average annual change in ambient air lead concentrations while the facility is operating ($\mu g/m^3$)
ΔC_{CANCER_i}	change in incidence of cancer from chemical i
ΔC_i	change in concentration of chemical i ($\mu g/m^3$)
ΔGM_t	the increment in the geometric mean of annual blood lead level (PbB) distribution in period t ($\mu g/dl$)
$\Delta RISK_i$	total inhalation plus ingestion risk for chemical i
α_i	weighting factors for the negative deviations from goal i
β_i	light extinction efficiency for species i (m^2/g)
β_i	weighting factors for the positive deviation from goal i

1.0 Introduction

1.1 Overview

Global Climate Change concerns have prompted governments to evaluate those anthropogenic activities that have significant environmental impacts. Centralized electric power generation, a basic necessity of most modern industrialized and developing societies is one such activity that has come under scrutiny worldwide. Over the past decade, these global concerns have led to multi-national protocols and agreements, which among others would directly impinge on the national and regional energy plans and goals in many jurisdictions. In addition to the international agreements, the electric power generation industry has also to comply with national regulations on priority pollutants and other residuals.

Specifically, efforts both locally and globally are being made to minimize the negative impact of power generation through several mitigating measures, many of which are region-specific. One such measure is the proper choice of primary fuel mix that will provide the targeted society a safe, secure, reliable and affordable electrical energy supply with minimized environmental impact.

There are various forms of solid, liquid, gaseous, thermal and noise emissions produced as a result of the different stages of electrical power production. The nature and degree of these emissions are dependent on the contribution from the different fuel technologies as the physical, chemical and nuclear processes involved in the production of energy and by-product pollutants differ for each fuel source. Consideration of the environmental effects of the different fuel choices, even at the planning stage can lead to a reduction in damages to human health and perhaps more importantly minimize the stress on the ecosystem that supports life on this planet.

1.2 Objectives and Scope

The overall objective of this work was to develop a decision making process to aid in the choice of fuel technologies to meet a specific electrical power demand. An emphasis was placed on the combination of technologies that would collectively lower the environmental damage subject to different constraints. This was accomplished through cost externalization of the environmental impacts as a result of power generation using full fuel cycle analysis. The multiple objective programming technique of satisficing was used to develop a goal programming fuel choice optimization model incorporating the environmental goals with other system objectives. The model robustness was evaluated through several power combination scenarios over a twenty-year modeling period. Results obtained for the different fuel mix scenarios aided in determining the usefulness of the model as a decision making tool as well as indicate the accompanying model limitations. Conclusions are made concerning the use of environmental externalities and multi-objective programming in fuel choice decisions.

Although there are numerous issues and interrelationships involved in the selection of power generation alternatives that cannot be easily resolved, this study outlines many of the key issues and provides a starting point for decision making with the goal of minimizing environmental effects. The work performed was limited to the electricity sector but consideration of the issues should extend to all energy sectors for effective resolution.

2.0 Background

The model developed through this analysis was based on a situation similar to the Ontario Power Generation scenario. A description of the specific Ontario situation is given. The need for a decision making tool to aid in the choice of fuel options is illustrated through the problem identification of various impacts that result from electricity production. The usefulness of externalizing the environmental impact costs from electric resource options is discussed, as are several issues associated with the process. As the decision problem faced by resource planners is one consisting of multiple objectives, the supporting theories of popular multiple criteria decision making methods are outlined.

2.1 Problem Identification

As the level of industrialization increases and technological progress continues, it is inherent that the required demand for electricity will also increase. The quantification of this increased demand has associated uncertainty, as it is difficult to precisely predict future behaviour. However, for most jurisdictions in North America the electricity demand is certain to grow, though not at the rapid rates of earlier decades. The growth in electrical demand is dependent on several influencing factors such as macroeconomic (industry and commercial demand) and demographic (residential demand) trends, international energy prices and the imposition of certain governmental and regulatory directives (Natural Resources Canada, 1999a).

In order to meet this growing demand in electricity requirements, decisions must be made on the fuel make up to provide this energy. There are a broad range of alternatives with diverse environmental, social, economic and public policy implications. Thus the decision for fuel supply is not simple. In terms of optimizing the combination of power generation technologies, there are different criteria and constraints to be considered. These include:

- electrical demand
- cost of generation
- reliability of the technology
- availability of fuel
- safety/risk implications (occupational and public)
- social effects
- economic effects
- environmental externalities, and
- environmental limits from policy instruments.

An optimum mix based on these criteria and constraints will result in a power system that will meet the required demand while minimizing costs and undesirable impacts. Perhaps the most significant impacts of power generation are those that affect the environment as well as human health and welfare. There are desired targets associated with these impacts that should be met to minimize damages. In many cases, it may not be possible to meet all of these targets with any specific fuel mix. Thus an approach is needed that will formulate a solution incorporating these targets that is as close as possible to the target values. The development of a decision making method to determine the fuel mix combination based on these aspects will aid in adhering to environmental legislation such as the proposed emissions caps on sulfur dioxide and nitrogen oxides and the Kyoto objective with consequent improvements to overall environmental quality.

2.2 Ontario Situation

The electrical demand for the province of Ontario is supplied by contributions from coal, oil, natural gas, nuclear, hydroelectric and purchased power. In terms of magnitude, three days of average demand in the province can be met with one terawatt-hour of electricity. There are a total of eighty

generating stations in Ontario with an installed production capacity of 30 873 MW.

At present, hydroelectric generation supplies 7309 MW of power. There are four major hydro stations and 65 smaller units throughout the province. The major stations are found in the Niagara area, Northeastern and Northwestern Ontario and in the Ottawa/St. Lawrence areas. There are six fossil-fuelled stations producing electricity. These are Lambton, Nanticoke, Lakeview, Lennox, Thunder Bay and Atikokan for a total of 9700 MW net capacity. The fossil fuel power for the province is generated primarily by coal with the exception of the Lennox station, which is fuelled by oil and natural gas. Lastly, the nuclear stations in Ontario have a net generating capacity of 13 864 MW which is approximately forty-five percent of the total installed production capacity for the province. The nuclear stations are sets of nuclear reactors known as Bruce A, Bruce B, Pickering A, Pickering B and Darlington. Currently, Bruce A units and Pickering A units are out of service and as a result the nuclear net capacity for the province is reduced (Ontario Power Generation, 1999). A more detailed description of the stations is provided in Appendix A.

2.3 Environmental Impacts Associated with Power Generation

There are various forms of solid, liquid, gaseous, thermal and noise emissions produced from electrical power generation. The nature and degree of emissions is very dependent on the fuel make up as the chemical processes contributing to the production of these emissions are different for each fuel source. The sections that follow provide a description of the impacts as well as the generation technologies responsible for the emissions.

2.3.1 Air Emissions

The majority of air pollutants released from power generation are from fossil-fuelled power plants. Those of major concern are sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM) and air toxics. Emissions of elemental carbon (soot), organic carbon and volatile organic carbons (VOCs) are negligible as the stations are designed for complete combustion to utilize the full energy content of the fuel. Power generation emissions of global concern are carbon dioxide (CO_2) and other greenhouse gas emissions.

The main contributor to SO_2 emissions is coal-fired generation and the amount produced is dependent on the sulfur content of the coal. Sulfur dioxide can contribute to both materials damage and acid precipitation from the atmospheric conversion of emissions to secondary pollutants such as sulfates and sulfuric acid. At high enough concentrations this acidic deposition can affect wildlife, vegetation, buildings and human health and has caused damage to many forests and lakes in North America. Some lakes have become so acidic that they can no longer support any aquatic life. Sulfur also plays an important role in the biogeochemical system and although there is limited understanding of its role, it could have a significant effect on the environment (Bellhouse and Whittington, 1996). Further, the effects from sulfur are not limited to the local scale and can range to regional scales and beyond (i.e. affecting other countries) (Chattopadhyay, 1995). The contributions of atmospheric sulfur dioxide are given in Figure 2.1. It is clearly illustrated by this figure that the power generation sector is the prime contributor to SO_2 emissions and should be a major consideration in the selection of fuel source make up.

Figure 2.1: Sulfur Dioxide Emissions by Sector

Figure 2.2: Nitrogen Oxides Emissions by Sector

Nitrogen oxides (Figure 2.2) are also major products from the combustion of fossil fuels. These pollutants also alter the chemical composition of rain from weak acid (rain is naturally acidic) to strong acids through the production of nitric acid in the atmosphere. The effects of this increased acidity were previously outlined in the effects of SO₂. In addition to this, NO_x play a significant role in the photochemical reactions leading to the production of ground level ozone. This can cause serious smog problems in urban areas (Bhattacharyya, 1995). As well, accumulations of ground level O₃ can lead to health effects such as asthma attacks and acute respiratory symptoms and even death (Rowe *et al.*, 1995a).

Another effect of NO_x in the case of nitrous oxide in the atmosphere is that it can react with other elements and behave as a greenhouse gas. This would contribute to global warming and ultimately an undesirable climate change. Figure 2.2 illustrates the contributions to nitrous oxides emissions. Figure 2.2 shows that the contribution of power generation to NO_x is not as serious as its contribution to SO₂ compared to the other sectors (Bellhouse and Whittington, 1996). However, NO_x emissions from power generating stations are still a major concern.

Particulate matter is a significant emission from power generation and is the result of either incomplete combusted soot or non-combustible inert material in the fuel. Particulates in large concentrations can cause damage to materials and decrease visibility by scattering and absorbing light. They can also cause outright reflection of solar energy before it reaches the earth. Human health can also be affected to different degrees depending on the size of the particle and ability to penetrate the lung. These health effects include, chronic bronchitis, child bronchitis and death (Rowe *et al.*, 1995b).

Lead, Mercury and other air toxic compounds are released from fossil fuel stations. Lead is emitted from power plants burning coal, oil and municipal solid waste (MSW). The lead emissions behave as particulates and

concentrations peak within ten to thirty kilometers of the release point. Even with the use of scrubbers or electrostatic precipitators to remove the particles, lead will still be released in certain concentrations. Lead is a serious concern as deposition over time into soils and dusts can persist for an extended period of time. The exact length of time is unknown, as there is a lack of detailed understanding for the persistence of lead in soil. The greatest concern with lead uptake is associated with children as they have a higher exposure to soil through daily activities. The health effects experienced by infants and children include asymptomatic children, IQ decrements, increased probability of mental retardation and learning difficulties (Rowe *et al.*, 1995a).

The combustion of fossil fuels may account for up to fifty percent of anthropogenic mercury emissions. Mercury readily bioaccumulates and biomagnifies in the environment. As a result, exposure routes are through ambient air, wet and dry deposition. Uptake at elevated levels may cause paraesthesia of the extremities, psychomotor retardation in prenatally exposed infants and neuro-response effects in young children. The populations most at risk are anglers and families who consume large amounts of fish containing mercury. Many of the air toxic emissions released from fossil fuel combustion are suspected or known carcinogens so there is a risk of cancer. The methods of uptake are:

- air inhalation
- soil ingestion
- beef and dairy ingestion
- fish ingestion and
- produce ingestion (Rowe *et al.*, 1995a).

The power generation emissions of greatest global concern are CO₂ and other greenhouse gases due to the implications of global climate change. Important gases including CO₂, nitrous oxide (N₂O), ozone (O₃) and methane

(CH₄) behave as an insulating blanket, absorbing much of the heat escaping from the earth's surface holding warmth within the lower atmosphere. This "greenhouse effect" is a natural phenomenon without which the temperature of the earth's surface would be thirty degrees lower and uninhabitable to most life forms. Global warming is a potential result of a relatively rapid increase in the build up of these greenhouse gases (GHG) due to the burning of fossil fuels and other industrial and agricultural processes. The burning of fossil fuels to produce energy releases CO₂, N₂O and also contributes to increased surface O₃ levels (NRCAN and CEA, 1999). The largest contributor to global warming is CO₂ at fifty percent (methane 18%, CFCs 14%, nitrous oxides 6% and surface ozone 12%). It has been estimated that a doubling of pre-industrial levels of CO₂ could result in an overall global temperature rise of between 1.5 and 4.5 degrees Celsius. This would in turn lead to a rise in sea level of between 25 and 140 cm due to thermal expansion and icecaps melting. This rise would result in widespread flooding and displacement of approximately 300 million people (Bellhouse and Whittington, 1996).

Figure 2.3 shows the contribution of the power sector to overall CO₂ emissions (Bellhouse and Whittington, 1996). The Kyoto conference resulted in a Canadian commitment to reduce CO₂ emissions by 6% from 1990 levels by the year 2012 (NRCAN and CEA, 1999). To meet this objective, substantial reductions in all fossil fuel generation is necessary with the greatest emphasis on coal fired power reduction as it is the highest carbon content fuel and thus creates the most CO₂ as a product of combustion (Elliot, 1997).

Figure 2.3: Carbon Dioxide Emissions by Sector

2.3.2 Water Emissions

Power plants generate various wastes that affect the surrounding water bodies during the production of electricity. Concerns include geothermal fluids containing toxic chemicals, acid drainage from mines, coal wastes, effluent containing hazardous chemicals from power plants and refineries and thermal pollution from the discharge of power plant cooling systems (Dincer, 1998). In addition to these concerns are damages from impingement and entrainment of organisms. Thermal plants require water for cooling which can be provided using one of two popular technologies, once-through or closed-cycle cooling. Closed-cycle systems discharge heat through evaporative processes in cooling towers and recycle water within the plant. As a result the required water withdrawals are small. Due to the lack of large water withdrawals, impingement and entrainment effects are very low and could possibly be neglected in analysis of major impacts. However, once-through cooling systems draw large volumes of water through the power plant in a continuous flow and discharge the heated water after use.

This large water withdrawal associated with once-through systems can cause fish, larvae and other organisms to become impinged on the intake structures or entrained in the flow circulating the plant resulting in death. Impingement has the greatest impact on juvenile fish less than three years old while entrainment usually affects large numbers of larvae and can be a significant problem during the spawning season. These impacts are dependent on several operating parameters as well as location. The factors affecting impingement and entrainment effects are:

- the amount of water withdrawn
- the aquatic ecosystem in surrounding water body
- the intake and discharge designs, and
- the inclusion of fish mitigation measures (Rowe *et al.*, 1995a).

The impacts that result affect both the commercial and recreational fishing industries. Thus in order to reduce the damages from impingement and entrainment, the design and location of the power generation facility must be considered.

Thermal discharge to the surrounding water body as a disposal method for waste heat is also a significant concern with once-through cooling systems. The addition of heat to the water body can have several effects. The water temperature increases and the oxygen levels decrease. If the levels of oxygen decrease to deficient amounts in the water, the fish cannot survive. Chemical reaction rates increase with temperature, and with the potential increase of toxic chemical products, the water toxicity could increase to hazardous levels for fish and other aquatic organisms. The formation of different temperature layers can confuse the fish as they depend on the water temperature as a signal for migration or spawning. As well, above certain temperatures, eggs will not hatch and the temperature difference will cause changes in the bodily functions of the organisms in the water. Finally, the viscosity of the water decreases with temperature increase, which will

affect the habitat for aquatic organisms and will ultimately affect their life span and quality of life (Liu, 1993). As with impingement and entrainment effects, the amount of thermal discharge is dependent on the plant capacity and technology.

There are serious human health effects resulting from chemical and metal discharge to surface water as a result of the power generation fuel cycle. The three primary sources of the surface water contamination are runoff from fuel and materials storage piles, direct discharge from sumps boiler blowdown and contaminant runoff and aerially transported emissions (wet deposition). The chemicals that are emitted vary, depending on the emission source. Coal ash piles contribute to heavy metal contamination while fuel oil plants are responsible for benzene, toluene, ethylbenzene and xylene (BTEX) compounds from the fuel oil storage tank berm sump. The health effect of greatest concern associated with the discharge of these compounds to surface water is the incidence of cancer. Intake exposure from surface water can occur through several pathways. The contaminated surface water can be ingested as drinking water or during recreation. Ingestion of fish from the contaminated source can lead to exposure. Dermal contact with the water can lead to exposure from organic compounds but is not a concern for metals exposure (Rowe *et al.*, 1995a).

2.3.3 Radioactive Emissions

There are four main aspects of nuclear operation to consider when assessing the damages associated with the generation of nuclear power. These are normal plant operation, nuclear accidents, radioactive waste and nuclear fuel acquisition. Radioactive releases can occur at all stages of the nuclear fuel cycle including the management of waste created in the process. The releases may be trapped in body tissue or remain in the environment as a continuing source of exposure. If radiation penetrates biological material it gives up energy through a series of collisions with the

atoms or nuclei. This radiation may alter any molecule present in the cells' deoxyribonucleic acid (DNA) macromolecules, which are the most critical biological targets. These DNA macromolecules carry the genetic information necessary for cell development, maintenance and division. Radiation can break one or both strands of DNA at one or many locations, which results in the destruction or alteration of genetic information (Rowe *et al.*, 1995a). The cell can repair much of this damage but in some cases the DNA is permanently damaged. The consequences can be death, or altered function of the cell including birth defects, cardiovascular disturbances, asthma or diabetes and the development of cancer. The amount of permanent cell damage depends on the type, intensity and duration of radiation exposure measured by the unit rem or millirem. A whole body dose between 20 and 200 rem will have significant effects and a whole body dose of 500 rem or more delivered acutely is fatal (Liu, 1993).

A rem (Roentgen Equivalent Man) is a measure of biological dose given by the product of the absorbed dose in rads and the relative biological efficiency of the radiation. A rad is a measure of absorbed dose and is the energy released by the radioactive reaction. Alpha particles and neutrons generally cause more damage per rad than beta or gamma radiation. One rad of beta or gamma radiation is equal to a dose of one rem, one rad of alpha radiation gives a dose of twenty rem and one rad of neutron radiation results in a dose of 10 rem. To account for this difference the rem unit is used for setting protection standards. A dose of radiation may be delivered to the whole body or to specific organs and tissues. Exposure pathways may include inhalation of contaminated air, ingestion of plant and animal food contaminated through radioactive materials deposition, or uptake of contaminated water (Rowe *et al.*, 1995a).

During normal plant operation, the radiation levels are low and so are the health risks. However, the isotopes from radioactive releases can be detected. The potential for accidents at a nuclear generating station are

considered to be among the major risks associated with nuclear power. This is due to the severity of resultant health impacts in the low probability event that a reactor failure occurred. Radioactive waste is a large concern for human health as the doses of radiation are continuous for a long period of time. There is also significant uncertainty associated with methods of disposal or storage to minimize the doses. The greatest concern with uranium mining and milling is the tailings pile. These piles contain daughter products of uranium that may continue to decay to radon for as long as 80 000 years (Rowe *et al.*, 1995a). Thus the human health effects are a concern for this entire period or until a safe method of disposal is developed.

2.3.4 Waste Disposal Impacts

Disposal of solid waste from power generation can pose environmental problems of two types. In the case of waste classified as hazardous it may release hazardous pollutants resulting in air, water and soil pollution. However, even if the waste is not considered hazardous, it can still cause disposal problems due to the difficulties of space and appropriate containment (Dincer, 1998). A large source of solid waste from power generation is the generation of ash from coal, oil, biomass and MSW facilities. The solid waste is a result of fuel combustion ash and flue gas desulfurization wastes as well as sludge cake from cleaning activities at oil facilities. The disposal of this waste can result in damages to the groundwater from leachate containing metals and other compounds. Waste piles can cause negative aesthetic impacts and loss of open space for landfills. Relative to ash production, other amounts of solid waste production related to power generation from construction, operation and decommissioning are smaller and less significant.

Most heavy metal cations will adsorb onto amorphous iron oxides and other minerals in soils at the pH conditions present in groundwater. These processes provide a natural limit to the spatial extent of groundwater

contamination. Landfills used to contain the solid waste should be equipped with a protective liner to prevent leaching to the groundwater. Yet even with liner systems there is still a risk of failure. This breach is not expected to occur until approximately thirty to forty years after the landfill is closed. In order to identify groundwater leachate, the flow from the landfill site should be monitored for the most mobile element as an indicator of liner failure. The aesthetic impacts associated with ash disposal are the creation of a visual blight, dust, noise and traffic congestion. The best way to mitigate these effects is to dispose of solid wastes on the facility site. These impacts can affect both the property value and health of residents near the disposal site (Rowe *et al.*, 1995a).

2.3.5 Hydroelectric Power Impacts

There are land-use and siting impacts associated with the generation of hydroelectric power that gives rise to concerns that land particularly suited for sustaining agriculture, housing, or natural ecosystems could be lost (Dincer, 1998). Environmental damages result from dam construction at the reservoir site as well as downstream. These include effects on the local climate, vegetation, fish and wildlife caused by the creation and expansion of a reservoir and the construction of a dam and generating station. Water levels and flows are affected above and below the dam as are the nutrient content and temperatures of the water bodies. However, some of these impacts could be perceived as positive from the human perspective such as the reduction of seasonal flooding and the creation of new wildlife reserves (Natural Resources Canada and Canadian Electricity Association, 1999).

The environmental impacts of hydroelectric facilities depend on different factors including the type of facility, regulation and license requirements, operation of the facility and the water body characteristics and ecology of the location. The generalization of the impacts from hydro facilities is difficult as the impacts are very site specific and dependent on a large number of

conditions including geology, river flow, aquatic species, riparian ecology, human infrastructure and others. In order to properly assess these damages an extensive site analysis is required before a new facility is approved or existing facility relicensed. It is feasible that many of the potential impacts of the generating station may be identified and mitigated during the process (Rowe *et al.*, 1995b).

2.3.6 Other Renewable Power Sources and Impacts

Sources of renewable energy other than hydraulic power include biomass, solar, wind, tidal and geothermal forms of energy. Renewable energy recovery is subject to many problems such as large land requirements, large material requirements for facility construction, health and safety problems during plant operation, large energy requirements to collect the renewable energy as well as air and water pollution by chemicals involved in the different processes (Liu, 1993).

Biomass, which includes dead trees, leaves, harvest residues, waste wood and sawdust can be used to produce energy. The collection of the biomass fuel itself requires energy (Liu, 1993). Significant air emissions from the combustion of wood include particulates, NO₂ and CO. As well, biomass burners are expected to release higher levels of CO than coal combustion. Uncontrolled wood emissions may also contain a variety of organic compounds including acids, aldehydes, phenols and carcinogens including benzo-a-pyrene. Combustion of biomass produces a considerable amount of bottom and fly ash, which is usually easier to control than coal ash due to smaller amounts of toxic substances. Waste solids from wood-fired combustion are composed of silica and alumina oxides with minor amounts of sodium, magnesium, potassium and lead. The amount of water used for a biomass facility is comparable to the requirement of a fossil-fueled plant. Any leachate from storage piles should be controlled as well as aqueous

combustion wastes because they may contain trace amounts of metals (Ottinger, 1991).

Solar energy is the energy that is received from the sun. The solar power that falls on the earth is estimated as 180 trillion kW. Ground-based thermal plants use a piping system enclosed in boxes with glass tops and a black metal plate bottom. The greenhouse effect allows these boxes to become solar energy collectors that heat incoming cold water. The heated water is accumulated in a tank and pumped to a heating coil to warm the facility, the cool water is then recycled through the thermal boxes. These plants can only be used during daylight hours (Liu, 1991). The most significant impact of these thermal plants during operation is the land requirements (Ottinger, 1991). Photovoltaic systems directly convert sunlight to electricity. The solar cells use semiconductor materials such as silicon that provide current when struck by solar radiation. An electric field is created when two thin silicon plates (positive and negative) are placed together. Solar cells are quiet, reliable and easy to operate and have no moving parts. The efficiency of solar cells is dependent on the material and is estimated as fifteen to forty percent (Liu, 1993). These direct systems do not cause environmental impacts during operation but the fabrication of materials and construction of the systems has an effect on the environment (Ottinger, 1991).

Wind energy is in fact a type of solar energy as unevenly distributed sunlight energy causes the movement of air. The kinetic energy of the wind produced can be converted to electric energy. Wind power is proportional to the cube of the wind velocity. As a result a small increase in wind velocity will cause a tremendous increase in power. The efficiency of the net energy conversion for wind power is estimated at twelve percent and the availability of wind is a constraint. Windmills are usually employed to convert the wind energy to electricity. The structure consists of blades mounted on a high tower. An air shaft transmits the blades' rotation to a gear box, which converts the shaft rotation from approximately forty rpm to 1800 rpm to drive

a power generator. The generated power is stored in batteries for future use. The generation of power from wind is aesthetically damaging, causes noise pollution and safety hazards due to falling blades and structural defects from vibration. The windmills also change the flight paths of birds affecting their migratory habits. Wind power also affects the environment through the large land requirements, which divert the areas from regular land use (Liu, 1993).

Another renewable form of energy is geothermal power. There are approximately ten crustal plates on the earth. These carry mountains and oceans, deserts and other geologic features. The plates move relative to each other grinding and overlapping in different directions. Beneath the soil layer the groundwater flows through a porous rock layer on top of a layer of solid rock. Below the solid rock hot magma (molten rock) generates heat that is transferred to the water that seeps down in the porous rock layer. When this water boils, steam is released through crustal lines and appears on the surface as fumaroles or geysers. This steam carries geothermal power. The steam has to be treated to remove molten materials and is then guided to a steam turbine to generate electric power (Liu, 1993). The environmental impacts associated with geothermal power include air emissions, solid wastes, brine disposal, chemical and thermal pollution of surface and groundwater, noise pollution and induced seismicity. The major gases released are usually CO₂, CH₄, hydrogen sulfide (H₂S), ammonia (NH₃), nitrogen and hydrogen with the greatest volume percentage belonging to CO₂. Minor concentrations of benzene, mercury, radon, and boron may also be released depending on the well type and operational practices. As well, the removal and subsequent re-injection of crustal fluids could cause land subsidence or increase seismicity (Ottinger, 1991).

Tidal energy is defined as the energy used to raise an ocean's elevation. This form of energy is mainly due to the earth's rotation and gravitational effects from the sun and moon on the earth. Tidal effects are determined

from predictions based on long-term statistical records for the location. This energy can be converted into electrical power energy. Tidal falls are guided to move turbine blades to generate power at the peak hour. The spent seawater is then pumped to a reservoir during the off-peak hours when the turbines are run as pumps (Liu, 1993). This form of power generation would have serious impacts on land use as well as the ocean's aquatic ecosystem. The environmental effects on the sea life would be similar to the effects felt by freshwater organisms from the operation of other power generation cooling systems.

2.4 Externalization of Environmental Impacts

Environmental externalities from electric resource options are environmental costs and benefits to society resulting from the production and consumption of electricity or from certain demand side management activities unaccounted for in electricity prices (Rowe *et al.*, 1995a). Potential externalities should be identified from all aspects of the full fuel cycle including:

- fuel acquisition
- electricity generation, and
- waste disposal.

The externalities associated with all air, water and land pollution from power generation sources should be considered in an analysis. The populations considered in the valuation process are human individuals, flora and fauna particularly crops, forests and fisheries, materials such as buildings, structural metals, textiles and art works and social assets such as climate, recreation and visibility. From past externalization studies the largest reported environmental costs electricity production imposes on society are from the risks to human health and the environment from air pollutants emitted by fossil fuel generation and from the radiation risks of nuclear facilities (Ottinger *et al.*, 1991).

2.4.1 Incorporation of Externalized Values

Environmental externality costs can be incorporated into the resource planning process for the power generation industry in different ways. The quantitative approach involves increasing the cost of a proposed resource by a specific amount per kWh reflecting the environmental implications of using the resource option. The alternative to increasing the cost of the resource is to subsidize less harmful options. There is a qualitative approach that is similar but involves a subjective and relative judgment of impacts without an easily comparable unit such as dollar amounts as in the quantitative method. Another method of incorporating the externality costs is through the rate of return. With this approach an increased rate of return is awarded specific non-polluting resource investments or on overall performance in using low impact resources. An increase in avoided cost can also be used to account for environmental costs. A utility may also be guided in selecting resources by a ranking system that weights the different resource options by the environmental impacts or other criteria not necessarily the costs. Another option for incorporation is to determine environmental costs and their treatment in a collaborative negotiating process involving regulators and public interest groups.

There are also incorporation options for existing resources such as environmental dispatch. This involves the inclusion of environmental costs in least cost dispatch of existing resources. Cost-charging can also be used which means that the quantified environmental costs are charged to the resource owner and the proceeds used to establish a pollution mitigation fund. Federal environmental regulations as well as pollution taxes or fees can also be used to include environmental externalities in planning and decision making (Ottinger *et al.*, 1991).

2.4.2 Valuation Issues

Environmental externality studies vary as to whether the costs of the damages inflicted on society as a result of pollutants or the costs of controlling or mitigating pollution effects are used to value the impacts. The main advantage of using damage costs is that they are more relevant because it is the cost to society that needs to be alleviated through the incorporation of environmental externality costs in power resource selection. Damage costs are difficult to determine, and require extensive studies and data to formulate the damage functions but can be used to determine health and safety standards. The complicated calculations are the main disadvantage with this method. Experts feel that regulatory bodies may have difficulty dealing with matters like valuation of human life and non-monetized costs like valuation of recreational facilities. If damage cost studies are not feasible then the use of control costs is an acceptable alternative. The use of the control cost method is preferred over disregarding the relevant issues.

The main advantage of control costs is that they are easier to determine than damage costs because the data is more readily available. The disadvantages of using control costs are that they bear little or no relationship to the cost of the damages imposed on society by the emissions. As well, statutory controls on pollutants usually fall substantially short of damage costs for political reasons and thus the full extent of the impact is not represented (Ottinger *et al.*, 1991).

Discount rates are used to assess the value today of economic benefits and costs that may occur in the future. Low discount rates give more weight to the future than high rates. A controversy exists among scientists and economists as to what discount rate if any should be applied to the environmental externalities. Some experts believe that the same discount rate that is applied to the utilities capital investment should be used for consistency because all resource selection decisions should be made on the

same financial basis. Others maintain that sound environmental stewardship demands a rate of zero especially for human health risks, as a life in the future is as valuable as a present life. Discounting of low probability catastrophic risk or long lasting risks may provide a misrepresentation of the environmental costs. The arguments for including a discount rate above zero include the idea that the value of risks will decrease with time and that technology may resolve the environmental concern before the future time. However there are serious problems with future risks that cannot be remedied by new technology such as loss of unique habitat and species. A discount rate of zero provides a better representation for these irreversible effects (Ottinger *et al.*, 1991).

There are site-specific considerations that must be considered when valuing the cost of an environmental impact. A power generation facility that operates in a highly populated city will create a greater human health risk than a plant in an unpopulated area. In the same way, agricultural damage costs are higher when emissions are deposited on farming communities rather than an urban center. Human exposure depends on many factors such as the distance of the source from the population, the meteorology and topography and the vegetation and water bodies in the area that may absorb the emissions. These factors vary from city to city and from urban to rural locations. As a result, the extrapolation of estimates for one location to another requires careful examination of the two locations for differences.

Requirements for the incorporation of environmental costs could have a significant impact on rates and the competitive position of the electric utilities. If full environmental damage costs are determined and used, and particularly if applied to existing resources the impact on rates could be considerable. Conversely, if the inclusion of the environmental costs encourages investment in more energy efficient resources, electric bills may be reduced as a result. There may also be competitive problems from the rate impacts. If the impact on rates from environmental costs is large enough, it may

overprice electricity compared to resources not incorporating environmental damages (Ottinger *et al.*, 1991). This situation could potentially promote the use of higher emission fuels from resources that exclude environmental considerations. Thus it would seem that universal application is required for the use of environmental externality costs to play a significant role in reducing environmental impacts from power production.

2.5 Multi-objective Decision Making

There are several objectives to consider in the decision of fuel make up for power generation to supply a given demand. Decision making methods to solve multi-objective problems are presented along with a discussion of the fuel substitution dilemma including past solutions and the more recent inclusion of environmental concerns.

2.5.1 Fuel Substitution

Substituting fuels to further the achievement of environmental goals has involved permanent shifts to energy alternatives, temporary fuel switching to minimize short-term or seasonal impacts and the use of lower polluting forms of the same fuel (i.e. from high to low sulfur coal). Recently, the increasing concern with environmental problems has affected the choice of fuel. To optimize the fuel combination, the comparative effects on the environment of different fuel choices must be determined through the evaluation of the fuel cycle and impacts from all stages of emissions.

In order to reduce air emissions from power generation, the use of natural gas is preferred over coal and oil fired electricity production. This is because the combustion of natural gas produces no SO₂ emissions and substantially less NO_x and CO₂ than the two other competing fuels. The viability of gas as an alternative has been questioned because of its high forecast prices and potentially unstable supply. Natural gas can become a desirable alternative with potential efficiency gains in production that may lower costs and

increase recoverable reserves coupled with the possibility of a premium for its environmentally desirable quantities. Thus the consumption of natural gas is expected to increase in the future to supply energy at lower environmental costs.

Nuclear energy was believed to be the solution to greenhouse gas emissions, acid rain and other air pollution problems. Yet the risks associated with nuclear generating stations while they are operating and their regular discharge of waste with the long-term problem of waste disposal does not make their use an environmentally sound alternative. It is expected that the growth rate of nuclear energy production will continuously decrease because of cost, regulations and pricing, long design and construction times and environmental and safety concerns (Dincer, 1998). Nuclear power may play an important role in mitigating the effect of greenhouse gases on the global climate. Thus more research into nuclear technology leading to inherently safe reactor designs and highly reliable waste management may make it a more desirable fuel alternative.

Compared to other generation technologies, hydroelectric power is a clean and renewable energy source and will continue to increase until options become more costly or more distant from major markets. In environmental terms, the development of new resources involves flooding large areas of land, which destroys agricultural land and often displaces large populations (Dincer, 1998). In a jurisdiction such as Ontario, much of the hydro potential has already been tapped and large increases in new hydro projects is unlikely in fuel choice decisions to minimize environmental impacts from power generation.

2.5.2 Compromise Programming

The multiple criteria decision making (MCDM) process consists of two stages. The first is to use multi-objective programming (MOP) to generate the subset of Pareto optimal solutions. A solution is Pareto efficient (non-dominated) when the element is a feasible solution such that no other feasible solution can achieve the same or better performance for all the criteria, being strictly better for at least one criterion (Ballestero and Romero, 1998). The second stage is to determine the best solution for the problem at hand from the efficient set. To do this, it is necessary to introduce the decision maker's preferences. One method to accomplish this task was introduced by Yu and Zeleny and is called Compromise Programming (CP).

Compromise Programming is based on the concept of an ideal point and by a behaviour postulate proposed by Zeleny and known as Zeleny's axiom of choice, which states that alternatives closer to the ideal are preferred to those that are farther. To be as close to the ideal as possible is the rationale of human choice. The ideal point is not feasible due to the conflict between objectives and so it is necessary to seek compromise solutions. To compromise is to make an effort to approach the ideal solution as closely as possible. In a technical sense, the "goodness" of any compromise is measured by its closeness to the ideal (or by its remoteness from the anti-ideal). Thus the notion of distance and its measurement is necessary in decision making. The degree of closeness d_i between the i^{th} objective and its ideal value is defined by:

$$d_i = |f_i^* - f_i(x)| \quad (2.1)$$

Next the different degrees of closeness are aggregated into a composite distance function. Frequently the units used to measure the attributes are different and to avoid meaningless summation in the distance function, these have to be normalised. Also, without this normalisation, solutions biased

towards those objectives which can achieve higher values may be obtained. To measure the difference between each solution and the ideal, CP introduces the family of distance functions $L_p(x)$:

$$L_p(x) = \left[\sum_{i=1}^l W_i^p \left| \frac{f_i^* - f_i(x)}{f_i^* - f_{i*}} \right|^p \right]^{1/p} \quad p = 1, 2, \dots, \text{infinity} \quad (2.2)$$

subject to $x \in X$.

where X = feasible set of decision variables
 x = vector of decision variables
 l = number of objectives
 p = metric defining the family of distance functions
 W_i = measures the relative importance of the discrepancy between the i^{th} objective and its ideal value
 $f_i(x)$ = value of the i^{th} objective achieved at x
 f_i^* = ideal value for the i^{th} objective
 $f_{i*} = \underset{x}{\text{Min}} f_i(x)$, is an anti-ideal value for the i^{th} objective
all values of the decision variables are non-negative.

The complete set of compromise solutions can be calculated as:

$$\text{Minimize} \quad L_p(x) = \left[\sum_{i=1}^l W_i^p \left| \frac{f_i^* - f_i(x)}{f_i^* - f_{i*}} \right|^p \right]^{1/p} \quad (2.3)$$

For $p = 1, 2, \dots, \text{infinity}$.

The corresponding solutions, members of the compromise set, are denoted x^p , that is x^1 , denotes the solution calculated for the L_1 metric, x^2 for the L_2 metric and ..., x^{infinity} for the L_{infinity} metric. From the compromise set, it is determined which solutions are closest to the ideal.

For the $p = 1$ and infinity metrics, model 2.2 is a linear problem. For all other metrics, the best-compromise solutions can only be obtained using non-linear mathematical programming (Zeleny, 1982).

2.5.3 Goal Programming

Compromise Programming and other multiple objective programming methods work efficiently for moderate size problems defined within a structured environment. For large size problems more flexible decision making approaches such as Goal Programming (GP) are necessary. GP is a widely used MCDM technique and is a modification and extension of linear Programming (LP). It was developed in 1961 by A. Charnes and W.W. Cooper, who introduced the theory behind GP formulation and applied it to industrial problems.

In general, in GP the objective is to find the solution that comes “as close as possible” to the indicated goals (Lee, 1972). This could be related to the satisficing philosophy as proposed by Herbert Simon. In today’s complex organizations, incomplete information, limited resources, conflicts of interest and other complications define the decisional context. Simon states that in contexts so complex the decision maker attempts to achieve a set of relevant goals as close as possible to the set targets established (Ballesteros and Romero, 1998).

The GP approach allows a solution of a system with multiple objectives and their target values rather than a single objective formulation. Thus, it is capable of handling decision problems that deal with multiple goals and the objective function of a GP model may be composed of non-homogeneous units of measure (i.e. Kg and dollars) (Lee, 1972).

A major advantage of GP over other LP models in dealing with actual decision problems is that it reflects the way in which decisions are really made. This is because GP allows the decision maker to incorporate the

environmental, organizational and managerial considerations into the model through goal levels and priorities. Within the GP model, goals can only be achieved at the expense of other goals. If it is not possible to achieve every goal, the GP formulation allows satisfactory goal attainment that represents the best possible combination of goal achievements. This requires the use of a weighting system for the goals such that the lower weighted goals are considered after the higher weighted goals are satisfied. GP being a variant of linear programming can be solved using the simplex method or its subsequent modifications (Lee *et al.*, 1981).

The first step in formulating the GP model is to establish the set of goals associated with the objective function. Next the deviational variables are introduced into the model. These variables represent the negative (n_i) (downward) deviations from the goal and the positive (p_i) (upward) deviations. The negative deviation variables represent the value by which the i^{th} goal falls short of the established target. The positive deviation variables represent the amount by which the i^{th} goal was surpassed. For each goal, either both or one of the variables has to be zero. If the goal is met exactly, then both deviation variables will be zero; otherwise one of the deviation variables will have a positive value. The i^{th} goal is expressed as:

$$f_i(x) + n_i - p_i = b_i \quad (2.4)$$

where x = the vector of decision variables and
 b_i = the goal target value.

If the goal is to be equal to or greater than the target value, the negative deviation variable should be minimized. Conversely, if it is desired for the goal to be less than or equal to the target, the positive deviation variable is minimized. If it is the desire of the decision maker to meet the target exactly, both deviation variables are minimized. The overall purpose of GP is to minimize the deviations between the achievements of the goals and their

target values. This minimization can be achieved with weighted goal programming (WGP) (Lee, 1972).

WGP considers all goals simultaneously in a composite objective function. This function minimizes the sum of all the deviations between the goals and target values. The weighting reflects the relative importance of the goals to the decision maker. The structure of the WGP model is:

$$\text{Minimize } \sum_{i=1}^k (\alpha_i n_i + \beta_i p_i) \quad (2.5)$$

Subject to:

$$Ax + n - p = b$$

$$Bx \leq h$$

$$x, n, p \geq 0$$

where

- n = vector of negative goal variable
- p = vector of positive goal variable
- α = vector of negative weighting factor
- β = vector of positive weighting factor
- A = matrix of the coefficients associated with the goal constraints
- B = matrix of the coefficients associated with the system constraints
- b = vector of target values
- h = vector of system constraint right hand sides
- x = vector of decision variables and
- k = total number of goal constraints ($i = 1, 2, \dots, k$)

(Lee, 1972).

There are difficulties associated with the use of GP for decision making. GP is susceptible to the generation of optimal solutions, which are not Pareto optimal. This occurs when a GP model is applied to a problem where the goal targets are set at pessimistic levels. Although the potential generation

of GP dominated solutions could be a major drawback, there are methods of verifying solutions for Pareto efficiency. If the solution is dominated then the target values on the goals need to be adjusted (Ballesteros and Romero, 1998).

Another critical issue in GP is that of naïve setting of weights in WGP. This is a result of the fact that in most GP problems the goals are measured in different units. These goals are said to be incommensurable. Under this situation the composite objective function of a WGP problem is skewed because the deviation variables are measured in different units. A similar problem arises when the target values for the goal constraints have different magnitudes of numerical values. In this case, the solution can be biased as more importance is placed on the goals with higher target values. In order to avoid these problems, the GP model should be normalized (Romero, 1991).

3.0 Literature Survey

The purpose of the literature review is to critically examine, evaluate and discuss the recent work that has been done concerning multi-objective decision making and externalization of environmental costs. As the literature reviewed did not reveal any specific studies using multi-objective programming for power generation fuel choice, the surveyed studies cover related topics in order to identify the most appropriate and robust programming method for the power generation decision problem. The works analyzed for externalization of electricity impacts explore different methods of quantifying impacts and the critiques on current externalization practices.

3.1 Multi-objective Programming for Decision Making

Two multi-objective programming methods commonly used for decision making are considered. Recent studies discuss several uses of each approach. The advantages and disadvantages of these programming techniques are discussed individually and their usefulness is compared for the specific fuel choice decision problem.

3.1.1 Compromise Programming

The technique of compromise programming (CP) is widely used in multi-criteria decision processes. The studies presented and discussed use compromise programming for various decision problems associated with design of printed wire boards, reservoir system planning, forest rotation planning and demand side management options for electric utility planning.

The benefits from demand side management (DSM) are usually measured in monetary terms without taking into consideration other associated benefits. A simultaneous integration method is proposed by Chattopadhyay *et al.* (1995) in a multi-objective framework using the compromise programming

technique. The advantages of Compromise Programming for this application include the explicit consideration of all associated benefits of DSM options as well as the consideration of the integration specific characteristics of various types of DSM options. As there are tradeoffs associated with the different objectives, it is impossible to obtain a solution that achieves all optima simultaneously. In the multi-objective context of compromise programming, optimization means finding the best compromise among the objectives. This is found as the smallest deviation or distance from the ideal solution.

The authors solved the problem of the best mix of DSM options according to each criterion cost, carbon dioxide emissions and supply system reliability separately. Then these solutions were compared to the solution obtained when all the criteria were considered together using compromise programming. The solution obtained using CP gives a different mix of DSM options than when only the criterion of cost is considered. The results of this study suggest that perhaps the selection of DSM options should be based on more criteria than just cost in order to choose the most efficient combination (Chattopadhyay *et al.*, 1995).

Romero *et al.* (1998) consider the inclusion of the carbon dioxide absorption value of forests in addition to the value of the timber when planning the forest rotation age. The decision problem posed was to develop an approach to determine the optimal forest rotation age when considering both timber production and carbon uptake. There are three separate objectives associated with this problem. These include:

- the private optimum of maximum net worth
- the environmental optimum of maximum carbon uptake, and
- the social optimum of maximum social welfare.

An overall solution is achieved through a compromise between all three objectives. Thus CP is a useful approach for the problem. The use of this approach for forestry management problems will allow policy makers to

understand and measure the tradeoffs and opportunity costs between net worth associated with both timber production and carbon uptake. From these tradeoffs and the ranking of alternative solutions it would be possible to design a system of subsidies to compensate forest owners for the provision to society of carbon dioxide captured from the atmosphere.

For the design of printed wire boards several factors have to be taken into account in the decision process such as cost of packaging, electrical performance, reliability and mechanical performance. There is often conflict among these design criteria. A method for solving the conflicts is presented by Tokat *et al.* (1998) and is illustrated by the example of system level considerations in selection of printed wire board technology to house a specified number of modules. The authors note that the most popular and frequently used methods in multi-criteria decision making involves the introduction of a single utility function which summarizes the different criteria into a single objective function. Compromise programming with norms l_1 , l_2 and l_{∞} and the Nash solution concept are applied with equal weights given to the objectives because they were normalized. For the norms other than 1 or infinity, the problem becomes non-linear and the algorithms are complex and computationally intense. The feasible solution with the minimal distance from the ideal point is accepted as the solution to the multi-criteria decision problem. With the Nash solution concept the solution is instead based on the maximum distance from the ideally bad point known as the nadir. One alternative is concluded to be the best using the results from all the norms and the Nash solution. The authors contend that the method presented can be used in decision making problems where more than one criterion is involved.

Reservoir system operational planning requires a multi-objective analysis of system benefits in order to plan the operation. The objectives include combinations of reservoir benefits from hydropower generation, water supply for irrigation, municipal and industrial use, flood control, navigation, water

quality improvement, recreation and ecology and environmental enhancement. There are many mathematical optimization models for reservoir system operation that have been developed but most do not directly consider all operational objectives simultaneously. Ko *et al.* (1994) consider a two-stage procedure combining multi-objective optimization and multi-criteria decision analysis techniques for reservoir system operational planning. The two-stage procedure involves separating the objectives into primary objectives, which are easily quantified, and secondary objectives, which are not easily quantified (such as environmental impacts) or deemed less important. The alternatives are generated in the first stage using the primary objectives and alternative selection is accomplished through various multi-criteria decision analysis techniques including compromise programming. The use of CP is beneficial in this study as it allows for the full ranking of the alternatives.

Through the analysis of recent work on compromise programming, several advantages of the technique were discovered. The CP technique is very useful under conditions when GP is not advantageous due to difficulty in assigning values to the various goals or assigning weights in the objective function (Hannan, 1985). Other advantages of CP include the resolution of conflict among objectives in order to find a solution (Tokat *et al.*, 1998). A major disadvantage with the CP process is that the mathematical programming model is non-linear for metrics defining the family of distance functions other than one or infinity (Ko *et al.*, 1994). This reduces the useful value of the CP approach as the solutions for anything other than one or infinity metrics becomes an intensive computational task.

3.1.2 Goal Programming

The goal programming problem solving procedure has been used extensively in the field of multi-objective decision making. The technique has been employed in many different areas where decision problems were encountered. Recent studies described and analyzed here are examples of goal programming solutions for different industry situations as well as military and energy resource allocation problems.

The case of energy resource allocation based on economic and environmental objectives was presented in Mezher *et al.* (1998). The specific resources of Lebanon were considered in this study. These include:

- diesel (mechanical and electricity)
- natural gas
- biogas
- fuelwood
- solar
- thermal electric power
- wind electric power and
- hydroelectric power.

The objective functions were quantified and then transformed to mathematical expressions to develop a multi-objective allocation model. The overall objective was to optimally allocate to a certain household end-use the amount of power to be supplied from a given resource. The resulting model consisted of six objectives and ten constraints. The objectives were to:

- minimize cost
- maximize system efficiency
- minimize use of petroleum products and natural gas
- maximize use of locally available resources
- maximize employment generation and

- minimize CO_x, SO_x and NO_x emissions.

The mathematical model was formulated as a weighted goal programming model. The resulting model was used as a decision making tool to evaluate six different scenarios with altered objective priorities. The different scenario conditions resulted in various resource solutions.

As a result the model created could be adapted to the specific situation of different countries through the use of priorities. For example, a developing country that desired low cost energy with the maximum amount of jobs would assign the highest priorities to the cost and employment objectives. This study is a good example of how the goal programming model can be easily altered for use as a tool for other decision making problems (Mezher *et al.*, 1998).

Radasch and Kwak (1998) present a goal programming model to resolve multiple conflicting goals with inconsistent units for offset (countertrade) planning. The term offset refers to defense, aerospace, or high-tech related reciprocal agreements while countertrade generally applies to commercial agreements. Numerous conflicting qualitative goals that cannot be easily prioritized or ranked, complicate the selection of an offset package. Thus there is a need to prioritize the multiple goals. The priorities obtained are used to formulate the weight factors for the GP model. The resulting model consists of 28 equations consisting of economic, social, political, and company objectives. Eleven are system constraints and the remaining seventeen are goal equations.

The developed model can be updated in future years as additional projects are identified. As well, the GP model can be easily modified to reflect changes in priorities and additional projects for consideration. The impact of modifying these priorities can be evaluated through performance of a sensitivity analysis on the weights assigned in the GP objective function. The study provided an approach that can be employed by other companies

to analyze offset alternatives identified during a proposal process and conveyed the flexibility and transfer abilities of the GP model (Radasch and Kwak, 1998).

The multi-criteria problem of efficiently determining the procurement amount of military resources over a time period of five years is approached by Choi *et al.* (1998). The military resource planning problem can be characterized by the conflicting objectives of required quantities, minimum cost and maximum effectiveness. In addition to these objectives, the military strategy can be changed with environmental factors. A model is required that can incorporate changes to the users' preferences explicitly. An expert system was developed that allows the user to choose the most appropriate of the three multi-objective GP models for a given decision situation based on the objective priorities. The use of the GP models saves time and money for managing military resources. The authors have illustrated that the GP model and its variations according to weight factors can be used to create a decision support system.

The decision problem presented by Yao and Min (1998) is to provide the optimal location of repair units (both vehicles and crew) in the event of significant damage to electric power transmission and distribution systems. The problem is similar to that of optimizing the location of fire trucks and fire stations. However, the authors believe that the demand for electric repair units for large-scale power failures is more predictable due to efficient weather forecasting. The GP problem consists of one system and two goal constraints and is formulated as a weighted problem. The weighted goal deviations are summed over all the nodes in the forecast region. As with the models developed by Radasch and Kwak (1998) and Mezher *et al.* (1998), the GP model can be extended and used for any transmission and distribution system. The model developed by Yao and Min (1998) was compared to the established maximum coverage location (MCLP) model

based on specific efficiency criteria and the GP model was found to be more efficient in determining the optimal location of repair units.

Economic dispatch (power dispatch based only on demand and cost) plays an important role in operation planning and real time control of modern power systems. Real time economic dispatch (RTED) provides the most economic dispatch for online units. The constraints considered in the past included only cost and demand. Now, the impact of deregulation and clean air requirements impose emission and security constraints. Fan and Zhang (1998) use quadratic programming techniques combined with GP to solve the RTED problem. Although quadratic programming could be used on its own, the solution strategy is enhanced through the inclusion of GP techniques. These are included in order to avoid infeasible solutions due to conflicts among the operation constraints as well as to provide the best available solution. The authors have demonstrated GP as a superior multi-objective decision making model through the inclusion of the process to improve the solution.

Gonzalez-Pachon and Romero (1999) proposed an improvement to social choice theory through the formulation of a goal programming (GP) problem to minimize the total absolute disagreement between committees. This was done in the hope of inducing distance-based consensus methods. Three different GP formulations were considered; a linear weighted GP model, a MINMAX GP model and an extended GP model using the first two formulations as specific cases. It was discovered that the optimization of a social choice function as GP models offers several advantages. These are:

- less intensive computations required to solve a linear weighted GP model
- generalization of the social choice function structure allowed through GP formulation, and
- solutions provided by the GP models that satisfy a sound axiomatic basis.

Through the analysis of current literature studies using and evaluating the GP technique, several advantages of the process have been identified.

These are:

- the inclusion of decision maker priorities
- the ability to resolve conflicting objectives and always achieve a feasible solution
- the ability to adapt GP models to other situations (flexibility)
- the ability to easily solve linear GP models using the Simplex Algorithm, and
- the ability to use GP techniques in conjunction with other decision making tools to improve solution quality.

As with any process there are also disadvantages associated with goal programming. Several of these criticisms of GP are given in Hannan (1985). The first problem is associated with choosing the goal weights to be representative of the true decision maker's aspirations. In some cases this is easily done as with financial aspirations where the values are predetermined. However, there are many instances in which the value of a goal is not apparent and as an alternative for these situations, the concept of compromise programming was introduced. Another problem that can occur is with a monotonic GP value function. This can result in a dominated solution. This is a result of goals being set too low and there are alternative optimal solutions that are better than the GP solution obtained. This situation also lends itself to the compromise programming technique. If this does occur, there are methods to convert the solution to a nondominated or Paretian efficient form. Finally, the use of preemptive weights in GP will result in a less optimal solution than if the weights are assigned directly to the value functions.

3.1.3 Comparison

The techniques of both goal programming and compromise programming are effective tools for multi-objective decision making. The evaluation of the

literature has shown circumstances under which each process is effective in providing a solution. Some advantages and disadvantages of each method have also been identified through discussion of the literature studies.

Romero *et al.* (1998) identifies the connections between two of the well known multi-criteria decision making methodologies, GP and CP. The authors state that the differences between CP and GP are more philosophical than analytical. CP has an underlying optimizing philosophy while GP has a satisficing philosophy. Technically the differences between the two approaches are minimal. However, it has been shown through a review of the literature that there are instances and decision problems that are better suited for one method or the other due to the specific nature of the problem.

Those considering building CP models should be aware that the two most commonly used CP metrics (one and infinity) can be reduced to GP problems. The metric of one corresponds to a weighted goal programming solution and the infinity metric can be converted to a Minmax goal programming formulation. This ability to reduce the CP model is an important result for multi-criteria decision making software developers as there is only a need to develop software to solve GP problems since CP models can be reduced to a GP form. As well, the algorithm to solve GP problems is relatively easy as it involves the use of the linear programming simplex technique.

Based on the comparative analysis of the literature, the goal programming technique will be used to develop the multi-objective decision making model for power generation fuel choice. The main arguments for using GP for this application are:

- multiple targets are to be evaluated
- all relationships are linear
- desired targets may not be achievable

- simplicity of solution algorithm (simplex method), and
- ability to identify which goal constraints are not achieved and by what magnitude through observing positive deviation variable values (to analyze the value of environmental damage tradeoffs in power generation and to identify which areas require more research into efficiency and technological improvements).

3.2 Externalization of Power Generation Environmental Costs

Several Studies have been performed on various aspects of environmental externality costs associated with electricity production. These studies explore different methods of quantifying these external costs as well as the general analysis procedure. It is also important to consider any shortcomings of the current practice in order to recognize areas that warrant future work. To this end, a review of some criticism of power generation externality studies is given.

3.2.1 Methods of Environmental Externalization

The three main approaches used for valuing environmental effects are the:

- use of cost of control
- use of cost of mitigation, and
- use of damage functions.

Externalizing these damages with the cost of abating or controlling emissions is an approximation of the external environmental cost that is avoided through the use of controls. However, Stirling (1998) states that the extent to which the costs of abating pollution are borne by the polluter may suggest that they cannot represent an externality. Another problem with this method is that using the cost of removal as a representation of externalities implies that the damage that would be incurred by any residual emission remains

unaccounted for. The second method of using the cost of measures taken to mitigate the environmental damage also has inherent shortcomings. Stirling points out that the costs of mitigating only tend to address certain aspects of an impact where the burden to future economics warrants expenditure. As a result, the mitigation costs are only a partial reflection of the total cost of environmental damage.

The use of the damage function approach to empirically establish the social cost of the environmental damage itself is described step by step in Freeman (1996). The first step is to estimate the emissions and other environmental stresses specific to the technology and fuel type being studied. Next, estimate changes in the relevant measures of environmental quality as functions of the emissions. Then estimate the physical effects of the changes in environmental quality on the relevant receptors. After this, unit values from the literature are applied to convert the physical effects to monetary damages for each end point. Finally the damages are aggregated across all receptors and end points. This method of determining damage costs has the hypothetical prospect of yielding systematically comprehensive values according to Stirling (1998).

There are both direct and indirect methods of deriving damage costs. Stirling (1998) presents three direct methods. These are methods of establishing a monetary value for an environmental asset such as a national park where there are no obvious financial indicators. Reference to surrogate or hedonic markets and the use of contingent valuation are used to derive this value by establishing experimental markets through responses to questionnaires. An advantage of the contingent valuation technique is that it offers the means to capture otherwise intangible benefits such as those due to the mere existence of an environmental amenity. The indirect damage cost methodologies attempt to sum the substantive economic costs incurred by all the individual environmental effects. Some of these cost items may be expressed in terms of market prices for goods and services required in the

replacement, repair, restoration or restitution of damages. These costs can be evaluated by establishing dose-response relationships between the precursors and the resulting environmental harm. Other cost items must however be assigned values by the analyst, which may in fact involve the use of any of the direct methods discussed.

3.2.2 The Externalization Analysis

The purpose behind valuing the external costs of environmental effects of different power generation technologies is to level the playing field in order to rank the fuel choice alternatives. Without the external costs of environmental effects included, an option that has a low private (internal generation) cost but a high external cost would have an unfair advantage in least-cost planning. An important issue to consider with environmental externalities is the extent of implementation. For example the use of externality costs in the selection of new resources only and not in dispatch decisions would lead to a bias against new sources while older polluting sources would theoretically be kept in service longer and dispatched heavily. In order to have a significant impact and avoid bias, the use of externalities should be included in all decision stages not just for resource decisions (Freeman, 1996).

To analyze the overall impacts of power generation technology it is logical that the consideration of the full fuel cycle including upstream, generation and downstream effects is necessary. Freeman (1996) concludes that it is reasonable to exclude the upstream and downstream effects. This conclusion was based on the study results revealing that the upstream and downstream impacts were small relative to the direct damages and the generation costs of the technologies considered. Klein (1999) disputes the presumption that the full fuel cycle analysis is not warranted. Several reasons are presented as to the need for the full cycle analysis. With emissions caps and new trading mechanisms, it is his contention that at some point trading will have to account for upstream emissions and other

impacts. While the high combustion emissions from coal and oil sources render the upstream emissions less significant in an analysis, the emissions from natural gas facilities are much lower. Thus, the relative amounts of upstream greenhouse gas (GHG) and other health affecting emissions are a more important consideration in the full fuel cycle analysis of natural gas impacts. This significance is intensified, as methane is the GHG of most concern due to the rapid increase in the atmosphere and there are a significant amount of methane emissions associated with natural gas and coalbed methane production. This must be considered in the emissions quantification stage of externality valuation.

There is also some concern on the upstream impacts of future power generation with most new types of natural gas systems for cogeneration, district energy and gas turbines, fuel cells and hybrid systems that could feasibly become part of a sustainable energy solution. The growth of this sector must be balanced with consideration of the methane, NO_x and SO₂ impacts from fuel production and delivery. With H₂S and air toxics, the health impacts of these upstream effects will be very important to the public located near gas producing areas (Klein, 1999).

The analysis of both the level of environmental risk incurred as well as the probability of such events occurring is required to value the external costs of electricity production. An area of concern for externality methods is the low probability, high-risk (cost) event such as a nuclear failure. Krupnick and Burtraw (1996) show through the analysis of several power generation externality studies that the damages from nuclear technologies appeared low relative to other technologies evaluated. This difference was attributed to the basis of probability on engineering estimates of the accident risk and not the risk perceived by the public. Freeman (1996) encounters the same phenomena of low nuclear externality damages. The author identifies the expected value of the nuclear damages valued in the studies reviewed as an ex post damage measure. This means the damage estimation is also based

on engineer and nuclear technician estimates of failure probability. Freeman states that for low probability, high-risk events ex ante value measures such as the “willingness to pay” (WTP) or “willingness to accept compensation” (WAC) methods may be preferred. The WTP method evaluates a monetary amount that the public would be willing to pay in order to avoid the risk of a nuclear failure. In a similar manner, the WAC method represents the dollar value that the public would accept as compensation in the event that a nuclear failure occurred. These ex ante value measures can yield different results because the public’s perception of risk is often different than the probability estimates determined by engineers and risk assessors.

This area of risk is also explored by Aronsson *et al.* (1998). The study was initiated due to the large amount of uncertainty associated with nuclear power externalities as well as the potential for environmental catastrophe. The risks of nuclear failure were endogenized using a utility function approach combined with the probability of survival of an accident. Results of the model and study imply that the external effects from nuclear power are largely impacted by the self-interest of the energy producer who is not concerned with the level of social welfare. The authors use the results to design a dynamic Pigouvian tax that would be imposed on the energy producer to force a socially optimal allocation of power generation resources in a decentralized economy.

Although the state of the environment in terms of global warming and climate change is currently a large concern, the amount of work done concerning GHG and CO₂ externalities thus far is limited. Krupnick and Burtraw (1996) recognize that there is more work required estimating the damages from both GHG and CO₂ emissions. It is also suggested that the reason these environmental externalities have not been valued widely is due to the expectation that the damages from these impacts will be large and will dominate the damages from other power generation pathways. This concern of large damages should not be a reason to exclude the impacts of GHG and

CO₂ from the externality valuation process according to the conclusions of Klein (1999). The author states that for most energy sectors, the integration of reductions in air pollution with GHG emissions will usually show that when CO₂ is prevented all of the other health-based emissions will fall automatically. This suggests that the main focus should be on GHG and CO₂ valuation methods and that other environmental impacts associated with fossil fueled electricity production are closely related to these emissions and will also be affected.

Some authors recognize other concerns with current externality practices. Freeman (1996) outlines the importance of valuing the effects of power generation technologies on ecosystems instead of focusing solely on the impact to human life. It is suggested that this could be accomplished through the establishment of links between ecosystem functions and economically valuable ecosystem service flows. Krupnick and Burtraw (1996) identify the importance of including energy security damages in electricity externalities. This would discourage the choice of generation technology that does not have a secure fuel supply to support it. These authors also question the transferability of damage results from studies. The units used to express the damages such as \$/kWh and \$/ton of emissions are less likely to be transferable as there would be no method to include the characteristics of a new location in the damage value.

Finally, Freeman (1996) also recognizes the importance of differentiating between the various groups affected when valuing human health effects. For morbidity and mortality effects, the age groups as well as social groups most affected should be identified. For example, a person who works in a nuclear power plant is more at risk of radiation exposure than the general public. In addition children are at greater risk of impacts from pollutants that accumulate in soil, as they tend to ingest more soil during daily activities. Due to the differences, a more effective valuation would be obtained through focus on the specific group affected rather than the entire population.

3.2.3 Criticisms of Environmental Externalization

The purpose of valuing the external environmental costs of electricity and internalizing them into the price of electricity implies that the electricity markets will select the mix of technologies that best satisfies the economic and environmental criteria. This process of environmental valuation is warranted in lieu of the amount of power generation emissions. However, according to Stirling (1998) the technique suffers from many of the general methodological difficulties faced by other quantitative appraisal methods. Despite the different methods in practice for valuing environmental externalities of power generation, there are many difficulties held in common across all the approaches.

The first difficulty is encountered when there are entire classes of environmental effects that the analyst is ignorant of and are thus excluded from the analysis. Second, the resolution of the analysis may be constrained by the degree to which a quantitative indicator can capture the full character of an environmental effect. Any lack of coherence in classificatory systems and their indices compound the problem through errors of omission or commission. There could also be dispute over the fidelity with which a simple numeric indicator tracks what are often non-linear dose-response dynamics in complex environmental systems. Problems associated with the relative importance of different effects such as health damage, reduced biodiversity and aesthetic impacts may arise when attempting to aggregate these effects. Finally, there is the question of the completeness of the analysis with respect to the full range of issues identified in the wider debate that it seeks to address (Stirling, 1998).

Stirling proposes that the aspirations of environmental valuation are the most ambitious of all approaches to environmental appraisal, thus making the methodological difficulties more serious. Through evaluation the author concludes that there is little or no definition of system boundaries in the "first

generation" environmental valuation studies for electricity production. Without the system boundaries clearly identified, the results from one valuation study cannot be compared to others as it is unclear as to which stages of the fuel cycle have been included. As well, the valuation analysis may lead to the exclusion of certain stages from a specific generation technology for various reasoning. These omissions could be intentionally used to impose serious systematic bias in favour of a particular technology.

Two specific difficulties observed by Stirling (1998) in the first generation studies were the use of contingent valuation (CV) and discounting in the externality valuation procedure. The problems with CV are presented, as it has tended to be the most used technique. The technique is based simply on the respondents stated willingness hypothetically to pay or be compensated for an environmental damage. Without detailed questioning of respondents on the rationale underlying their stated views, the monetary values produced pose difficulties of interpretation. As well, respondents generally cite significantly lower values for what they would be willing to pay to secure an environmental benefit than for what they would be willing to accept as compensation for its loss. Overall, the author believes that CV is too sensitive to the socioeconomic and psychological circumstances of respondents and to the context of the studies themselves.

A prominent issue associated with the environmental valuation process is the practice of discounting the future. Stirling (1998) describes the procedure as diminishing the magnitude of an effect that will occur at some point in the future by an amount proportional to the time from the present. In principle this procedure could be applied to any numerical index. Mortality rates or pollutant burdens may be discounted as readily as monetary values. Although in practice, discounting of environmental effects has tended to be limited to a monetary index. Ultimately depending on the discount rate employed, discounting the damage costs of a future impact may make an option with very large externalities preferred to an option that has smaller but

more immediate effects. Although there is a need to measure the cost of a future impact in present terms in order to allocate resources, there can be difficulty associated with the use of a discount rate.

Although Stirling contests that the methods of environmental costing have associated methodological difficulties, Klein (1999) suggests that a simple approximation may be recommended in many cases. According to Klein, the major impediments to the use of full fuel cycle analysis in power generation decision making lie with complexities from the following factors:

- a lack of information on methodology and emission factors for relevant pollutants
- whether or not to average emissions across a regional or industrial sector to arrive at an appropriate approximation for long term planning
- the tradeoffs associated with impacts of air emissions versus other significant environmental impacts such as land and water use, visual and noise impacts, public safety and other social consequences of construction, and
- whether or not extensive computer modeling is required.

Simplicity can be important in evaluating choices when detailed specific information is unavailable. The use of estimates is better than the disregard of the relevant issues.

Klein concludes that, as there is variation in assumptions and detailed site-specific emissions data, a simple approximate approach is recommended in many cases. It would be unusual for a more detailed analysis with more precise data to cause a major shift in the comparison of choices. As well, simple conservative externality values on all emissions throughout the fuel cycle can help to gain understanding of the relevant economic and environmental tradeoffs, the relationship between various issues and the

implications of future international environmental economic initiatives such as the Kyoto agreement.

Despite criticisms presented on the methods for determining environmental externality costs as well as the usefulness of their results, the values are a useful tool for fuel mix decision making. Without the technique of transferring the damages incurred through the emissions from the different power generation technologies to a monetary estimate, it would be difficult to relate those effects to the amount of electricity produced using a specific technology. Through the valuation of the environmental effects, it is possible to reduce the environmental impacts through the minimization of the approximated external costs.

4.0 Methodology (Model Development)

The purpose of this multi-objective model was to optimize the fuel mix scenario employed to provide the necessary power for a demand situation similar to that of the province of Ontario. In order to optimize the sources of fuel contribution, several criteria and constraints were imposed. The model constraints include:

- electrical demand
- reliability of generation technology
- safety/risk (occupational and public)
- economic effects
- environmental externalities, and
- environmental limits.

The different criteria considered were:

- availability (and security of supply) of fuel, and
- social effects.

Some of the constraints included in the model were of higher importance. The relative importance of the various objectives was achieved through the assigned weightings in the goal programming method. These weightings were based on the financial costs of the environmental damages to society.

The contributions to generated power from six fuel sources were evaluated in the model and were identified as the main decision variables. These being:

- coal (x_1)
- natural gas (x_2)
- oil (x_3)
- nuclear (x_4)
- hydroelectric (x_5), and

- purchased power (x_6).

The linear model was solved as a minimization weighted goal programming problem using the revised simplex method. Setup of the model allows the fuel mix to be optimized for the twenty-year period from 2000 to 2020 in time steps of five years. Following the procedure for model development, the model equations can be altered for use with any power demand situation.

4.1 Major Assumptions

The overall system assumptions that apply to each component of the multi-objective model are included here. Other assumptions that are relevant to specific constraints will be presented and discussed in the formulation for that constraint.

4.1.1 Natural Resources Canada (NRCAN) Projections

Figure 4.1: NRCAN Demand Projections

It is assumed for the purpose of developing this model that the overall demand projections made in Natural Resources Canada (1999a) are

applicable to a power system similar to that of Ontario for the period of 2000 to 2020. The NRCAN trends in electrical demand and fuel requirements can be seen in Figures 4.1 and 4.2 respectively.

Figure 4.2: NRCAN Projected Fuel Requirements

The projections made by NRCAN are “policy as usual” estimations. This means that all federal and provincial energy, environmental and related policies are held constant over the projection period and no new policies are introduced. As a result of this simplification, Canada’s Kyoto commitment of six percent below 1990 CO₂ emissions levels by the 2008 to 2010 period is not incorporated in these projections. The energy supply and demand projections outlined in the report are influenced by external factors such as macroeconomic (industry and commercial demand) and demographic (residential demand) trends, international energy prices and the characterization of current policy.

Energy efficiency and process improvements are considered in the determination of the projections. However, NRCAN has scaled down its

estimates of these improvements from what was previously believed achievable based on reports from the Canadian Association of Petroleum Producers (CAPP) and several large companies in the industry. As well, the supply of fossil fuels is expected to increase with increases in oil sands and East coast (Hibernia) oil production combined with higher natural gas supplies with pipeline expansions. Another important assumption included in the NRCAN projections is that the Bruce A nuclear generating units (rated at about 800 MW each) currently shut down, may not be returned to service (Natural Resources Canada, 1999a).

One area of concern with this assumption of applicability is the price of oil used for the NRCAN projections. Despite the current high price of oil, recent projections from national and international organizations call for oil prices to average \$US 18.35 per barrel in 2010 to \$US 23 per barrel in 2020. NRCAN assumed the price of oil to be constant over the projection period at \$US 20.60 per barrel (Natural Resources Canada, 1999a). Although this price does not support high trends in oil prices, it is assumed to be reasonable for the twenty-year modeling period. If high oil prices persist in future years, the projected values used in the model can be adjusted to reflect this.

4.1.2 Fuel Characteristic Assumptions

The assumed emission rates and facility characteristics used to calculate the environmental externality costs from major air pollutants are discussed in section 4.2.7.1.1 Dispersion Modeling. The amount of ash and sulfur in the fuels contributing to the fossil generation emissions are important considerations. These components are directly related to the amount of ash and sulfur dioxide emissions that result during combustion and are crucial aspects when comparing impacts from other stations that may use fuel with different ash and sulfur contents. The assumed fuel characteristics are shown in Table 4.1.

Table 4.1: Fuel Characteristics

Fuel	Heat Content (Btu/lb)	Ash Content (weight %)	Sulfur Content (weight %)
Coal	13 100	9.1	2.1
Oil	19 000	0.02	1.0
Natural Gas	21 824	0	0

The above values were obtained from the New York State Electricity Externality Study (NYSEE) by Rowe *et al.* (1995a).

4.2 Constraint Consideration and Formulation

To optimize the fuel alternatives the predetermined constraints were quantified for use in the mathematical model. The constraints considered as well as the methodologies used to calculate the impact from each specific power generation source are presented and described in detail here.

4.2.1 Demand

To ensure that the fuel mix meets the required electricity demand for the system, a constraint on the minimum required supply is included. This constraint simply states that the sum of the six fuel sources must meet the projected total demand for the model year. The demand constraint is thus of the form:

$$x_1 + x_2 + x_3 + x_4 + x_5 + x_6 = TotalDemand \quad (4.1)$$

where, x_1 = coal power contribution (GWh)

x_2 = natural gas power contribution (GWh)

x_3 = oil power contribution (GWh)

x_4 = nuclear power contribution (GWh)

x_5 = hydro power contribution (GWh)

x_6 = purchased power contribution (GWh)

The total demand used for the right hand side of the constraint is obtained from NRCAN projections (Natural Resources Canada, 1999a).

4.2.2 Reliability

Electricity supply is considered reliable if customers continuously receive the amount of power they require without interruptions (blackouts) or drops in voltage (brownouts). However, a generating system would not be available 100 percent of the time as a result of both scheduled downtimes for tests and maintenance as well as unscheduled downtime as a result of accidents and other non-routine causes. Based on the past yearly performance of each generating station, an annual capacity factor (CF) is calculated:

$$\%Capacity = \frac{EnergyProduced}{PlantCapacity * Timeperiod} * 100 \quad (4.2)$$

(Ontario Hydro, 1989).

The CF is used to measure the reliability of the power plant and represents the amount of time (over a year period) that the plant was fully operational and producing electricity. As the reliability of the power source is an important consideration in determining a fuel mix to supply power needs, CFs are used in the development of the demand constraint.

In order to group the CF from each plant into the categories used for the decision variables, the arithmetic averages of the factors were used (see Appendix B). It was assumed that the reliability of purchased power is in fact 100% as anything less would be a failure to supply a purchased commodity. Inclusion of these factors forced the model to favour the more reliable sources in an attempt to meet the required demand. The constraint equation to be satisfied is:

$$1.28x_1 + 1.15x_2 + 1.11x_3 + 1.26x_4 + 1.96x_5 + x_6 \leq TotalCapacity \quad (4.3)$$

where, x_1 = coal power contribution (GWh)

x_2 = natural gas power contribution (GWh)

x_3 = oil power contribution (GWh)

x_4 = nuclear power contribution (GWh)

x_5 = hydro power contribution (GWh)

x_6 = purchased power contribution (GWh).

For modeling purposes it was assumed that the capacity factors used for the different types of power generation would remain constant over the twenty-year modeling period. If there are improvements to the technologies that render the fuel source more reliable in the future, these factors can be easily adjusted. Purchased power is not included in the remainder of constraints as there is limited reliable data available on the fuel type sources of the purchased power for use in the calculation procedures.

4.2.3 Availability and Security of Supply

Another important constraint on the choice of fuel is the availability. If the supply of a certain fuel is rapidly depleting then it is not an effective option for the long-term supply of power. Availability of resources is a major concern for fossil fuel generation and is not applicable (at this time) to the other three decision variables for fuel choice. The National Energy Board (1999) has done extensive research into the reserves and remaining supplies of natural gas, natural gas liquids, coal and crude oil (and equivalent). In the report, the worst case demand for the year 2025 (using assumptions similar to those of the NRCAN projections) is:

- natural gas – 6030 PJ
- natural gas liquids – 572 PJ
- coal – 1294 PJ, and
- oil – 5058 PJ.

Availability of these fossil fuels during the twenty-year model period (to 2020) is not a constraining factor. According to National Energy Board (1999), the

total reserve of natural gas (not including undiscovered resources) was 207 900 PJ in 1997. Propane, ethane and butane demands are shown not to exceed the supply available before 2020. The supply of oil remaining in 1997 was 32 278 PJ heavy crude, 5000 PJ light crude and $4.9 \times 10^{10} \text{ m}^3$ of oil sands. The analysis also shows that in 2025, the demand for light crude will be 263 000 m^3/d with an anticipated worst-case supply of 351 000 m^3/d and for heavy crude will be 63 000 m^3/d with a supply of 123 000 m^3/d . The established coal reserves of 7298 Mt in 1985 will not be exhausted during the modeling period (coal demand in 1997 was 56 Mt).

Although the physical supply of energy resources is believed to be sufficient, the security of these supplies is an important consideration. In terms of energy security the resource in question is oil. There is an abundant supply of oil for a projected period into the future but the geographical distribution of the sources is highly uneven and there is a potential for supply instability (Matsui, 1998). The Persian Gulf region contains 65 percent of the proven crude oil reserves and in 1997 supplied more than 39 percent of the oil required by industrialized nations (Salameh, 2000). There is a projected rise in the dependence on Persian Gulf oil exports. In 2010, the remainder of Oil Producing and Exporting Countries (OPEC) will constitute a smaller share of world oil production than in the early 1970's. At that time, the small share in oil production resulted in an oil crisis with the Arab-Israeli "October War" in 1973, which triggered the imposition of the Arab Oil Embargo. This rise in dependence again reinforces the importance of security in the Gulf region focused on limiting the vulnerability to disruption in the Middle East (Martin *et al.*, 1996). Thus the economic and political stability in the Persian Gulf region is crucial to maintain energy security.

Based on the fossil fuel resources still available in Canada, the availability and security of supply of these fuels is not a consideration for mix optimization. Should these reserves become threatened in the future, an availability and security constraint must be added to the model.

4.2.4 Safety/Risk Implications

The evaluation of risk to both the public and the worker from an energy source is an important inclusion in the fuel mix decision-making process. The risk is defined here as the collective chance or probability of accidents and disease resulting in injury or death. This risk should be considered for the full energy cycle and not just the final stage (generation). Risk estimates can be affected in the future by:

- stricter pollution standards (lower risk)
- discovery of new risk from old pollutants (higher risk)
- technological advance requiring new material with higher risk
- extraction of leaner ores for metal production (higher risk) and
- less productive fields for fuels (higher risk/unit product)

(Inhaber, 1982).

As updated risk factors for nuclear power production could not be located, it was assumed that the risk probabilities provided for nuclear generation are applicable to current practice although they may underestimate the actual risk. It was also assumed that the risk probabilities are constant throughout the twenty-year model. If this is not the case in future years, the probability and risk calculations can be adjusted accordingly.

To analyze the risk, the individual risk of accidents, disease and death incurred in producing a unit of energy are added together. The components of risk in energy production as outlined by Inhaber (1982) are material and fuel production, component fabrication, plant construction, operation and maintenance, public health, transportation and waste disposition. Even though some energy technologies do not use fuel in the traditional sense, each requires raw materials and every type of raw material production generates risk.

The ranges of both public and occupational risk values associated with each type of generation per MW-year electrical output are given in Appendix B, Tables B1-B5 (Inhaber, 1982). These ranges were then multiplied by the demand projected by NRCAN (converted to MW-year outputs) for each year considered in the model (2000, 2005, 2010, 2015 and 2020). Finally, the overall death risk factors were quantified to monetary values using the average value of a statistical life from Krupnick and Burtraw (1996) of \$3.4 million (Appendix B, Tables B6-B26). The occupational and public risks of death were used because the number of deaths could easily be converted to a monetary value and death was considered a more severe consequence than injury. The upper bounds of the ranges for the costs of public and occupational risk were used as worst-case scenario estimations.

The monetary valued costs of the death risks were then converted to a cost/GWh for each specific production technology to determine coefficient values for use in the model. This was achieved through the use of the 2000 demand projections by NRCAN for each generation source. It was assumed that the damage from a particular source per GWh is a constant and would not change in future model years. The cost/GWh does increase with time due to other factors such as the time value of money and population growth. The values associated with the risk of death from both accident and disease were added together and divided by the demand projection for the appropriate source (Appendix B). To calculate the upper bounds of the safety constraints, it was assumed that the year 2000 fuel mix projected by NRCAN is correct and the calculated occupational and public costs of risk for the year 2000 were summed. To project the maximum costs of risk to the future model years for the upper bound of the safety constraints, it was assumed that the overall risk of providing electricity would increase proportionally with the increase in the demand for the electricity itself (Appendix B). This assumption is reasonable as the risk can be expressed per unit energy and thus if more energy is produced, the risk will increase accordingly. However, in future modeling efforts the upper bound of this risk

constraint could be altered to impose either a lower or higher limit (i.e. twenty percent decrease) on the acceptable risk from electricity.

Based on these calculations, the safety constraint equation is as follows:

$$ax_1 + bx_2 + cx_3 + dx_4 + ex_5 \leq \$Max.Risk \quad (4.4)$$

where,

- a = the risk per unit of coal power (\$/GWh)
- b = the risk per unit of natural gas power (\$/GWh)
- c = the risk per unit of oil power (\$/GWh)
- d = the risk per unit of nuclear power (\$/GWh)
- e = the risk per unit of hydro power (\$/GWh), and
- \$Max. Risk = Total annual risk from all sources (\$).

4.2.5 Social Effects

Two main aspects of concern when considering the social effects of fuel mix choices are employment effects and fiscal effects. Although there is limited information on these effects from power generation and thus they cannot be quantified, these social effects may be mentioned. Drastic or unexplained changes in employment from the conventional rate can be considered as damage. The estimation of these damage values is being developed but there is still a lot of uncertainty. However, the initial estimates seem to suggest that the damages could be significant, making it an important consideration for future inclusion in the model.

In terms of fiscal effects, the differences in tax payments embedded in choices among fuel cycles to generate power can be viewed as externalities in the consideration of social cost of electricity power production. These differences in tax payments have the potential to create financial advantages and disadvantages with the different fuel cycle options. Further research in these areas would deliver valuable information about the social costs of electricity (Krupnick and Burtraw, 1996).

4.2.6 Economic Effects

To obtain a cost value per unit of energy produced for each fuel type, three different contributors to the overall cost are considered. These are:

- operation, maintenance and administration
- fuel used for generation (water for hydro), and
- depreciation.

The first two aspects of cost will have a continuous impact on the overall cost. Depreciation however, should decrease over time if no new capital is invested. Accordingly, the only source that is largely affected by depreciation is nuclear power due to the amount of capital still being invested into nuclear stations (Pickering and Bruce) (Ontario Hydro, 1999a). To simplify the economic calculations, it is assumed for nuclear that depreciation has an effect on the overall cost but there is not enough information to include that effect in these calculations. Also, it is assumed for the other sources that the payments on capital are included in the operation and maintenance costs.

Past data on the costs of nuclear, fossil and hydraulic power was obtained from Ontario Hydro (1999a) (Appendix B). The published data was available for the years 1994 to 1998 and is broken down into the three areas of overall cost previously outlined in this section. In order to estimate the cost of each power source in the future, the data was evaluated for possible trends. The data plots can be seen in Figures 4.3 to 4.5.

The operation and maintenance trends calculated from the plots are as follows (see Appendix B for calculations):

Nuclear:
$$y = 0.1665x + 0.965 \quad (4.5)$$

where: y = annual cost of nuclear power generation (cents/kWh) and
 x = desired year for cost calculation (1994 = year 0)

Hydroelectric: $y = 0.013x^2 - 0.035x + 0.3252$ (4.6)

where: y = annual cost of hydroelectric power generation (cents/kWh) and
 x = desired year for cost calculation (1994 = year 0)

Fossil: $y = 0.023x^2 - 0.201x + 1.338$ (4.7)

where: y = annual cost of fossil fueled power generation (cents/kWh) and
 x = desired year for cost calculation (1994 = year 0).

The same method is employed to calculate the trend in fuel costs for nuclear and hydroelectric power generation. The equations used to represent these trends are:

Nuclear: $y = 0.0276x^2 - 0.0795x + 0.2973$ (4.8)

where: y = annual cost of nuclear power generation (cents/kWh) and
 x = desired year for cost calculation (1994 = year 0)

Hydroelectric: $y = 0.0074x^2 - 0.014x + 0.3403$ (4.9)

where: y = annual cost of hydroelectric power generation (cents/kWh) and
 x = desired year for cost calculation (1994 = year 0).

Instead of using the trend line for fossil fuel costs, the projected oil prices to the year 2020 (Natural Resources Canada, 1999a) are combined with the prices for coal and natural gas. The coal and gas prices are obtained from (NEB, 1999) for the year 2000 and are assumed to remain constant over the modeling period as there are abundant reserves. This method was chosen over the trend method in order to reflect the projected rise in oil prices. To make the economic effects of each fuel source compatible for use in the model, the units of cents/kWh are converted to dollars/GWh (Appendix B).

Figure 4.3: Nuclear Cost Data (1994-1998)

Figure 4.4: Hydroelectric Cost Data (1994-1998)

Figure 4.5: Fossil Cost Data (1994-1998)

The projections of total fuel costs from NRCAN are used as the upper bound for the economic constraints. In order to obtain the overall total cost in dollars for the right hand side of the constraint equation, the cost in dollars/GJ from NRCAN (1999a) are converted to dollars/GWh and multiplied by the overall demand for the specific model year (Appendix B). Thus, the economic constraint for the model is of the form:

$$ax_1 + bx_2 + cx_3 + dx_4 + ex_5 \leq \$Generation \quad (4.10)$$

where,

a = the cost per unit of coal power (\$/GWh)

b = the cost per unit of natural gas power (\$/GWh)

c = the cost per unit of oil power (\$/GWh)

d = the cost per unit of nuclear power (\$/GWh)

e = the cost per unit of hydro power (\$/GWh) and

\$Generation = total annual cost of power (\$).

4.2.7 Environmental Externalities

The concept of environmental externalities involves the calculation of damages based on the concentration of pollutant that a population is exposed to. In order to determine this overall effect for power generation, the concentration of the pollutant caused by the power generation facility is calculated and is then added to the baseline environmental conditions for the area. This gives the total concentration of the pollutant that will impact living creatures and their surrounding environment. Consideration of these baseline conditions is most important for air emissions as some regions may have high background concentrations of certain air pollutants making the added impacts from power generation of greater concern (Rowe *et al.*, 1995a). For the purposes of model development based on a situation similar to that of Ontario, baseline atmospheric conditions for the province of Ontario were used (NAPS Network, 1998). To adapt the model for a different scenario, the baseline data must be altered for the new situation.

Where damage functions are available, the potential externalities are developed for the full fuel cycles of the alternatives considered. This includes fuel acquisition, power generation and waste disposal. There are currently no developed damage functions for the fuel acquisition stage of the fossil fuel cycle and thus this stage is not included in the analysis. The damage function method is employed to quantify the environmental damages incurred by electricity generation that are not internalized in the pricing of the electricity. The damage function approach is essentially a five-step process. The first step is to identify the emissions and resource usage of a specific source. The second step involves determining the dispersal of emissions and the changes to environmental quality as a result of the pollution source. The third step identifies the populations (people, flora, fauna and materials) exposed to the source and the resultant environmental and social impacts. The fourth step determines the exposed population's

responses to the pollutant as changes in well being or damages and is measured by willingness to pay (WTP). The final step determines the cost (damage) of the expected outcome and is aggregated across time.

It is the risk of damage, rather than the damage itself that is determined in valuing environmental damages. The value of the environmental risk is the value that the society is willing to pay to avoid that risk (Ottinger *et al.*, 1991). Some pollutants remain at toxic levels long after they are emitted. Ambient concentrations in soils and water may accumulate over time and result in latent exposure and impacts (a lag between the emissions and the health risk). This latent exposure is considered in this analysis for air toxics and some radioactive releases. The damages are discounted back to the period where the emission occurred to calculate the average annual damage (discount rates are used to calculate the present worth of future damages). There can also be a lag between exposure and the health impact as in the case of cancer damages. The general method used for these cases was to apply an average annual risk factor based on lifetime exposure to the exposure modeled in each year. This introduces a certain amount of bias to the damage estimates, as the annual risk may be higher or lower at times than the average (Rowe *et al.*, 1995a).

4.2.7.1 Air Externalities

The pollutants released from fossil-fuelled power plants that are of major concern are sulfur dioxide (SO₂), nitrogen oxides (NO_x), particulate matter (PM) and air toxics. These stations are designed for complete combustion to utilize the full energy content of the fuel. As a result, emissions of elemental carbon (soot), organic carbon and volatile organic carbons (VOCs) are minimal and are considered with PM and O₃ effects. Power generation emissions of global concern are carbon dioxide (CO₂) and other greenhouse gas emissions.

Stack emissions are removed from the atmosphere after a time period in days by precipitation and dry deposition processes. Before these emissions are deposited, they are transported, dispersed and chemically transformed to other species. SO_2 is oxidized into sulfuric acid and sulfate particulate matter, NO_x is oxidized to nitric acid and nitrate particulates and can be photochemically converted to ozone (O_3) and other toxic chemicals in the presence of VOCs and sunlight.

The primary and secondary air emissions from power generation can affect human health and welfare, crops, fisheries and various ecosystems both while in the atmosphere and after deposition (Rowe *et al.*, 1995a). Thus it is necessary for steps to be taken to reduce the impacts of these emissions through their externalization and inclusion in the minimization model.

While the direct damage functions for health effects from SO_2 , NO_x , VOC, or nitrogen oxide (NO) emissions have not been included due to lack of available data and supporting literature, the indirect impacts such as visibility and materials damage and O_3 effects are considered in this analysis.

4.2.7.1.1 *Dispersion Modeling*

In order to use established externalization procedures for the impacts of the various air emissions from power generation, the emission rates from the different stations were converted to concentrations. To estimate these concentrations the SCREEN3 model developed by the United States Environmental Protection Agency (U.S. EPA) was used. The SCREEN model was developed to provide an easy-to-use method of obtaining pollutant concentration estimates. SCREEN is able to perform single source short-term calculations, including estimating maximum ground-level concentrations and the distance to the maximum. The model can also incorporate the effects of simple elevated terrain or complex terrain.

The SCREEN model can provide estimated concentrations for distance less than one hundred meters and up to distances of fifty kilometers. The model results provide a “worst-case” estimation of the pollutant concentration as SCREEN examines a full range of meteorological conditions, including all stability classes and wind speeds to find the maximum impacts (U.S. EPA, 1995).

Further considerations in the dispersion modeling for the externality calculations involve merged parameters for multiple stacks and topographic considerations. Sources that emit the same pollutant from several stacks with similar parameters may be analyzed by treating all emissions as coming from a single representative stack. For each stack and pollutant the parameter M (which accounts for the relative influence of stack height, plume rise and emission rate on concentration) was computed:

$$M = \frac{h_s V T_s}{Q} \quad (4.11)$$

where, M = merged stack parameter

h_s = stack height (m)

$V = \frac{\pi}{4} d_s^2 v_s$ = stack gas volumetric flow rate (m^3/s)

d_s = inside stack diameter (m)

v_s = stack gas exit velocity (m/s)

T_s = stack gas exit temperature (K) and

Q = pollutant emission rate (g/s).

The stack that has the lowest value of M is used as a representative stack. Then the sum of the emissions from all the stacks considered is assumed to be emitted from the single representative stack (U.S. EPA, 1992).

Topographical maps of Ontario were also consulted in order to obtain the terrain specifications required for input to the SCREEN model (Natural

Resources Canada, 1999b). The elevation of the terrain surrounding the plant is important when considering the effect on the plume rise and dispersion of the pollutant, which will ultimately affect the concentration calculation.

It was assumed for the purpose of calculation of externality values for use in the model that the existing system will be modified in future years but that the emissions based on current capacity will be relatively constant over the modeling period. The merged stack parameter calculations for each pollutant and related assumptions (emission rates and facility characteristics) can be seen in Appendix B. SCREEN model verification is found in Appendix C. The model results of pollutant concentrations from SCREEN were converted to average annual concentrations and added to the background ambient concentrations to obtain the total pollutant concentration in the atmosphere for use in externality calculations. Some of these ambient concentrations were compared to the available Canadian ambient standards and air emission limits by province and maximum Canadian acceptable values to further assess their validity. The available standards are shown in Table 4.2.

Table 4.2: Canada and Ontario Air Emission Standards

Pollutant	Maximum Canadian Acceptable Values ($\mu\text{g}/\text{m}^3$)	Standards and Limits for Ontario($\mu\text{g}/\text{m}^3$)
NO _x	200 (24 hr avg. as NO ₂)	200 (24 hr avg. as NO ₂)
SO ₂	300 (24 hr avg.)	55 (annual avg.)
O ₃	50 (annual avg.)	N/A
PM	120 (24 hr avg.)	60 (annual avg.)

(Radian Canada Inc., 1995).

4.2.7.1.2 *Morbidity Effects*

The air emissions from power generation sources that cause the most concern for non-cancer, human health impacts are:

- particulate matter $<10\mu\text{m}$ (PM₁₀)
- ozone (O₃)
- lead, and
- mercury.

To study the effects that various substances have on human health, different types of study methods are used. These include epidemiological, clinical and laboratory studies. Epidemiological studies involve the study of a certain population in their everyday surroundings. Clinical studies involve the study of a selected target population and the effects of known pollutant levels. Finally, laboratory studies are conducted on test animals under controlled conditions. Epidemiological studies are the most relied upon for environmental valuation because they most readily lend themselves to quantifying (through dose-response relationships) the expected benefits to a given population for a decrease in ambient outdoor air pollutant levels. The primary advantage with an epidemiological study is that it directly observes the actual health effects on the population at ambient levels. However, the drawback with this type of study is that it is difficult to isolate the cause of the health effect when the population under investigation is exposed to various factors.

The study of these effects results in the formulation of dose-response relationships. These relationships predict the effects of exposure to certain levels of the pollutant. Most dose-response relationship functions are developed for moderate to high doses. Extrapolating the function below the dose range observed involves uncertainty as some literature on specific health effects reports the slope of the function becomes less steep at lower doses and may even have a zero slope below a “threshold” dose (below

which no adverse effects are observed). It was assumed for this analysis that there is a zero threshold for all pollutants considered obtaining a worst-case scenario.

The equation used to calculate the annual number of morbidity cases for both PM₁₀ and ozone is as follows:

$$Annual \Delta C = R * PoP * \Delta c \quad (4.12)$$

where, Annual ΔC = the annual number of morbidity cases
 R = the annual dose-response coefficient (effect/ $\mu\text{g}/\text{m}^3$ or ppm)
 PoP = the affected population, and
 Δc = the change in annual average concentration ($\mu\text{g}/\text{m}^3$ or ppm).

After calculating the number of annual cases each year as a result of the concentration of pollutant, the total annual economic value of the health effects is calculated using the high estimates of monetary values for non-cancer morbidity effects given in Rowe *et al.*, (1995a). The dollar values were then converted to current dollars using the consumer price index (Natural Resources Canada, 1999a). See Appendix B for calculations.

The possible health effects experienced from particulate matter are chronic respiratory disease, chronic bronchitis, respiratory hospital admissions, emergency room visits, asthma attacks, restricted activity days, acute respiratory symptoms and lower respiratory illness in children. The possible effects from ozone include respiratory hospital admissions, asthma attacks, minor restricted activity days, and acute respiratory symptom days (Rowe *et al.*, 1995a).

The damage valuation for lead and mercury is much more complex due to their ability to bioaccumulate and biomagnify in the environment. The methods for valuation will be discussed in section 4.2.7.1.4.

4.2.7.1.3 *Mortality Effects*

The procedure for calculating the number of annual deaths as a result of a certain emission is very similar to the calculation of morbidity cases. An equation very similar to equation 4.12 is used with an annual death risk factor instead of a dose-response coefficient:

$$AnnualDeaths = R * PoP * \Delta c \quad (4.13)$$

where, Annual Deaths = the annual number of deaths
 R = the annual death risk factor (effect/ $\mu\text{g}/\text{m}^3$ or ppm)
 PoP = the affected population, and
 Δc = the change in annual average concentration ($\mu\text{g}/\text{m}^3$ or ppm).

The number of annual deaths was transferred to a monetary value using the high estimate of selected values for mortality as a result of all causes affecting all age groups. This estimate in 1992 dollars was \$6.6 million. The dollar value was then converted to current dollar value using the consumer price index (CPI) (Natural Resources Canada, 1999a). See Appendix B for calculations.

4.2.7.1.4 *Lead and Mercury Effects*

The general approach for quantifying the effects of lead and mercury emissions is similar. The first step is to estimate the emission rates and changes to ambient air concentrations. The next step is to calculate the change in annual blood lead levels (PbB) or the change in total uptake of mercury in humans through air inhalation and fish ingestion. Finally, the effects on human health as a result of these changes are evaluated and quantified based on the affected populations.

Lead uptake can occur through four pathways, ambient air, soil/house dust, dietary lead and drinking water. Damages due to lead emissions are a significant concern as they may persist for years after the closure of a facility

(currently believed to be 80 years). The U.S. EPA has developed a model to calculate the uptake of lead for children but currently there is no such model for adult uptake. As there is limited information and research available for adult health effects, this study concentrates on the effects to infants and children who are more susceptible due to their increased ingestion of soil. The possible effects to children include asymptomatic children, IQ decrements (central nervous system and behaviour), increased probability of mental retardation and possible learning difficulties due to impaired intelligence levels (Rowe *et al.*, 1995a).

To quantify the health damages due to lead emissions, the annual change in blood lead levels were calculated using the following equation:

$$\Delta GM_t = (0.22 + 0.014 * (t - 1)) * \left(\frac{\Delta C_{air}}{0.0047} \right) \quad (4.14)$$

for $t = 1, 2, \dots, 30$.

Where, ΔGM_t = the increment in the geometric mean of PbB distribution in period t ($\mu\text{g/dl}$)

ΔC_{air} = average annual change in ambient air lead concentrations while the facility is operating ($\mu\text{g/m}^3$).

A baseline blood-lead distribution for children is assumed to be $4.65 \mu\text{g/dl}$ which is the high estimate given by Rowe *et al.* (1995a). The health damages from power generation emissions of lead were quantified using the blood lead levels and the high dollar estimate of child damages of \$49.72 (1992) per $\mu\text{g/dl}$ per person. This is converted to current dollars using the CPI (Natural Resources Canada, 1999a) (Appendix B).

The major exposure pathways for mercury uptake are through fish ingestion, sediments and ambient air. Ingestion is the route for exposure to methyl mercury and elemental mercury is usually inhaled. Uptake at elevated levels can cause adult paraesthesia, psychomotor retardation in prenatally exposed

infants and neuro-response effects in young children. The valuation of damages for mercury is extremely complicated and requires an extensive amount of site specific information and data. In order to include mercury considerations in the model, the high estimate of damages per pound of mercury emitted by power plants based on dose-response relationships and annualized over 30 years (plant life) calculated by Rowe *et al.* (1995a) were used (Appendix B for calculations).

4.2.7.1.5 *Cancer Effects*

A distinct method is required to quantify and value cancer risks from releases of air toxics other than lead and mercury. The method is based on six steps. These are:

- Identification and quantification of the air toxic emission
- Calculation of dispersion and deposition
- Quantification of the human uptake of the carcinogen
- Application of the dose-response information to predict increased cancer risk
- Application of the increased risk to the exposed population, and
- Valuation of the increased risk.

There are several uptake pathways to consider for toxic air emissions from power generation. These routes of exposure include, air inhalation, soil ingestion, beef and dairy ingestion, fish ingestion and produce (plant) ingestion.

A risk factor is used to estimate the cancer risk from these emissions. This represents the increase in lifetime cancer risk that occurs to an individual exposed continuously from birth to death, to a one-unit increase in the air or water concentration of the pollutant. Inhalation risk factors were estimated from data on exposure to high doses. As there are not an abundance of

pathway and species specific risk factors available, ingestion risk factors were assumed to equal the inhalation factors.

The increased risk of cancer from air toxic emissions is calculated as the sum of risk from inhalation plus the risk from ingestion times the assumed constant risk factor:

$$\Delta RISK_i = \left(\Delta C_i * \frac{R_{Fi}}{70} \right) * (1 + R_i * D_i) \quad (4.15)$$

where, $\Delta RISK_i$ = total inhalation plus ingestion risk for chemical i
 ΔC_i = change in concentration of chemical i ($\mu\text{g}/\text{m}^3$)
 R_{Fi} = cancer risk factor for inhalation of chemical i ($\mu\text{g}/\text{m}^3$)
 R_i = total ingestion/inhalation ratio for chemical i, and
 D_i = 0 for metals (central and low estimates), 1 for metals (high estimate).

The estimates of cancer incidence for the different air toxic emissions is then calculated using:

$$\Delta CANCE R_i = PoP * \Delta RISK_i \quad (4.16)$$

where, $\Delta CANCE R_i$ = change in incidence of cancer from chemical i
 $\Delta RISK_i$ = total inhalation plus ingestion risk for chemical i, and
 PoP = population exposed to chemical i.

The incidence of cancer cases is valued using the central estimate of the average dollar value for fatal cancer cases from Rowe *et al.*, (1995a). This value is \$3.3 million (1995). Finally, the economic valuation of cancer risk is converted to current dollars using the CPI (Natural Resources Canada, 1999a) (Appendix B).

The toxic air emissions considered in this analysis were arsenic, chromium (VI), nickel and formaldehyde. With the exception of formaldehyde (which is

a Group B1 carcinogen – suspected human carcinogen), these emissions are Group A carcinogens. These are of greatest importance for minimizing the effects through fuel choices as there has been enough human evidence presented to label the chemicals as known human carcinogens.

4.2.7.1.6 Visibility Effects

Visibility impairment from power plants is found using the short and long-range ambient concentrations of directly emitted particulate matter (PM), nitrogen dioxide (NO₂) and secondary particles (sulfates and nitrates). VOCs also contribute but their emissions are not significant from electricity sources. The total light extinction coefficient, b_{ext} is the sum of the contributions from clean-air (Rayleigh) scattering and from the light extinction caused by various particulate and gaseous components:

$$b_{ext} = \frac{\left(b_{Ray} + \sum_i \beta_i C_i \right)}{1000} \quad (4.17)$$

where, b_{ext} = total light extinction coefficient (Mm⁻¹)
 b_{Ray} = Rayleigh light scattering coefficient (11.6 Mm⁻¹)
 β_i = light extinction efficiency for species i (m²/g)
 (11 for sulfates and nitrates, 0.13 for NO₂ and 1 for PM_{2.5})
 C_i = atmospheric concentration for species i (μg/m³), and
 1000 = factor used to convert Mm⁻¹ to Km⁻¹.

The visual range V_r (common visibility) is the furthest distance at which a large black object is visible through the haze and is found using:

$$V_r = \frac{3.912}{b_{ext}} \quad (4.18)$$

where, b_{ext} = total light extinction coefficient (Mm⁻¹).

The contingent valuation method (CVM) is used to quantify the effects of visibility conditions. This method involves the use of surveys to ask respondents how much they would be willing to pay for specified changes in visibility conditions. This method is used for visibility because there is a lack of direct market prices for goods and services. As a result the estimates obtained using this method may be high as a survey is a hypothetical exercise and individuals are not actually parting with the money. The following equation is used to find the total annual WTP for visibility changes:

$$WTP_i = b * \ln \left(\frac{VR2_i}{VR1_i} \right) * HH_i \quad (4.19)$$

where, WTP_i = total annual WTP for visibility changes in area i for residents of area i (\$1992)
 $VR1_i$ = starting annual average visual range (Mm)
 $VR2_i$ = annual average visual range after the change in emissions (Mm)
 b = estimated coefficient, and
 HH_i = households in the affected area i.

As the model situation is for a power system similar to that of Ontario, the population data for Ontario from NRCAN (1999a) is used to determine the number of households, assuming there are 2.63 persons per household. The high residential use value estimate is used for the b-coefficient (Rowe *et al.*, 1995a). The CPI is employed here as well to convert to present dollar value and the calculations are found in Appendix B.

4.2.7.1.7 *Materials Damage Effects*

Damage to materials can occur due to emissions of particulate matter (<10 μ m) and sulfur dioxide. This damage is recognized as a source of economic loss. The damage that can occur includes:

- soiling of exposed surfaces

- surface erosion
- blistering and discolouration of paint
- corrosion and tarnishing of structural metals and electrical components
- fading, soiling and reduction of fabric tensile strength, and
- soiling and spalling of stone buildings and monuments.

The valuation process involves quantifying the monetary value that individuals place on preventing such damage.

For the materials impacts of both PM₁₀ and SO₂, the high estimates of annual damage dollar values per unit increase in concentration per household (\$1992) are used. These values are \$7.00/μg/m³/HH and \$2.80/μg/m³/HH for PM₁₀ and SO₂ respectively (Rowe *et al.*, 1995a). The size of each household is assumed to be 2.63 persons and the damage values are converted to current dollar values using the CPI (Appendix B).

4.2.7.1.8 *Other Air Effects*

Other impacts worth considering that occur due to power plant air emissions include the effects of greenhouse gas emissions and radiation emissions from coal piles. There is insufficient literature to develop a damage function for global climate change impacts from greenhouse gas emissions. It has been suggested that valuing gas emissions through mitigation costs can provide damage estimations. Mitigation options that could be used are tree planting to fix carbon, energy conservation and fuel switching. This method would be an approximation, as it is not known how the actual damages of greenhouse gas emissions relate to the mitigation costs. To obtain an estimate of externalities for greenhouse gases for use in the fuel source selection model established values from Rowe *et al.* (1995a) were considered. The value of \$1.4/Short Ton of CO₂ (in \$1992) obtained from the DICE model was chosen as the literature stated it was based on a damage function approach. The two greenhouse gases that were

considered in the analysis were carbon dioxide (CO₂) and nitrous oxide (N₂O). To relate N₂O to the externality value in terms of CO₂, the global warming potential index was used. This index states that the global warming potential of N₂O is 270 times that of CO₂. Thus, the damage value for N₂O is \$378/Short Ton of N₂O (Rowe *et al.*, 1995a).

Coal contains trace amounts of uranium, thorium and their daughter products. As a result there is potential radiation exposure to workers and public from coal fly ash piles. Rowe *et al.* (1995a) developed base externality costs for radiation releases from coal for a 1000 MW plant. These factors can be linearly scaled for use as a basis for all coal plants. See Appendix B for calculations.

4.2.7.2 Water Externalities

The optimization model considers three major impacts on water bodies surrounding power plants for externalization and valuation. These impacts affect both the fish stocks and the human populations using the water either for recreation or as a source of drinking water.

4.2.7.2.1 Impingement and Entrainment

Thermal power plants require water for cooling purposes. This cooling can be achieved using two different technologies, once through or closed cycle cooling. Once through cooling systems draw large amounts of water through the plant in a continuous flow and discharge heated water. The withdrawal of large volumes of water from a water body can kill fish, larvae and other aquatic organisms impinged on intake structures and entrained in the flow through the plant. The major fish populations affected by impingement are juvenile fish, less than three years old and for entrainment mostly larvae and smaller organisms are affected. If the mortality rates of the fish are large enough there will also be impacts to commercial and recreational fishing. The impacts of the once through cooling system vary depending on the

amount of water withdrawn (nuclear plants withdraw the most), the aquatic ecosystem, the intake and discharge designs as well as any mitigation measures.

Closed cycle cooling systems discharge heat through evaporative processes in cooling towers and recycle the water within the plant. This results in a small amount of water withdrawal. Without large amounts of water being withdrawn, the damages from impingement and entrainment of organisms are very low (Rowe *et al.*, 1995a). For modeling purposes, it was assumed that all power sources considered use once through cooling systems. If the model were to be adapted to a specific power system that does not use once through systems exclusively, the resulting damages from a closed cycle system would be set to zero.

A case study was performed on the lower Hudson River to obtain estimates of total damages due to impingement and entrainment. These damages based on the Hudson River ecosystem may provide upper bound estimates for fish mortality resulting in impacts to fisheries. Rowe *et al.* (1995a) give an equation to convert the estimated damages per unit flow from the case study to other plants:

$$D = \frac{D}{cfs} * cfs * \left(\frac{CF}{0.80} \right)^{10} \quad (4.20)$$

where, D = total annual damages to commercial and recreational fishing for a specific plant (\$1992)
 D/cfs = damages per flow from Hudson River case study (\$1992/cfs)
 cfs = design flow of desired station (cfs) and
 CF = capacity factor of desired station

The high estimate of annual damages per flow for once through cooling plants was used in the calculations to obtain the worst-case scenario (Rowe *et al.*, 1995a). The total annual damages were then converted to current dollars using the CPI (Appendix B).

Although the impacts from impingement and entrainment are of significant importance, there is a great deal of uncertainty associated with the extent of the impact and thus its valuation. If mitigation to prevent the problem continues, these damage estimates may overstate future damages. Also, it is feasible that the population will naturally reach a sustainable level that offsets the mortality created by impingement and entrainment and there would be no damages to the fisheries. The analysis does however exclude any non-fishing impacts and damages which may cause a lower than actual damage estimate (Rowe *et al.*, 1995a).

4.2.7.2.2 Thermal Discharge

The once through cooling systems previously evaluated also draw large amounts of water through heat exchangers and discharge this heated water into the surface water. In warmer months, thermal discharge may reduce oxygen levels and have other impacts that cause stress on aquatic life. In the cooler months, fish are attracted to warmer waters in the mixing zone. If this is close to the discharge point, the fish may be attracted to higher pollutant levels. As well, the attraction to warmer waters can cause fishing "hot spots" where catch rates are higher, depleting the fish stock. The thermal impacts can reduce the bioproductivity of the fish populations. The amount of thermal discharge is dependent on the plant capacity and technology (nuclear plants discharge the most heated water).

To obtain an externalized value for the impact of thermal discharge, the economic loss due to the effect on angler days was evaluated. The total annual damages per unit flow can be calculated using:

$$\frac{D}{cfs} = \frac{TAD_j * \left(\frac{A_{MZ}}{A_{WB}} \right) * DAD_j}{Flow_j} \quad (4.21)$$

where, D/cfs = total annual damages at site j per unit flow (\$1992/cfs)

TAD_j = total annual recreation angler days in water body j

A_{MZ} = affected area in the mixing zone

A_{WB} = total area of water body

DAD_j = damage per affected angler-day at site j , and

$Flow_j$ = design flow of discharge at site j

The weighted average of the estimates for mixing zone damages from once through cooling systems was used to quantify the effects of thermal discharge (Rowe *et al.*, 1995a) (Appendix B).

4.2.7.2.3 Chemical and Metal Discharge

The discharge of chemicals and metals to surface waters can cause serious impacts to human health. The three primary sources of this surface water contamination are:

- runoff from fuel and material storage piles
- direct discharges from sumps, boiler blowdowns and contaminant runoff, and
- aerially transported emissions.

The four major pathways of concern for these emissions are ingestion of contaminated drinking water, ingestion of surface water during recreation, fish ingestion and dermal exposure (not a concern for metals). The toxicity values used are from the EPA Integrated Risk Information System (IRIS) and EPA Health Effects Assessment Summary Tables (HEAST).

The chemicals emitted to the surface waters depend on the source of the emission. Coal ash pile emissions consist of heavy metals while fuel oil plants emit benzene, toluene, ethylbenzene and xylene (BTEX) compounds and other sources are responsible for chlorine and fluorides. The compounds considered in the valuation are arsenic, benzene, chromium (VI), copper, ethylbenzene, nickel, toluene and xylene. Risks due to aluminum, chlorine, fluorides, iron and zinc are not assessed due to a lack of toxicity

information. The chemical intake is calculated separately for each pathway due to the specific nature of uptake. The dermal contact and fish ingestion pathways are not considered here, as the permeability constants for dermal contact and the bioconcentration factors for the chemicals in the fish were not available. Thus the two remaining pathways of interest are ingestion of surface water and drinking water.

The equation used to calculate the intake of the chemicals of concern was of the form:

$$Intake_{JP} = \frac{[CC_{JP} * IR_{JP} * ET_{JP} * EF_{JP} * ED_{JP}]}{[BW * AT]} \quad (4.22)$$

where,

Intake_{jp} = Intake of chemical j through pathway p (mg/Kg/d)

p = pathway (drinking water or surface water ingestion)

CC_{jp} = chemical concentration of chemical j in pathway p

IR_{jp} = ingestion rate of chemical j through pathway p

ET_{jp} = exposure time to chemical j through pathway p (hrs/event)

EF_{jp} = exposure frequency to chemical j through pathway p (days or events/yr)

ED_{jp} = exposure duration to chemical j through pathway p (years)

BW = body weight (Kg), and

AT = average daily intake, non-carcinogen = $\text{ED} \times 365$

(dose over exposure time)

Carcinogen = 70×365

(total dose over lifetime).

A dilution factor of ten from effluent levels for non-drinking water sources and a factor of one hundred for drinking water sources obtained the levels of contamination in surface waters. The other parameters needed to calculate the intake for each chemical were given in Rowe *et al.*, (1995a). For non-carcinogens the hazard index or hazard quotient (HQ) is calculated:

$$HQ_j = \frac{Intake_j}{RfD_j} \quad (4.23)$$

where, $Intake_j$ = Intake of chemical j (mg/Kg/d), and
 RfD_j = oral reference dose for chemical j (mg/Kg/d).

If HQ is less than one there is an unlikely chance of adverse health effects. An HQ value greater than one indicates a potential problem. To evaluate the carcinogenic risk of chemical and metal discharge, the following equation was used:

$$TotalAnnualAdditionalCancers_p = \frac{Intake_p * cancerslopefactor_j}{lifetime} * PoP_p \quad (4.24)$$

where, $Total\ annual\ additional\ Cancers_p$ = chemical j through pathway p
 $Intake_p$ = Intake of chemical j through pathway p (mg/Kg/d)
 Cancer Slope Factor = oral cancer slope factor for chemical j
 (mg/Kg/d)⁻¹
 Lifetime = lifetime (years), and
 PoP_p = population exposed through pathway p.

The evaluation of carcinogenic risk was only performed for arsenic and benzene due to the availability of carcinogenic toxicity factors. Arsenic can cause cancer of the liver, kidney and bladder and benzene can cause nonlymphocytic leukemia (Rowe *et al.*, 1995a). The occurrence of cancers is valued using the same procedure as for the air toxic emission cancers in section 4.2.7.1.5 (Appendix B).

4.2.7.3 Radiation Externalities

The human health effects of radiation for the purposes of model development are based on damage function methods for boiling water reactor (BWR) and pressurized water reactor (PWR) technologies and are assumed to have impacts similar to those of the Canadian CANDU reactors.

Radioactive releases normally occur during all stages of the nuclear fuel cycle. These stages include:

- mining and tailings of uranium ore
- waste disposal of mine tailings
- transport to nuclear power operating plant
- nuclear power operations
- transport and waste disposal of fuel, and
- disposal of all other radioactive materials produced during normal operations.

These releases may be trapped in body tissue or remain in the environment as a continuing source of radiation. A radiation dose may be delivered externally to the whole body or to specific organs and tissues through ingestion, inhalation and other routes. A rem (Roentgen Equivalent Man) is a measure of biological dose given by the product of the absorbed dose in rads and the relative biological efficiency of the radiation. A rad is a measure of absorbed dose and is the energy released by the radioactive reaction (one rad is the amount of radiation depositing 100 ergs of energy per gram of tissue). Whole body doses of 500 rem or more delivered acutely are usually fatal within weeks.

4.2.7.3.1 *Normal Plant Operation*

During normal plant operation the radiation levels are low but the isotopes from radioactive releases can be detected. These extremely low levels may still cause cancer. Thus a zero threshold level for effects is assumed. Both fatal and non-fatal cancer risks are evaluated. To calculate the fatal cancer risks during normal plant operation, data on exposure and cancer deaths is required. This data is presented in the form of number of excess lifetime cancer deaths per 100 000 persons exposed to radiation (single exposure of 10 rem). To calculate the dose required for a cancer death the following equation was used:

$$\frac{\text{rem}}{\text{cancer death}} = \frac{100000 \text{ exposures}}{\# \text{ of cancer deaths}} * \frac{10 \text{ rem}}{\text{exposure}} \quad (4.25)$$

where, #of cancer deaths = excess lifetime cancer deaths per 100000 persons exposed to radiation.

Then to calculate the number of cancer deaths per year as a result of radiation from normal plant operation, the total exposure (person rem/year) is divided by the rem required per cancer death from equation 4.25. This is calculated for occupational exposure.

To calculate the non-fatal cancer risks, the rem per survived cancer low estimate from Rowe *et al.* (1995a) is used to obtain high damages. Then the number of survived cancers per year is calculated using the total exposure (person rem/year).

The incidence of both fatal and non-fatal cancers are valued for each model year using the monetary values for cancer deaths and survived cancers from Rowe *et al.* (1995a). These are 3.3 million and 408 000 in \$1992 respectively. The overall calculated dollar values for fatal and non-fatal cancers are converted to \$/GWh using the NRCAN estimate of nuclear contribution for the year 2000. The calculated values are converted to present dollar value for each model year using the CPI (Appendix B).

4.2.7.3.2 *Plant Operation Accidents*

Potential accidents at nuclear power plants are considered by many to be one of the major risks associated with nuclear power. As a result, the perceived operational risk is an important factor in calculating the damages for plant operation accidents. The accident can occur for a number of reasons and the release depends on the type of accident. If an accident occurs, public costs for evacuation, business and personal property losses and potential loss of income are covered by required insurance. In order to

quantify the damages associated with nuclear accidents, the accident scenarios must be considered with all initiating events that need to occur to result in a significant release.

The risks of fatal and non-fatal cancers are calculated and valued in the same manner as in section 4.2.7.3.1 with the exception of dose levels. The amount of exposure used in the calculations is the high probability estimate of the annual accident person-rem per reactor year from Rowe *et al.* (1995a) (Appendix B).

4.2.7.3.3 *Radioactive Waste*

The by-products of nuclear generation include both high and low-level waste. The damages from high-level radioactive wastes are included in the calculations for normal plant operation. Low-level radioactive wastes are processed on site or packaged in boxes and drums and shipped to low-level waste sites where they are typically buried in trenches. There are two modes of exposure to low-level wastes, normal operation and accidents that occur in handling, transportation and final disposal. The risks from low-level wastes during normal operation are expected to be very small due to low exposure.

The total radiation dose per year as a result of radioactive waste is calculated as follows:

$$\frac{TotalDose}{Year} = \frac{Ex}{V} * V_T \quad (4.26)$$

where, Ex/V = exposure levels (person-rem/yr/m³ of waste) and
 V_T = total volume of radioactive waste produced (m³).

To obtain the exposure levels from the radioactive waste, the method of disposal is assumed to be earth mounded concrete bunkers because it has the highest occupational dose equivalent according to Rowe *et al.* (1995a) at

1.81×10^{-3} person-rem/m³-yr. As the model is meant for application to a region similar to Ontario, the total volume of low-level radioactive waste produced annually in Ontario is the value used in the model. Using this volume, the total radiation dose per year from low-level wastes is obtained. The risks of fatal and non-fatal cancers are then calculated and valued using this dose with the same procedure as in section 4.2.7.3.1 (Appendix B).

4.2.7.3.4 *Nuclear Fuel Acquisition*

The risks from uranium mining, milling and nuclear fuel production are included in fuel acquisition calculations. Uranium mining and milling results in radioactive effluents from the process of extracting the uranium from the ore and concentrating it into yellow cake which is eventually produced into nuclear fuel. The three emissions of concern are:

- radon emitted during mining and milling process
- uranium and its daughter products emitted during the mining and milling process, and
- long-term storage of uranium daughter products which continue to decay for as long as 80 000 years.

The mill tailings piles are of greatest concern due to the uranium daughter products (Th-230, Ra-226 and Rn-222). Mitigation measures can be employed such as covering the piles with six feet of soil, which will decrease the radon releases, by a factor of ten.

To obtain a damage valuation for uranium mining and milling, a dose equivalent was required. The sum of the doses from all radiation sources involved was used as the worst-case estimate. This included the dose from radon, uranium and daughter products, milling and mill tailings storage (Rowe *et al.*, 1995a).

The production of nuclear fuel involves the conversion of yellow cake (U₃O₈) to uranium oxide to the eventual fuel rod fabrication. There is very little

radiation exposure or risk associated with this stage of fuel acquisition as the solid effluent from the process is combusted and the liquids are pumped to a storage pond. The dose commitment assigned for the production of nuclear fuel is obtained from Rowe *et al.* (1995a) with a value of 9.3 person-rem/yr. This dose is added to the dose from mining and milling of uranium for an overall fuel acquisition exposure level. Using this total, the risks of fatal and non-fatal cancers are then calculated and valued according to the same procedure as in section 4.2.7.3.1 (Appendix B).

4.2.7.4 Waste Disposal Externalities

Coal, oil, biomass and municipal solid waste power plants generate ash. Ash that is not used for concrete or other products must be landfilled. Disposal of ash can create impacts from ash leachate to groundwater, aesthetic impacts (trucking and landfills) as well as loss of open spaces occupied by the landfills. The focus of this study is on coal facilities as they produce the largest amounts of ash (Rowe *et al.*, 1995a). Coal ash consists primarily of oxides of silicon, aluminum, iron and calcium with smaller amounts of magnesium, potassium, sodium and titanium. The ash also contains trace amounts of other elements including heavy metals.

4.2.7.4.1 *Impact on Groundwater*

Polluted groundwater poses a threat to humans and livestock if the water supply or irrigation wells become polluted. Even with elaborate landfill liner systems, there is a risk of breach. A contingent valuation method was employed to obtain non-use values for these groundwater impacts. The total present value damages were calculated using:

$$D_{PV} = \frac{\left\{ \sum_{i=t}^{t+9} \left[12 * \left((V_L * H_L) + \left(\frac{V_N}{S_N} * H_N \right) \right) \right] \right\} / (1+r)^i}{300000} * tons \quad (4.27)$$

where, D_{PV} = present value of total damages due to contamination of groundwater summed over ten years of WTP starting at time of initial leachate contamination (\$1992)

V_L = local groundwater use value (\$WTP/ H_L /month)

V_N = national groundwater use value (\$WTP/ H_N /month)

H_L = number of local households

H_N = number of national households

S_N = number of national sites expected to leak

r = discount rate (%)

t = time when initial leachate contamination is discovered, and

tons = net tons of ash landfilled per year.

These total present value damages can be converted to annual damages by multiplying the damages by a capital recovery factor. The capital recovery factor for a plant lifetime of thirty years is:

$$CR_{30} = \frac{r * (1+r)^{30}}{(1+r)^{30} - 1} \quad (4.28)$$

where, r = discount rate (%) (Rowe *et al.*, 1995a).

4.2.7.4.2 Impact on Aesthetics

The aesthetic impacts of ash disposal include visual blight, dust, noise, traffic congestion and truck emissions. The potential for perceived or actual aesthetic impacts and health risks of living near such a facility may be reflected in decreased housing prices near the site due to declining property values. The total present value damages to housing asset values

attributable to aesthetic impacts from proximity to an ash landfill and its transportation routes are quantified:

$$D_{PV} = (D_{LF} + D_{TR}) * share \quad (4.29)$$

where, D_{PV} = total present value of damages due to landfill plus access road aesthetics (\$1992)
 D_{LF} = present value of damages due to landfill aesthetics (\$1992)
 D_{TR} = present value of damages due to aesthetics associated with new truck miles to support landfill, and
share = share of landfill volume utilized by an electricity generating facility.

This present value of damages was converted to an annual damage value using the same capital recovery factor as for the impact on groundwater. As the amount of specific coal ash landfill information required to calculate the damages is not available for the power situation in this analysis, the high estimate of annualized total aesthetic damages due to coal ash disposal from Rowe *et al.* (1995a) was used.

The annual damages for both coal ash disposal impacts are converted from 1992 dollars to present dollar value for each model scenario using the CPI (Natural Resources Canada, 1999a). The calculations are found in Appendix B.

4.2.7.5 Other Externalities

One of the major contributors to power generation was not considered in the environmental externality analysis due to a lack of reliable information and developed damage functions to value the impacts. This option is hydroelectric power. The production of hydropower does not cause air pollution impacts. However, the development of new stations can result in long-term removal, destruction or alteration of environmental resources. The

major impacts are related to land, water, wildlife, fish and flora and are a result of:

- changes in river flow characteristics
- changes in aquatic and terrestrial ecosystems due to flooded land for reservoirs
- erection of barriers which interfere with fish and wildlife movements and
- potential loss of habitat due to flooded land for reservoirs.

Hydraulic generation facilities may also have a direct effect on the human population with the most serious impact being catastrophic dam failure and disastrous flooding (this risk is included in the public risk constraint). On a smaller scale the developments could affect water and outdoor recreation through the alteration of water system behaviour. Small and large hydraulic power facilities are similar in impact but it is possible for the impact of small hydro facilities to be greater than larger stations. Small stations can cause severe effects when many are stacked along a river and its tributaries (Ottinger, 1991).

The impacts of other renewable resources such as wind, solar, biomass, geothermal and tidal power are discussed in section 2.3.6. These impacts are difficult to quantify and transfer to externalities due to the lack of health and other impacts studies performed to date. As well, the technology for most renewable energy is new and not fully developed with some of the technologies resulting in low efficiencies and serious availability issues (solar and wind power). Although some of these technologies may become available in the future, in comparison to current primary sources, they may not make a significant contribution to large-scale power generation over the time period considered in this study.

Some aspects of demand side management (DSM) programs may also be a potential source of environmental and social impacts. In order to make

personal homes more energy efficient, weatherization of houses may take place. This procedure may lead to poor indoor air quality due to reduced building ventilation. The more efficient light sources may have impacts associated with them. As well, disposal of some of the existing light fixtures in conjunction with these DSM programs may also cause waste impacts. Another disposal concern associated with DSM is the disposal of inefficient consumer appliance that uses chlorofluorocarbons (CFCs) as a cooling fluid. This could result in increased CFC emissions. If the DSM program includes load shifting this may cause another impact due to the possibility of increased fossil fuel power generation. There has not been enough research performed on certain DSM initiatives to determine if there would be any externalities and whether they would be positive or negative (Rowe *et al.*, 1995a).

Other potential externalities that warrant further investigation are socioeconomic impacts, resource depletion and upstream manufacturing.

4.2.7.6 Externality Constraint Equations

To calculate the targets of the externality constraints, the method of section 4.2.4 for the right hand side calculations of the safety constraints was used. Again, it was assumed that the year 2000 fuel mix projected by NRCAN is correct and the environmental externality costs of risk for the year 2000 were calculated. To project the maximum costs of risk to the future model years for the upper bound of the constraints, it was assumed that the overall environmental risk associated with providing electricity increases proportionally with the increase in the demand for the electricity itself (Appendix B). This assumption is reasonable as the risk can be expressed per unit energy and thus if more energy is produced, the risk will increase accordingly. However, the flexibility of the model will allow these target values to be altered to represent more or less progressive levels of acceptable environmental damages in future modeling.

In order to use the calculated environmental externality values in the model, the numbers had to be adjusted for use with the decision variables of fuel options. As the fuel options are in units of energy and the upper bounds of the constraints are dollar values, the externalities had to be converted to constraint equation coefficients in units of dollars per unit energy. To do this, the different environmental emission concerns were attributed to a particular source of power generation. This apportionment is shown in Table 4.3.

Table 4.3: Source Apportionment of Externalities

Environmental Concern	Specific Externality	Power Generation Emission Source
Air Emissions	All air impacts	Coal, oil and gas
Water Emissions	Impingement and entrainment	Coal, oil, gas and nuclear
	Thermal discharge	Coal, oil, gas and nuclear
	Chemical and metal discharge	Coal and oil
Nuclear emissions	All radiation impacts	Nuclear
Waste Disposal	Coal ash impacts	Coal

Using the total NRCAN projected demand for the year 2000 in gigawatt-hours from the appropriate sources, the externalities were converted to dollar per gigawatt-hour values (conversion method is found in Appendix B). All environmental externality constraints in the model are given the following format:

$$ax_1 + bx_2 + cx_3 + dx_4 \leq \$Max.EC \quad (4.30)$$

where,

a = externality cost per unit of coal power (\$/GWh)

b = externality cost per unit of natural gas power (\$/GWh)

c = externality cost per unit of oil power (\$/GWh)

d = externality cost per unit of nuclear power (\$/GWh) and

Max. EC = maximum overall cost of environmental damage (\$)

4.2.8 Environmental Limits

The final constraints added to the model were the limits on certain environmental emissions. The emissions considered are produced from fossil-fueled power generation and were further constrained due to environmental regulations as well as the goals of the industry. The inclusion of these constraints was to identify whether these regulations and goals were achievable during the model period of twenty years. The release of the following compounds were of concern:

- carbon dioxide (CO₂)
- nitrogen oxides (NO_x)
- sulfur dioxide (SO₂)
- particulate matter (PM₁₀)
- Mercury and
- Lead.

The carbon dioxide constraint was added to simulate the reduction in emissions suggested by the Kyoto agreement. This protocol commits Canada to reduce the total CO₂ emissions to six percent below 1990 levels by the period of 2008 to 2012 (NRCAN and CEA, 1999). This level is quantified and adjusted for use as a constraint in the model for the years 2010, 2015 and 2020. The total level to be achieved by the 2008 to 2012 period for the Kyoto target nationally is 7.4×10^{10} Kg of CO₂. However, this value is not directly applicable to power generation in Ontario. To approximate the level to be achieved by the electricity production industry in Ontario it was assumed that the amount of CO₂ produced is proportional to the amount of power generated. This assumption allows the use of the ratio of Ontario power production to generation in all of Canada to scale the CO₂ limit. As well, Figure 2.3 illustrated that power stations are responsible for 34 percent of overall carbon dioxide emissions. Using this value, the limit was further adjusted to represent the proportion of CO₂ from the electricity sector (6.66×10^9 Kg) (Appendix B).

Emission performance standards are being imposed on the electricity sector that will limit the amount of NO_x and SO₂ that can be emitted per unit of electricity produced from coal and oil fired plants. These standards apply to any electricity generated by stations greater than 25 MW and located in Ontario. The annual net emissions caps for the electricity sector beginning in January of 2001 are shown in Table 4.4.

Table 4.4: Annual Net Emissions Caps for Electricity Sector

Pollutant	Cap	Units
Nitrogen Oxides (NO _x)	36	kilotonnes of NO _x (reported as NO)
Sulfur Dioxide (SO ₂)	157.5	kilotonnes of SO ₂

(Ministry of Energy and Environment, 2000a).

These emissions caps are included as constraints in the model to evaluate the required fuel choices to meet such standards. Also, several substances have been identified for proposed mandatory emissions reporting in the electricity sector (Ministry of Energy and Environment, 2000b). The cut-off levels for mandatory reporting of particulate matter (<10 µm), mercury and lead were included as model constraints to estimate the amount of emissions that would be reported under mandatory reporting. The format for the environmental limits constraints in the model was as follows:

$$ax_1 + bx_2 + cx_3 \leq \text{Max.}E \quad (4.31)$$

where,

a = emission per unit of coal power (Kg/GWh)

b = emission per unit of natural gas power (Kg/GWh)

c = emission per unit of oil power (Kg/GWh) and

Max. E = maximum annual emission according to limits (Kg).

Calculations of the coefficients for the various environmental limits considered in the model can be found in Appendix B.

4.3 Classification of Constraints

The fuel mix optimization model consists of 32 constraint equations (including the CO₂ constraint that only applies to model years after 2010). The constraints of a goal programming model are of two types: goal equations and ordinary linear programming constraints. These can be termed goal constraints and system constraints respectively. The classification of the model constraints and the corresponding justifications are given in Table 4.5.

The system constraints remain in the format presented in section 4.2. However, the goal constraints are created through the addition of deviational variables. Constraints of the form:

$$ax_1 + bx_2 + cx_3 + dx_4 + ex_5 \leq Value \quad (4.32)$$

becomes:

$$ax_1 + bx_2 + cx_3 + dx_4 + ex_5 + n - p = Value \quad (4.33)$$

as a goal constraint, where n = the negative deviation variable and
 p = the positive deviation variable.

(Romero,1991).

The system constraints are hard constraints that cannot be violated to achieve a solution. The goal equations can be violated (as represented by the value in the solution associated with either positive or negative deviation) but the penalty for doing so is reflected in the coefficient of the deviational variable in the objective function (Anderson *et al.*, 1997). Of the 32 model constraints, five are system constraints and the remaining 27 are goal constraints.

Table 4.5: Classification of Model Constraints

Constraint	Constraint Type	Justification
Demand	System	Must meet power demand
Reliability	System	Extension of demand
Safety (Production)	Goal	Desire to decrease risk
Economics	Goal	Desire to decrease cost
Environmental Externalities	Goal	Desire to decrease emissions
Environmental Limits	System	Must meet regulations

4.4 Formulation of Objective Function

The method employed to find a solution to the goal programming problem was weighted goal programming (WGP). This means that all goals were considered simultaneously as they were embodied in a composite objective function of the form:

$$\text{Minimize } \sum_{i=1}^{27} (\alpha_i n_i + \beta_i p_i) \quad (4.34)$$

Subject to:

$$Ax + n - p = b$$

$$Bx \leq h$$

$$x, n, p \geq 0$$

where

n = vector of negative goal variable

p = vector of positive goal variable

α = vector of negative weighting factor

β = vector of positive weighting factor

A = matrix of the coefficients associated with the goal constraints

B = matrix of the coefficients associated with the system constraints

b = vector of target values

h = vector of system constraint right hand sides

x = vector of decision variables and

The purpose of the composite objective function is to minimize the sum of all the deviations between the goals and their aspiration levels. The deviation variables were weighted according to their relative importance in the fuel mix model. The vector of weighting factors (α_i) is set to zero in the model as the desired achievement of all the goal equations is less than the established target value and thus they need not appear in the objective function (Romero, 1991). The main directive for the model was to minimize any positive deviations from the set target levels. In the event that there are no non-zero values for the positive deviation variables, the negative deviation variables could be maximized to observe the fullest possible extent of goal underachievement. However, for this application there may be further implications associated with the relationships and tradeoffs among the constraints and thus exceedance of the target levels is the primary focus. This means that the objective function will minimize the positive (upward) deviations from the target values (p). Using this approach, the solution will identify all x values which satisfy $Ax \leq b$ provided such solutions are possible. If the model cannot minimize p to zero, the solution consists of all x values which minimize $(Ax - b)$ to the fullest possible extent (Lee, 1972).

The weighting factors, β_i were determined based on the relative importance of the goal constraints. An arbitrary scale of zero to ten was used to represent the relative importance of constraint satisfaction. The more important constraints received higher weighting factors. All environmental externality constraints were considered of greater importance than the public and occupational safety and economics goal constraints as the reduction of environmental impacts is the main objective of the model. The relative importance (priority) among the environmental externalities was based on the magnitude of the financial damages to society. Thus it was not necessary to use another method such as AHP to determine the relative

priorities. Power generation emissions resulting in higher financial damages were considered to be more important targets for reduction. The weighting factors assigned for the positive deviation variables are given in Table 4.6.

Table 4.6: Weighting Factors for Positive Deviation Variables

Deviation Variable (β_i)	Value	Deviation Variable (β_i)	Value
1. Safety (Occupational)	0.1	15. I&E Damages	1.0
2. Safety (Public)	0.1	16. Thermal Discharge	1.0
3. Economics	0.1	17. C&M Discharge	0.1
4. PM10 (Morbidity)	10	18. Normal Op (Fatal)	1.0
5. PM10 (Mortality)	10	19. Normal Op. (survived)	0.7
6. Ozone (Morbidity)	0.1	20. Accidents (Fatal)	0.7
7. Ozone (Mortality)	0.1	21. Accidents (Survived)	0.1
8. Lead Damages	3.5	22. Waste (Fatal)	0.1
9. Mercury Damages	0.5	23. Waste (Survived)	0.1
10. Air Toxics	3.5	24. Fuel (Fatal)	2.0
11. Visibility Damages	3.5	25. Fuel (Survived)	0.1
12. Materials Damages	3.5	26. Groundwater	2.0
13. CO2 Damages	3.5	27. Aesthetics	3.5
14. Ash Radiation	0.1		

The highest weighting factor of ten was assigned to the constraints relating to the health effects of PM₁₀. This is considered the most important goal relative to the remaining environmental externalities, as the total annual financial damage costs to society are the highest at over 1 trillion dollars (Appendix B, RHS calculations for Externalities). After the particulate matter effects, the next group of externalities of major concern are damages from the effects of:

- lead
- air toxics
- visibility
- materials damages
- CO₂ and
- coal ash piles on aesthetics.

This weighting was assigned a value of 3.5. These constraints were weighted heavily as they result in the second highest grouping of externalities with total annual financial costs to society in the range of 100 to 800 million dollars (approximately 3 times lower costs than PM_{10} damages which are weighted as 10 and the ratio of 10 to 3 results in a weight factor value of approximately 3.5). The next highest weighting value used in the objective function is two. This was used for two environmental externalities (fatal cancer damages as a result of nuclear fuel acquisition and groundwater effects from coal ash) that resulted in annual damage costs to society of similar magnitude at 13 million dollars.

The constraint equations for impingement and entrainment, thermal damages and fatal cancer from normal nuclear operation received a value of one for the weighting factor in the objective function. These damages resulted in the next highest annual monetary damage to society. These environmental damages were in the range of 3 to 5 million dollars.

The remaining externalities were assigned weighting factors in a similar fashion with declining values for smaller monetary damages to society until the lowest damage range is evaluated and the externality constraints that remain are considered to be the lowest priority and are assigned 0.1 as weighting factors.

4.5 Model Setup

The model equations and objective function were entered into a spreadsheet following the format required by the Microsoft Excel solver. To test the Solver in obtaining solutions for WGP problems, several examples including one from Anderson *et al.* (1997) were solved as a diagnostic case study. The Suncoast Office Supplies example was chosen from the more complex goal programming problems in the above reference (Chapter 15 section 15.2). This example used multiple goals and priority levels. To represent these priority levels in the Microsoft Excel solution, weighting factors were

used. The Solver settings were the same as those used for the fuel choice model. Using the Excel Solver the result obtained was identical to the solution given in Anderson *et al.* (1997).

The Microsoft Solver options used to obtain optimal solutions to the model scenarios were the suggested default options. Namely:

- maximum time limit of 100 seconds
- maximum of 100 iterations
- precision of 0.000001
- assumption of linear model
- assumption of non-negative values for adjustable cells
- use of automatic scaling
- use of linear extrapolation from a tangent vector
- use of Forward differencing to estimate partial derivatives of functions and
- use of the Newton algorithm.

The analytical model setup is presented in Appendix D.

4.6 Model Scenarios Considered

To evaluate the usefulness of the multi-objective fuel mix model, several scenarios were considered. The first scenario (Scenario 1) involved the assignment of an electrical supply baseline. The baseline consisted of the NRCAN projections for demand contributions of hydraulic and purchased power. These values were obtained for each model year (Natural Resources Canada, 1999a). This scenario was chosen to analyze the required fuel mix to meet the electricity demand in the future for a situation similar to Ontario. To satisfy the demand in Ontario, purchased power is required and the amount of power supplied from hydraulic resources is expected to remain constant through station rehabilitation and new resource discovery (Ontario Hydro, 1999a).

The second scenario involved the use of a different supply baseline consisting of only purchased power. This was included to evaluate the expected fuel mix that would reduce the environmental impacts if there were unlimited hydroelectric resources. This scenario (Scenario 2) provides a rough approximation to this mix, as the model at present does not include externalized damage values for hydraulic power due to a lack of research and available data to date.

Due to the expected decrease in the nuclear contribution to meet the electrical demand (NEB, 1999), a scenario was considered in which the nuclear power contribution decreased linearly to fifteen percent by the final model year of 2020. There is also an assumed baseline of hydraulic and purchased power for this scenario. The baseline is included to reflect the environmental implications of decreasing the system dependence on nuclear power. Without the baseline, the model attributes the increased demand to hydraulic power, which does not have any quantified environmental constraints in the model. Thus the scenario (Scenario 3), which envisages a reduced contribution from nuclear generation illustrates the areas of generation modes that come under increased pressure to satisfy the overall electricity demand.

Another scenario (Scenario 4) considered the exclusion of purchased power contribution to the fuel mix starting in 2005. This was considered with the same baseline as Scenario 3 with a zero value for the contribution of purchased power. This scenario was included to evaluate the change in generation contribution if there was no power available to be purchased.

The final scenarios included in this analysis were almost identical to the first three scenarios but with the exclusion of the Kyoto constraint on CO₂ for the model years 2010, 2015 and 2020. These were identified as Scenarios 5, 6 and 7. The model results for these scenarios will determine the fuel mix combinations that meet all the model constraints except CO₂. These results

can be used in conjunction with the results obtained using the Kyoto constraint in order to determine the areas of power generation technology that require the most attention in terms of efficiency and technology improvements in order to meet the Kyoto protocol.

4.7 Pareto Efficiency and the Magnitude Effect

The difficulties associated with the use of GP mentioned in section 2.5.3 must be addressed. GP is susceptible to the generation of optimal solutions, which are not Pareto efficient. To check for Pareto efficiency, the value of the objective function was first considered. In the event that the optimal objective function value was zero (thus all targets were met) the solution was not analyzed for Pareto efficiency because the decision maker was not interested in any solutions that may increase the negative deviation variable values (which are not included in the objective function), as that was not the purpose of this GP model. In the cases where the optimal value of the objective function of the GP model was different than zero, the magnitudes of the positive deviation variables were used to identify the Pareto efficient solution from any other feasible solutions.

Another critical issue that must be avoided is that of naïve setting of weights in WGP. This is a result of the fact that in most GP problems the goals are measured in different units. These goals are said to be incommensurable. Under this situation the composite objective function of a WGP problem is skewed because the deviational variables are measured in different units. Another problem arises when the target values for the goal constraints have different magnitudes of numerical values, as implicitly more weight would be given to the goals with higher target values. This is because the higher target value causes an artificial extra weight that does not reflect the actual preference of the decision-maker. To avoid these problems, the GP model was normalized in the following manner according to Romero (1991):

$$\left(\frac{ax_1}{RHS} + \frac{bx_2}{RHS} + \frac{cx_3}{RHS} + \dots + \frac{x_6}{RHS} \right) * 100 + \left(\frac{n}{RHS} + \frac{p}{RHS} \right) * 100 = \frac{RHS}{RHS} * 100 \quad (4.35)$$

Calculations were conducted with and without these normalized goals to determine if the GP model was impacted by a magnitude effect for the scenarios considered.

5.0 Results and Discussion

Results are presented and discussed for the various stages in the model development. As well, the model equations for each year considered are given. The fuel mix results obtained for each scenario and model year using the multi-objective model are compared to the projected fuel choices by NRCAN. The limitations and sensitivity of the model are discussed as well as the reliability of the data used for calculations and model development.

5.1 Externality and Dispersion Calculations

Various emission rates from the different stations considered were converted to concentrations using the SCREEN3 model developed by the United States Environmental Protection Agency (U.S. EPA). To verify the model performance, a test scenario was evaluated using the SCREEN3 program. The expected output for this scenario was included in the SCREEN3 package. Thus, after running the same input values with the SCREEN3 model on a personal computer, the output was compared to the expected output for model verification (Appendix C). This comparison showed the results were the same, which instilled confidence in the model performance.

The model dispersion calculations were employed to obtain maximum ground-level concentrations for the following emissions:

- PM₁₀
- SO₂
- NO_x(including NO)
- VOC
- CO₂
- lead
- mercury
- nickel

- chromium (VI)
- arsenic, and
- formaldehyde.

These concentrations were obtained using the merged stack parameters for the different Ontario stations considered in the analysis. The effects of simple elevated and complex terrain were evaluated where appropriate. The maximum concentration results from the SCREEN3 modeling can be seen in Table 5.1 and sample SCREEN3 model output for SO₂ is found in Appendix C. The use of the merged stack parameter may overestimate the ground level concentrations for the pollutants considered, as stacks from different power plants were merged in order to reduce the overall amount of calculations and dispersion modeling.

Table 5.1: Summary of SCREEN3 Concentration Results

Pollutant	Average Annual Concentration (µg/m³)	Pollutant	Average Annual Concentration (µg/m³)
PM ₁₀	20	Mercury	0.0006
SO ₂	260	Nickel	0.14
NO _x (including NO)	273	Chromium (VI)	0.0033
VOC	3	Arsenic	0.0021
CO ₂	158957	Formaldehyde	0.0059
lead	0.01		

According to the Canadian ambient standards and air emission limits for Ontario and the maximum Canadian acceptable values for NO_x and SO₂ (Table 4.2), the results obtained using the SCREEN3 dispersion calculations are high. This is expected however, as the SCREEN3 program provides a worst case scenario and would be especially high in the case of these acid gases as the effects of deposition and chemical transformation to secondary pollutants are not considered. The calculated amount of PM₁₀ (20.4 µg/m³ annual avg.) using SCREEN3 is less than the Ontario ambient standard of

60 $\mu\text{g}/\text{m}^3$ averaged on an annual basis. This is logical as the Ontario standard is for total particulates of which PM_{10} is included. Ozone and VOC values used in the analysis are comparable to the standards discussed in section 4.2.7.1.1 (Dispersion Modeling).

5.2 Model Equations

The model equations that were developed for each model year for the various constraints are presented in Appendix D. The units of the different coefficients and upper bound values were discussed for each constraint equation in the methodology.

5.3 Model Results

In this section the results of the analysis are presented and discussed. The model formulation was tailored for the seven different scenarios considered in the analysis. The features of these scenarios are as follows:

- Scenario 1 – Hydroelectric and Purchased power baseline
- Scenario 2 – Purchased power baseline
- Scenario 3 – Hydroelectric and Purchased power baseline with a linear decrease in Nuclear power contribution
- Scenario 4 – scenario 3 conditions with zero Purchased power contribution
- Scenario 5 – scenario 1 conditions without the Kyoto constraint
- Scenario 6 – scenario 2 conditions without the Kyoto constraint, and
- Scenario 7 – scenario 3 conditions without the Kyoto constraint.

Three of the model constraints originally included in the model were removed, as they were not attainable limits for the situation considered.

These constraints were the environmental limits on particulate matter (PM₁₀), mercury and lead. The limits considered for use in the model were the proposed levels for mandatory emissions reporting in the electricity sector (Ministry of Energy and Environment, 2000b). Preliminary model results indicated that the limits could not be met for the earlier model years (2000 and 2005). This suggested a large amount of emissions reporting under the proposed mandatory plan. In the latter model years, the limits were achieved as a result of the decreased apportionment of coal and oil generation to meet the Kyoto carbon dioxide constraint. Thus it was not necessary to evaluate these emission limit constraints in the modeling of the years 2010 to 2020.

The model results for the different scenarios considered over the twenty-year modeling period are given in Appendix E, Table E2. The table shows the contributions of each fuel type (GWh) in satisfying the total electrical demand as well as the percentage of each for the system fuel make-up. The table also shows the NRCAN projected fuel mix for each model year (2000 to 2020). For the 2000 model year, the results obtained from the model using the Scenario 1 and 3 simulations are very similar to the NRCAN estimations. However, the results for the remaining model years for all scenarios considered, do not reflect the same trends as the NRCAN projections due to differences in model considerations and constraints. Specifically, the NRCAN numbers are “policy as usual” projections, which do not include the specific safety and environmental objectives that are considered in the multi-objective fuel mix model. As well, the Kyoto limit for CO₂ production is not included in the NRCAN projections but is a major system model constraint in the fuel optimization model. The differences in the projected fuel mixes are visualized more efficiently through graphing methods. The fuel mix results obtained from the goal-programming model are given in Figures 5.1 to 5.7.

5.3.1 *Hydroelectric and Purchased Power Baseline* (Scenario1) Results

The results of the fuel mix for Scenario 1 are given in Figure 5.1. As the demand for power rises in 2005, the model predicts a large natural gas contribution to minimize the overall environmental damages. This large contribution does not continue in the 2010 model year, as the Kyoto limit is imposed. The contribution from oil increases slightly in 2005 and then falls to zero for the remainder of the modeling period. The contribution from coal also decreases to zero in 2010 to satisfy the Kyoto objective. Nuclear however, increases after 2005 to a supply of over 140 000 GWh in 2020. This differs greatly from the NRCAN demand projections (Figure 4.1), which show a general decrease in coal and nuclear but a steady increase in natural gas electricity production. If nuclear technology was more reliable and there was no issue of nuclear waste disposal and other risks to consider, Scenario 1 might be a reasonable option to reduce environmental impacts.

Figure 5.1: Fuel Mix Results for Scenario 1

5.3.2 Purchased Power Baseline (Scenario 2) Results

The fuel mix results are given in Figure 5.2. This figure shows a decrease in coal contribution for the 2010 model year, which corresponds to the imposition of the Kyoto Limit. There is an initial decrease in natural gas in 2005 predicted by the model to decrease overall impacts followed by an increase in 2010 to compensate for the drop in coal contribution. There is almost no contribution from oil, and nuclear power shows a fairly constant contribution over the modeling period. The hydroelectric contribution in this scenario increases steadily to 2020.

Figure 5.2: Fuel Mix Results for Scenario 2

This scenario illustrates the optimal fuel choices for electricity production for a situation similar to Ontario if there were an abundant supply of hydraulic resources. The scenario was able to meet all objectives and targets with zero deviation variables in finding an optimal solution. In other words the objective function was minimized to a value of zero for each year modeled (Table E1). Thus, the scenario 2 results are more promising in terms of

reducing the environmental problems of power generation. However, it should be pointed out that this model result, which implied minimization of environmental and other concerns, was arrived at without the inclusion of environmental externalities of hydro power, as reliable damage value functions for such externalities are currently unavailable.

5.3.3 *Restricted Nuclear Contribution (Scenario 3)*

Results

The effects of imposing a reduction on the nuclear contribution are seen in Figure 5.3.

Figure 5.3: Fuel Mix Results for Scenario 3

Again the model constraints result in a reduction for the contributions of coal and oil to meet the objectives. There is also a steady and significant decrease in the nuclear contribution. To offset these decreases in coal, oil and nuclear contributions, the model indicates a significant compensatory increase in natural gas power. If the current trend in decreased nuclear

power continues, it is obvious that more gas power generating stations will be required to meet the overall power demand with minimized environmental impact. This third scenario is in agreement with the NRCAN demand estimation trends for future years.

5.3.4 *Exclusion of Purchased Power (Scenario 4) Results*

The fourth scenario considered was to have the same baseline as Scenario 3 (restricted nuclear and hydro power) with zero purchased power contribution. In the 2010 model year, this resulted in a direct increase in natural gas contribution to compensate for the loss of the purchased power option. After this model year, the Kyoto CO₂ limit cannot be met due to the increased gas generation. If this constraint on CO₂ is removed from the model, the loss of demand from purchased power is compensated by an increase of the same amount in gas fired electricity production for each model year. An analysis of this situation was not considered to be a worthwhile activity to further the understanding of the model behaviour. Thus in order to evaluate the scenario with the imposition of the Kyoto constraint, the nuclear restriction for the last three model years (2010, 2015 and 2020) was removed. This resulted in the model output shown in Figure 5.4. The contributions from the different generation technologies are similar to that of Scenario 3 but with slightly higher nuclear contributions in the last three model years. Thus, as the results are almost identical, further analysis of this scenario would be redundant.

Figure 5.4: Fuel Mix Results for Scenario 4

Figures 5.5 to 5.7 show the optimized fuel mix results from the model if the Kyoto constraint on carbon dioxide is not included but all other environmental constraints are still considered. As the Kyoto constraint was only included for the model years 2010, 2015 and 2020, the results for the last three scenarios are different for these years only.

5.3.5 *Hydroelectric and Purchased Power Baseline Without Kyoto Constraint (Scenario 5) Results*

For Scenario 5 (Figure 5.5), a decrease would still be experienced for coal but at a slower rate than the results show with the inclusion of the Kyoto constraint (Scenario 1). The model predicts a larger contribution from oil power in this scenario with the maximum observed in 2010. The amount of natural gas powered generation increases throughout the twenty-year modeling period. This increase in natural gas generation was expected, as there is no limit on carbon dioxide production and gas power is favoured over both coal and oil generation in terms of environmental damages. This gas

trend is similar to the trend observed in the NRCAN projections (Figure 4.1). In fact, the overall results from Scenario 5 are very close to the projections seen in Figure 4.1, which is logical as these projections were also determined without the consideration of the Kyoto Protocol.

Figure 5.5: Fuel Mix Results for Scenario 5 (Hydro and Purchased Baseline) Without Kyoto Constraint

Further investigation into the relationships between the three fossil fuel generation technologies illustrated that the model favours gas over both coal and oil. The emphasis placed on environmental impacts is responsible for this behaviour. The constraint equations for NO_x and SO_2 show higher impacts for coal and oil, as do the externality constraints for several water and air pollutant effects (Analytical Model, Appendix D). Electricity production using coal is also less desirable in many cases than oil due to environmental externalities associated with coal ash such as radiation, groundwater contamination and aesthetic value as well as the water effects externalities.

In addition to the environmental impact differences, the occupational and public safety goals have a greater effect for both oil and coal when compared to the natural gas fuel cycle. It is also observed from Figure 5.5 that the nuclear contribution for this scenario is much lower compared to Scenario 1 with the Kyoto constraint. This was anticipated, as there is less dependence on this essentially CO₂-free option with the removal of the CO₂ limit.

5.3.6 *Purchased Power Baseline Without Kyoto Constraint (Scenario 6) Results*

The trends for Scenario 6 (Figure 5.6) show more coal and gas production without the Kyoto constraint, which is expected. Again as in Figure 5.5, there is a much greater increase in gas generation than coal due to the environmental constraints other than CO₂ previously mentioned that favour the natural gas option. The trend in nuclear power is the same as in Figure 5.2 (Scenario 2) with the Kyoto limit imposed on the fuel mix. This is because the higher levels of gas and coal generation correspond to an overall decline in the large hydro contribution predicted by the model for Scenario 2. Although it may seem that the model would apportion most of the power generation to the hydro technology (due to the lack of constraints), it is logical that the model would allocate a certain amount of fossil and nuclear contribution as long as the corresponding constraints are satisfied and the objective function is minimized. Should the decision maker have a preference for a certain technology, the constraints can be suitably altered.

Figure 5.6: Fuel Mix Results for Scenario 6 (Unlimited Hydro) Without Kyoto Constraint

5.3.7 Restricted Nuclear Contribution Without Kyoto Constraint (Scenario 7) Results

With the Kyoto constraint removed from Scenario 7 (Figure 5.7) the contributions from the different generation technologies are essentially the same as the trends observed with the limit on CO₂ (Figure 5.3). The restriction on nuclear generation caused an increased demand in fossil generation to compensate. The fuel choice model result favours natural gas power generation over coal and oil without the CO₂ constraint. This outcome of exclusive natural gas generation without the Kyoto limit was unexpected and occurred because the increased demand on fossil power was such that contributions from coal and oil power would result in higher environmental and safety impacts.

Figure 5.7: Fuel Mix Results for Scenario 7 (Restricted Nuclear) Without Kyoto Constraint

These model results for scenarios 5, 6 and 7 are variations of the original scenarios omitting the Kyoto constraint. The outcomes suggest that coal and oil contributions to electricity generation should be reduced even without CO₂ restrictions as a result of other environmental constraints. However, the amount of natural gas fired power would still remain a major contributor to power generation even if there were no strict limit on CO₂ emissions. This observation suggests that in order to meet the restrictions imposed by the Kyoto summit, an area of concern should be technology improvements in natural gas power generation (full fuel cycle analysis) and corresponding flue gas controls. As the gas generation process has relatively lower impacts than coal and oil generation, improvements to these technologies could effect a greater reduction in CO₂ emissions making them more competitive fuel options. The model illustrated that the coal and oil generation options were limited due to the CO₂ limit as well as other constraints. Thus, the larger deviations from the model results (larger p_i values) can provide insight

into which areas require more research. These improvements become increasingly important if the amount of nuclear contribution continues to decrease as in Scenario 3. Without these improvements, efforts toward the Kyoto target may lead to increased research and development into nuclear technology particularly in the areas of reliability and waste disposal and methods to reduce the public perception of nuclear risk.

5.3.8 *Environmental Externality Costs*

The overall environmental externality costs for each of the scenarios is shown in Figure 5.8 in millions of dollars for each year in the modeling period. The model results show that Scenarios 2 and 6 have the largest overall environmental externality costs in the 2000 model year. This high cost is due to a larger coal contribution suggested by the model than for all other scenarios. In the 2005 model year, the overall costs of all scenarios are very similar. This is expected, as the predicted amounts of the higher environmental damaging fossil contributions are similar for 2005. After the 2005 model year, Scenarios 1,2 and 3 have a much lower environmental cost compared to the other scenarios due to the high contributions of hydro and/or nuclear generation as a result of the Kyoto constraint. This illustrates the conflict between the damage values for high probability, low impact effects such as steady air emissions from fossil fuels versus low probability, high impact events associated with nuclear generation. The highest overall costs for the 2010 model year are predicted for scenarios 5 and 6. The higher cost of these scenarios is due to the large contribution of air pollution damages. In 2010, the model predicts a sharp decrease in environmental costs for Scenario 7, which occurs due to the substantially lower coal contribution when compared to Scenarios 5 and 6. These results indicate that the external damages representing the impact of air pollution from fossil power are more severe than the damages of other generation technologies.

Figure 5.8: Total Environmental Externality Costs

5.3.9 Carbon Dioxide Results

The levels of carbon dioxide production in annual gigagrams for the first three scenarios are shown in Figure 5.9. The CO₂ levels for all three scenarios are the same in the 2000 model year. This is due to the similar contributions of the different fossil generation sources. With the model constraint added in the year 2010 model to simulate the Kyoto CO₂ restriction, the production of CO₂ for scenarios 1 and 2 decreases. Scenario 2 produces less CO₂ than Scenario 1 due to the unlimited hydroelectric contribution. For Scenario 3, the level of CO₂ production is fairly constant until 2010, after which the amount of natural gas production undergoes a large increase to compensate for the imposed nuclear generation reductions and thus there is an increase in CO₂ emissions.

Figure 5.9: Carbon Dioxide Production Results

These results imply that under the assumption of nuclear power reductions, it will be difficult to meet the Kyoto objective. However, the model does provide insight into the probable generation method that would replace the nuclear power source in order to minimize the environmental impact of electricity production. Thus the results suggest that under Scenario 3 with a nuclear power restriction, CO₂ reduction to meet the Kyoto commitments can only be achieved by means of CO₂ controls and sequestration from the emissions of the fossil fuel generating facilities, which, even if technically feasible, would be a very expensive proposition.

Figure 5.10 shows the model output for the last three scenarios without the CO₂ constraint. Scenario 7 results in the same fuel mix as Scenario 3 thus producing the same amount of CO₂. The reasoning behind the identical fuel mix result was considered in the discussion for Figure 5.7. For Scenarios 5 and 6 in Figure 5.10, the amount of carbon dioxide production is similar with

higher emissions from Scenario 5 predicted as a result of higher fossil generation contribution.

Figure 5.10: Carbon Dioxide Production Results Without Kyoto Constraint

Without the Kyoto constraint, the CO₂ levels do not decrease to the levels observed in Figure 5.9 as the model apportioned more of the required demand to fossil fuel sources, particularly natural gas and coal. The emissions of CO₂ are fairly constant over the modeling period for Scenarios 5 and 6, as the amount of fossil generation predicted by the model does not significantly decrease.

The results shown in Figure 5.10 indicate the importance of the Kyoto targeted CO₂ reductions in efforts to decrease the high production of this greenhouse gas and ultimately the effects of global climate change.

5.3.10 Nitrogen Oxides Results

The production of nitrogen oxides from power generation is a concern as it may react with VOCs in the atmosphere and produce ground level ozone. Figures 5.11 and 5.12 show the model results for NO_x production in megagrams with and without the inclusion of the CO₂ model constraint respectively.

Figures 5.11 and 5.9 show that NO_x and CO₂ emissions follow similar trends. Scenarios 1 and 2 display similar trends with a decrease in NO_x production to low levels corresponding to the 2010 model year and the imposition of the Kyoto constraint. As seen in Figure 5.9, Scenario 2 produces lower pollutant levels than Scenario 1 as a result of the hydroelectric contribution. The results for the third scenario indicate a decrease in 2010 which results from a fuel switch from coal to natural gas in the model results. After this model year, the NO_x production for Scenario 3 increases steadily for the remainder of the modeling period. This is because the increasing electrical demand is met by natural gas to compensate for the imposed restriction on nuclear generation and thus as the amount of electricity production increases so do the levels of NO_x. These results imply that if Scenario 3 were to occur, (i.e. a decrease in nuclear production) the area of concern for NO_x output in combination with other environmental impacts would be natural gas. To avoid such NO_x increases the incorporation of low NO_x burners or combustion technologies that operate at lower adiabatic flame temperatures assume great importance and urgency.

Figure 5.11: Nitrogen Oxides Production Results

In Figure 5.12, the levels of NO_x produced according to the model do not decrease to the same minimal amounts for Scenarios 5 and 6 that were seen with the use of the constraint on CO_2 production (Figure 5.11). This is because the other model constraints do not force as sharp a reduction in fossil fuel production to reduce overall impacts. The production of NO_x does decline for these scenarios but at much slower rates due to larger fossil fuel power contributions that were not constrained by the CO_2 limit. In 2010, the model predicts a larger fossil fuel generation contribution for Scenario 5 resulting in higher NO_x production over Scenario 6. The opposite is true in the 2015 and 2020 model years as there is a higher fossil contribution with Scenario 6. Without the Kyoto constraint, the NO_x production for Scenario 7 is the same as Scenario 3 due to similar fuel mix predictions except for the 2010 model year, which has small amounts of coal and oil power in Scenario 7. Thus Figure 5.12 illustrates that without strict restrictions imposed on fossil fuel power generation, as with the limit on CO_2 emissions, the

production of NO_x will be significant and may contribute to increased levels of ground level ozone.

Figure 5.12: Nitrogen Oxides Production Results Without Kyoto Constraint

5.3.11 Sulfur Dioxide Results

Many of the environmental externalities considered in the model were direct or indirect effects of sulfur dioxide emissions in the air. The effects include acid rain, visibility reductions and materials damage. Figure 5.13 shows the model results for SO_2 production for the first three scenarios under modeling conditions that consider the Kyoto objective. This figure shows that the production of SO_2 will not be a concern in future years with the implementation of the fuel mixes suggested by any of the three scenario model results. The amount of SO_2 produced is essentially the same for the three scenarios over the entire modeling period. This is due to the similar fuel make-up of all three scenarios for the first two model years (2000 and 2005) followed by the exclusive natural gas generation prediction by the

model for the last three model years, which results in no SO₂ production. Even though the fuel mix model results for Scenario 3 do not meet the CO₂ restrictions, the production of SO₂ is still reduced to zero levels through the fuel switch to natural gas to achieve other environmental objectives.

Figure 5.13: Sulfur Dioxide Production Results

The model results obtained without the imposition of the CO₂ constraint shown in Figure 5.14 imply that even without this constraint, the SO₂ levels will decrease as a result of the other model goals and objectives such as safety and environmental externality costs. This is because these model constraints result in lower overall damages from large natural gas power contributions. SO₂ amounts released with Scenario 7 are similar to the levels produced with the use of the CO₂ constraint in Figure 5.13 (Scenario 3) with some SO₂ production in the 2010 model year due to the small coal and oil contributions predicted by the model. The production of SO₂ is shown to reach zero levels by the end of the modeling period for Scenario 5, as the last two model years have no coal and oil power contribution.

However, there is still a significant amount of SO₂ produced with Scenario 6 in the final model year (2020) due to a predicted oil contribution. This implies that there may still be high enough emission rates of SO₂ to cause undesirable impacts in the case of unlimited hydroelectric contribution (Scenario 6). Thus to minimize the impacts as a result of SO₂ emissions, the Kyoto target should be included in fuel mix decision making.

Figure 5.14: Sulfur Dioxide Production Results Without Kyoto Constraint

5.3.12 Goal Achievement

The non-normalized model results for the deviation variables for the three scenarios are given in Appendix E, Tables E3 to E5. These values are presented in order to evaluate the achievement of the multi-objective model goals. The non-normalized deviation variable values are presented to clearly illustrate the magnitude to which any environmental targets are exceeded. Although the underachievement of goals was not of significant concern in the modeling procedure (i.e. values other than zero for n_i) as it was desired that

the solution be less than or equal to the targets and the negative deviation variables were not included in the objective function, it will be discussed. This underachievement is acknowledged to fully report the results of the modeling procedure as well as to recognize the difference in these values among the different scenarios.

It is seen from Table E3 that for Scenario 1, the model overachieves most of the goals for air emission externalities, especially the effects from PM₁₀. As well, the goal constraint for aesthetic impacts from coal ash piles is largely overachieved. Most of the water effects are also overachieved with Scenario 1. Before the 2005 model year, most of the nuclear externalities are overachieved but in 2010 with the imposition of the Kyoto Protocol limits, have negative deviation variable values of zero. The model results for the positive deviation variables over the modeling period for Scenario 1 (Table E3) confirm the conclusions derived from the negative deviation variable results as it shows that none of the nuclear externality goals were achieved from the 2010 model year onward with the fuel mix model projected output. These goal compromises are due to the absence of an upper model limit on the amount of production of nuclear power for the first scenario. Increased nuclear production directly causes the environmental impacts of the nuclear fuel cycle to increase.

The deviation variables used to obtain feasible solutions for Scenario 2 are shown in Table E4. These results indicate that for the second scenario all of the goals are either overachieved or exactly achieved as the model output for the deviation variables shows that the fuel mix did not cause any goal to be underachieved (all p_i values are zero). This seemingly "optimal" scenario provides a solution without compromising any of the goals through large hydraulic power contributions. This scenario would appear to be ideal for power generation for a situation similar to Ontario provided that there are available resources. It should be restated however that the minimization of

environmental impacts through the model choice of fuel mix is biased due to the lack of environmental externality values for hydraulic power impacts.

The deviation variable results for Scenario 3 are presented in Table E5. All of the externality goals are met or overachieved with the exception of ozone morbidity and mortality in the last two model years. As well, the upper bound for the CO₂ effects goal is grossly exceeded in the last two model years even though it has the highest weighting in the objective function. The Kyoto constraint had to be adjusted to a goal constraint from a system constraint for this scenario in order to obtain a feasible solution. The carbon dioxide target is underachieved by a factor of 10¹⁰. The failure to meet ozone and materials damage goals is a result of the increased natural gas power generation to compensate for the reduction in nuclear energy.

For all three scenarios, the economic and occupational and public risk goal constraints were always overachieved. This may suggest that the fuel mix results provided by the model reflect the safest and cheapest alternatives. However, it may be an indication that these constraints required more work in order to impose more stringent model goals. These goals were not the main focus of this analysis as the primary objective was to reduce the environmental impacts of power generation.

The results from the multi-objective fuel mix model using the different scenarios provided insight into the implications of different fuel mix choices. In order to satisfy the goals, certain penalties were imposed and these varied depending on which areas of the fuel mix were increased and decreased to meet the required demand. This analysis of the goal achievements for the different fuel mix situations illustrated the concept of trade-offs when reducing the environmental impacts of production processes. For example, the decrease in nuclear power generation with Scenario 3 satisfied the nuclear externality goals that were not met with Scenario 1 at the expense of several air pollution externality goals.

5.3.13 *Sensitivity Analysis*

In linear programming the purpose of the sensitivity analysis is to study how the optimal solution will change with adjustments to the various model coefficients. The areas to be examined are the objective function coefficients as well as the constraint bounds (RHS) and shadow prices. The sensitivity analysis for an objective function coefficient involves determining a range on the coefficient value. This is the range of optimality. For weighted goal programming (WGP) problems, the coefficients of the objective function are the weights assigned to the various objectives in the model. Thus, the range of optimality for WGP problems describes the amount of change required for a constraint weighting in the objective function to effect a change in the optimal solution. It was assumed for the purpose of this analysis that any variable that requires a change of more than 1000 in the weighting (objective coefficient) to effect a change represents an insensitive variable.

The Microsoft Excel solver calculates a sensitivity report for all the adjustable cells including the decision variables but it is important to acknowledge that changing one parameter at a time created these sensitivity reports.

Combined changes would require a more complicated analysis. Sample reports for the year 2020 normalized model are given in Appendix E for Scenarios 1 and 5. The range of optimality is calculated as well as the reduced cost for each positive deviation variable coefficient. This is because the only non-zero adjustable parameters included in the objective function were the positive deviation variables. Thus the range of optimality analysis does not apply to the adjustable cells for the decision variables and negative deviation variables (which had values of zero).

In a linear programming problem, the RHS of the constraint equations is also evaluated for sensitivity. This is done through the evaluation of the shadow price. This is the value of providing a single extra unit of a fully constrained resource (Pidd, 1996). The Excel solver also calculated the shadow price

and the results of this from the normalized model results are also seen in the reports given in Appendix E. The sensitivities for the three scenarios over the modeling period were evaluated. In the following sections, Sensitivity results for paired scenarios are presented together as the latter is a sub-scenario of the first in each case.

5.3.13.1 Scenarios 1 and 5

The sensitivity reports presented in Appendix E for the normalized model results were analyzed. Scenario one sensitivity results show no sensitivity in the objective function weights for any model year. The only shadow price results are for the demand constraint and these results from the normalized model are shown with the applicable ranges in Table 5.2. The shadow price has a value of zero for the 2000 and 2005 model years as the objective function was minimized to zero in these two cases.

Table 5.2: Normalized Shadow Price Results for Scenario 1

Model Year	Shadow Price	Applicable Range (GWh)
2000	0	N/A
2005	0	N/A
2010	17.96	70.60 - 119.81
2015	20.04	65.43 – 109.97
2020	22.10	62.56 – 100.69

The sensitive objective function weightings for Scenario 5 (sub-scenario without the Kyoto constraint) are given in Table 5.3. This table shows model years 2015 and 2020 with the allowable range of the weight factor value before the minimized solution is affected. The sensitivity analyses for the other model years considered (2000, 2005 and 2010) identified no sensitive weightings for this scenario.

Table 5.3: Normalized Model Sensitivity Analysis Results for Scenario 5 Objective Function Weights

Year 2015 Weight Factor Range	Year 2020 Weight Factor Range
Ozone (Morbidity) $\beta_6 = 0.02 - 3.54$	Ozone (Morbidity) $\beta_6 = 0.00 - 1.11$
Ozone (Mortality) $\beta_7 = 0.02 - 3.54$	Ozone (Mortality) $\beta_7 = 0.00 - 1.11$
Nuclear Accidents (Survived) $\beta_{21} = 0.00 - 0.17$	(CO ₂ Damages) $\beta_{13} = 0.90 - 4.65$
	Nuclear Accidents (Fatal) $\beta_{20} = 0.00 - 2.78$
	Nuclear Accidents (Survived) $\beta_{21} = 0.00 - 2.17$
	Nuclear Waste Disposal (Fatal) $\beta_{22} = 0.00 - 2.18$

Again, the only shadow price results are for the demand constraint and these results from the normalized model are shown for Scenario 5 with the applicable ranges in Table 5.4. There are no shadow price values shown in the table for the 2000 and 2005 model years as the scenario is the same as Scenario 1 until the 2010 model year with the addition of the Kyoto constraint on CO₂. The shadow price for 2010 has a value of zero due to a minimized objective function value of zero.

Table 5.4: Normalized Shadow Price Results for Scenario 5

Model Year	Shadow Price	Applicable Range (GWh)
2010	0	N/A
2015	0.49	98.19 – 100.72
2020	9.56	91.86 – 117.42

5.3.13.2 Scenarios 2 and 6

The model output from Scenario 2 does not show any sensitivity in the objective function weightings. The shadow price for the demand constraint was consistently zero for all five model years. This is expected, as the value for the minimized objective function for Scenario 2 is zero over the entire modeling period. As a result, it is impossible to further minimize the

objective function and there can be no non-zero value for the shadow price. Similarly, the results of the sensitivity analysis for Scenario 6 (sub-scenario of 2 without the Kyoto constraint) show no specific sensitivities.

5.3.13.3 Scenarios 3 and 7

The sensitivity analysis of the results for Scenarios 3 and 7 yielded results similar to the analysis of Scenario 1. The sensitivity analyses of all model years for both scenarios identified no sensitive weightings. As with Scenario one, the only shadow price results for the two scenarios were on the demand constraint and the results are shown with the applicable ranges in Tables 5.5 and 5.6 for Scenario 3 and 7 respectively. In Table 5.5, the shadow price value for the demand constraint is zero for the first two model years because the objective function was minimized to zero.

Table 5.5: Normalized Shadow Price Results for Scenario 3

Model Year	Shadow Price	Applicable Range (GWh)
2000	0	N/A
2005	0	N/A
2010	19.51	63.14 – 102.67
2015	28.14	89.04 – 133.12
2020	29.07	75.67 – 107.87

Table 5.6 does not include the 2000 and 2005 model year shadow price results because Scenario 7 is the same as Scenario 3 until the 2010 model year when the Kyoto constraint is added. The shadow price value for 2010 is zero, which was an expected result as the objective function for that model year was minimized to zero.

Table 5.6: Normalized Shadow Price Results for Scenario 7

Model Year	Shadow Price	Applicable Range (GWh)
2010	0	N/A
2015	8.63	89.04 – 133.12
2020	9.56	75.67 – 107.87

5.3.13.4 Other Sensitivities and Model Behaviour

In order to evaluate the effect of the different model constraints and the resultant model behaviour under extreme conditions, several cases were considered. The first investigation was of the possibility of nuclear generation having the lowest environmental damages but with varying fuel cost and decreased reliability. It was desired to determine how extreme the reliability and cost coefficients must be in order to force a switch in the fuel choice away from nuclear. This case was evaluated without the inclusion of the Kyoto limit on CO₂ emissions. It was found that even with a decrease in the nuclear capacity factor to 30 percent combined with a decreased cost, the model still favoured nuclear power.

This would suggest that the low nuclear fuel cost generally overrides the low capacity factors i.e. nuclear is still favoured despite inefficient and unreliable generation presumably due to overwhelming environmental advantages over fossil fuels. However, when the economic coefficient for nuclear was increased by a factor of seven with the reliability held constant at 30 percent, the nuclear contribution fell to zero. The rejection of nuclear power under these conditions shows that the model no longer considers the environmental advantage of nuclear generation to outweigh the low reliability and high costs. If the nuclear capacity factor remains at the average calculated level of 79.4 percent (Appendix B), the economic coefficient requires an increase of a factor of 14 to bring down the nuclear contribution to zero. Similarly, retaining the calculated economic coefficient for nuclear

power allows the reliability to go down as low as 6 percent (a factor of approximately 13) before the model suggests the total rejection of nuclear power. Thus, the result of this sensitivity analysis shows that the sensitivities of the reliability factor and the cost factor are similar for nuclear.

The same procedure was repeated to evaluate the effect of reliability and economics on the nuclear contribution with the imposition of the Kyoto limit. Under the Kyoto constraint, nuclear generation was insensitive to either reliability or its economics, indicating that the Kyoto target cannot be met without the nuclear contribution. This result implies that the costs required to meet the Kyoto agreement may be very large in the event that nuclear technology is not improved and the cost of the full nuclear fuel cycle were to increase.

To determine the relationship between the economic and reliability constraints and environmental constraints, the effect on coal power contribution in the 2020 model year was considered. The first case did not include the CO₂ constraint in order to observe the model behaviour and goal effects without it. This case involved the model response to low costs and high reliability of coal generation with increased SO₂ damages. Initially the expected SO₂ emissions from coal were doubled which had no effect on the fuel mix. This is because the upper limit (emission cap) for the SO₂ constraint was not reached. Next the effects of economics and reliability were evaluated with this increased SO₂ emission. An increase in the average capacity factor for coal generation to 90 percent resulted in an immediate increase in the coal contribution.

With this reliability improvement, the effect of lower coal costs was investigated. To do this, the coefficient for coal in the economic constraint equation was significantly reduced which did not increase the coal contribution. In response to this result, the coefficients for the other generation technologies were doubled to emphasize the cost difference.

This caused an increase to nuclear power with still no effect on the coal contribution. In order to discourage the gas contribution, the cost of this option was doubled again. This resulted in no nuclear or coal contribution, decreased gas and the remaining demand went to oil power. The reason for the model choice of oil over coal despite the low cost and high reliability of coal is the SO_2 constraint. The contribution from oil instead of nuclear is a result of the economic constraint. This implies that the environmental system constraint governing SO_2 has a greater effect than both economics and reliability. The hypothesis is confirmed through the increase of modeled SO_2 emissions for oil power, which results in a switch to coal. The impact of a high sulfur coal confirmed the effect of the SO_2 constraint with an increase in SO_2 emissions from coal in the model, which forces some of the demand to go to gas power. This is a direct result of the SO_2 system constraint overriding the imposed low cost and high reliability of coal power.

Under these circumstances, the economic constraint is most sensitive when the goal has been achieved and even more sensitive when severely underachieved (i.e. $p_3 > 0$). This was confirmed with the increase in gas cost relative to nuclear power in the economic constraint equation. Originally, the economic constraint was not met as a result of the high cost gas power employed to meet the SO_2 emission cap. As a result of the limit on SO_2 , nuclear was the only remaining option that will allow a feasible solution. The increase in gas costs effected a direct switch to nuclear power as a result of the economic constraint.

The impact of the Kyoto constraint was evaluated by decreasing all the environmental externality costs for coal below the externalities for the other generation options and the CO_2 system constraint was included in the model run. A major decrease in the coal contribution results with a corresponding nuclear increase. All the environmental externality constraints for nuclear power are exceeded and the economics constraint is beyond the upper cost limit by a factor of 10^{10} . The objectives for environmental damages and

economics could be easily met using the adjusted coal power option but the model does not allow the CO₂ constraint to be compromised. To determine the fuel mix without the limit on CO₂ the same model run is performed without the Kyoto constraint. This results in a very large coal contribution and a significant oil contribution with decreased nuclear. As a result, the environmental externality damages are lower and the economic constraint is met. The economic goal was met because it was assigned a larger weighting factor in the objective function. The result of an oil contribution instead of entirely coal power is a result of safety constraints.

In general, this targeted sensitivity evaluation determined that the environmental system constraints (NO_x, SO₂ and CO₂) have the greatest effect over all goal constraints (safety, environmental and economics). This is expected as the system constraints do not have deviation variables and must be satisfied in order to arrive at a fuel choice solution. However, when the governing system constraints are removed from the model, the weighting factors used in the objective function can prioritize the remaining goal constraints.

5.3.14 *Data Reliability and Model Limitations*

Most of the data used for environmental emissions and facility characteristics were typical data averages for the power generation types considered in the analysis. Although it was suggested that the model developed would be suitable for a situation such as Ontario, it must be emphasized that the environmental emissions and facility characteristics (with the exception of the capacity factors) for the most part are not directly from Ontario power generators. Hence the model results should be used with caution to any specific jurisdiction including Ontario. This does not affect the performance of the model but the output of model results can only be as reliable as the input calculations. The results from typical data are still applicable but they will be either over or underestimated depending on the correlation between

actual and typical emission rates. Also, nuclear generation technology in Canada consists of the CANDU reactor system. However, more extensive typical data was available on other technologies as discussed in model development. Thus the data used for nuclear generation is not directly applicable to a pseudo-Ontario situation but should yield a good approximation. In general, the model is limited by the quality of input data that is available.

When performing the SCREEN3 dispersion modeling the concept of merged stack parameters was realized to reduce the total amount of model runs required to obtain the ambient concentrations necessary to value the air pollution damages. As a result the maximum ground level concentrations obtained with SCREEN3 may be higher than the actual concentrations as a result of fossil power generation. The use of these merged stack parameters may also have an effect on the model results through the air externality constraints as the concentration values were used in the externalization calculations. Also, the conversion of one-hour and 24-hour maximum concentrations to annual averages may have added error to the air emission valuation procedure. Despite the overestimated values in the model calculations these simplifications may have caused, the resultant model coefficients are conservative, which allow for other data uncertainties and system changes.

Several of the assumptions necessary to develop the model result in a circular problem of analysis. It was assumed that the existing system would be slightly modified but that the emissions based on the current overall capacity would be relatively constant over the modeling period. This assumption affected the emission calculations that allowed the determination of externality values for use in the model. Also, the use of the NRCAN year 2000 projections to convert the overall externality costs to costs per unit of energy for each specific technology implies that the model results will follow these projections. However, the model results from some of the scenarios

that meet this objective suggest a different fuel mix, which would in turn cause a change in the emissions make-up and the damage cost per unit energy. This would mean that the externality damages should be recalculated and the model rerun to obtain a more accurate fuel mix result. This result could again show a difference in the power generation choices, which would effect another adjustment to the generated emissions. Thus, the process may become iterative or circular in order to attain more accurate results. These assumptions were made to calculate the environmental externality values necessary to accomplish the objective of developing a model to minimize environmental impacts through fuel-mix choice.

It should also be noted that the model results do not necessarily mean that there must be compatible generating stations available in the system to match the fuel mix. Instead, the results suggest the fuel mix that would be required to meet the environmental and other constraints imposed by the model. In other words, it is intended that the modeling procedure is utilized with any desired scenarios to answer the question, can the required power be produced for our society while minimizing the effects on the environment? The analysis presented is not for any specific power system but was fashioned for a system that would be similar to the situation and demographics of Ontario.

6.0 Conclusions and Recommendations

Evaluation of current literature indicated that goal programming would be a useful multiple objective decision making technique for the power generation fuel choice problem. Environmental externalities were used to develop the necessary constraints for the goal programming model. The computation of these externalities involved air dispersion modeling. The model results indicate that goal programming is a promising method for multi-criteria fuel choice decision making.

6.1 Dispersion Modeling

The air dispersion modeling was performed using the SCREEN3 model developed by the United States Environmental Protection Agency. This program provides a worst-case pollutant concentration scenario by evaluating all possible combinations of meteorological conditions and stability classes. For the purpose of the multi-objective fuel choice model, it was assumed that the worst-case concentration values were applicable. In order to reduce the amount of modeling, the merged stack parameter was used to combine the emissions from the different fossil fuel generating stations. As there was limited site-specific emission data available, typical emission rates from coal, oil and natural gas power stations were used. The resultant maximum ground level concentrations from the SCREEN3 output were then converted to annual average concentrations for use in the externality damage functions. These values are comparable to national and provincial standards.

In order to improve the dispersion modeling results, it is recommended that site-specific data for each of the stations be obtained. As well, if the required input data is available the modeling should be done using a long-range program such as the Industrial Source Complex (ISCLT) model, which includes calculations of secondary pollutants (nitrates and sulfates) and

provides results in annual average concentrations. Finally, for increased accuracy the dispersion calculations should be performed for each stack individually. Although the computation would be intense and time consuming, the concentration results would be more applicable than with the use of merged stack parameters.

6.2 Environmental Externalities

The environmental impacts of power generation were converted to monetary damage values using the externality approach in order to formulate constraint equations for use in the MCDM fuel choice model. These externalized values allow easy comparison between the fuel choices while representing the dollar values of the differences in the extent of damages themselves.

The morbidity and mortality effects of PM_{10} resulted in the largest damage with upper constraint limits over 1 billion dollars. After the PM_{10} effects, the next group of externalities of major concern were the health effects of lead, air toxics and CO_2 , as well as visibility and materials damage with right hand side constraint values above 100 million dollars. The damages from fatal cancer as a result of nuclear fuel acquisition and the groundwater impacts of coal ash resulted in environmental externalities of similar magnitude with upper bounds of approximately 13 million dollars. The environmental concerns presented resulted in the highest monetary external damages and the remaining environmental impacts were also ranked in a similar fashion using their externalized values.

To calculate the environmental externalities, several initial assumptions concerning the starting fuel mix as well as the consistency of emissions over time were necessary. However, some of the model results obtained in this analysis suggested a different fuel mix than the original assumption. As a result the emissions would be altered. As stated earlier, to improve the model performance, the sensitive externality values should then be

recalculated which would likely result in different fuel choices causing another adjustment to the emissions profile. Thus an iterative process should be employed to obtain more accurate fuel choice results.

6.3 Fuel Choice Model

The weighted goal programming model was developed to obtain optimal fuel mix scenarios under specified power conditions to minimize the environmental impact of power generation. This model is a starting point for future works in the area of impacts from electricity production. To further develop the model, several improvements can be made. These include:

- research and development of fossil fuel acquisition damage functions
- research and development of hydraulic power damage functions
- detailed description of purchased power contributions to identify possible impacts for externalization (although this may fall outside the regional boundary)
- incorporation of future efficiency and technology improvements and
- detailed data on the CANDU nuclear fuel cycle.

In developing the model, a majority of the available data relating to fossil-fueled power was presented as a single value combining the coal, oil and natural gas technologies together. As a result, the relative contributions from each fossil source were used as a percentage to proportion the relative damages from each source. To increase the model effectiveness in choosing a fuel mix to minimize environmental impacts, differentiation between the fossil technologies is recommended. This would involve the collection of source-specific emission data and intensive air dispersion modeling. More externality damage calculations would also be necessary at each plant location rather than calculations using the overall ambient pollutant concentration from all three fossil sources.

The following results, which are discussed in an earlier section are summarized and reemphasized below.

6.3.1 Hydroelectric and Purchased Power Baseline

Scenarios

The model results for scenario 1 (hydroelectric and purchased power baseline) clearly showed that the model chose nuclear power over fossil power to reduce the environmental damages from overall generation. The reason that fossil power was reduced was due to the constraint on CO₂ emissions. The environmental externality goals for nuclear were exceeded in the last three model years with the imposition of the Kyoto objective. However, all air emission externality constraints were met. The removal of the Kyoto constraint and subsequent model run for scenario 5 resulted in a switch from nuclear to gas power. There was still a substantial nuclear contribution but the limits on the externality constraint equations caused a slightly larger amount of the demand to be supplied by natural gas. The contribution from nuclear still seems high and this may be due to the difficulties associated with valuing the impacts of low probability, high-risk events such as a nuclear accident. The outcome of this scenario suggests that in order to meet the Kyoto objective with no increase in hydroelectric resources, increased dependence on nuclear and natural gas power is necessary.

6.3.2 Purchased Power Baseline Scenarios

The fuel choice outcome for scenario 2 achieved the best environmental performance of the scenarios considered. This scenario only used purchased power as a baseline and allowed an unlimited contribution from hydroelectric sources. This was the only scenario considered, which satisfied all the model system and goal constraints including the environmental limits for the entire modeling period. Even with the removal of

the Kyoto constraint (Scenario 6), the CO₂ limit was still achieved. These results involving an unlimited amount of hydroelectric power suggest that to meet demand while reducing the environmental impacts of generation, the focus should be on hydro power. However, it may not be possible to develop hydroelectric stations to the extent indicated by the model due to resource limitations. As well, the damage functions for externalizing the impacts from hydroelectric power are in the development stage and thus the environmental externality constraints were not included in the model. With the inclusion of these externalities, hydroelectric power may no longer result in the lowest environmental impacts.

6.3.3 Restricted Nuclear Power Contribution Scenarios

The results of the generation technology contributions for scenario 3 represent the fuel mix required to meet electrical demand in the event that there is a restriction on nuclear power. This restriction could occur due to concern over the adverse effects of radiation and nuclear accidents as well as the public reaction and opposition to new developments. The model predicted that in the absence of nuclear power, the burden of increased demand would be provided largely by natural gas generation (without the benefit of increased hydro resources). All nuclear externality goals were met with this scenario. However, the fuel mix results predicted by the model with this restriction on nuclear generation implied that the Kyoto objective would not be met, nor would some of the air environmental externality constraints. Again the fuel choice model suggests that the CO₂ limit will not be achieved without a significant amount of nuclear power production.

Examination of the model results for the different scenarios emphasized the importance of nuclear and gas technology improvements and hydroelectric development in meeting the Kyoto objective for carbon dioxide. As well, the analysis has indicated that the development of renewable technology may be instrumental in reducing these target environmental impacts. However, it is

unclear whether these renewable technologies will result in lesser damages when evaluated with the full fuel cycle analysis.

6.3.4 Environmental Limits

Limits on three pollutants were included as system constraints. The pollutants considered were CO₂, NO_x and SO₂. The constraint bound used for CO₂ was the Kyoto objective and was achieved for scenarios one and two. Without the use of a CO₂ limit, scenario 2 resulted in the lowest amount of carbon dioxide emissions followed by scenario one. The NO_x and SO₂ limits were included as system constraints to represent proposed regulatory emissions caps. When the CO₂ constraint was included in the model run, the levels of NO_x emitted for scenario one and two were almost zero. The amount of NO_x production was substantially higher for scenario three due to the increased pressure on fossil fuels. A similar increase in SO₂ emissions was not experienced with the third scenario as the majority of fossil production is provided by natural gas. Without the Kyoto objective, the levels of overall emissions production were higher and scenario five resulted in lesser amounts of NO_x while scenarios five and seven resulted in the lowest SO₂ production.

Evaluation of these environmental limits through the model results illustrates that targeting CO₂ emissions may also result in the emissions reduction of other air pollutants.

6.3.5 Sensitivity and Model Limitations

The sensitivity analysis found that without the Kyoto limit, the constraints on reliability and economics had similar effects on the choice of generation technologies. However, the imposition of the CO₂ constraint overruled the effects of the other constraint equations. Adjustments to the other model equations had no effect on the solution when the changes in the fuel mix would theoretically result in the CO₂ constraint being compromised.

Similarly, it was discovered that the SO₂ constraint had a greater effect on fuel choice than the reliability or economics constraints. In general, the environmental system constraints (NO_x, SO₂ and CO₂) had a greater effect on the model solution than all the goal constraints (safety, economics and environmental). However, when the governing system constraint was removed, the goal constraints could be prioritized using the weighting factors of the objective function. These goal constraints were found to be most sensitive when the upper limit was reached or exceeded.

The development of this multiple objective fuel choice decision making tool is an important contribution toward understanding the complex relationships and tradeoffs between power generation and environmental impacts.

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Appendix A

Appendix A: Ontario Station Description

Table A1: Ontario Hydroelectric Power Stations

Hydroelectric Station	Year	MW	Area	Number of Units
Caribou Falls (1958)	1958	87		3
Whitedog Falls (1958)	1958	68		3
Ear Falls (1930)	1930	17		4
Manitou Falls (1956)	1956	66		6
Pine Portage (1950)	1950	131		4
Cameron Falls (1921)	1921	78		7
Alexander (1930)	1930	67		5
Silver Falls (1959)	1959	48		1
Kakabeka Falls (1906)	1906	25		4
Aguasabon (1948)	1948	46		2
Kipling	1966	141		2
Harmon	1965	141		2
Smoky Falls		56		
Little Long	1963	133		2
Otter Rapids	1961	182		4
Abitibi Canyon	1933	314		5
Lower Sturgeon	1923	5	Timmins	2
Sandy Falls	1911	4	Timmins	3
Wawaitin	1912	11	Timmins	4
Indian Chute	1923	3		2
Hound Chute	1910	4		4
Matabitchuan	1910	10		4
Lower Notch	1971	274		2
Aubrey Falls	1969	162		2
Wells	1970	232		2
George W. Rayner	1950	46		2
Red Rock Falls	1960	41		2
Stinson	1925	5		2
Coniston	1905	4		3
McVittie	1912	2		2
Crystal Falls	1921	8	North Bay	4
Nipissing	1921	2	North Bay	2
Bingham Chute	1923	1	North Bay	2
Elliott Chute	1929	1	North Bay	1
Otto Holden	1952	243	North Bay	8
Des Joachims	1950	429	North Bay	8
Eugenia	1915	6		3
Big Eddy	1941	8		2
Ragged Rapids	1938	8	Toronto	2
South Falls	1916	4	Toronto	3
Hanna Chute	1926	1	Toronto	1
Tretheway Falls	1929	2	Toronto	1

Table A1 (continued)

Big Chute	1993	10	Toronto	1
Lakefield	1928	2	Toronto	1
Auburn	1911	2	Toronto	3
Seymour	1909	6	Toronto	5
Meyersberg	1924	5	Toronto	3
Decew Falls 1	1904	23		6
Decew Falls 2	1943	144		2
Sir Adam Beck no.1	1921	496		10
Sir Adam Beck no.2	1954	1360		16
Sir Adam Beck PGS	1957	174		6
Ontario Power	1905	81		12
Frankford	1913	3		4
Sidney Rehab.	1994	5		4
Sills Island	1926	2		2
Hagues Reach	1925	4		3
Ranney Falls	1922	9		3
Healey Falls	1913	11		3
High Falls	1920	2		3
Merrickville Rehab.	1994	2		2
Robert H. Saunders	1958	1005	Ottawa	16
Chats Falls	1931	96	Ottawa	4
Stewartville	1948	182	Ottawa	5
Amprior	1976	82	Ottawa	2
Mountain Chute	1967	170	Ottawa	2
Barrett Chute	1942	176	Ottawa	4
Calabogie	1917	5	Ottawa	2
Chenau	1950	139	Ottawa	8
Total		7312		

Table A2: Ontario Fossil Power Stations

Fossil Fuel Station	Year	MW	Area	Number of Units	Fuel Type	Turbine type
Atikokan	1985	215		1	coal	steam
Thunder Bay	1981	310		1	coal	steam
Lakeview	1962	1140	Toronto	8	coal	steam
Lambton	1969	1975	Windsor	7	coal oil	steam gas
Nanticoke	1973	3920		8	coal	steam
Lennox	1976	2140		6	oil oil	steam gas
Total	9700					

Table A3: Ontario Nuclear Power Stations

Nuclear Station	Year	MW	Area	Number of Units	Fuel Type	Turbine type
Bruce A	1977	3076		4	UO ₂	steam
Bruce B	1977	3140		4	UO ₂	steam
Pickering A	1971	2060		4	UO ₂	steam
Pickering B	1971	2064		4	UO ₂	steam
Darlington	1990	3524		4	UO ₂	steam
Total	13864					

Appendix B

Appendix B – Sample Calculations

These sample calculations are provided to supplement the descriptions of calculations given in the methodology section. All sample calculations are given for year 2000 data unless otherwise specified.

Reliability Constraint Calculations

Using the nuclear CF data (Ontario Hydro, 1989) to demonstrate the arithmetic average of CF calculations:

Pickering A = 0.86

Bruce A = 0.58 (all values are used to compute avg. CF as status of closures in the Pickering B = 0.85 future model years is not known)

Bruce B = 0.83

Darlington = 0.85

$$CF_{avg} = \frac{0.86 + 0.58 + 0.85 + 0.83 + 0.85}{5} = 79.4$$

To develop the reliability constraint equation, the inverse of the capacity factors for each type of technology was used:

$$1.28x_1 + 1.15x_2 + 1.11x_3 + 1.26x_4 + 1.96x_5 + x_6 \leq TotalCapacity$$

The RHS value of total capacity was obtained from Ontario Hydro (1999a) as 38 873 MW of installed production capacity. This value was converted to GWh (assuming 8760 hours per year and 1000 MW per GW) for use in the constraint equation.

Safety Constraints Calculations

The ranges of public and occupational risk values are given in Tables B1 – B5.

To quantify the public and occupational risk of death, the upper bounds of the total risk values in Tables B1 to B5 are converted to overall risk by multiplying the risk factor by the NRCAN projected demand for that year:

The NRCAN projections are in GWh, and are converted to MW-yr using:

$$1GWh = \frac{3.6TJ}{31579200s/yr} = 1.14 \times 10^{-7} \text{ TW-yr} = 0.114 \text{ MW-yr}$$

Occupational risk factor of accidental death for coal = 0.0067/MW-yr

$$\begin{aligned} \text{Occupational overall risk of accidental death for coal} \\ &= 0.0067/\text{MW-yr} * 2668.74 \text{ MW-yr} \\ &= 17.88 \end{aligned}$$

To quantify the risk of accidental death for coal, the value of \$3.4 million for a statistical life (Krupnick and Burtraw, 1996) is used:

$$\text{Value} = 17.88 * 3.4 * 10^6 = \$60.79 \text{ million.}$$

The quantified death risks for all model years are given in Tables B6 to B26.

To convert the valued risk to a \$/GWh value for use in the model, the total dollar value is divided by the year 2000 projected NRCAN demand for the fuel source considered.

$$\begin{aligned} \text{Total Occupational Death risk of coal (2000)} &= (\text{accident risk} + \text{disease risk})/\text{demand} \\ &= \frac{(\$60.79 \text{ million} + \$6.8 \text{ million})}{23410 \text{ GWh}} \\ &= \$2887.23/\text{GWh} \end{aligned}$$

To calculate the RHS of the occupational safety constraint equation for the year 2000, the occupational damage costs for each fuel type are added:

$$\text{Occupational} = 60.8 + 6.8 + 0.32 + 3.5 + 20.6 + 21.9 + 36.1 = \$150 \text{ million}$$

To project the upper bound value for occupational risk for future years, it is assumed that the increase in overall risk associated with providing electricity will be proportional to the increase in projected demand itself. The demand increase between 2000 and 2005 is 7.5%, so the right hand side of the occupational risk constraint in the 2005 model will be:

$$\text{RHS} = \$150 \text{ million} * 1.075 = \$161.25 \text{ Million}$$

The RHS values for all model years using this method are presented in the following table:

	2005	2010	2015	2020
Demand Increase (%)	7.5	5.9	7.5	7.5
Occupational Risk Upper Bound	\$161 Million	\$170 Million	\$183 Million	\$197 Million

Economic Constraints Calculations

The equations presented in methodology for operation and maintenance as well as fuel cost calculations (equations 4.5 to 4.9) were obtained using linear regression on the plots of cost data. The closer the r-squared value of the trend is to unity, the more accurately the trendline will represent the actual cost behaviour. These values for the equations are given in the following table:

Equation	R-Squared Value
Nuclear O&M	0.8830
Hydro O&M	0.8847
Fossil O&M	0.9828
Nuclear Fuel Costs	0.9171
Hydro Water rental Costs	0.9457

It is clear from these values that the linear trends are good approximations of the cost behaviour previously observed.

Sample calculation on use of trend equations to calculate future costs:

$$\begin{aligned}
 \text{Year 2000, Nuclear O\&M, Cost} &= 0.1665(6) + 0.965 = 1.964 \text{ cents/kWh} \\
 \text{This value is converted to dollars/GWh} &- 1.964 \text{ cents/kWh} / 3.6 \cdot 10^6 \text{ J/kWh} \\
 &= 5.46 \cdot 10^{-7} \text{ cents/J} * \$/100 \text{ cents} \\
 &= 5.46 \cdot 10^{-9} \$/J * 10^{12} \text{ J/TJ} * 3.6 \text{ TJ/GWh} \\
 &= 19656 \$/GWh
 \end{aligned}$$

The calculated cost coefficients for all fuel sources and model years are given in Table B28.

The upper bound for the RHS of the economic constraint is found through the multiplication of the total electricity price in dollars/GWh by the total demand to obtain a dollar value (NRCAN, 1999). This calculation for the year 2000 is:

$$\text{RHS} = \$246\,024/\text{GWh} * 152679 \text{ GWh} = \$3.76 \cdot 10^{10}$$

Environmental Externality Constraints Calculations

Assumptions:

Typical emission rates for the fuel sources considered and the assumed facility characteristics are given in Spreadsheet B1.

Some of the damage functions require the use of affected population. In the development of the model, it was recognized that the emissions from power generation plants would not affect the entire province. As well, the radius of influence surrounding the facilities would be fairly large due to the nature of air and water pollutant transport. It was assumed that airborne and waterborne pollutants have the potential to impact at least twenty percent of the total Ontario population.

To convert the damages to a dollar/GWh value for use as coefficients in the model constraint equations, the damage costs for the year 2000 are assumed to be constant over the modeling period. This is reasonable as the \$/GWh value for damages from a specific generation source is not likely to change drastically (i.e. technology improvements or emissions controls) in the twenty year period. The only change in the coefficient values between model years occurs due to the time value of money and damage function specific factors such as population.

Merged Stack Parameters and Conversion of SCREEN results:

Calculations presented for SO₂ emissions from the Atikokan and Thunder Bay stations:

$$V = \frac{\pi}{4} d_s^2 V_s = \frac{\pi}{4} (4)^2 (30) = 377 \frac{m^3}{s}$$

$$\text{Atikokan, } M = \frac{h_s V T_s}{Q} = \frac{150(377)(400)}{104.13} = 217114 \frac{m^4 K}{g}$$

$$\text{Thunder Bay, } M = \frac{h_s V T_s}{Q} = \frac{150(377)(400)}{159.83} = 141543 \frac{m^4 K}{g}$$

(U.S. E.P.A., 1992).

The Thunder Bay station has a lower M value, therefore it is the representative stack with a merged emission rate of:

$$Q = Q_{\text{Atikokan}} + Q_{\text{Thunder Bay}} = 104.13 + 159.83 = 263.96 \text{ g/s.}$$

The remainder of the merged stack parameter calculations are found in Spreadsheet B1.

The SCREEN results (Appendix C) give the ambient concentrations in 1 hour and 24 hour maximum concentrations. To use these concentrations in the externality damage functions, annual concentrations are needed. Thus, these maximum concentrations are converted to annual averages. The method for conversion was obtained from U.S. EPA (1992). To convert 24-hr concentrations to 1-hr concentrations, the division factor is 0.4 ± 0.2 . It was assumed that 0.6 would provide a worst case estimate of concentration. Then the 1-hr concentrations were converted to annual average concentrations through multiplying by a factor of 0.08.

Sample calculations of the conversion are given for SO₂ emissions:

There were two concentration results from SCREEN with the merged stack parameters M₁ and M₂,

M₁ result = $166.9 \mu\text{g}/\text{m}^3$ (24-hr max)

M₂ result = $2973 \mu\text{g}/\text{m}^3$ (1-hr max)

The M₁ result is converted to 1-hr max = $166.9/0.6 = 278.17 \mu\text{g}/\text{m}^3$

The 2 results are summed to obtain the total increase in SO₂ concentrations as a result of power generation,

SO₂ = $2973 + 278.2 = 3251.2 \mu\text{g}/\text{m}^3$

Conversion to average annual concentration = $3251.2 * 0.08 = 260.1 \mu\text{g}/\text{m}^3$.

This calculation is done for all emissions considered in the SCREEN model and the calculations are shown in Spreadsheet B2. After all the concentrations have been converted to annual averages, they are added to the ambient background concentrations to obtain the total concentration of the pollutant in the atmosphere (Spreadsheet B2).

Air Externalities:

For all air externalities, it was assumed that the relative damages from each fossil fuel source are directly proportional to the typical pollutant emission rate from a facility powered by that fuel source.

Sample morbidity calculations are provided for PM₁₀ Chronic Bronchitis effects

(assumed to affect the population that is 25 years and older):

$$Annual\Delta C = R * PoP * \Delta PM = (9.3 * 10^{-5}) (0.64 * 2371800) (20.39) = 2878.92 \text{ cases}$$

(Rowe *et al.*, 1995a).

The number of cases is then converted to a monetary value using the annual cost estimate for a chronic bronchitis case of \$ 336 000 (1992 dollars). This cost is then converted to 2000 dollars using the CPI (NRCAN, 1999),

Annual Chronic Bronchitis cost from power generation =

$$2878.92 * 336000 * \left(\frac{CPI_{2000}}{CPI_{1992}} \right) = 967317120 * \left(\frac{1.465}{1.25} \right) = \$1\,133 \text{ million}$$

The same conversion is used as was used for the safety constraints calculations to convert the annual dollar value to a \$/GWh value. As PM₁₀ emissions are caused by power generation from coal, oil and gas fuel sources, the total projected demand of the three contributing sources is summed. This total amount of generation responsible for the PM₁₀ emissions (in GWh) is applied to the annual dollar amount to yield the \$/GWh value required for the model coefficients.

$$Cost/GWh = \frac{Total PM_{10} Morbidity}{Fossil Generation} = \frac{\$1143061827.05}{42045 GWh} = \$27186.63/GWh$$

This is the model coefficient for PM₁₀ morbidity damages from oil power, as the emission rate of PM₁₀ is highest from an oil-powered station (Rowe *et al.*, 1995a).

Correspondingly, the coefficient for coal is eighty percent of this and the value for natural gas is almost negligible in comparison (2.5 %).

Note: the conversion from other year dollar values (i.e. \$1992) to current year values using the CPI relationship is performed throughout the externality calculations but the sample calculation will not be repeated. The same applies to the conversion to \$/GWh from annual dollars as the calculation is similar for all externalities.

Sample mortality calculations are given for PM₁₀:

$$\text{Annual Deaths} = (0.00001) * (2\,371\,800) * (20.39) = 483.69 \text{ deaths}$$

The number of deaths is then valued and converted to current dollars per GWh,

$$\$/GWh = \frac{483.69 * \$6.6 \text{ million}}{42045 GWh} * \frac{1.465}{1.25} = \$88986.37 / GWh$$

Calculations for PM₁₀ and ozone morbidity and mortality damages for all model years is shown in Spreadsheet B3.

Sample calculations for lead externalities:

The calculation of the change in mean blood-lead levels in a child as a result of lead emissions from power plants is given for year 1,

$$\Delta GM_t = (0.22 + 0.014 * (1 - 1)) * \left(\frac{0.01126}{0.0047} \right) = 0.527$$

This change in mean blood lead level is added to the estimate of the child blood lead level,

$$\text{Mean PbB} = 4.65 + 0.527 = 5.177 \mu\text{g/dl}$$

This process is repeated for the assumed thirty-year plant life (which may underestimate damages as lead can still have effects up to 80 years) and the damages are valued based on the blood lead levels up to the end of the twenty-year modeling period.

The damage estimate for children was used - \$497 200 per 0.01 µg/dl per one million people. This simplifies to \$49.72 per µg/dl per child. The population used for children was 18 years old and under (assumed to be 17%).

$$\$/GWh = \frac{4.65 * \$49.72 * 0.17 * 2371800}{42045GWh} * \left(\frac{1.465}{1.25} \right) = \$2598.51/GWh$$

Calculations for lead damages for all model years can be viewed in Spreadsheet B3.

Sample Calculations for Mercury Externalities:

The calculation for annual mercury emission is given for the Atikokan station (coal-fired),

$$Kg/yr = \frac{0.0002403 \frac{g}{s}}{1000 \frac{g}{Kg}} * \frac{86400s}{day} * \frac{365d}{yr} = 7.578Kg/yr$$

To convert this emission of mercury to a dollar value, the estimate of damages from mercury power generation emissions of \$ 0.198/Kg (in 1992 dollars) per MW- yr of capacity for coal plants is used. The Atikokan station has a capacity of 215 MW. Thus the damage value for this station is,

$$\$/GWh = \frac{\$0.198 * 7.578 * 215}{23410GWh} * \left(\frac{1.465}{1.25} \right) = \$0.016/GWh$$

The total damage values for all the stations considered for a situation similar to Ontario for all model years are presented in Spreadsheet B3.

Sample Calculations for Air Toxics Externalities:

The calculation of damages is given for nickel.

$$\Delta RISK_i = \left(0.1379 * \frac{0.00024}{70} \right) * (1 + (15.76 * 1)) = 0.000007926$$

To calculate the incidence of cancer, it was assumed that the entire population is affected by the air toxic emissions from power plants.

$$\Delta CANCE R_i = PoP * \Delta RISK_i = 2371800 * 0.000007926 = 18.80$$

(Rowe *et al.*, 1995a).

The average value for a fatal or non-fatal cancer case is used to value the damage from the air toxic cancer cases,

$$\$/GWh = \frac{18.80 * \$3.4 \text{ million}}{42045 GWh} * \left(\frac{1.465}{1.335} \right) = \$1668.17 / GWh$$

The total damage values for the air toxic substances considered for a situation similar to Ontario for all model years are shown in Spreadsheet B3.

Sample Calculations for Visibility Externalities:

The calculations for the total light extinction coefficient and the visual range are shown for the starting concentrations of PM, NO₂ and sulfates.

$$b_{ext} = \frac{\left(b_{Ray} + \sum_i \beta_i C_i \right)}{1000} = \frac{(11.6 + (1 * 23.4 + 0.13 * 35.27 + 11 * 5.85))}{1000} = 0.1039$$

$$\text{The Visibility Range, } V_r = \frac{3.912}{b_{ext}} = \frac{3.912}{0.1039} = 37.64$$

(Rowe *et al.*, 1995a).

These parameters are then calculated for each model year. Then the visibility damages from power generation sources are quantified using WTP. The damage valuation for the year 2000 is shown.

Damage = - (WTP_i)

$$\begin{aligned} -WTP_i &= (-1)b * \ln\left(\frac{VR2_i}{VR1_i}\right) * HH_i = -200 * \ln\left(\frac{18.11}{37.64}\right) * 901825 \\ &= \$ 131\,955\,582.80 * (1.465/1.25) = \$154 \text{ million} \end{aligned}$$

(Rowe *et al.*, 1995a).

The damage value is negative due to the method of WTP, which determines the amount of money that an individual is willing to part with to avoid the risk. The damage values are converted to \$/GWh using the total fossil fuel generation and relative emission rates as with the other air externalities.

The damage values for visibility effects for each model year are given in Spreadsheet B4.

Sample Calculations for Materials Damage Externalities:

The calculation of materials damage effects from PM₁₀ is shown.

The assumed damage value for PM₁₀ effects is used to calculate the damages,

$$\$/GWh = \frac{\$7.00 * 20.39 * 901825 HH}{42045 GWh} * \left(\frac{1.465}{1.335} \right) = \$3360.09 / GWh$$

The annual materials damage values from both PM₁₀ and SO₂ from power generation sources are given in Spreadsheet B4.

Sample Calculations for Greenhouse Gas Externalities:

Calculations are presented for NO effects.

The damage estimate used for GG effects was \$1.4/short ton of CO₂ (in 1992 dollars). To convert this to a cost for NO, the global warming potential for NO of 270 was used yielding a damage cost of \$ 378/short ton of NO (in 1992 dollars). This value was used with the assumed emission rates of NO from the power damage sources to arrive at a damage estimate.

$$\$/GWh = \frac{\frac{\$378}{907.18} * \frac{394.04 \frac{g}{s}}{1000} * \frac{31536000 s}{yr} * \left(\frac{1.465}{1.25} \right)}{42045 GWh} = \$144.33 / GWh$$

The annual damages of CO₂ and NO are given for each model year in Spreadsheet B4.

Sample Calculations for Coal Ash Radiation Externalities:

The Calculations of this externality are provided for the Atikokan coal station.

The annual radiation dose from the coal ash at this station is 0.0002866 rem. The damages per rem are assumed to be \$3417 (1992).

$$\$/GWh = \frac{\$3417 * 0.000286}{23410GWh} * \left(\frac{1.465}{1.25} \right) = \$0.00005/GWh$$

The total ash radiation damages from all coal plants considered for each model year is presented in Spreadsheet B4.

Water Externalities:

Sample Calculations for Impingement and Entrainment Externalities:

The damages for the Bruce A nuclear station are shown.

$$D = \frac{D}{cfs} * cfs * \left(\frac{CF}{0.80} \right)^{10} = \$725 * 4521.72 * \left(\frac{0.65}{0.80} \right)^{10} * \left(\frac{1.465}{1.25} \right) = \$481729.21$$

(Rowe *et al.*, 1995a).

The total damages from impingement and entrainment effects of all power generation facilities converted to dollar per GWh values are given in Spreadsheet B5.

Sample Calculations for Thermal Discharge Externalities:

The sample calculations given are for the Atikokan coal station. The estimated thermal damages from coal plants are \$95/cfs.

$$Damages = \frac{\$95 * 264.45 * 1.465}{1.25} = \$29443.86$$

The damages are calculated for each station and are added together and converted to dollars per GWh using the total generation of nuclear, coal gas and oil stations (Spreadsheet B5).

Sample Calculations for Chemical and Metal Discharge:

The calculations shown are for arsenic.

The total intake of arsenic from power generation sources through the drinking water exposure route is,

$$\begin{aligned}
 Intake_p &= \frac{[CC_p * IR_p * ET_p * EF_p * ED_p]}{[BW * AT]} \\
 &= \frac{[0.0005 * 1.39 * 1 * 365 * 30]}{[70 * 2555]} = 4.262 * 10^{-6} \text{ mg/ Kg/ day}
 \end{aligned}$$

The hazard index for total arsenic intake through drinking and surface water is,

$$HQ_j = \frac{Intake_j}{RfD_j} = \frac{4.2627 * 10^{-6}}{3 * 10^{-4}} = 0.0142$$

(Rowe *et al.*, 1995a).

Since the hazard index is less than one, there is no need to quantify the non-carcinogenic risk, as there is no concern for potential health effects.

The incidence of cancers is calculated for arsenic,

$$\begin{aligned}
 TotalAnnualAdditionalCancers_p &= \frac{Intake_p * cancerslopefactor_j}{lifetime} * Pop_p \\
 &= \frac{4.2627 * 10^{-6} * 2}{30} * 0.35 * 2371800 = 0.2359
 \end{aligned}$$

(Rowe *et al.*, 1995a).

The resulting damages from cancer cases is then calculated for arsenic (which is an emission from coal generation),

$$\$/GWh = \frac{0.2359 * \$3.4\text{million}}{23410GWh} * \left(\frac{1.465}{1.335} \right) = \$37.60/GWh$$

This process is repeated for benzene and the damages are totaled for an overall damage coefficient for chemical and metal discharge carcinogenic effects for use in the model (Spreadsheet B5).

Radiation Externalities:

The sample calculations presented are for normal operation externalities of nuclear generation as the calculations for all four aspects of nuclear power effects are similar.

The dose corresponding to a cancer death is found by the following,

$$\text{rem/cancerdeath} = \frac{100000 \text{ exposures}}{\# \text{ of cancer deaths}} * \frac{10 \text{ rem}}{\text{exposure}} = \frac{100000}{488} * 10 = 2049.18$$

The average collective dose for normal operation is 3006 person-rem/yr. Thus

$$\text{cancerdeaths/yr} = \frac{\text{dose}}{\text{rem / death}} = \frac{3006}{2049.18} = 1.47 \text{ deaths.}$$

(Rowe *et al.*, 1995a).

The same method is used to value the damages from cancer deaths,

$$\$/\text{GWh} = \frac{1.47 * \$3.3 \text{ million}}{69830 \text{ GWh}} * \left(\frac{1.465}{1.25} \right) = \$81.25/\text{GWh}$$

The number of survived cancers per year is found using an assumed value of 2080 for the dose in rem per survived cancer (Rowe *et al.*, 1995a).

$$\text{survived/yr} = \frac{\text{dose}}{\text{rem / death}} = \frac{3006}{2080} = 1.4 \text{ survived cancers}$$

Survived cancers are valued using a damage estimate of \$408 000 in 1992 dollars.

$$\$/\text{GWh} = \frac{1.4 * \$408000}{69830 \text{ GWh}} * \left(\frac{1.465}{1.25} \right) = \$9.65/\text{GWh}$$

The procedure for valuing damages from nuclear power generation is similar for the four aspects analyzed with different dose levels. The calculations of all aspects for each model year can be seen in Spreadsheet B6.

Waste Disposal Externalities:

Sample Calculations for Groundwater Effects:

The present value of the damages from coal facility ash is

$$D_{PV} = \frac{\left\{ \sum_{i=1}^{t+9} \left[12 * \left((V_L * H_L) + \left(\frac{V_N}{S_N} * H_N \right) \right) \right] \right\} / (1+r)^i}{300000} * tons$$

(Rowe *et al.*, 1995a).

The calculations for the summation term are shown in Spreadsheet B7. The present value of damages is,

$$D_{PV} = \frac{15037809.72}{300000} * 4633200 = \$232 \text{million}$$

The annual damages are found using the capital recovery factor,

$$CR_{30} = \frac{(0.03 * (1+0.03)^{30})}{((1+0.03)^{30} - 1)} = 0.051$$

$$\text{Annual Damages} = \$232\,331\,636.50 * 0.051 = \$11.8 \text{ million } (\$1992)$$

These annual damages are converted to current dollars per GWh for each model year using the same methods as for all externality calculations (Spreadsheet B7).

Sample Calculations for Aesthetic Impacts:

The assumed value for aesthetic damages from coal fueled power generation is \$3911/ton in 1992 dollars (Rowe *et al.*, 1995a) and the amount of coal ash produced in Ontario is approximately 4 633 200 tons/yr (Spreadsheet B7). The value of \$3911/ton is the damage value affecting residents in the assumed impact radius of ten miles and these impacts are assumed to extend 0.25 miles from the truck route on both sides of the access roads (Rowe *et al.*, 1995a). The damage value for aesthetics for the remainder of Ontario residents is assumed to be \$0/ton. An overall damage value for the entire province is estimated since no information on the locations and exact demographics of the coal ash landfills could be located. In Ontario there are five generating plants fueled primarily by coal. These are Atikokan, Thunder Bay, Lakeview, Lambton and Nanticoke. For the most part, these stations are relatively

close to major centers so a population of approximately 100 000 in a ten mile radius is assumed. As there are five plants, the total population affected in Ontario would be 500 000 people. According to NRCAN (1999), the population of Ontario in 2000 is expected to reach 11 589 000. Thus the percentage of Ontario residents affected by coal ash pile aesthetics is approximately 4.2. It is also assumed that this percentage of people affected is applicable over the entire modeling period (to 2020). The calculation of annual damages for 2000 is given below.

$$\text{Annual Damages} = \frac{\$3911 * 4633200}{23410 \text{ GWh}} * \left(\frac{1.465}{1.25} \right) * (0.042) = \$38101.70 / \text{GWh}$$

These damages are calculated for each model year in Spreadsheet B7.

Upper Bounds of Externalities:

Sample Calculations are given for the upper bound or right hand side (RHS) of the PM₁₀ morbidity constraint.

To obtain the RHS of the constraint equation for the year 2000, the overall annual costs, which are based on the total annual GWh of electricity produced, are used

$$RHS = \$1143.1 \text{ million}$$

For all air externality goals, the contributions from coal, gas and oil power were assumed to be directly proportional to the pollutant emission rate. As a result, the individual goal equation coefficients are calculated from the \$/GWh calculation based on year 2000 power production. This value is adjusted to represent the relative damages from coal, gas and oil power. To allow for this overestimation in equation coefficients, the RHS of the air externality equations are increased by 10 percent:

$$RHS = \$1257 \text{ million}$$

To project the upper bound value for future years, the assumption that the overall risk of providing electricity will increase proportionally with the increase in demand itself is used. The demand increase between 2000 and 2005 is 7.5%, so the right hand side of the PM_{10} morbidity constraint in the 2005 model will be:

$$RHS = \$1\,257\,368\,010 \times 1.075 = \$1352 \text{ Million.}$$

The RHS values for all other environmental externality goals are calculated in a similar manner without the ten percent increase from the overall annual externality cost. The calculations for the RHS of all the externality goal constraints for all model years are presented in Table B29.

Environmental Limits Calculations

To include the six compounds considered as environmental limits, the assumed emissions rates in g/s had to be converted to Kg/GWh for use as coefficients in the multi-objective fuel choice model. The sample calculations are given for CO_2 . The total emissions for CO_2 from coal fired power generation sources is,

$$\begin{aligned} CO_2 \text{ coal emission rate} &= 0.000273208 \text{ g/J (from Spreadsheet B1)} \\ &= 0.000273208 \text{ g/J} \times 3.6 \times 10^{12} \text{ J/GWh} \times 1 \text{ Kg/ 1000 g} \\ &= 983\,549 \text{ Kg/GWh} \end{aligned}$$

The calculations for CO_2 oil and gas emission rates in Kg/GWh as well as all calculations for the other environmental limit pollutants can be found in Spreadsheet B1 for each model year.

Calculation of the Kyoto Limit for 2010, 2015 and 2020:

$$\begin{aligned} 1990 \text{ } CO_2 \text{ level for Canada} &= 7.87 \times 10^{10} \text{ Kg } CO_2 \quad (\text{NRCAN, 1999}) \\ 6 \% &= 7.87 \times 10^{10} \text{ Kg } (0.06) = 4.72 \times 10^9 \text{ Kg} \\ \text{Kyoto} &= 1990 \text{ level} - 6\% \text{ of } 1990 \text{ level} \\ &= 7.87 \times 10^{10} - 4.72 \times 10^9 = 7.40 \times 10^{10} \text{ Kg } CO_2 \end{aligned}$$

The Kyoto target applies to all CO₂ emissions and has to be adjusted for the power generation contribution (34%). This results in the national level for CO₂ emissions according to the Kyoto conference:

$$\text{Limit} = 7.40 \times 10^{10} (0.34) = 2.52 \times 10^{10} \text{ Kg}$$

The calculation of the limit on CO₂ for Ontario was based on the electricity production in Ontario compared to the production in all of Canada in 1997:

$$\text{ratio} = \frac{\text{Ontario}(GWh)}{\text{Canada}(GWh)} = \frac{146566}{553855} = 0.265 * 100 = 26.5 \%$$

Thus the assumed limit for Ontario is 26.5% of the national limit as per the Kyoto agreement.

$$\text{Limit} = 2.52 \times 10^{10} (0.265) = 6.66 \times 10^9 \text{ Kg}$$

This is the limit for the first model year that considers the Kyoto target (2010). To determine the limits for the 2015 and 2020 model years, the target was assumed to increase proportionally with electricity demand. This gives limits of:

$$\text{Limit}_{2015} = 6.66 \times 10^9 * 1.0747 = 7.17 \times 10^9 \text{ Kg and}$$

$$\text{Limit}_{2020} = 7.17 \times 10^9 * 1.07503 = 7.70 \times 10^9 \text{ Kg.}$$

Model Set-up

The analytical form of the model equations is presented in Appendix D.

Table B1: Coal-Fired Electrical Production System Risk Ranges (per MW-yr Electrical Output)

Risks	Gathering and Handling Fuel		Transportation		Electricity Production		Total
<i>Occupational</i>							
Accidental							
Death	0.0007	0.0015	0.0016	0.005	0.000013	0.0025	0.0067
Injury	0.04	0.07	0.013	0.048	0.0016	0.056	0.083
Man-days lost	8	16	10	32	0.16	20	51
Disease							
Death	0	0.00075				0	0.00075
Disability	0.0042	0.0084				0.0042	0.0084
Man-days lost	0.2	5				0.2	5
<i>Public</i>							
Accidental							
Death			0.0008	0.0019		0.0008	0.0019
Injury			0.0016	0.0016		0.0016	0.0016
Man-days lost			5	11.6		5	11.6
Disease							
Death	0.0014	0.014			0.016	0.017	0.061
Disability					94	94	280
Man-days lost	8.4	84			580	590	1830

Table B2: Oil-Fired Electrical Production System Risk Ranges (per MW-yr Electrical Output)

Risks	Gathering and Handling Fuel Transportation			Electricity Production Total		
<i>Occupational</i>						
Accidental						
Death	0.0014	0.00004	0.00014	0.000013	0.00005	0.002
Injury	0.015	0.0016	0.013	0.0009	0.002	0.15
Man-days lost	1.6	0.32	1.5	0.13	0.4	19
Disease						
Death						
Disability						
Man-days lost						
<i>Public</i>						
Accidental						
Death						
Injury						
Man-days lost						
Disease						
Death				0.006	0.017	0.017
Disability				35	105	105
Man-days lost				215	650	650

Table B3: Gas-Fired Electrical Production System Risk Ranges (per MW-yr Electrical Output)

Risks	Gathering and Handling Fuel			Transportation			Electricity Production			Total
<i>Occupational</i>										
Accidental										
Death	0.000039	0.00031	0.000029	0.000034	0.000014	0.000053	0.00016	0.00048		
Injury	0.004	0.031	0.0017	0.0019	0.0009	0.0021	0.013	0.041		
Man-days lost	0.43	3.4	0.18	0.22	0.13	0.42	1.5	4.8		
Disease										
Death										
Disability										
Man-days lost										
<i>Public</i>										
Accidental										
Death						0.000009	0.000009	0.000009		
Injury						0.000047	0.000047	0.000047		
Man-days lost						0.06	0.06	0.06		
Disease										
Death										
Disability										
Man-days lost										
						0.0000024	0.000024	0.000007		
							0.013	0.04		
							0.086	0.27		

Table B4: Nuclear Electrical Production System Risk Ranges (per MW-yr Electrical Output)

Risks	Gathering and Handling Fuel		Emissions (Sulfur Oxides)		Transportation		Electricity Production		Waste Management		Total
<i>Occupational</i>											
Accidental											
Death	0.00012	0.00057			0.0000027	0.000012	0.000013	0.000017	0.000005	0.0003	0.00078
Injury	0.0034	0.016			0.00006	0.0002	0.0017	0.0017	0.00027	0.016	0.029
Man-days lost	0.9	4.2			0.019	0.082	0.16	0.19	0.04	2.5	6
<i>Disease</i>											
Death	0.000022	0.0008			3E-08	0.000004	0.00013	0.00013	0.000074	0.00024	0.00081
Disability	0.000011	0.000016			6E-08	0.000008	0.00006	0.00022	0.00015	0.00022	0.00039
Man-days lost	0.1	3.6			0.0002	0.025	0.8	0.8	0.46	1.6	4.9
<i>Public</i>											
Accidental											
Death					0.000012	0.000012				0.000012	0.000012
Injury					0.00011	0.00011				0.00011	0.00011
Man-days lost					0.08	0.08				0.08	0.08
<i>Disease</i>											
Death	0.000031	0.000031	0.00001	0.000013	0.0000013	0.0000013	0.00003	0.00023	0.000005	0.00007	0.00052
Disability			0.000036	0.0000044	4.4E-07	0.00000044	0.0000007	0.000026	0.00025	0.02	0.063
Man-days lost	0.19	0.19	0.13	0.41	0.0078	0.0078	0.18	1.4	0.03	0.5	3.5

Table B6: Coal-Fired Electrical Production System Risk Ranges (Million \$) (for year 2000)

Risks	Gathering and Handling Fuel		Transportation		Electricity	Production	Total	
Occupational Accidental Death	6.3516012	13.610574	14.51795	45.36858	0.11795831	0.81663444	22.68429	60.7939
Disease Death	0	6.805287	0	0	0	0	0	6.805287
Public Accidental Death Injury Man-days lost Disease Death Disability Man-days lost	0	0	7.258973	17.24006	0	0	7.258973	17.24006
	12.7032024	127.032024	0	0	145.179456	426.464652	154.2532	553.4967

Table B7: Coal-Fired Electrical Production System Risk Ranges (million \$) (for year 2005)

Risks	Gathering and Handling Fuel		Transportation		Electricity Production		Total
<i>Occupational</i>							
Accidental							
Death	6.3977256	13.709412	14.62337	45.69804	0.1188149	0.82256472	22.84902
Injury							61.23537
Man-days lost							
Disease							
Death	0	6.854706	0	0	0	0	6.854706
Disability							
Man-days lost							
<i>Public</i>							
Accidental							
Death	0	0	7.311686	17.36526	0	0	7.311686
Injury							17.36526
Man-days lost							
Disease							
Death	12.7954512	127.954512	0	0	146.233728	429.561576	155.3733
Disability							557.5161
Man-days lost							

Table B8: Coal-Fired Electrical Production System Risk Ranges (Million \$) (for year 2010)

Risks	Gathering and Handling Fuel		Transportation		Electricity Production		Total
<i>Occupational</i>							
Accidental							
Death	5,29074	11,3373	12,09312	37,791	0,0982566	0,660238	18,8955
Injury							50,63994
Man-days lost							
Disease							
Death	0	5,66865	0	0	0	0	0
Disability							5,66865
Man-days lost							
<i>Public</i>							
Accidental							
Death	0	0	6,04656	14,36058	0	0	6,04656
Injury							14,36058
Man-days lost							
Disease							
Death	10,58148	105,8148	0	0	120,9312	355,2354	128,4894
Disability							461,0502
Man-days lost							

Table B9: Coal-Fired Electrical Production System Risk Ranges (million \$) (for year 2015)

Risks	Gathering and Handling Fuel		Transportation		Electricity Production		Total
<i>Occupational</i>							
Accidental							
Death	3.3155304	7.104708	7.578355	23.68236	0.06157414	0.42628248	11.84118
Injury							
Man-days lost							
Disease							
Death	0	3.552354	0	0	0	0	0
Disability							
Man-days lost							3.552354
<i>Public</i>							
Accidental							
Death	0	0	3.789178	8.999297	0	0	3.789178
Injury							
Man-days lost							
Disease							
Death	6.6310608	66.310608	0	0	75.783552	222.614184	80.52002
Disability							
Man-days lost							288.9248

Table B10: Coal-Fired Electrical Production System Risk Ranges (million \$) (for year 2020)

Risks	Gathering and	Handling Fuel	Transportation	Electricity	Production	Total
<i>Occupational</i>						
Accidental						
Death	0.8980692	1.924434	2.05273	6.41478	0.01667843	0.11546604
Injury						3.20739
Man-days lost						8.595805
Disease						
Death	0	0.962217	0	0	0	0
Disability						0.962217
Man-days lost						
<i>Public</i>						
Accidental						
Death	0	0	1.026365	2.437616	0	1.026365
Injury						2.437616
Man-days lost						
Disease						
Death	1.7961384	17.961384	0	0	20.527296	60.298932
Disability						21.81025
Man-days lost						78.26032

Table B11: Oil-Fired Electrical Production System Risk Ranges (million \$)

Risks	Gathering and Handling Fuel		Transportation		Electricity		Production	Total
<i>Occupational</i>								
Accidental								
Death	0.22682352	2.7542856	0.006481	0.022682	0.002106218	0.00810084	0.048605	0.324034
Injury								
Man-days lost								
Disease								
Death	0	0	0	0	0	0	0	0
Disability								
Man-days lost								
<i>Public</i>								
Accidental								
Death	0	0	0	0	0	0	0	0
Injury								
Man-days lost								
Disease								
Death	0	0	0	0	0.9721008	2.7542856	0.972101	2.754286
Disability								
Man-days lost								

Table B12: Gas-Fired Electrical Production System Risk Ranges (Million \$) (for Year 2000)

Risks	Gathering and Handling Fuel	Transportation	Electricity Production		Total
<i>Occupational</i>					
Accidental					
Death	0.281694114	2.23910706	0.209465	0.245579	0.101121
Injury					0.382815078
Man-days lost					
Disease					
Death	0	0	0	0	0
Disability					
Man-days lost					
<i>Public</i>					
Accidental					
Death	0	0	0	0	0.0650063
Injury					0.065006334
Man-days lost					
Disease					
Death	0	0	0	0	0
Disability					
Man-days lost					0.017335
					0.065006
					0.05056

Table B13: Gas-Fired Electrical Production System Risk Ranges (million \$) (for Year 2005)

Risks	Gathering and Handling Fuel		Transportation		Electricity Production		Total
<i>Occupational</i>							
Accidental							
Death	0.349974893	2.781851712	0.260238	0.305106	0.125632	0.475606906	1.435794
Injury							4.307383
Man-days lost							
Disease							
Death	0	0	0	0	0	0	0
Disability							
Man-days lost							
<i>Public</i>							
Accidental							
Death	0	0	0	0	0.0807634	0.080763437	0.080763
Injury							
Man-days lost							
Disease							
Death	0	0	0	0	0	0	0.021537
Disability							0.062816
Man-days lost							

Table B14: Gas-Fired Electrical Production System Risk Ranges (million \$) (for Year 2010)

Risks	Gathering and Handling Fuel		Transportation		Electricity Production		Total
<i>Occupational</i>							
Accidental							
Death	0.677124022	5.382267864	0.503502	0.590313	0.2430702	0.920194183	2.777945
Injury							8.333834
Man-days lost							
Disease							
Death	0	0	0	0	0	0	0
Disability							
Man-days lost							
<i>Public</i>							
Accidental							
Death	0	0	0	0	0.1562594	0.15625939	0.156259
Injury							
Man-days lost							
Disease							
Death	0	0	0	0	0	0	0.121535
Disability							
Man-days lost							

Table B15: Gas-Fired Electrical Production System Risk Ranges (million \$) (for Year 2015)

Risks	Gathering and Handling Fuel	Transportation	Electricity Production	Total
<i>Occupational</i>				
Accidental				
Death	1.158596478	0.86152	0.4159064	4.753216
Injury				14.25965
Man-days lost				
Disease				
Death	0	0	0	0
Disability				
Man-days lost				
<i>Public</i>				
Accidental				
Death	0	0	0	0.267368
Injury				0.267368
Man-days lost				
Disease				
Death	0	0	0	0.071298
Disability				0.207953
Man-days lost				

Table B16: Gas-Fired Electrical Production System Risk Ranges (million \$) (for Year 2020)

Risks	Gathering and Handling Fuel Transportation			Electricity Production			Total
<i>Occupational</i>							
Accidental							
Death	1.391963461	11.08432495	1.03505	1.213507	0.4996792	1.891642652	5.710619
Injury							17.13186
Man-days lost							
Disease							
Death	0	0	0	0	0	0	0
Disability							
Man-days lost							
<i>Public</i>							
Accidental							
Death	0	0	0	0	0.3212223	0.321222337	0.321222
Injury							
Man-days lost							
Disease							
Death	0	0	0	0	0	0	0.24984
Disability							
Man-days lost							

Table B17: Nuclear Electrical Production System Risk Ranges (million \$) (for Year 2000)

Risks	Gathering and Handling Fuel	Emissions (Sulfur Oxides)	Transportation	Electricity	Production	Waste Management	Total
<i>Occupational</i>							
Accidental							
Death	3.24793296	0	0.073078	0.324793	0.46012384	0.1353305	8.119832
Injury							20.57024
Man-days lost							
Disease							
Death	0.595454376	0	0.000812	0.108264	3.51859404	2.002892	6.495866
Disability							21.92355
Man-days lost							
<i>Public</i>							
Accidental							
Death	0	0	0.324793	0.324793	0	0	0.324793
Injury							0.324793
Man-days lost							
Disease							
Death	0.839049348	0.097438	0.035186	0.035186	6.22520484	0.1353305	1.894628
Disability		0.27066108					14.07438
Man-days lost							

Table B18: Nuclear Electrical Production System Risk Ranges (million \$) (for Year 2005)

Risks	Gathering and Handling Fuel	Emissions (Sulfur Oxides)	Transportation	Electricity	Production	Waste Management	Total
<i>Occupational</i>							
Accidental							
Death	3.51677232	0	0.079127	0.351677	0.49820941	0.1465322	8.791931
Injury							
Man-days lost	16.70466852	0				0.1465322	22.27289
Disease							
Death	0.644741592	0	0.000879	0.117226	3.80983668	2.1686763	23.73821
Disability							
Man-days lost	17.5838616	0				2.1686763	23.73821
<i>Public</i>							
Accidental							
Death	0	0	0.351677	0.351677	0	0	0.351677
Injury							
Man-days lost							
Disease							
Death	0.908499516	0.1055032	0.038098	0.038098	6.74048028	0.1465322	2.051451
Disability							
Man-days lost	0.908499516	0.1055032	0.038098	0.038098	6.74048028	7.326609	15.23935

Table B19: Nuclear Electrical Production System Risk Ranges (million \$) (for Year 2010)

Risks	Gathering and Handling Fuel	Emissions (Sulfur Oxides)	Transportation	Electricity Production	Waste Management	Total
<i>Occupational</i>						
Accidental						
Death	3.00653568	0	0.067647	0.32570803	0.1252723	7.516339
Injury	14.28104448			0.42592589	0.1252723	19.04139
Man-days lost						
Disease						
Death	0.551198208	0	0.000752	3.25708032	1.8540303	6.013071
Disability	15.0326784			3.25708032	1.8540303	20.29412
Man-days lost						
<i>Public</i>						
Accidental						
Death	0	0	0.300654	0	0	0.300654
Injury	0					
Man-days lost						
Disease						
Death	0.776688384	0.0901961	0.032571	0.75163392	0.1252723	1.753812
Disability	0.776688384	0.25054464	0.032571	5.76252672	6.263616	13.02832
Man-days lost						

Table B20: Nuclear Electrical Production System Risk Ranges (million \$) (for Year 2015)

Risks	Gathering and Handling Fuel	Emissions (Sulfur Oxides)	Transportation	Electricity	Production	Waste Management	Total
<i>Occupational</i>							
Accidental							
Death	2.44327536	0	0.054974	0.244328	0.34613068	0.1018031	6.108188
Injury							15.47408
Man-days lost	11.60555796	0					
Disease							
Death	0.447933816	0	0.000611	0.081443	2.64688164	1.5066865	4.886551
Disability							16.49211
Man-days lost	12.2163768						
<i>Public</i>							
Accidental							
Death	0	0	0.244328	0.244328	0	0	0.244328
Injury							
Man-days lost							
Disease							
Death	0.631179468	0.0732983	0.026469	0.61081884	4.68294444	5.090157	1.425244
Disability							10.58753
Man-days lost	0.631179468	0.20360628					

Table B21: Nuclear Electrical Production System Risk Ranges (million \$) (for Year 2020)

Risks	Gathering and Handling Fuel	Emissions (Sulfur Oxides)	Transportation	Electricity	Production	Waste Management	Total
Occupational							
Accidental							
Death	2.78792928	0	0.062728	0.278793	0.39495665	0.1161637	6.969823
Injury	13.24266408						17.65689
Man-days lost							
Disease							
Death	0.511120368	0	0.000697	0.092931	3.02025672	1.7192231	5.575859
Disability	13.9396464						18.81852
Man-days lost							
Public							
Accidental							
Death	0	0	0.278793	0.278793	0	0	0.278793
Injury							
Man-days lost							
Disease							
Death	0.720215064	0.23232744	0.030203	0.69698232	5.34353112	5.808186	1.626292
Disability							12.08103
Man-days lost							

Table B22: Hydroelectric Power Risk Ranges (million \$) (for Year 2000)

Risks	Material Aquisition and Construction		Operation and Maintenance		Transportation	Dam	Failures	Total
<i>Occupational</i>								
Accidental								
Death	12.3497112	27.75216	8.7419304	8.7419304	0	0	0	20.81412
Injury								36.07781
Man-days lost								
Disease								
Death	0	0	0	0	0	0	0	0
Disability								
Man-days lost								
<i>Public</i>								
Accidental								
Death	0	0	0	0	0	15.2637	22.2017	15.26369
Injury								22.20173
Man-days lost								
Disease								
Death	0	0	0	0	0	0	0	0.015264
Disability								0.044403
Man-days lost								

Table B23: Hydroelectric Power Risk Ranges (million \$) (for Year 2005)

Risks	Material Acquisition and Construction		Operation and Maintenance		Transportation	Dam	Failures	Total
<i>Occupational</i>								
Accidental								
Death	12.70157448	28.542864	8.99100216	8.99100216	0	0	0	21.40715
Injury								37.10572
Man-days lost								
Disease								
Death	0	0	0	0	0	0	0	0
Disability								
Man-days lost								
<i>Public</i>								
Accidental								
Death	0	0	0	0	0	15.6986	22.8343	15.69858
Injury								22.83429
Man-days lost								
Disease								
Death	0	0	0	0	0	0	0	0.015699
Disability								0.045669
Man-days lost								

Table B24: Hydroelectric Power Risk Ranges (million \$) (for Year 2010)

Risks	Material Acquisition and Construction		Operation and Maintenance		Transportation	Dam	Failures	Total
<i>Occupational</i>								
Accidental	13.30	18.184	29.89	17.12				
Death			9.41	588928	0	0	0	22.41878
Injury								38.85923
Man-days lost								
Disease								
Death	0	0	0	0	0	0	0	0
Disability								
Man-days lost								
<i>Public</i>								
Accidental								
Death	0	0	0	0	0	16.4404	23.9134	16.44044
Injury								23.91337
Man-days lost								
Disease								
Death	0	0	0	0	0	0	0	0.01644
Disability								0.047827
Man-days lost								

Table B25: Hydroelectric Power Risk Ranges (million \$) (for Year 2015)

Risks	Material Acquisition and Construction		Operation and Maintenance		Transportation	Dam	Failures	Total
<i>Occupational</i>								
Accidental								
Death	13.30181184	29.891712	9.41588928	9.41588928	0	0	0	22.41878
Injury								38.85923
Man-days lost								
Disease								
Death	0	0	0	0	0	0	0	0
Disability								
Man-days lost								
<i>Public</i>								
Accidental								
Death	0	0	0	0	0	16.4404	23.9134	16.44044
Injury								23.91337
Man-days lost								
Disease								
Death	0	0	0	0	0	0	0	0.01644
Disability								0.047827
Man-days lost								

Table B26: Hydroelectric Power Risk Ranges (million \$) (for Year 2020)

Risks	Material Acquisition and Construction		Operation and Maintenance		Transportation	Dam	Failures	Total
<i>Occupational</i>								
Accidental								
Death	13.30181184	29.891712	9.41588928	9.41588928	0	0	0	22.41878
Injury								38.85923
Man-days lost								
Disease								
Death	0	0	0	0	0	0	0	0
Disability								
Man-days lost								
<i>Public</i>								
Accidental								
Death	0	0	0	0	0	16.4404	23.9134	16.4404
Injury								23.91337
Man-days lost								
Disease								
Death	0	0	0	0	0	0	0	0.01644
Disability								0.047827
Man-days lost								

Spreadsheet B1: Emission Rates and Merged Stack Parameters for SCREEN3

Facility Characteristics:

		Capacity (MW)	Lifetime (yrs)	Avg. CF (%)	Heat Rate (Btu/kWh)	Stack Height (m)	Stack Diameter (m)	Gas Velocity (m/s)	Exhaust gas Volume (ACFM)	Exhaust Gas Temp. (K)
Coal-Steam		300	30	65	9856	150	150	4	30	784300
Oil-Steam		300	30	65	9400	150	150	4.3	16	748100
Station	Type	Capacity	Location							
Atikokan	Coal-Steam		215	Rural						
Thunder Bay	Coal-Steam		330	Urban						
Lakeview	Coal-Steam		1140	Urban						
Lambton	Coal-Steam		2081	Urban						
Nanticoke	Coal-Steam		3976	Urban						
Lennox	Oil-Steam		2140	Urban						

Conversion Factors:
mmBtu = 1000000 Btu
lb = 453.6 g
kWh = 3.6 MJ
MJ = 1000000 J

SO2

		Emission Rate		Emission Rate		Emission Rate	
		(lb/mmBtu)	(g/J)	(g/J)	(Kg/GWh)	Rate	
Coal		0.39		4.84324E-07	1743.566		
Oil		0.32		3.79008E-07	1364.429		
Emission Rate Stack Parameters							
		(g/s)	(m4K/g)				
Atikokan		104.13	217114.00				
Thunder Bay		159.83	141453.06		Rep. Q =	263.96	
Lakeview		552.13	40946.94				
Lambton		998.19	22648.96				
Nanticoke		1925.67	11740.32				
Lennox		811.08	17179.70		Rep. Q =	4287.07	

PM10

	Emission rate (lb/mmBtu)	Emission Rate (g/J)	Emission Rate
Coal	0.032	3.97394E-08	143.082
Oil	0.007	8.2908E-09	29.847
	Emission Rate (g/s)	Stack Parameters (m4K/g)	
Atikokan	8.54	2646076.93	
Thunder Bay	13.11	1723959.21	Rep. Q = 21.66
Lakeview	45.30	499040.82	
Lambton	81.90	276034.23	
Nanticoke	158.00	143085.15	
Lennox	17.74	785357.85	Rep. Q = 302.95

VOC

	Emission rate (lb/mmBtu)	Emission Rate (g/J)	Emission Rate (Kg/GWh)
Coal	0.003	3.72557E-09	13.412
Oil	0.005	5.922E-09	21.319
	Emission Rate (g/s)	Stack Parameters (m4K/g)	
Atikokan	0.80	28224820.58	
Thunder Bay	1.23	1838898.26	Rep. Q = 2.03
Lakeview	4.25	5323102.13	
Lambton	7.68	2944365.08	
Nanticoke	14.81	1526241.56	
Lennox	12.67	1099500.99	Rep. Q = 39.41

CO2

	Emission rate		Emission Rate		Emission Rate
	(lb/mmBtu)	(g/J)	(lb/mmBtu)	(g/J)	(Kg/GWh)
Coal	220	0.000273208	0.000273208	983549.952	
Oil	169	0.000200164	720588.960		
Gas	117	0.000138575	498869.280		
	Emission Rate		Stack Parameters		
	(g/s)	(m4K/g)	(m4K/g)		
Atkokan	58739.79	394.88			
Thunder Bay	90158.75	250.76	Rep. Q =	148898.53	
Lakeview	311457.48	72.59			
Lambton	563082.35	40.15			
Nanticoke	1086276.28	20.81			
Lennox	428350.10	32.53	Rep. Q =	2389166.22	

NO

	Emission rate		Emission Rate		Emission Rate
	(lb/mmBtu)	(g/J)	(lb/mmBtu)	(g/J)	(Kg/GWh)
Coal	0.0325	4.03603E-08	145.297		
Oil	0.0325	3.8493E-08	138.575		
Gas	0.0078	9.23832E-09	33.258		
	Emission Rate		Stack Parameters		
	(g/s)	(m4K/g)	(m4K/g)		
Atkokan	8.68	2605368.05			
Thunder Bay	13.32	1697436.76	Rep. Q =	22.00	
Lakeview	46.01	491363.27			
Lambton	83.18	271787.55			
Nanticoke	160.47	140883.84			
Lennox	82.38	169154.00	Rep. Q =	372.04	

Lead

	Emission rate		Emission Rate		Emission Rate
	(lb/mmBtu)	(g/J)	(lb/mmBtu)	(g/J)	(Kg/GWh)
Coal	0.0000168		2.08632E-11		0.075
Oil	0.000007		8.2908E-12		0.030
	Emission Rate		Stack Parameters		
	(g/s)	(m4K/g)	(g/s)	(m4K/g)	
Atikokan	0.00	5040146532.79			
Thunder Bay	0.01	3283731831.97	Rep. Q =		0.01
Lakeview	0.02	950553951.36			
Lambton	0.04	525779478.19			
Nanticoke	0.08	272543134.95			
Lennox	0.02	785357849.64	Rep. Q =		0.17

Mercury

	Emission rate		Emission Rate		Emission Rate
	(lb/mmBtu)	(g/J)	(lb/mmBtu)	(g/J)	(Kg/GWh)
Coal	0.0000009		1.11767E-12		0.004
Oil	0.0000005		5.922E-13		0.002
	Emission Rate		Stack Parameters		
	(g/s)	(m4K/g)	(g/s)	(m4K/g)	
Atikokan	0.00024	94082735278.75			
Thunder Bay	0.00037	61296327530.09	Rep. Q =		0.0006
Lakeview	0.00127	17743673758.71			
Lambton	0.00230	9814550259.55			
Nanticoke	0.00444	5087471852.35			
Lennox	0.00127	10995009894.99	Rep. Q =		0.009

Nickel

	Emission rate (lb/mmBtu)	Emission Rate (g/J)	Emission Rate (Kg/GWh)	Emission Rate
Coal	0.0000029	3.60138E-12	0.013	
Oil	0.00072	8.52768E-10	3.070	
	Emission Rate (g/s)	Stack Parameters (m4K/g)		
Atikokan	0.00077	29198090258.92		
Thunder Bay	0.00119	19022998198.99	Rep. Q =	0.0020
Lakeview	0.00411	5506657373.39		
Lambton	0.00742	3045894908.14		
Nanticoke	0.01432	1578870574.87		
Lennox	1.82492	7635423.54	Rep. Q =	1.851

Chromium

	Emission rate (lb/mmBtu)	Emission Rate (g/J)	Emission Rate (Kg/GWh)	Emission Rate
Coal	0.0000032	3.97394E-12	0.014	
Oil	0.0000052	6.15888E-12	0.022	
	Emission Rate (g/s)	Stack Parameters (m4K/g)		
Atikokan	0.00085	26460769297.15		
Thunder Bay	0.00131	17239592117.84	Rep. Q =	0.0022
Lakeview	0.00453	4990408244.64		
Lambton	0.00819	2760342260.50		
Nanticoke	0.01580	1430851458.47		
Lennox	0.01318	1057212489.90	Rep. Q =	0.042

Arsenic

	Emission rate		Emission Rate		Emission Rate
	(lb/mmBtu)	(g/J)	(lb/mmBtu)	(g/J)	(Kg/GWh)
Coal	0.0000015		1.86278E-12		0.007
Oil	0.0000055		6.5142E-12		0.023
	Emission Rate		Stack Parameters		
	(g/s)	(m4K/g)	(g/s)	(m4K/g)	
Atlikokan	0.00040		58449841167.25		
Thunder Bay	0.00061		36777796518.08	Rep. Q =	0.0010
Lakeview	0.00212		10646204255.23		
Lambton	0.00384		5886730155.73		
Nanticoke	0.00741		3052483111.41		
Lennox	0.01394		989546354.09	Rep. Q =	0.027

Formaldehyde

	Emission rate		Emission Rate		Emission Rate
	(lb/mmBtu)	(g/J)	(lb/mmBtu)	(g/J)	(Kg/GWh)
Coal	0.000003		3.72557E-12		0.013
Oil	0.00002		2.3688E-11		0.085
	Emission Rate		Stack Parameters		
	(g/s)	(m4K/g)	(g/s)	(m4K/g)	
Atlikokan	0.00080		28224820583.62		
Thunder Bay	0.00123		18388898259.03	Rep. Q =	0.0020
Lakeview	0.00425		5323102127.61		
Lambton	0.00768		2944365077.86		
Nanticoke	0.01481		1526241555.70		
Lennox	0.05069		274875247.37	Rep. Q =	0.077

Spreadsheet B2: Annual Average Concentrations (from SCREEN results)

Conversions (from 1 hour max. concentrations):		
Averaging Time	Multiplying Factor	
3 hours	0.9 +/- 0.1	
8 hours	0.7 +/- 0.2	
24 hours	0.4 +/- 0.2	
Annual	0.08 +/- 0.02	

SO2

Screen results:
Plants 1& 2: 166.9 ug/m3 24 -hr
Plants 3-6: 2973 ug/m3 1-hr
Total Conc = 3251.167 ug/m3 1-hr
260.0933 ug/m3 Annual

278.1667 ug/m3 1-hr

Nox

Screen results:
Plants 1& 2: 179.8 ug/m3 24 -hr
Plants 3-6: 3111 ug/m3 1-hr
Total Conc = 3410.667 ug/m3 1-hr
272.8533 ug/m3 Annual

299.6667 ug/m3 1-hr

PM10

Screen results:
Plants 1& 2: 13.69 ug/m3 24 -hr
Plants 3-6: 232.1 ug/m3 1-hr
Total Conc = 254.9167 ug/m3 1-hr
20.39333 ug/m3 Annual

22.81667 ug/m3 1-hr

VOC

Screen results:			
Plants 1& 2:	1.284 ug/m3	24 -hr	1-hr
Plants 3-6:	36.67 ug/m3	1-hr	2.14 ug/m3
Total Conc =	38.81 ug/m3	1-hr	
	3.1048 ug/m3	Annual	

CO2

Screen results:			
Plants 1& 2:	94180 ug/m3	24 -hr	1-hr
Plants 3-6:	1830000 ug/m3	1-hr	156966.7 ug/m3
Total Conc =	1986967 ug/m3	1-hr	
	156957.3 ug/m3	Annual	

NO

Screen results:			
Plants 1& 2:	13.92 ug/m3	24 -hr	1-hr
Plants 3-6:	285 ug/m3	1-hr	23.2 ug/m3
Total Conc =	308.2 ug/m3	1-hr	
	24.666 ug/m3	Annual	

LEAD

Screen results:			
Plants 1& 2:	0.006325 ug/m3	24 -hr	1-hr
Plants 3-6:	0.1302 ug/m3	1-hr	0.010542 ug/m3
Total Conc =	0.140742 ug/m3	1-hr	
	0.011259 ug/m3	Annual	

Mercury

Screen results:			
Plants 1& 2:	0.00038 ug/m3	24 -hr	1-hr
Plants 3-6:	0.006895 ug/m3	1-hr	0.000633 ug/m3
Total Conc =	0.007528 ug/m3	1-hr	
	0.000602 ug/m3	Annual	

Nickel

Screen results:			
Plants 1& 2:	0.001265 ug/m3	24 -hr	1-hr
Plants 3-6:	1.722 ug/m3	1-hr	0.002108 ug/m3
Total Conc =	1.724108 ug/m3	1-hr	
	0.137929 ug/m3	Annual	

Chromium

Screen results:			
Plants 1& 2:	0.001392 ug/m3	24 -hr	1-hr
Plants 3-6:	0.03908 ug/m3	1-hr	0.00232 ug/m3
Total Conc =	0.0414 ug/m3	1-hr	
	0.003312 ug/m3	Annual	

Arsenic

Screen results:			
Plants 1& 2:	0.000633 ug/m3	24 -hr	1-hr
Plants 3-6:	0.02512 ug/m3	1-hr	0.001054 ug/m3
Total Conc =	0.026174 ug/m3	1-hr	
	0.002094 ug/m3	Annual	

Formaldehyde

Screen results:

Plants 1& 2:	0.001265 ug/m3	24 -hr	0.002108 ug/m3	1-hr
Plants 3-6:	0.07164 ug/m3	1-hr		

Total Conc =	0.073748 ug/m3	1-hr
	0.0059 ug/m3	Annual

Background Concentrations (from NAPS 1996)

So2	5.78 ppb	15.38867 ug/m3	MW	64 kg/kmol
NO2	18.43 ppb	35.26765 ug/m3		46 kg/kmol
NO	18.13 ppb	22.62624 ug/m3		30 kg/kmol
Lead	0.026 ug/m3			
PM10	23.4 ug/m3			

***** no other pollutants that were modeled in SCREEN have background conc in NAPS.*****

Total Annual Average Concentrations (ug/m3)

note: if there were no levels measured in NAPS , the background conc are assumed to be zero.

SO2	275.482 ug/m3	
Nox	308.121 ug/m3	(used NO2 for background levels)
PM10	43.79333 ug/m3	
VOC	3.1048 ug/m3	
CO2	158957.3 ug/m3	
NO	47.28224 ug/m3	
Lead	0.037259 ug/m3	
Hg	0.000602 ug/m3	

Ozone (estimation)	9.98 ug/m3
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Spreadsheet B3: Health Effects of Air Emissions

Assumed POP Demographics (NYS ext. study, 1995):	
65 yrs and up:	12.5 %
under 65 yrs:	87.5 %
25 yrs and up:	64 %
under 18 yrs:	17 %
asthma:	4.3 %

	2000	2005	2010	2015	2020
Affected Ontario Population:	2371800	2493600	2623600	2785400	2969000
CPI:	1.465	1.606	1.77	1.946	2.148

(Canada's Emission Outlook, NRC, 1999)

PM10:

Annual change in PM10: 20.39 ug/m3

Morbidity Effects:

Chronic Bronchitis (CB):	2000	2005	2010	2015	2020
Cases =	2878.92	3026.76	3184.56	3380.95	3603.81
Children w/ Bronchitis (B):	19734.51	20747.95	21829.61	23175.86	24703.51

Valuation:

Chronic Bronchitis (CB):	2000	2005	2010	2015	2020
Cost (\$) =	1133684642.42	1306630330.24	1515134870.28	1768523406.26	2080773841.47
Children w/ Bronchitis (B):	9367184.64	10796070.74	12518845.50	14612475.58	17192453.80
Annual Morbidity Costs:	1143061827.05	1317426400.98	1527653715.79	1783135881.84	2097966296.27

Chronic Bronchitis (CB):	Cost (\$/GWh) =	26963.84	31076.95	36036.03	42062.63	49488.21
Children w/ Bronchitis (B):	Cost (\$/GWh) =	222.79	256.77	297.75	347.54	408.91
Total Morbidity Effects:	Cost (\$/GWh) =	27186.63	31333.72	36333.78	42410.18	49898.12

Coal Effects	Cost (\$/GWh) =	21749.30	25066.98	29067.02	33928.14	39918.49
Gas Effects	Cost (\$/GWh) =	679.67	783.34	908.34	1060.25	1247.45
Oil Effects	Cost (\$/GWh) =	27186.63	31333.72	36333.78	42410.18	49898.12

PM10 Mortality Effects:

Deaths =	2000	2005	2010	2015	2020
	483.69	508.53	535.04	566.04	605.48

Valuation:

	2000	2005	2010	2015	2020
Annual Mortality Costs (\$) =	3741431772	4312156088	5000265089	5836500777	6866993164
Annual Mortality Costs (\$/GWh) =	88986.37	102560.50	118926.51	138815.57	163324.85
Coal Effects	Cost (\$/GWh) =	82048.40	95141.21	111052.46	130659.88
Gas Effects	Cost (\$/GWh) =	2564.01	2973.16	3470.39	4083.12
Oil Effects	Cost (\$/GWh) =	102560.50	118926.51	138815.57	163324.85

Ozone:

Annual Change in ozone = 9.98 ug/m3
0.005 ppm

Morbidity Effects:

Asthma Attacks (AA)	Cases =	2000	2005	2010	2015	2020
Acute Respiratory Symptoms (ARS)	Cases =	21,417	22,517	23,691	25,152	26,810
		189,744	199,488	209,888	222,832	237,520

Valuation:

Asthma Attacks (AA)	Cost (\$) =	2000	2005	2010	2015	2020
Acute Respiratory Symptoms (ARS)	Cost (\$) =	1380.56	1591.16	1845.06	2153.63	2533.87
Total Morbidity Costs:	Cost (\$) =	3335.70	3844.53	4458.02	5203.57	6122.32
Asthma Attacks (AA)	Cost (\$/GWh) =	4716.26	5435.69	6303.08	7357.20	8656.19
Acute Respiratory Symptoms (ARS)	Cost (\$/GWh) =	0.03284	0.03784	0.04388	0.05122	0.06027
Total Morbidity Effects:	Cost (\$/GWh) =	0.07934	0.09144	0.10603	0.12376	0.14561
	Cost (\$/GWh) =	0.11217	0.12928	0.14991	0.17498	0.20588

Coal Effects	Cost (\$/GWh) =	0.112	0.129	0.150	0.175	0.206
Gas Effects	Cost (\$/GWh) =	0.054	0.062	0.072	0.084	0.099
Oil Effects	Cost (\$/GWh) =	0.067	0.078	0.090	0.105	0.124

Mortality Effects:

Deaths =	2000	2005	2010	2015	2020
	6.26E-03	6.58E-03	6.93E-03	7.35E-03	7.84E-03

Valuation:

	2000	2005	2010	2015	2020	
Annual Mortality Costs (\$) =	48434.36	55822.62	64730.47	75555.88	88896.02	
Annual Mortality Costs (\$/GWh) =	1.15196	1.32769	1.53955	1.79702	2.11431	
Coal Effects	Cost (\$/GWh) =	1.152	1.328	1.540	1.797	2.114
Gas Effects	Cost (\$/GWh) =	0.553	0.637	0.739	0.863	1.015
Oil Effects	Cost (\$/GWh) =	0.691	0.797	0.924	1.078	1.269

Lead

Annual Change in Lead = 0.00690 ug/m3

Year	Change in		Mean PbB (ug/dl)	Damage	
	Geometric Mean PbB (ug/dl)	Value(\$1992)			
0	0	4.65			93220420.79 (year 2000)
1	0.323	4.973			
2	0.343	5.316			
3	0.364	5.680			
4	0.384	6.064			
5	0.405	6.469			136348738.3 (year 2005)
6	0.425	6.895			
7	0.446	7.341			
8	0.467	7.807			

9	0.487	8.294	195183344.6 (year 2010)
10	0.508	8.802	
11	0.528	9.330	
12	0.549	9.878	
13	0.569	10.448	
14	0.590	11.037	
15	0.610	11.648	274225269.3 (year 2015)
16	0.631	12.279	
17	0.651	12.930	
18	0.672	13.602	
19	0.692	14.294	
20	0.713	15.007	376607571.7 (year 2020)
21	0.734	15.741	
22	0.754	16.495	
23	0.775	17.269	
24	0.795	18.064	
25	0.816	18.880	
26	0.836	19.716	
27	0.857	20.573	
28	0.877	21.450	
29	0.898	22.348	
30	0.918	23.267	
31-80	0.616		

	2000	2005	2010	2015	2020
Annual Lead Costs (\$1992) =	93220420.79	136348738.34	195183344.60	274225269.29	376607571.75
Annual Lead Costs (\$) =	109254333.16	175180859.02	276379615.95	426913899.23	647162451.29
Annual Lead Costs (\$/GWh) =	2598.51	4166.51	6573.42	10153.74	15392.14
Coal Effects	Cost (\$/GWh) =	2598.510	4166.509	6573.424	10153.738
Gas Effects	Cost (\$/GWh) =	129.925	208.325	328.671	507.687
Oil Effects	Cost (\$/GWh) =	1091.374	1749.934	2760.838	4264.570
					6484.698

Mercury

Annual Change in Mercury = 0.000602 ug/m3

Damages (NYS study)

Coal 500 MW
Oil 500 MW

\$/Kg of Hg Emitted

99 1992 dollars
319 1992 dollars

\$/Kg of Hg Emitted/MW Capacity

0.198 1992 dollars
0.638 1992 dollars

Station	Type	Capacity	Emission Rate (g/s)	Annual Hg Emission (Kg)
Atikokan	Coal-Steam	215	0.0002403	7.5781
Thunder Bay	Coal-Steam	330	0.0003688	11.6315
Lakeview	Coal-Steam	1140	0.0012741	40.1814
Lambton	Coal-Steam	2061	0.0023035	72.6438
Nanticoke	Coal-Steam	3976	0.0044439	140.1415
Lennox	Oil-Steam	2140	0.0012673	39.9858

	Annual		Annual		Annual	
	2000 (\$)	Damages 2005 (\$)	Damages 2010 (\$)	Damages 2015 (\$)	Damages 2020 (\$)	
Coal-Steam	378.09	414.47	456.80	502.22	554.35	
Coal-Steam	890.72	976.45	1076.16	1183.17	1305.98	
Coal-Steam	10629.75	11652.81	12842.76	14119.78	15585.46	
Coal-Steam	34743.15	38087.03	41976.36	46150.28	50940.80	
Coal-Steam	129302.20	141746.98	156221.77	171755.69	189584.38	
Total Annual (\$) =	175943.90	192877.74	212573.85	233711.14	257970.98	
Total Annual (\$/GWh	7.52	8.24	9.08	9.98	11.02	
Oil-Steam	63951.52	70106.58	77265.65	84948.57	93766.46	
Total Annual (\$/GWh	3.43	3.76	4.15	4.56	5.03	

Air Toxics

	Annual Conc.	Rfl (ug/m3)	RI	DI	Total Risk
Nickel	0.1379 ug/m3	0.00024		15.76	1 7.92578E-06
Chromium	0.0033 ug/m3	0.012		0.84	1 1.0447E-06
Arsenic	0.0021 ug/m3	0.0043		88.51	1 1.15134E-05
Formaldehyde	0.0059 ug/m3	0.000013		0	0 1.09569E-09
Cancer Cases Estimate:					
Cancer (cases):	2000	2005	2010	2015	2020
Nickel	18.79835	19.76371	20.79406	22.07645	23.53163
Chromium	2.47782	2.60506	2.74087	2.90891	3.10171
Arsenic	27.30756	28.70990	30.20664	32.06952	34.18338
Formaldehyde	0.00260	0.00273	0.00287	0.00305	0.00325
Valuation:					
Annual Cancer Effects Costs (\$)		2000	2005	2010	2015
Nickel =		70138277.29	80837288.10	93736836.79	109413223.30
Chromium =		9244952.79	10655193.44	12355487.82	14421798.25
Arsenic =		101886856.67	117428849.18	136167468.37	158939880.34
Formaldehyde =		9696.18	11175.26	12958.54	15125.70
					17796.30
Total Air Toxics Considered (\$) =					
Total Air Toxics Considered (\$/GWh) =		181279782.94	208932505.97	242272751.53	282790027.59
Coal Effects		Cost (\$/GWh) =	4311.57	4969.26	5762.23
Gas Effects		Cost (\$/GWh) =	1293.470	1490.778	1728.668
Oil Effects		Cost (\$/GWh) =	215.578	248.463	288.111
		Cost (\$/GWh) =	4311.566	4969.259	5762.225
					6725.890
					7913.412
					2374.024
					395.671
					7913.412

Spreadsheet B4: Other Air Externalities

Visibility Effects:

household = 2.63 persons.

(NYS ext. study, 1995)

	Conc After		Constants	
	Starting Conc. (ug/m3)	Emission Effect Conc. (ug/m3) 2000	Emissions (ug/m3)	
PM	23.4	20.4	43.8	11.6 1/Mm
NO2	35.27	272.85	308.12	Bl =
sulfate	5.85	5.1	10.95	Sulfates=
				NO2=
				PM2.5 (fly ash)=
Starting Annual Visual Range:				

bext = 0.1039351 (1/Mm)

VR = 37.63887272 Mm

Annual Visual Range After the Change In Emissions:

bext (1/Mm) = 0.2159058 2000 2005 2010 2015 2020

VR (Mm) = 18.1190298 0.3278761 0.4398466 0.5518171 0.6637876

8.894009866 7.089305496 5.893451459

	2000	2005	2010	2015	2020
Households	901825	948137	997567	1059087	1128897
Annual WTP (\$)	154540254.95	101788637.60	82998927.74	74785901.23	71677481.51
Annual WTP (\$/GWh)	3675.59	2420.95	1974.05	1778.71	1704.78
Coal Cost (\$/GWh) =	3675.592	2420.945	1974.050	1778.711	1704.780
Gas Cost (\$/GWh) =	91.890	60.524	49.351	44.468	42.620
Oil Cost (\$/GWh) =	2940.473	1936.756	1579.240	1422.969	1363.824

Materials Damage From PM and SO2:

PM10 = 20.39333333 ug/m3
SO2 = 260.0933333 ug/m3

	2000	2005	2010	2015	2020
Households =	901825	948137	997567	1059087	1128897
Annual PM10 Damages (\$)	141274875.48	162825182.63	188807887.17	220383791.76	259294746.88
Annual SO2 Damages (\$)	720718926.68	830658604.13	963210318.40	1124295946.62	1322801602.47
Total Annual Damages (\$)	861993802.16	993483786.76	1152018205.57	1344679738.38	1582086349.35
Total Annual Damages (\$/GWh)	20501.70	23629.06	27399.65	31981.92	37628.64
Coal Cost (\$/GWh) =	20501.686	23629.059	27399.648	31981.918	37628.644
Gas Cost (\$/GWh) =	512.542	590.726	684.991	799.548	940.716
Oil Cost (\$/GWh) =	16401.357	18903.247	21919.719	25585.534	30102.915

CO2 and other Greenhouse gas Effects:

Global Warming potential (Rowe et al., 1995a)

Gas	
CO2	1
CH4	11
N2O	270
CFC-11	3400
CFC-12	7100
HCFC-22	1600

The global warming potential values are used to convert othe GG emissions to values of CO2

	Emission (g/s)	GW Potential	Damage Estimate (1992\$/Short ton)
CO2 =	2538064.76	1	1.4
N2O =	394.04	270	378

Damage Estimate (\$/Kg)				
	2000	2005	2010	2016
	0.001808682	0.00198276	0.002185233	0.002402522
	0.488344099	0.535345135	0.590013007	0.648680967
Annual Damage Estimates (\$)				
CO2 =	144767637.26	158700904.74	174906974.71	192298854.69
N2O =	6068381.31	6852437.12	7331764.44	8060798.65
Total =	150836018.57	165353341.86	182238739.16	200359653.34
Damages (\$/GWh)	3587.49	3932.77	4334.37	4765.36
Coal Cost (\$/GWh) =	3587.490	3932.771	4334.374	4765.362
Gas Cost (\$/GWh) =	1901.370	2084.368	2297.218	2525.642
Oil Cost (\$/GWh) =	2762.367	3028.233	3337.468	3669.329

Radiation Emissions From Coal Piles:

Cost (\$/rem) = 3417
Annual Does = 0.001333 rem (for 1000MW plant with 60% CF)

Station	Type	Capacity (MW)	Annual Dose (rem)
Atikokan	Coal-Steam	215	0.000286595
Thunder Bay	Coal-Steam	330	0.00043989
Lakeview	Coal-Steam	1140	0.00151962
Lambton	Coal-Steam	2061	0.002747313
Nanticoke	Coal-Steam	3976	0.005300008

Annual Radiation Damages (\$):		2000	2005	2010	2015	2020
Atkokan		1,147,733,875	1,258,198,384	1,386,681,883	1,524,566,635	1,682,820,726
Thunder Bay		1,761,638,04	1,931,188,186	2,128,395,448	2,340,032,51	2,582,934,137
Lakeview		6,085,658,685	6,671,377,371	7,352,638,821	8,083,748,669	8,922,863,382
Lambton		11,002,230,31	12,061,148,04	13,292,797,03	14,614,566,67	16,131,597,75
Nanticoke		21,225,068,24	23,267,891,6	25,643,940,31	28,193,846,24	31,120,442,81
Total System		41,222,330,14	45,189,803,56	49,804,453,49	54,756,760,72	60,440,658,81
Damages (\$/GWh)		0.00176	0.00193	0.00213	0.00234	0.00258

Spreadsheet B5: Water Externalities

Station	Type	Capacity (MW)	Water Use (cfs)
Bruce A	Nuclear - CANDU	3076	4521.72
Bruce B	Nuclear - CANDU	3140	4615.8
Pickering A	Nuclear - CANDU	2080	3028.2
Pickering B	Nuclear - CANDU	2084	3034.08
Darlington	Nuclear - CANDU	3524	5180.28
Atikokan	Coal-Steam	215	264.45
Thunder Bay	Coal-Steam	330	405.9
Lakeview	Coal-Steam	1140	1402.2
Lambton	Coal-Steam	2061	2535.03
Nanticoke	Coal-Steam	3976	4890.48
Lennox	Oil-Steam	2140	2589.4

Impingement and Entrainment Effects:

Damages per flow from Hudson River Case Study =

725 \$1992/cfs

Annual Damages (\$)	2000	2005	2010	2015	2020
Bruce A	481729.21	528093.59	582020.96	639894.23	706316.96
Bruce B	491752.18	539081.23	594130.63	653208.02	721012.76
Pickering A	322614.49	353664.76	389779.96	428537.75	473021.11
Pickering B	323240.93	354351.49	390536.82	429369.86	473939.60
Darlington	551890.03	605007.09	666788.64	733090.79	809187.57
Total Nuclear Damage (\$):	1366883.14	1498439.81	1651456.08	1815668.66	2004139.92
Nuclear Damage (\$/GWh):	19.57	21.46	23.65	26.00	28.70
Atikokan	28173.64	30885.23	34039.14	37423.82	41308.51
Thunder Bay	43243.25	47405.23	52246.12	57441.21	63403.76
Lakeview	149385.79	163763.53	180486.58	198433.27	219031.17
Lambton	270073.78	298067.23	326300.74	358746.46	395985.31
Nanticoke	521015.69	571161.23	629486.53	692079.54	763919.25
Total Coal Damage (\$):	1011892.14	1109282.44	1222559.11	1344124.31	1483648.00
Coal Damage (\$/GWh)	43.22	47.38	52.22	57.42	63.38

Lennox	275866.18	302417.12	333299.07	366440.67	404478.19
Total gas and oil Damage (\$):	275866.18	302417.12	333299.07	366440.67	404478.19
Gas and oil damage (\$/GWh):	14.48	15.87	17.49	19.23	21.23
Total Overall I&E Annual Damage (\$):					
	3456985.16	3719233.16	3938587.30	4232909.73	4550499.73

Thermal Discharge Effects:

Type	Damage (\$/cfs)
Nuclear	102
Oil/Gas	43
Coal	95
(Table 17-6, Rowe et al., 1995a)	

Annual Damages (\$)	2000	2005	2010	2015	2020
Bruce A	540544.50	592569.60	653081.06	718020.20	792552.61
Bruce B	551791.20	604898.74	666669.23	732959.50	809042.65
Pickering A	362003.14	396844.40	437368.98	480858.76	530773.21
Pickering B	362706.06	397614.97	438218.24	481792.49	531803.83
Darlington	619271.39	678873.62	748198.20	822595.31	907982.90
Total Nuclear Damage (\$):	1533768.65	1681387.34	1853085.67	2037347.29	2248829.39
Nuclear Damage (\$/GWh):	21.96	24.08	26.54	29.18	32.20
Attkokan	29443.86	32277.71	35573.81	39111.10	43170.93
Thunder Bay	45192.91	49542.53	54601.67	60030.99	66262.36
Lakeview	156120.95	171146.92	188623.94	207379.77	228906.35
Lambton	282250.24	309415.62	341012.24	374920.80	413838.58
Nanticoke	544506.04	596912.43	657867.37	723282.43	798361.08
Total Coal Damage (\$):	1057514.00	1159295.21	1277679.03	1404725.08	1550539.30
Coal Damage (\$/GWh)	45.17	49.52	54.58	60.01	66.23

Lennox	132652.35	145419.57	160269.39	176205.79	194496.42
Total gas and oil Damage (\$):	132652.35	145419.57	160269.39	176205.79	194496.42
Gas and oil damage (\$/GWh):	6.96	7.63	8.41	9.25	10.21
Total Overall I&E Annual Damage (\$):	3626482.64	3899332.85	4129308.97	4437883.63	4770852.57

Chemical and Metal Discharge to Water

Chemical	Status	Source	CC (can't do fish ingestion conc w/o BCFs)			
			Effluent Level (mg/L)	Surface Water (mg/L)	Drinking Water (mg/l)	Oral RfD (mg/Kg/d)
Arsenic	Carcinogen	coal	0.05	0.005	0.0005	0.0003
Benzene	Carcinogen	oil	0.1	0.01	0.001	0.005
Chromium (VI)	Carcinogen	coal	0.5	0.05	0.005	0.005
Copper	?	coal	0.4	0.04	0.004	0.037
Ethylbenzene	?	oil	0.1	0.01	0.001	0.1
Nickel	Carcinogen	coal	1	0.1	0.01	0.02
Toluene	?	oil	0.1	0.01	0.001	0.2
Xylene	?	oil	0.1	0.01	0.001	2

***only have oral slope factors for benzene and arsenic

Pathways	% of Pop	IR	ET (hrs/event)	EF	ED (Years)	BW Kg)
Drinking water ingestion		10	1.39	1	365	30
Surface water ingestion		25	0.05	2.6	7	30
fish ingestion		11.2	0.0082	1	365	30
Dermal contact		25	1.82*PC^3	2.6	7	30
Units						
Drinking water ingestion		L/d	hrs/event	days/yr	years	Kg
Surface water ingestion		L/hr	hrs/event	events/yr	years	Kg
fish ingestion		Kg/d	hrs/event	days/yr	years	Kg
Dermal contact		L/hr	hrs/event	events/yr	years	Kg
Non-carcinogen	AT (Days)					
	10950					
Carcinogen	25550					

Intake Calculations:

Chemical	Drinking water (mg/Kg/d)	Surface Water (mg/Kg/d)	Total Intake (mg/Kg/d)	HQ (Hazard Quotient)
Arsenic	4.2551E-06	7.63209E-09	4.26273E-06	0.014209114
Benzene	8.5102E-06	1.52642E-08	8.52547E-06	N/A
Chromium (VI)	4.2551E-05	7.63209E-08	4.26273E-05	0.008525468
Copper	7.94286E-05	1.42466E-07	7.9571E-05	0.002150569
Ethylbenzene	1.98571E-05	3.56184E-08	1.98928E-05	0.000198928
Nickel	0.000198571	3.56184E-07	0.000198928	0.00994638
Toluene	1.98571E-05	3.56184E-08	1.98928E-05	9.94638E-05
Xylene	1.98571E-05	3.56184E-08	1.98928E-05	9.94638E-06

All Hazard Quotients are less than unity, thus there is no concern for potential systemic health effects!!
Valuation is not necessary as the economic value for these non-carcinogenic risks is \$0

Carcinogenic Risk:

Chemical	Oral Cancer Slope Factor (mg/Kg/d)^-1	Cancer Site liver, kidney, 2 bladder nonlymphocytic leukemia	Additional Lifetime Cancer Risk	
Arsenic			8.52547E-06	
Benzene	0.029		2.47239E-07	
Total Annual Additional Cancers				
Arsenic (coal)	0.235908232	2000	2005	2010
Benzene (oil)	0.006841339	0.248022923	0.260853216	0.277046459
		0.007192865	0.007567643	0.008034347
				0.295308012
				0.008563932
Total Annual Cancer Cases	0.242749571	0.255215588	0.26852086	0.303871944

Economic Valuation:

Annual Damages (\$)				
Arsenic	880193.9371	2000	2005	2010
Benzene	25525.62418	1014460.201	1176341.915	1373071.303
Total	905719.5613	29419.34583	34113.91554	39819.06778
		1043879.547	1210455.831	1412890.371
Annual Damages (\$/GWh)				
Arsenic (coal)	37.60	43.33	50.25	58.65
Benzene (oil)	61.07	70.38	81.61	95.26
Total	98.67	113.72	131.86	153.91
				69.01
				112.08
				181.09

Spreadsheet B6: Radiation Externalities
Effects From normal Nuclear Power plant Operation

Excess Lifetime Cancer Deaths per 100000 persons exposed to radiation (single exposure of 10 rem):
High estimate = 488 total deaths (non-leukemia and leukemia)

Population Group	Average Collective Dose (Person rem/yr)	CPI: (Canada's Emission Outlook, NRC, 1997)				
		2000	2005	2010	2015	2020
Occupational	3006					
Public	3.06	1.465	1.606	1.77	1.946	2.148

Fatal Cancer Cases:

Valuation:

Rem/cancer death	2049.180					
Cancer deaths/yr	1.467	2000	2005	2010	2015	2020
Annual Damages =		5673490.73	6219540.01	6854661.16	7536254.58	8318637.95
Annual Damages (\$/GW/h) =		81.25	89.07	98.16	107.92	119.13

Non-Fatal Cancer Cases:

Survived Cancers/yr. =	1.409					
rem/survived canc =	2080.000	2000	2005	2010	2015	2020
Annual Damages =		673941.93	738805.97	814250.66	895215.70	988141.48
Annual Damages (\$/GW/h) =		9.65	10.58	11.66	12.82	14.15

Effects from Nuclear power plant operation Accidents

Excess Lifetime Cancer Deaths per 100000 persons exposed to radiation (single exposure of 10 rem):
 High estimate = 488 total deaths (non-leukemia and leukemia)

Total Ontario Population:	2000	2005	2010	2015	2020
CPI:	1,465	1,606	1,77	1,946	2,148
(Canada's Emission Outlook, NRC, 1997)					

NY data = 249.72 Accident person-rem/reactor yr.

Fatal Cancer Cases:

Valuation:

rem/cancer death = 2049,180 rem/death
 cancer deaths/yr = 0.122

	2000	2005	2010	2015	2020
Annual Damages (\$) =	471318.73	516681.15	569443.11	626065.70	691052.99
Annual Damages (\$/GWh) =	6.76	7.40	8.15	8.97	9.90

Non-Fatal Cancer Cases:

Survived Cancers = 0.117
 Rem/survived cancer = 2080.000
 (Low estimate from Table 22-9, NYSEE)

	2000	2005	2010	2015	2020
Annual Damages (\$) =	55986.95	61375.46	67642.94	74369.02	82086.72
Annual Damages (\$/GWh) =	0.80	0.88	0.97	1.07	1.18

Effects from Radioactive Waste

Only low-level and intermediate level radioactive wastes are considered here as used fuel (high-level) is considered with normal operations.

Occupational Dose						
Disposal Method	Equiv. (person-rem/m3-yr)					
Shallow Land Burial	1.38E-03					
Below Ground Vaults	1.47E-03					
Above Ground Vaults	1.61E-03					
Earth Mounded -						
Concrete Bunkers	1.81E-03					
Augured Holes	1.29E-03					
Low and Intermediate level wastes:		Year	1994	1995	1996	1997
			0	1	2	3
		cubic meters =	5460	6860	6300	6860

1998 4
4960

(1998 Progress Report, OPG)

Average of Volumes =

6088 m3 of low and intermed. Waste

Assuming earth mounded concrete bunkers are used for storage,

Dose/yr = 11,019 person-rem/yr

Excess Lifetime Cancer Deaths per 100000 persons exposed to radiation (single exposure of 10 rem):
High estimate = 488 total deaths (non-leukemia and leukemia)

Fatal Cancer Cases:

Rem/Cancer death =	2049,180	Valuation:					
Cancer Deaths/yr. =	0.00538	Annual Damages (\$)	20797.67	2005	22799.35	2010	2015
		Annual Damages (\$/GWh) =	0.30	0.33	0.36	0.40	0.44
						27626.11	30493.78
							2020

Non-Fatal Cancer Cases:

Rem/survived cancer =	2080	Valuation:					
Survived cancers/yr =	0.00530	Annual Damages (\$)	2533.25	2005	2777.08	2010	2015
		Annual Damages (\$/GWh) =	0.04	0.04	0.04	0.04	0.05
						3364.98	3714.28
							2020

Effects from Nuclear Fuel Acquisition

Mining:

Fuel Production:

Radiation Source Dose (person-rem/yr)

Dose = 9.3 person-rem/yr.

Radon 90
Uranium (& products) 7000
milling 6.6
tailings storage 11.3

Total 7107.9

Thus the total dose overall from nuclear fuel acquisitic 7117.2 person-rem/yr

Excess Lifetime Cancer Deaths per 100000 persons exposed to radiation (single exposure of 10 rem):

High estimate = 488 total deaths (non-leukemia and leukemia)

Fatal Cancer Cases:

Valuation:

Rem/Cancer death =	2049.180	Annual Damages (\$)	13432923.57	2000	2005	2010	2015	2020
Cancer Deaths/yr. =	3.473	Annual Damages (\$/GWh) =	192.37	210.88	232.41	255.53	282.05	

Non-Fatal Cancer Cases:

Valuation:

Rem/survived cancer =	2080	Annual Damages (\$)	1636189.53	2000	2005	2010	2015	2020
Survived cancers/yr =	3.422	Annual Damages (\$/GWh) =	23.43	25.69	28.31	31.12	34.35	

Spreadsheet B7: Waste Disposal Externalities

Assume that a 500 MW plant operating at 65% capacity produces 300000 tons of ash/yr.

Station	Type	Capacity (MW)	Ash Production (tons/yr)
Atikokan	Coal-Steam	215	129000
Thunder Bay	Coal-Steam	330	198000
Lakeview	Coal-Steam	1140	684000
Lambton	Coal-Steam	2081	1236600
Nanticoke	Coal-Steam	3976	2385600
Total Ontario Ash Production =			4633200 tons/yr

Impact on Groundwater:

VI =	2000	2005	2010	2015	2020
Vn =	17.5	17.5	17.5	17.5	17.5
HI =	4.4	4.4	4.4	4.4	4.4
Hn =	895019	940981	990038	1051094	1120377
Sn =	14728302	14799734	14871513	14943640	15016116
r =	1370	1370	1370	1370	1370
t =	0.03	0.03	0.03	0.03	0.03
t =	85	80	75	70	65
tons =	4633200	4633200	4633200	4633200	4633200
Present Value of Total Damages, summed over 10 years (\$1992)					
Year					
1	1311755.76	1595563.84	1949533.77	2399070.08	2984059.56
2	1351108.43	1646520.75	2008019.79	2471042.16	3052981.35
3	1391641.69	1695916.38	2068260.38	2545173.42	3144570.79
4	1433390.94	1746793.87	2130308.19	2621528.63	3238907.91
5	1476392.66	1799197.68	2194217.44	2700174.49	3336075.15
6	1520684.44	1853173.61	2260043.96	2781179.72	3436157.41

7	1566304.98	1908768.82	2327845.28	2864615.11	3539242.13
8	1613294.13	1966031.89	2397680.64	2950553.56	3645419.39
9	1661692.95	2025012.84	2469611.06	3039070.17	3754781.97
10	1711543.74	2085763.23	2543699.39	3130242.28	3867425.43
Sum of PV (\$1992) =	15037809.72	18325742.92	22349219.89	27502649.6	33979621.1
Capital Recovery Factor =	0.051019259	0.057427871	0.067215708	0.08376658	0.117230507
Annual Damages (\$1992)	11848913.46	16253395.35	23200284.50	35579932.15	61520373.94
Annual Damages (\$)	13866926.58	20882362.34	32851574.54	55390838.37	105716610.57
Annual Damages (\$/GWh)	593.20	892.03	1403.31	2366.12	4515.87

Impact on Aesthetics:

Aesthetic Damage (\$1000)

Impact	
PV Damages:	
Truck Route	4554
Landfill	18444
Total	22997
Annualized Total Damages:	1173
\$/ton	3.911
mills/kWh	0.4121

Assuming all ash produced is disposed in landfill:
Ash for landfill (Ontario) = 4633200 tons/yr

Annual Aesthetic Damages (\$)

	2000	2005	2010	2015	2020
Local Annual (\$)	21237161774.40	23281147992.96	25658550403.20	28209909087.36	31138173031.68
Overall Annual (\$)	891960794.52	977808215.70	1077659116.93	1184816181.67	1307803267.33
Local Damages (\$/GWh)	907183.33	994495.86	1096050.85	1205036.70	1330122.73
Overall Damages (\$/GWh)	38101.69989	41768.82596	46034.13571	50611.54129	55865.15452

Table B27: Cost Data

Average Cost (cents/KWh)	1994	1995	1996	1997	1998
Hydroelectric					
O&M and Admin	0.318	0.316	0.312	0.318	0.402
Water rentals	0.336	0.344	0.335	0.362	0.404
Depreciation, debt guarantee fee and financing charges	0.543	0.415	0.313	0.274	0.294
Other Revenues	-0.011	-0.003	-0.006	-0.003	-0.002
Total	1.186	1.072	0.954	0.951	1.098
Nuclear					
O&M and Admin	1.032	1.066	1.228	1.533	2.151
Uranium	0.285	0.268	0.255	0.277	0.436
guarantee fee and	3.53	3.946	4.143	4.526	5.203
Other Revenues	-0.118	-0.103	-0.118	-0.098	-0.069
Total	4.729	5.177	5.508	6.238	7.721
Fossil					
O&M and Admin	1.331	1.166	1.051	0.905	0.917
Coal, Gas and Oil	2.378	2.394	2.218	2.113	2.225
Depreciation, debt guarantee fee and financing charges	3.732	3.229	2.496	1.86	1.169
Other Revenues	-0.02	-0.121	-0.073	-0.023	-0.018
Total	7.421	6.668	5.692	4.855	4.293

(Ontario Hydro Final Annual Report, Jan.98-Mar.31/99)

Table B28: Economic Coefficient Calculations (cents/Kwh)

Year	6	11	16	21	26
Generation Type	2000	2005	2010	2015	2020
Nuclear					
O&M	1.964	2.7965	3.629	4.4615	5.294
Fuel	0.8139	2.7624	6.0909	10.7994	16.8879
Depreciation	5.4695	7.062	8.6545	10.247	11.8395
Total	2.7779	5.5589	9.7199	15.2609	22.1819
Total (\$/J)	7.72256E-09	1.55E-08	2.7E-08	4.24E-08	6.17E-08
Total (\$/Gwh)	27801.2232	55633.47	97276.76	152731.1	221996.5
Fossil					
O&M	0.9623	1.9198	4.0323	7.2998	11.7223
Fuel	5.2	5.36	5.52	5.7	5.86
Total	6.1623	7.2798	9.5523	12.9998	17.5823
Total (\$/J)	1.71312E-08	2.02E-08	2.66E-08	3.61E-08	4.89E-08
Total (\$/Gwh)	61672.2984	72856.24	95599.42	130102	175963.7
Hydroelectric					
O&M	0.5832	1.5132	3.0932	5.3232	8.2032
Fuel	0.5209	1.0784	2.0059	3.3034	4.9709
Total	1.1041	2.5916	5.0991	8.6266	13.1741
Total (\$/J)	3.0694E-09	7.2E-09	1.42E-08	2.4E-08	3.66E-08
Total (\$/Gwh)	11049.8328	25936.73	51031.79	86335.01	131846.4

Table B29: Upper Bounds of Environmental Externality Constraints

	2000	2005	2010	2015	2020
Total Demand (GWh)	152679	164174	173860	186859	200868
Increase		0.075	0.059	0.075	0.075
Increase (%)		7.524	5.898	7.473	7.503
PM10 Morbidity:	1257368009.76	1351970179.91	1431707118.31	1538695609.00	1654142045.94
PM10 Mortality:	4115574948.78	4425223610.55	4686215892.55	5036407044.73	5414282463.97
Ozone Morbidity:	5187.89	5578.22	5907.21	6348.64	6824.97
Ozone Mortality:	53277.79	57286.32	60664.97	65198.34	70090.09
Lead Damages:	120179766.48	129221881.94	136843172.25	147069177.47	158103596.77
Mercury Damages:	239895.41	257944.72	273157.87	293570.39	315596.61
Air Toxics Mortality:	199407761.23	214410852.46	227056445.68	244023900.90	262332713.72
Visibility Effects:	169994280.44	182784352.82	193564668.02	208029352.46	223637538.63
Material Damage Effects:	948193182.38	1019533579.21	1079663963.30	1160345002.32	1247404259.11
CO2 Effects:	165919620.43	178403122.51	188925040.08	203043014.79	218277082.18
Ash Pile Effects:	41.22	44.32	46.94	50.45	54.23
Impingement and Entrainment Effects:	3458985.16	3719233.16	3938587.30	4232909.73	4550499.73
Thermal Discharge Effects:	3626482.64	3899332.85	4129308.97	4437883.63	4770852.57
Chemical and Metal Discharge Effects:	905719.56	973864.32	1031301.20	1108368.20	1191527.70
Normal Operation Fatal Cancer:	5673490.00	6100354.25	6460142.94	6942895.96	7463812.90
Normal Operation non-fatal Cancer:	673941.00	724648.14	767386.68	824731.88	886610.50
Nuclear Accidents Fatal Cancer:	471318.00	506779.93	536668.96	576773.11	620047.69
Nuclear Accidents non-fatal Cancer:	55987.00	60199.31	63749.77	68513.65	73654.15
Radioactive Waste Fatal Cancer:	20798.00	22362.45	23681.35	25451.00	27360.56
Radioactive Waste non-fatal Cancer:	2533.00	2723.84	2884.49	3100.04	3332.64
Fuel Acquisition fatal Cancer:	13432923.00	14443593.24	15295452.20	16438449.48	17671806.11
Fuel Acquisition non-fatal Cancer:	1636189.00	1759293.57	1863053.76	2002275.89	2152504.18
Impact on GW:	13868926.58	14931754.65	15812404.54	16994032.60	18269073.94
Impact on Aesthetics:	891960794.5	959070364.8	1015634730	1091530998	1173427224

Appendix C

SCREEN3 Model Verification

02/21/96
14:28:56

*** SCREEN3 MODEL RUN ***
*** VERSION DATED 96043 ***

POINT SOURCE EXAMPLE WITH BUILDING DOWNWASH

SIMPLE TERRAIN INPUTS:

SOURCE TYPE = POINT
EMISSION RATE (G/S) = 100.000
STACK HEIGHT (M) = 100.0000
STK INSIDE DIAM (M) = 2.0000
STK EXIT VELOCITY (M/S)= 15.0000
STK GAS EXIT TEMP (K) = 450.0000
AMBIENT AIR TEMP (K) = 293.0000
RECEPTOR HEIGHT (M) = .0000
URBAN/RURAL OPTION = URBAN
BUILDING HEIGHT (M) = 80.0000
MIN HORIZ BLDG DIM (M) = 80.0000
MAX HORIZ BLDG DIM (M) = 100.0000

THE REGULATORY (DEFAULT) MIXING HEIGHT OPTION WAS SELECTED.
THE REGULATORY (DEFAULT) ANEMOMETER HEIGHT OF 10.0 METERS
WAS ENTERED.

BUOY. FLUX = $51.319 \text{ M}^{**4}/\text{S}^{**3}$; MOM. FLUX = $146.500 \text{ M}^{**4}/\text{S}^{**2}$.

*** FULL METEOROLOGY ***

*** SCREEN AUTOMATED DISTANCES ***

*** TERRAIN HEIGHT OF 0. M ABOVE STACK BASE USED FOR FOLLOWING
DISTANCES ***

DIST (M)	CONC ($\mu\text{G}/\text{M}^{**3}$)	U10M STAB	USTK (M/S)	MIX HT (M)	PLUME HT (M)	SIGMA Y (M)	SIGMA Z (M)	DWASH
100.	.0000	0	.0	.0	.00	.00	.00	NA
200.	.0000	0	.0	.0	.00	.00	.00	NA
300.	631.6	1	1.5	2.1	480.0	125.11	90.71	SS
400.	517.4	1	1.5	2.1	480.0	140.59	118.85	SS

500.	494.6	6	1.0	2.0	10000.0	113.08	50.21	50.05	SS
600.	578.0	6	1.0	2.0	10000.0	113.08	59.27	54.62	SS
700.	638.4	6	1.0	2.0	10000.0	113.08	68.06	59.18	SS
800.	715.3	6	1.0	2.0	10000.0	113.08	76.59	65.44	SS
900.	699.4	6	1.0	2.0	10000.0	113.08	84.89	68.33	SS
1000.	681.9	6	1.0	2.0	10000.0	113.08	92.97	71.13	SS

MAXIMUM 1-HR CONCENTRATION AT OR BEYOND 100. M:

800.	715.3	6	1.0	2.0	10000.0	113.08	76.59	65.44	SS
------	-------	---	-----	-----	---------	--------	-------	-------	----

DWASH= MEANS NO CALC MADE (CONC = 0.0)

DWASH=NO MEANS NO BUILDING DOWNWASH USED

DWASH=HS MEANS HUBER-SNYDER DOWNWASH USED

DWASH=SS MEANS SCHULMAN-SCIRE DOWNWASH USED

DWASH=NA MEANS DOWNWASH NOT APPLICABLE, X<3*LB

*** REGULATORY (Default) ***

PERFORMING CAVITY CALCULATIONS
WITH ORIGINAL SCREEN CAVITY MODEL
(BRODE, 1988)

*** CAVITY CALCULATION - 1 *** *** CAVITY CALCULATION - 2 ***

CONC ($\mu\text{G}/\text{M}^3$) = 3168.	CONC ($\mu\text{G}/\text{M}^3$) = 1691.
CRIT WS @10M (M/S) = 3.32	CRIT WS @10M (M/S) = 7.77
CRIT WS @ HS (M/S) = 5.26	CRIT WS @ HS (M/S) = 12.32
DILUTION WS (M/S) = 2.63	DILUTION WS (M/S) = 6.16
CAVITY HT (M) = 114.88	CAVITY HT (M) = 105.20
CAVITY LENGTH (M) = 142.41	CAVITY LENGTH (M) = 101.30
ALONGWIND DIM (M) = 80.00	ALONGWIND DIM (M) = 100.00

END OF CAVITY CALCULATIONS

*** SUMMARY OF SCREEN MODEL RESULTS ***

CALCULATION PROCEDURE	MAX CONC (μG/M**3)	DIST TO MAX (M)	TERRAIN HT (M)
SIMPLE TERRAIN	715.3	800.	0.
BLDG. CAVITY-1	3168.	142.	-- (DIST = CAVITY LENGTH)
BLDG. CAVITY-2	1691.	101.	-- (DIST = CAVITY LENGTH)

** REMEMBER TO INCLUDE BACKGROUND CONCENTRATIONS **

04/27/00

16:15:46

*** SCREEN3 MODEL RUN ***

*** VERSION DATED 96043 ***

SO2 Emissions For Plants 1 and 2 merged

COMPLEX TERRAIN INPUTS:

SOURCE TYPE = POINT
 EMISSION RATE (G/S) = 263.920
 STACK HT (M) = 150.0000
 STACK DIAMETER (M) = 4.0000
 STACK VELOCITY (M/S) = 30.0000
 STACK GAS TEMP (K) = 400.0000
 AMBIENT AIR TEMP (K) = 293.0000
 RECEPTOR HEIGHT (M) = .0000
 URBAN/RURAL OPTION = URBAN

THE REGULATORY (DEFAULT) MIXING HEIGHT OPTION WAS SELECTED.
 THE REGULATORY (DEFAULT) ANEMOMETER HEIGHT OF 10.0 METERS
 WAS ENTERED.

BUOY. FLUX = $314.778 \text{ M}^{**4}/\text{S}^{**3}$; MOM. FLUX = $2637.000 \text{ M}^{**4}/\text{S}^{**2}$.

FINAL STABLE PLUME HEIGHT (M) = 299.0

DISTANCE TO FINAL RISE (M) = 200.2

VALLEY 24-HR CALCS **SIMPLE TERRAIN 24-HR CALCS**
 TERR MAX 24-HR PLUME HT PLUME HT
 HT DIST CONC CONC ABOVE STK CONC ABOVE STK U10M
 USTK
 (M) (M) (UG/M**3) ($\mu\text{G}/\text{M}^{**3}$) BASE (M) (UG/M**3) HGT (M) SC (M/S)

213.	7000.	166.9	39.61	299.0	166.9	128.0	6	1.0	2.3
------	-------	-------	-------	-------	-------	-------	---	-----	-----

04/27/00

16:15:46

*** SCREEN3 MODEL RUN ***

*** VERSION DATED 96043 ***

SO2 Emissions For Plants 1 and 2 merged

SIMPLE TERRAIN INPUTS:

SOURCE TYPE = POINT
 EMISSION RATE (G/S) = 263.920

STACK HEIGHT (M) = 150.0000
 STK INSIDE DIAM (M) = 4.0000
 STK EXIT VELOCITY (M/S)= 30.0000
 STK GAS EXIT TEMP (K) = 400.0000
 AMBIENT AIR TEMP (K) = 293.0000
 RECEPTOR HEIGHT (M) = .0000
 URBAN/RURAL OPTION = URBAN
 BUILDING HEIGHT (M) = .0000
 MIN HORIZ BLDG DIM (M) = .0000
 MAX HORIZ BLDG DIM (M) = .0000

THE REGULATORY (DEFAULT) MIXING HEIGHT OPTION WAS SELECTED.
 THE REGULATORY (DEFAULT) ANEMOMETER HEIGHT OF 10.0 METERS
 WAS ENTERED.

BUOY. FLUX = 314.778 M**4/S**3; MOM. FLUX = 2637.000 M**4/S**2.

*** FULL METEOROLOGY ***

*** SCREEN AUTOMATED DISTANCES ***

*** TERRAIN HEIGHT OF 0. M ABOVE STACK BASE USED FOR FOLLOWING
 DISTANCES ***

DIST (M)	CONC ($\mu\text{G}/\text{M}^3$)	U10M STAB	U5TK (M/S)	MIX HT (M)	PLUME HT (M)	SIGMA Y (M)	SIGMA Z (M)	DWASH
100.	.5345E-13	6	1.0	2.3	10000.0	277.98	31.63	30.65 NO
200.	.9452E-03	3	10.0	17.2	3200.0	221.02	42.79	40.48 NO
300.	1.639	3	10.0	17.2	3200.0	221.02	62.89	60.55 NO
400.	20.87	2	5.0	7.5	1600.0	312.65	120.95	115.79 NO
500.	56.36	2	5.0	7.5	1600.0	312.65	148.37	149.27 NO
600.	82.53	2	5.0	7.5	1600.0	312.65	174.92	184.52 NO
700.	92.98	2	5.0	7.5	1600.0	312.65	200.67	221.47 NO
800.	94.49	2	4.0	6.0	1280.0	353.31	227.25	261.43 NO
900.	94.03	2	3.5	5.3	1120.0	382.35	253.05	302.80 NO
1000.	113.7	1	2.0	3.0	640.0	556.61	289.61	354.86 NO
1100.	132.8	1	1.5	2.3	693.2	692.15	328.18	409.90 NO
1200.	145.9	1	1.5	2.3	693.2	692.15	351.61	454.39 NO
1300.	153.2	1	1.5	2.3	693.2	692.15	371.28	497.88 NO
1400.	156.0	1	1.5	2.3	693.2	692.15	390.71	543.09 NO
1500.	155.4	1	1.5	2.3	693.2	692.15	409.87	589.91 NO

1600.	152.5	1	1.5	2.3	693.2	692.15	428.76	638.26	NO
1700.	148.5	1	1.5	2.3	693.2	692.15	447.38	688.07	NO
1800.	143.8	1	1.5	2.3	693.2	692.15	465.71	739.28	NO
1900.	142.1	3	1.5	2.6	624.5	623.50	342.89	403.36	NO
2000.	145.8	3	1.5	2.6	624.5	623.50	354.76	422.26	NO
2100.	148.1	3	1.5	2.6	624.5	623.50	366.48	441.25	NO
2200.	149.3	3	1.5	2.6	624.5	623.50	378.03	460.33	NO
2300.	149.6	3	1.5	2.6	624.5	623.50	389.43	479.48	NO
2400.	149.2	3	1.5	2.6	624.5	623.50	400.67	498.70	NO
2500.	148.2	3	1.5	2.6	624.5	623.50	411.77	517.98	NO
2600.	146.7	3	1.5	2.6	624.5	623.50	422.71	537.31	NO
2700.	144.9	3	1.5	2.6	624.5	623.50	433.51	556.69	NO
2800.	142.8	3	1.5	2.6	624.5	623.50	444.17	576.11	NO
2900.	140.6	3	1.5	2.6	624.5	623.50	454.70	595.57	NO
3000.	138.3	3	1.5	2.6	624.5	623.50	465.08	615.06	NO
3500.	126.5	3	1.5	2.6	624.5	623.50	515.12	712.95	NO
4000.	125.5	4	1.5	3.0	564.5	563.53	414.12	395.61	NO
4500.	124.9	4	1.5	3.0	564.5	563.53	446.21	427.61	NO
5000.	122.3	4	1.5	3.0	564.5	563.53	476.75	458.21	NO
5500.	129.5	6	1.0	2.3	10000.0	277.98	340.18	149.22	NO
6000.	136.0	6	1.0	2.3	10000.0	277.98	359.80	156.13	NO
6500.	140.7	6	1.0	2.3	10000.0	277.98	378.61	162.76	NO
7000.	144.0	6	1.0	2.3	10000.0	277.98	396.69	169.13	NO
7500.	146.1	6	1.0	2.3	10000.0	277.98	414.12	175.28	NO
8000.	147.2	6	1.0	2.3	10000.0	277.98	430.95	181.23	NO
8500.	147.7	6	1.0	2.3	10000.0	277.98	447.24	186.99	NO
9000.	147.5	6	1.0	2.3	10000.0	277.98	463.04	192.58	NO
9500.	146.9	6	1.0	2.3	10000.0	277.98	478.37	198.02	NO
10000.	146.0	6	1.0	2.3	10000.0	277.98	493.29	203.31	NO

MAXIMUM 1-HR CONCENTRATION AT OR BEYOND 100. M:
1427. 156.1 1 1.5 2.3 693.2 692.15 395.71 555.11 NO

DWASH= MEANS NO CALC MADE (CONC = 0.0)

DWASH=NO MEANS NO BUILDING DOWNWASH USED

DWASH=HS MEANS HUBER-SNYDER DOWNWASH USED

DWASH=SS MEANS SCHULMAN-SCIRE DOWNWASH USED

DWASH=NA MEANS DOWNWASH NOT APPLICABLE, $X < 3 \cdot LB$

*** SUMMARY OF SCREEN MODEL RESULTS ***

CALCULATION PROCEDURE	MAX CONC ($\mu\text{G}/\text{M}^3$)	DIST TO MAX (M)	TERRAIN HT (M)
SIMPLE TERRAIN	156.1	1427.	0.
COMPLEX TERRAIN	166.9	7000.	213. (24-HR CONC)

** REMEMBER TO INCLUDE BACKGROUND CONCENTRATIONS **

04/27/00
16:19:40

*** SCREEN3 MODEL RUN ***
*** VERSION DATED 96043 ***

SO2 Emissions for Plants 3-6 merged

SIMPLE TERRAIN INPUTS:

SOURCE TYPE = POINT
EMISSION RATE (G/S) = 3880.10
STACK HEIGHT (M) = 150.0000
STK INSIDE DIAM (M) = 4.0000
STK EXIT VELOCITY (M/S)= 30.0000
STK GAS EXIT TEMP (K) = 400.0000
AMBIENT AIR TEMP (K) = 293.0000
RECEPTOR HEIGHT (M) = .0000
URBAN/RURAL OPTION = URBAN
BUILDING HEIGHT (M) = .0000
MIN HORIZ BLDG DIM (M) = .0000
MAX HORIZ BLDG DIM (M) = .0000

THE REGULATORY (DEFAULT) MIXING HEIGHT OPTION WAS SELECTED.
THE REGULATORY (DEFAULT) ANEMOMETER HEIGHT OF 10.0 METERS
WAS ENTERED.

BUOY. FLUX = 314.778 M**4/S**3; MOM. FLUX = 2637.000 M**4/S**2.

*** FULL METEOROLOGY ***

*** SCREEN AUTOMATED DISTANCES ***

*** TERRAIN HEIGHT OF 37. M ABOVE STACK BASE USED FOR
FOLLOWING DISTANCES ***

DIST (M)	CONC ($\mu\text{G}/\text{M}^3$)	U10M STAB	USTK (M/S)	MIX HT (M)	PLUME HT (M)	SIGMA Y (M)	SIGMA Z (M)	DWASH
100.	.2151E-07	6	1.0	2.3	10000.0	240.98	31.63	30.65 NO
200.	1.347	3	10.0	17.2	3200.0	184.02	42.79	40.48 NO
300.	186.1	3	10.0	17.2	3200.0	184.02	62.89	60.55 NO
400.	799.5	3	10.0	17.2	3200.0	184.02	82.29	80.60 NO
500.	1351.	2	5.0	7.5	1600.0	275.65	148.37	149.27 NO
600.	1670.	2	5.0	7.5	1600.0	275.65	174.92	184.52 NO

700.	1707.	2	5.0	7.5	1600.0	275.65	200.67	221.47	NO
800.	1665.	2	4.0	6.0	1280.0	316.31	227.25	261.43	NO
900.	1719.	3	5.0	8.6	1600.0	255.05	173.10	183.13	NO
1000.	1984.	1	1.5	2.3	656.2	655.15	303.67	366.43	NO
1100.	2265.	1	1.5	2.3	656.2	655.15	328.18	409.90	NO
1200.	2421.	1	1.5	2.3	656.2	655.15	351.61	454.39	NO
1300.	2493.	1	1.5	2.3	656.2	655.15	371.28	497.88	NO
1400.	2499.	1	1.5	2.3	656.2	655.15	390.71	543.09	NO
1500.	2462.	1	1.5	2.3	656.2	655.15	409.87	589.91	NO
1600.	2398.	1	1.5	2.3	656.2	655.15	428.76	638.26	NO
1700.	2321.	1	1.5	2.3	656.2	655.15	447.38	688.07	NO
1800.	2345.	3	1.5	2.6	587.5	586.50	330.87	384.58	NO
1900.	2399.	3	1.5	2.6	587.5	586.50	342.89	403.36	NO
2000.	2431.	3	1.5	2.6	587.5	586.50	354.76	422.26	NO
2100.	2444.	3	1.5	2.6	587.5	586.50	366.48	441.25	NO
2200.	2442.	3	1.5	2.6	587.5	586.50	378.03	460.33	NO
2300.	2428.	3	1.5	2.6	587.5	586.50	389.43	479.48	NO
2400.	2405.	3	1.5	2.6	587.5	586.50	400.67	498.70	NO
2500.	2375.	3	1.5	2.6	587.5	586.50	411.77	517.98	NO
2600.	2340.	3	1.5	2.6	587.5	586.50	422.71	537.31	NO
2700.	2301.	3	1.5	2.6	587.5	586.50	433.51	556.69	NO
2800.	2261.	3	1.5	2.6	587.5	586.50	444.17	576.11	NO
2900.	2219.	3	1.5	2.6	587.5	586.50	454.70	595.57	NO
3000.	2178.	3	1.5	2.6	587.5	586.50	465.08	615.06	NO
3500.	2287.	6	1.0	2.3	10000.0	240.98	251.19	117.82	NO
4000.	2556.	6	1.0	2.3	10000.0	240.98	275.32	126.35	NO
4500.	2741.	6	1.0	2.3	10000.0	240.98	298.07	134.39	NO
5000.	2861.	6	1.0	2.3	10000.0	240.98	319.64	141.99	NO
5500.	2931.	6	1.0	2.3	10000.0	240.98	340.18	149.22	NO
6000.	2965.	6	1.0	2.3	10000.0	240.98	359.80	156.13	NO
6500.	2973.	6	1.0	2.3	10000.0	240.98	378.61	162.76	NO
7000.	2961.	6	1.0	2.3	10000.0	240.98	396.69	169.13	NO
7500.	2935.	6	1.0	2.3	10000.0	240.98	414.12	175.28	NO
8000.	2899.	6	1.0	2.3	10000.0	240.98	430.95	181.23	NO
8500.	2857.	6	1.0	2.3	10000.0	240.98	447.24	186.99	NO
9000.	2810.	6	1.0	2.3	10000.0	240.98	463.04	192.58	NO
9500.	2759.	6	1.0	2.3	10000.0	240.98	478.37	198.02	NO
10000.	2707.	6	1.0	2.3	10000.0	240.98	493.29	203.31	NO

MAXIMUM 1-HR CONCENTRATION AT OR BEYOND 100. M:

6419.	2973.	6	1.0	2.3	10000.0	240.98	375.58	161.69	NO
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DWASH= MEANS NO CALC MADE (CONC = 0.0)

DWASH=NO MEANS NO BUILDING DOWNWASH USED

DWASH=HS MEANS HUBER-SNYDER DOWNWASH USED

DWASH=SS MEANS SCHULMAN-SCIRE DOWNWASH USED
 DWASH=NA MEANS DOWNWASH NOT APPLICABLE, X<3*LB

* SUMMARY OF TERRAIN HEIGHTS ENTERED FOR *

* SIMPLE ELEVATED TERRAIN PROCEDURE *

TERRAIN HT (M)	DISTANCE MINIMUM	RANGE (M) MAXIMUM
37.	100.	10000.

*** SUMMARY OF SCREEN MODEL RESULTS ***

CALCULATION PROCEDURE	MAX CONC ($\mu\text{G}/\text{M}^3$)	DIST TO MAX (M)	TERRAIN HT (M)
SIMPLE TERRAIN	2973.	6419.	37.

** REMEMBER TO INCLUDE BACKGROUND CONCENTRATIONS **

Appendix D

Analytical Model

(Non-normalized year 2000 Values)

For

$$i = 1, \dots, 27 \text{ and } j = 1, \dots, 6;$$

and

x_j = decision variables

n_i = negative (downward) deviation variable

p_i = positive (upward) deviation variable

α_i = negative deviation variable weight factor

β_i = positive deviation variable weight factor

$$\text{Minimize } \sum_{i=1}^{27} (\alpha_i n_i + \beta_i p_i)$$

subject to:

System Constraints:

Demand $x_1 + x_2 + x_3 + x_4 + x_5 + x_6 = 152679$

Reliability $1.28x_1 + 1.15x_2 + 1.11x_3 + 1.26x_4 + 1.96x_5 + x_6 \leq 412646$

Kyoto (CO₂) N/A (only applies to model years 2010, 2015 and 2020)

NO_x $145.3x_1 + 33.3x_2 + 138.6x_3 \leq 36000000$

SO₂ $1743.6x_1 + 0x_2 + 1364.4x_3 \leq 158000000$

Goal Constraints:

Safety (Occupational)

$$2900x_1 + 190x_2 + 760x_3 + 610x_4 + 1000x_5 + n_1 - p_1 = 150000000$$

Safety (Public)

$$24400x_1 + 6.23x_2 + 6600x_3 + 210x_4 + 620x_5 + n_2 - p_2 = 610000000$$

Economics

$$61672x_1 + 61672x_2 + 61672x_3 + 27801x_4 + 11049x_5 + n_3 - p_3 = 37600000000$$

PM ₁₀ (Morbidity)	$21749x_1 + 680x_2 + 27187x_3 + n_4 - p_4 = 1257368010$
PM ₁₀ (Mortality)	$71189x_1 + 2225x_2 + 88986x_3 + n_5 - p_5 = 4115574949$
Ozone (Morbidity)	$0.16x_1 + 0.08x_2 + 0.10x_3 + n_6 - p_6 = 5188$
Ozone (Mortality)	$1.15x_1 + 0.55x_2 + 0.69x_3 + n_7 - p_7 = 53278$
Lead Damages	$2598x_1 + 130x_2 + 1091x_3 + n_8 - p_8 = 120179767$
Mercury Damages	$5.71x_1 + 0.28x_2 + 5.71x_3 + n_9 - p_9 = 239895$
Air Toxics	$1293x_1 + 216x_2 + 4312x_3 + n_{10} - p_{10} = 199407761$
Visibility Damages	$3676x_1 + 92x_2 + 2940x_3 + n_{11} - p_{11} = 169994280$
Materials Damages	$20502x_1 + 512x_2 + 16401x_3 + n_{12} - p_{12} = 948193182$
CO ₂ Damages	$3587x_1 + 1901x_2 + 2762x_3 + n_{13} - p_{13} = 165919620$
Ash Radiation	$0.0018x_1 + n_{14} - p_{14} = 41$
I&E Damages	$43.2x_1 + 14.5x_2 + 14.5x_3 + 31.1x_4 + n_{15} - p_{15} = 3458985$
Thermal Discharge	$45.2x_1 + 6.7x_2 + 6.7x_3 + 34.9x_4 + n_{16} - p_{16} = 3626482$
C&M Discharge	$37.6x_1 + 61.1x_3 + n_{17} - p_{17} = 905720$
Normal Op (Fatal)	$81.2x_4 + n_{18} - p_{18} = 5673490$
Normal Op. (survived)	$9.7x_4 + n_{19} - p_{19} = 673941$
Accidents (Fatal)	$6.75x_4 + n_{20} - p_{20} = 471318$
Accidents (Survived)	$0.8x_4 + n_{21} - p_{21} = 55987$
Waste (Fatal)	$0.3x_4 + n_{22} - p_{22} = 20798$
Waste (Survived)	$0.04x_4 + n_{23} - p_{23} = 2533$
Fuel (Fatal)	$192.4x_4 + n_{24} - p_{24} = 13432923$
Fuel (Survived)	$23.4x_4 + n_{25} - p_{25} = 1636189$
Groundwater	$593.2x_1 + n_{26} - p_{26} = 13886927$
Aesthetics	$38102x_1 + n_{27} - p_{27} = 891960795$

Where, x, n, p, α, β are all non-negative (greater than or equal to zero).

Appendix D: Model Equations

Fuel Mix Optimization Model Equations for the Year 2000

Decision Variables:

- X1 = Coal power contribution (GWh)
 X2 = Natural Gas power contribution (GWh)
 X3 = Oil Power Contribution (GWh)
 X4 = Nuclear Power Contribution (GWh)
 X5 = Hydro Power Contribution (GWh)
 X6 = Purchased Power Contribution (GWh)

Decision Variable Coefficients:						
Constraint Equations:	X1	X2	X3	X4	X5	X6
Demand	1	1	1	1	1	1
Reliability	1.28	1.15	1.11	1.26	1.96	1
Safety (Occupational)	2900	190	760	610	1000	0
Safety (Public)	24400	6.23	6600	210	620	0
Economics	61672	61672	61672	27801	11049	0
<i>Air Externalities</i>						
PM10 (Morbidity)	21749.30	679.67	27186.63	0.00	0.00	0.00
PM10 (Mortality)	71189.09	2224.66	88986.37	0.00	0.00	0.00
Ozone (Morbidity)	0.112	0.054	0.067	0.00	0.00	0.00
Ozone (Mortality)	1.152	0.553	0.691	0.00	0.00	0.00
Lead Damages	2598.51	129.93	1091.37	0.00	0.00	0.00
Mercury Damages	5.71	0.29	5.71	0.00	0.00	0.00
Air Toxics	1293.47	215.58	4311.57	0.00	0.00	0.00
Visibility Damages	3675.59	91.89	2940.47	0.00	0.00	0.00
Materials Damages	20501.70	512.54	16401.36	0.00	0.00	0.00
CO2 Damages	3587.49	1901.37	2762.37	0.00	0.00	0.00
Ash Radiation	0.0018	0.00	0.00	0.00	0.00	0.00
<i>Water Externalities</i>						
I&E Damages	43.22	14.48	14.48	31.09	0	0
Thermal Discharge	45.17	6.96	6.96	34.89	0	0
C&M Discharge	37.60	0	61.07	0	0	0
<i>Radiation Externalities</i>						
Normal Op (Fatal)	0	0	0	81.25	0	0
Normal Op. (survived)	0	0	0	9.65	0	0
Accidents (Fatal)	0	0	0	6.75	0	0
Accidents (Survived)	0	0	0	0.800	0	0
Waste (Fatal)	0	0	0	0.300	0	0
Waste (Survived)	0	0	0	0.040	0	0
Fuel (Fatal)	0	0	0	192.37	0	0
Fuel (Survived)	0	0	0	23.43	0	0
<i>Waste Disposal Ext.</i>						
Groundwater	593.20	0	0	0	0	0
aesthetics	38101.70	0	0	0	0	0
<i>Environmental Limits</i>						
CO2 (Kyoto)	N/A					
NOx	145.30	33.3	138.60	0	0	0
SO2	1743.60	0	1364.40	0	0	0

Fuel Mix Optimization Model Equations for the Year 2005

Decision Variables:

- X1 = Coal power contribution (GWh)
 X2 = Natural Gas power contribution (GWh)
 X3 = Oil Power Contribution (GWh)
 X4 = Nuclear Power Contribution (GWh)
 X5 = Hydro Power Contribution (GWh)
 X6 = Purchased Power Contribution (GWh)

Decision Variable Coefficients:						
Constraint Equations:	X1	X2	X3	X4	X5	X6
Demand	1	1	1	1	1	1
Reliability	1.28	1.15	1.11	1.26	1.96	1
Safety (Occupational)	2887.62	186.048	775.2	608.532	1007.76	0
Safety (Public)	24380.04	6.2016	6589.2	206.2032	621.4003	0
Economics	72856.238	72856.238	72856.238	55633.47	25936.73	0
<i>Air Externalities</i>						
PM10 (Morbidity)	25066.98	783.34	31333.72	0	0	0
PM10 (Mortality)	82048.40	2564.01	102560.50	0	0	0
Ozone (Morbidity)	0.129	0.062	0.078	0	0	0
Ozone (Mortality)	1.328	0.637	0.797	0	0	0
Lead Damages	4908.11	245.41	2061.41	0	0	0
Mercury Damages	8.24	0.19	3.76	0	0	0
Air Toxics	1490.78	248.46	4969.26	0	0	0
Visibility Damages	2420.95	60.52	1936.76	0	0	0
Materials Damages	23629.06	590.73	18903.25	0	0	0
CO2 Damages	3932.77	2084.37	3028.23	0	0	0
Ash Radiation	0.0019	0.0000	0.0000	0	0	0
<i>Water Externalities</i>						
I&E Damages	47.38	15.87	15.87	21.46	0	0
Thermal Discharge	49.52	7.63	7.63	24.08	0	0
C&M Discharge	43.33	0	70.38	0	0	0
<i>Radiation Externalities</i>						
Normal Op (Fatal)	0	0	0	89.07	0	0
Normal Op. (survived)	0	0	0	10.58	0	0
Accidents (Fatal)	0	0	0	7.40	0	0
Accidents (Survived)	0	0	0	0.879	0	0
Waste (Fatal)	0	0	0	0.326	0	0
Waste (Survived)	0	0	0	0.040	0	0
Fuel (Fatal)	0	0	0	210.88	0	0
Fuel (Survived)	0	0	0	25.69	0	0
<i>Waste Disposal Ext.</i>						
Groundwater	892.03	0	0	0	0	0
aesthetics	41768.83	0	0	0	0	0
<i>Environmental Limits</i>						
CO2 (Kyoto)	N/A					
NOx	145.30	33.26	138.60	0	0	0
SO2	1743.60	0	1364.40	0	0	0

Fuel Mix Optimization Model Equations for the Year 2010

Decision Variables:

- X1 = Coal power contribution (GWh)
 X2 = Natural Gas power contribution (GWh)
 X3 = Oil Power Contribution (GWh)
 X4 = Nuclear Power Contribution (GWh)
 X5 = Hydro Power Contribution (GWh)
 X6 = Purchased Power Contribution (GWh)

Decision Variable Coefficients:						
Constraint Equations:	X1	X2	X3	X4	X5	X6
Demand	1	1	1	1	1	1
Reliability	1.28	1.15	1.11	1.26	1.96	1
Safety (Occupational)	2887.62	186.048	775.2	608.532	1007.76	0
Safety (Public)	24380.04	6.2016	0	206.2032	621.4003	0
Economics	95599.418	95599.42	95599.418	97276.76	51031.79	0
<i>Air Externalities</i>						
PM10 (Morbidity)	29067.02	908.34	36333.78	0	0	0
PM10 (Mortality)	95141.21	2973.16	118926.51	0	0	0
Ozone (Morbidity)	0.150	0.072	0.090	0	0	0
Ozone (Mortality)	1.540	0.739	0.924	0	0	0
Lead Damages	8536.03	426.80	3585.13	0	0	0
Mercury Damages	9.08	0.21	4.15	0	0	0
Air Toxics	1728.67	288.11	5762.23	0	0	0
Visibility Damages	1974.05	49.35	1579.24	0	0	0
Materials Damages	27399.65	684.99	21919.72	0	0	0
CO2 Damages	4334.37	2297.22	3337.47	0	0	0
Ash Radiation	0.0026	0	0	0	0	0
<i>Water Externalities</i>						
I&E Damages	52.22	17.49	17.49	23.65	0	0
Thermal Discharge	54.58	8.41	8.41	26.54	0	0
C&M Discharge	50.25	0	81.61	0	0	0
<i>Radiation Externalities</i>						
Normal Op (Fatal)	0	0	0	98.16	0	0
Normal Op. (survived)	0	0	0	11.66	0	0
Accidents (Fatal)	0	0	0	8.15	0	0
Accidents (Survived)	0	0	0	0.170	0	0
Waste (Fatal)	0	0	0	0.360	0	0
Waste (Survived)	0	0	0	0.044	0	0
Fuel (Fatal)	0	0	0	232.41	0	0
Fuel (Survived)	0	0	0	28.31	0	0
<i>Waste Disposal Ext.</i>						
Groundwater	1403.31	0	0	0	0	0
aesthetics	46034.14	0	0	0	0	0
<i>Environmental Limits</i>						
CO2 (Kyoto)	983549.95	498869.3	720588.96	0	0	0
NOx	145.30	33.25795	138.60	0	0	0
SO2	1743.60	0	1364.40	0	0	0

Fuel Mix Optimization Model Equations for the Year 2015

Decision Variables:

- X1 = Coal power contribution (GWh)
 X2 = Natural Gas power contribution (GWh)
 X3 = Oil Power Contribution (GWh)
 X4 = Nuclear Power Contribution (GWh)
 X5 = Hydro Power Contribution (GWh)
 X6 = Purchased Power Contribution (GWh)

Constraint Equations:	Decision Variable Coefficients:					
	X1	X2	X3	X4	X5	X6
Demand	1	1	1	1	1	1
Reliability	1.28	1.15	1.11	1.26	1.96	1
Safety (Occupational)	2887.62	186.048	775.2	608.532	1007.76	0
Safety (Public)	24380.04	6.2016	6589.2	206.2032	621.4003	0
Economics	130102	130102	130102	152731.1	86335.01	0
<i>Air Externalities</i>						
PM10 (Morbidity)	33928.14	1060.25	42410.18	0	0	0
PM10 (Mortality)	111052.46	3470.39	138815.57	0	0	0
Ozone (Morbidity)	0.175	0.084	0.105	0	0	0
Ozone (Mortality)	1.797	0.863	1.078	0	0	0
Lead Damages	14014.96	700.75	5886.28	0	0	0
Mercury Damages	9.98	0.23	4.56	0	0	0
Air Toxics	2017.77	336.29	6725.89	0	0	0
Visibility Damages	1778.71	44.47	1422.97	0	0	0
Materials Damages	31981.92	799.55	25585.53	0	0	0
CO2 Damages	4765.36	2525.64	3669.33	0	0	0
Ash Radiation	0.0045	0	0	0	0	0
<i>Water Externalities</i>						
I&E Damages	57.42	19.23	19.23	26.00	0	0
Thermal Discharge	60.01	9.25	9.25	29.18	0	0
C&M Discharge	58.65	0	95.26	0	0	0
<i>Radiation Externalities</i>						
Normal Op (Fatal)	0	0	0	107.92	0	0
Normal Op. (survived)	0	0	0	12.82	0	0
Accidents (Fatal)	0	0	0	8.97	0	0
Accidents (Survived)	0	0	0	1.07	0	0
Waste (Fatal)	0	0	0	0.396	0	0
Waste (Survived)	0	0	0	0.048	0	0
Fuel (Fatal)	0	0	0	255.53	0	0
Fuel (Survived)	0	0	0	31.12	0	0
<i>Waste Disposal Ext.</i>						
Groundwater	2366.12	0	0	0	0	0
aesthetics	50611.54	0	0	0	0	0
<i>Environmental Limits</i>						
CO2 (Kyoto)	983549.95	498869.28	720588.96	0	0	0
NOx	145.30	33.26	138.60	0	0	0
SO2	1743.60	0	1364.40	0	0	0

Fuel Mix Optimization Model Equations for the Year 2020

Decision Variables:

- X1 = Coal power contribution (GWh)
 X2 = Natural Gas power contribution (GWh)
 X3 = Oil Power Contribution (GWh)
 X4 = Nuclear Power Contribution (GWh)
 X5 = Hydro Power Contribution (GWh)
 X6 = Purchased Power Contribution (GWh)

Decision Variable Coefficients:						
Constraint Equations:	X1	X2	X3	X4	X5	X6
Demand	1	1	1	1	1	1
Reliability	1.28	1.15	1.11	1.26	1.96	1
Safety (Occupational)	2887.62	186.048	775.2	608.532	1007.76	0
Safety (Public)	24380.04	6.2016	6589.2	206.2032	621.4003	0
Economics	175963.658	175963.658	175963.658	221996.5	131846.4	0
<i>Air Externalities</i>						
PM10 (Morbidity)	39918.49	1247.45	49898.12	0	0	0
PM10 (Mortality)	130659.88	4083.12	163324.85	0	0	0
Ozone (Morbidity)	0.206	0.099	0.124	0	0	0
Ozone (Mortality)	2.114	1.015	1.269	0	0	0
Lead Damages	22116.09	1105.80	9288.76	0	0	0
Mercury Damages	11.02	0.25	5.03	0	0	0
Air Toxics	2374.02	395.67	7913.41	0	0	0
Visibility Damages	1704.78	42.62	1363.82	0	0	0
Materials Damages	37628.64	940.72	30102.92	0	0	0
CO2 Damages	5260.02	2787.81	4050.22	0	0	0
Ash Radiation	0.0183	0	0	0	0	0
<i>Water Externalities</i>						
I&E Damages	63.38	21.23	21.23	28.70	0	0
Thermal Discharge	66.23	10.21	10.21	32.20	0	0
C&M Discharge	69.01	0.00	112.08	0.00	0	0
<i>Radiation Externalities</i>						
Normal Op (Fatal)	0	0	0	119.13	0	0
Normal Op. (survived)	0	0	0	14.15	0	0
Accidents (Fatal)	0	0	0	9.90	0	0
Accidents (Survived)	0	0	0	1.18	0	0
Waste (Fatal)	0	0	0	0.437	0	0
Waste (Survived)	0	0	0	0.050	0	0
Fuel (Fatal)	0	0	0	282.05	0	0
Fuel (Survived)	0	0	0	34.35	0	0
<i>Waste Disposal Ext.</i>						
Groundwater	4515.87	0	0	0	0	0
aesthetics	55865.15	0	0	0	0	0
<i>Environmental Limits</i>						
CO2 (Kyoto)	983549.952	498869.28	720588.96	0	0	0
NOx	145.30	33.26	138.60	0	0	0
SO2	1743.60	0	1364.40	0	0	0

Appendix E

Table E1: Objective Function Comparison (Normalized Values)

	2000	2005	2010	2015	2020
Scenario 1	0.000E+00	0.000E+00	5.282E+02	6.930E+02	8.710E+02
Scenario 2	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Scenario 3	0.000E+00	0.000E+00	7.191E+02	9.993E+02	1.321E+03
Scenario 4	0.000E+00	0.000E+00	7.191E+02	9.993E+02	1.321E+03
Scenario 5	0.000E+00	0.000E+00	0.000E+00	9.417E-01	8.056E+01
Scenario 6	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Scenario 7	0.000E+00	0.000E+00	0.000E+00	9.590E+01	2.353E+02

Table E2: Model Outputs and NRCAN Projections

Year 2000							
	x1	x2	x3	x4	x5	x6	Total
Scenario 1	16315.38	27452.94	4785.67	63325.00	35800.00	5000.00	152679.00
(% of total)	10.69	17.98	3.13	41.48	23.45	3.27	100.00
Scenario 2	22550.83	19261.28	946.59	63325.00	41595.28	5000.00	152679.00
(% of total)	14.77	12.62	0.62	41.48	27.24	3.27	100.00
Scenario 3	16315.38	27452.94	4785.67	63325.00	35800.00	5000.00	152679.00
(% of total)	10.69	17.98	3.13	41.48	23.45	3.27	100.00
Scenario 4	16315.38	32453.00	4785.67	63325.00	35800.00	5000.00	152679.00
(% of total)	10.69	21.26	3.13	41.48	23.45	3.27	100.00
Projected Mix	23410.00	18635.00	0.00	69830.00	35800.00	5000.00	152679.00
(NRCAN)	15.33	12.21	0.00	45.74	23.45	3.27	100.00
Year 2005							
	x1	x2	x3	x4	x5	x6	Total
Scenario 1	16739.12	33592.51	3530.53	68491.84	36820.00	5000.00	164174.00
(% of total)	10.96	22.00	2.31	44.86	24.12	3.27	107.53
Scenario 2	16739.12	3299.78	3530.53	68491.84	67112.72	5000.00	164174.00
(% of total)	10.96	2.16	2.31	44.86	43.96	3.27	107.53
Scenario 3	16739.12	39698.23	3530.53	62386.12	36820.00	5000.00	164174.00
(% of total)	10.96	26.00	2.31	40.86	24.12	3.27	107.53
Scenario 4	16739.12	44698.00	3530.53	62386.12	36820.00	5000.00	164174.00
(% of total)	10.96	29.28	2.31	40.86	24.12	3.27	107.53
Projected Mix	23580.00	23152.00	0.00	75610.00	36820.00	5000.00	164174.00
	14.36	14.10	0.00	46.05	22.43	3.05	100.00
Year 2010							
	x1	x2	x3	x4	x5	x6	Total
Scenario 1	0.00	13366.23	0.00	116933.77	38560.00	5000.00	173860.00
(% of total)	0.00	8.75	0.00	76.59	25.26	3.27	113.87
Scenario 5	11267.90	47541.48	5681.58	65809.03	38560.00	5000.00	173860.00
(% of total)	7.38	31.14	3.72	43.10	25.26	3.27	113.87
Scenario 2	0.00	13366.23	0.00	65809.03	89684.74	5000.00	173860.00
(% of total)	0.00	8.75	0.00	43.10	58.74	3.27	113.87
Scenario 6	11267.90	34850.08	5698.98	65809.03	51234.00	5000.00	173860.00
(% of total)	7.38	22.83	3.73	43.10	33.56	3.27	113.87
Scenario 3	0.00	77446.56	0.00	52853.44	38560.00	5000.00	173860.00
(% of total)	0.00	50.73	0.00	34.62	25.26	3.27	113.87
Scenario 7	4288.37	73158.19	0.00	52853.44	38560.00	5000.00	173860.00
(% of total)	2.81	47.92	0.00	34.62	25.26	3.27	113.87
Scenario 4	0.00	77446.56	0.00	57853.00	38560.00	5000.00	173860.00
(% of total)	0.00	50.73	0.00	37.89	25.26	3.27	113.87
Projected Mix	19500.00	44794.00	0.00	64640.00	38560.00	5000.00	173860.00
	11.22	25.76	0.00	37.18	22.18	2.88	100.00

Table E2 (continued)

Year 2015							
	x1	x2	x3	x4	x5	x6	Total
Scenario 1	0.00	14365.29	0.00	128933.71	38560.00	5000.00	186859.00
(% of total)	0.00	9.41	0.00	84.45	25.26	3.27	122.39
Scenario 5	0.00	100882.01	0.00	42416.99	38560.00	5000.00	186859.00
(% of total)	0.00	66.07	0.00	27.78	25.26	3.27	122.39
Scenario 2	0.00	14365.29	0.00	64031.45	103462.26	5000.00	186859.00
(% of total)	0.00	9.41	0.00	41.94	67.76	3.27	122.39
Scenario 6	0.00	57528.00	11635.19	64031.45	48664.36	5000.00	186859.00
(% of total)	0.00	37.68	7.62	41.94	31.87	3.27	122.39
Scenario 3	0.00	100882.01	0.00	42416.99	38560.00	5000.00	186859.00
(% of total)	0.00	66.07	0.00	27.78	25.26	3.27	122.39
Scenario 7	0.00	100882.01	0.00	42416.99	38560.00	5000.00	186859.00
(% of total)	0.00	66.07	0.00	27.78	25.26	3.27	122.39
Scenario 4	0.00	100882.01	0.00	47417.00	38560.00	5000.00	186859.00
(% of total)	0.00	66.07	0.00	31.06	25.26	3.27	122.39
Projected Mix	12220.00	76645.00	0.00	52530.00	38560.00	5000.00	186859.00
	6.54	41.02	0.00	28.11	20.64	2.68	100.00
Year 2020							
	x1	x2	x3	x4	x5	x6	Total
Scenario 1	0.00	15443.16	0.00	141864.84	38560.00	5000.00	200868.00
(% of total)	0.00	10.11	0.00	92.92	25.26	3.27	131.56
Scenario 5	0.00	94652.99	0.00	62655.01	38560.00	5000.00	200868.00
(% of total)	0.00	61.99	0.00	41.04	25.26	3.27	131.56
Scenario 2	0.00	12557.70	0.00	62418.77	120891.50	5000.00	200868.00
(% of total)	0.00	8.22	0.00	40.88	79.18	3.27	131.56
Scenario 6	0.00	56141.51	10337.45	62418.77	66970.28	5000.00	200868.00
(% of total)	0.00	36.77	6.77	40.88	43.86	3.27	131.56
Scenario 3	0.00	127177.80	0.00	30130.20	38560.00	5000.00	200868.00
(% of total)	0.00	83.30	0.00	19.73	25.26	3.27	131.56
Scenario 7	0.00	127177.80	0.00	30130.20	38560.00	5000.00	200868.00
(% of total)	0.00	83.30	0.00	19.73	25.26	3.27	131.56
Scenario 4	0.00	127177.80	0.00	35130.00	38560.00	5000.00	200868.00
(% of total)	0.00	83.30	0.00	23.01	25.26	3.27	131.56
Projected Mix	3310.00	92083.00	0.00	59940.00	38560.00	5000.00	200868.00
	1.65	45.84	0.00	29.84	19.20	2.49	100.00

Non-normalized Deviation Variable Results:

Table E3: Scenario 1 Non-normalized Goal Deviation Variables

	2000	2005	2010	2015	2020
Negative (n_i)					
Safety - Occ. (1)	19138915	31349965	57496072	63007851	68938312
- Public (2)	149269415	190481877	646843793	696363172	749690048
Economics (3)	32449525187	30651788941	30888370224	28043948134	22185147236
PM10 (4)	857339294	783457640	1419565980	1523464751	1634877426
PM10 (5)	2806214324	2564387364	4646475925	4986553909	5351226155
Ozone (6)	0	107	4945	5142	5299
Ozone (7)	15995	1100	50788	52807	54417
Lead (8)	70869200	27791557	131138447	137002734	141026473
Mercury (9)	131622	97553	270384	290295	311713
Air Toxics (10)	170163953	159767920	223205485	239192934	256222308
Visibility (11)	103105402	132463777	192905028	207390560	222979359
M. Damage (12)	575100759	528391567	1070508215	1148859267	1232876626
CO2 Effects (13)	44228688	0	158219903	166761445	175224470
Ash Piles (14)	11	12	47	50	54
I&E (15)	286264	952480	939324	604225	151082
Thermal (16)	413442	1389277	913792	543258	44514
C&E (17)	250736	0	1031301	1108368	1191528
Normal Op. (18)	528334	1361472	0	0	0
Normal Op. (19)	62855	161726	0	0	0
Accidents (20)	43874	113103	0	0	0
Accidents (21)	5327	13435	43871	0	0
Waste (22)	1801	4991	0	0	0
Waste (23)	0	608	0	0	0
Fuel Acq. (24)	1251093	3223510	0	0	0
Fuel Acq. (25)	152484	392638	0	0	0
GW (26)	3553434	0	15812405	16994033	18269074
Aesthetics (27)	228237975	259896961	1015634730	1091530998	1173427224
CO2 (28)	N/A	N/A	N/A	N/A	N/A

Table E3 (continued)

Positive (p _i)					
Safety - Occ. (1)	0	0	0	0	0
- Public (2)	0	0	0	0	0
Economics (3)	0	0	0	0	0
PM10 (4)	0	0	0	0	0
PM10 (5)	0	0	0	0	0
Ozone (6)	0	0	0	0	0
Ozone (7)	0	0	0	0	0
Lead (8)	0	0	0	0	0
Mercury (9)	0	0	0	0	0
Air Toxics (10)	0	0	0	0	0
Visibility (11)	0	0	0	0	0
M. Damage (12)	0	0	0	0	0
CO2 Effects (13)	0	0	0	0	0
Ash Piles (14)	0	2	0	0	0
I&E (15)	0	0	0	0	0
Thermal (16)	0	0	0	0	0
C&E (17)	0	0	0	0	0
Normal Op. (18)	0	0	5018325	6972002	9435915
Normal Op. (19)	0	0	596061	828198	1120777
Accidents (20)	0	0	416892	579191	783878
Accidents (21)	0	0	0	69445	93746
Waste (22)	0	0	18396	25558	34590
Waste (23)	0	0	2241	3113	3761
Fuel Acq. (24)	0	0	11881710	16507982	22341083
Fuel Acq. (25)	0	0	1447341	2010670	2720553
GW (26)	0	0	0	0	0
Aesthetics (27)	0	0	0	0	0
CO2 (28)	N/A	N/A	N/A	N/A	N/A

Table E4: Scenario 2 Non-normalized Goal Deviation Variables

	2000	2005	2010	2015	2020
Negative (n_j)					
Safety - Occ. (1)	0	25095659	13357901	11959834	23062239
- Public (2)	14304959	183977399	456321808	490064343	615681326
Economics (3)	32742900403	31117018045	33546185782	32658608017	29520617455
PM10 (4)	728077306	783457640	1234646555	1294798113	1483335891
PM10 (5)	2383118306	2564387364	4041203841	4238089911	4855205527
Ozone (6)	0	107	4891	5075	5254
Ozone (7)	15995	1100	50228	52115	53958
Lead (8)	58045607	27791557	78972958	46266679	60375177
Mercury (9)	100332	97553	211597	221821	269138
Air Toxics (10)	162005335	159767920	215336904	229462847	249774004
Visibility (11)	82553297	132463777	180181550	195245104	216422567
M. Damage (12)	460465336	528391567	893907405	930479216	1088152178
CO2 Effects (13)	45781090	0	159540052	168299081	176180471
Ash Piles (14)	2	12	30	18	0
I&E (15)	222676	1288647	2028173	2151687	2344144
Thermal (16)	257726	1766487	2012913	2136844	2416506
C&E (17)	0	0	690633	687107	912350
Normal Op. (18)	528334	2756794	188	32437	28142
Normal Op. (19)	62855	327474	53	3849	3385
Accidents (20)	43874	229017	16	2695	2338
Accidents (21)	5327	27205	52562	0	0
Waste (22)	1801	10106	1	119	103
Waste (23)	0	1231	0	14	212
Fuel Acq. (24)	1251093	6527164	446	76492	66630
Fuel Acq. (25)	152484	795037	0	9355	8419
GW (26)	509665	0	6298606	0	0
Aesthetics (27)	32735926	259896961	703545226	728026754	947423426
CO2 (28)	N/A	N/A	N/A	N/A	N/A

Table E4 (continued)

Positive (p)						
Safety - Occ. (1)	0	0	0	0	0	0
- Public (2)	0	0	0	0	0	0
Economics (3)	0	0	0	0	0	0
PM10 (4)	0	0	0	0	0	0
PM10 (5)	0	0	0	0	0	0
Ozone (6)	0	0	0	0	0	0
Ozone (7)	0	0	0	0	0	0
Lead (8)	0	0	0	0	0	0
Mercury (9)	0	0	0	0	0	0
Air Toxics (10)	0	0	0	0	0	0
Visibility (11)	0	0	0	0	0	0
M. Damage (12)	0	0	0	0	0	0
CO2 Effects (13)	0	0	0	0	0	0
Ash Piles (14)	0	2	0	0	0	0
I&E (15)	0	0	0	0	0	0
Thermal (16)	0	0	0	0	0	0
C&E (17)	0	0	0	0	0	0
Normal Op. (18)	0	0	0	0	0	0
Normal Op. (19)	0	0	0	0	0	0
Accidents (20)	0	0	0	0	0	0
Accidents (21)	0	0	0	0	0	0
Waste (22)	0	0	0	0	0	0
Waste (23)	0	0	0	0	0	0
Fuel Acq. (24)	0	0	0	0	0	0
Fuel Acq. (25)	0	0	0	0	0	0
GW (26)	0	0	0	0	0	0
Aesthetics (27)	0	0	0	0	0	0
CO2 (28)	N/A	N/A	N/A	N/A	N/A	N/A

Table E5: Scenario 3 Non-normalized Goal Deviation Variables

	2000	2005	2010	2015	2020
Negative (n_i)					
Safety - Occ. (1)	19138915	27471463	84568987	99559781	116144408
- Public (2)	149269415	188645815	659659963	713666654	772037154
Economics (3)	32449525187	30809897990	30995854781	30001742692	27328605040
PM10 (4)	857339294	790648913	1361358964	1431735015	1495493730
PM10 (5)	2806214324	2587925600	4455954666	4686307204	4895000098
Ozone (6)	0	677	334	0	0
Ozone (7)	15995	6950	3433	0	0
Lead (8)	70869200	30044436	103788865	76376326	17469783
Mercury (9)	131622	99280	257088	270569	283611
Air Toxics (10)	170163953	162048868	204743220	210097839	212012195
Visibility (11)	103105402	133019398	189742584	203543354	218217284
M. Damage (12)	575100759	533814575	1026613751	1079685001	1127766054
CO2 Effects (13)	44228688	19134992	11013407	0	0
Ash Piles (14)	11	12	47	50	54
I&E (15)	286264	901199	1333828	1190053	985770
Thermal (16)	413442	1238299	2075270	2267175	2502044
C&E (17)	250736	0	1031301	1108368	1191528
Normal Op. (18)	528334	543817	1271937	2365132	3874536
Normal Op. (19)	62855	64599	151116	280946	460268
Accidents (20)	43874	45177	105665	196481	321873
Accidents (21)	5327	5366	54765	23127	38101
Waste (22)	1801	1994	4663	8670	14203
Waste (23)	0	243	568	1056	1826
Fuel Acq. (24)	1251093	1287577	3011520	5599635	9173602
Fuel Acq. (25)	152484	156833	366773	682085	1117532
GW (26)	3553434	0	15812405	16994033	18269074
Aesthetics (27)	228237975	259896961	1015634730	1091530998	1173427224
CO2 (28)	N/A	N/A	0	0	0

Table E5 (continued)

Positive (p_i)						
Safety - Occ. (1)	0	0	0	0	0	0
- Public (2)	0	0	0	0	0	0
Economics (3)	0	0	0	0	0	0
PM10 (4)	0	0	0	0	0	0
PM10 (5)	0	0	0	0	0	0
Ozone (6)	0	0	0	2125	5743	
Ozone (7)	0	0	0	21820	58978	
Lead (8)	0	0	0	0	0	
Mercury (9)	0	0	0	0	0	
Air Toxics (10)	0	0	0	0	0	
Visibility (11)	0	0	0	0	0	
M. Damage (12)	0	0	0	0	0	
CO2 Effects (13)	0	0	0	51748815	136270504	
Ash Piles (14)	0	0	0	0	0	
I&E (15)	0	0	0	0	0	
Thermal (16)	0	0	0	0	0	
C&E (17)	0	0	0	0	0	
Normal Op. (18)	0	0	0	0	0	
Normal Op. (19)	0	0	0	0	0	
Accidents (20)	0	0	0	0	0	
Accidents (21)	0	0	0	0	0	
Waste (22)	0	0	0	0	0	
Waste (23)	0	0	0	0	0	
Fuel Acq. (24)	0	0	0	0	0	
Fuel Acq. (25)	0	0	0	0	0	
GW (26)	0	0	0	0	0	
Aesthetics (27)	0	0	0	0	0	
CO2 (28)	N/A	N/A	3.20E+10	4.32E+10	5.57E+10	

Microsoft Excel 8.0 Sensitivity Report - Scenario 1
Worksheet: [Revised_Model3-normalize.xls]2020

Adjustable Cells

Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
\$C\$6	Solution: x1	0	0.010690551	0	1E+30	0.010690551
\$D\$6	Solution: x2	15443.16379	0	0	0.003385695	1E+30
\$E\$6	Solution: x3	0	0.004890448	0	1E+30	0.004890448
\$F\$6	Solution: x4	141864.8362	0	0	1E+30	0.011003507
\$I\$6	Solution: n1	34.99406708	0	0	6.767388972	0.1
\$J\$6	Solution: n2	93.3611517	0	0	3.494162751	0.1
\$K\$6	Solution: n3	36.08510377	0	0	146.9596466	0.1
\$L\$6	Solution: n4	98.83537091	0	0	1.681939194	10
\$M\$6	Solution: n5	98.83537091	0	0	1.681939194	10
\$N\$6	Solution: n6	77.63912139	0	0	66.0546406	0.1
\$O\$6	Solution: n7	77.63912139	0	0	66.0546406	0.1
\$P\$6	Solution: n8	89.19877594	0	0	0.847822986	3.5
\$Q\$6	Solution: n9	98.7693291	0	0	3.2059591	0.5
\$R\$6	Solution: n10	97.67074181	0	0	1.747403894	3.5
\$S\$6	Solution: n11	99.70569343	0	0	8.398364982	3.5
\$T\$6	Solution: n12	98.83537091	0	0	2.122301456	3.5
\$U\$6	Solution: n13	80.27616489	0	0	456.6168025	3.5
\$V\$6	Solution: n14	100	0	0	0.317498594	0.1
\$W\$6	Solution: n15	3.320121556	0	0	9.84674787	1.5
\$X\$6	Solution: n16	0.93303637	0	0	6.590148953	1.5
\$Y\$6	Solution: n17	100	0	0	0.519905766	0.1
\$Z\$6	Solution: n18	0	1.5	0	1E+30	1.5
\$AA\$6	Solution: n19	0	0.7	0	1E+30	0.7
\$AB\$6	Solution: n20	0	0.7	0	1E+30	7
\$AC\$6	Solution: n21	0	0.1	0	1E+30	0.1
\$AD\$6	Solution: n22	0	0.1	0	1E+30	0.1
\$AE\$6	Solution: n23	0	0.1	0	1E+30	0.1
\$AF\$6	Solution: n24	0	3	0	1E+30	3
\$AG\$6	Solution: n25	0	0.7	0	1E+30	0.7
\$AH\$6	Solution: n26	100	0	0	0.432488722	3
\$AI\$6	Solution: n27	100	0	0	2.2455112	3.5
\$AJ\$6	Solution: n28	0	0	0	1E+30	0
\$AM\$6	Solution: p1	0	0.1	0.1	1E+30	0.1
\$AN\$6	Solution: p2	0	0.1	0.1	1E+30	0.1
\$AO\$6	Solution: p3	0	0.1	0.1	1E+30	0.1
\$AP\$6	Solution: p4	0	10	10	1E+30	10
\$AQ\$6	Solution: p5	0	10	10	1E+30	10
\$AR\$6	Solution: p6	0	0.1	0.1	1E+30	0.1
\$AS\$6	Solution: p7	0	0.1	0.1	1E+30	0.1
\$AT\$6	Solution: p8	0	3.5	3.5	1E+30	3.5
\$AU\$6	Solution: p9	0	0.5	0.5	1E+30	0.5
\$AV\$6	Solution: p10	0	3.5	3.5	1E+30	3.5
\$AW\$6	Solution: p11	0	3.5	3.5	1E+30	3.5
\$AX\$6	Solution: p12	0	3.5	3.5	1E+30	3.5

\$AY\$6	Solution: p13	0	3.5	3.5	1E+30	3.5
\$AZ\$6	Solution: p14	0	0.1	0.1	1E+30	0.1
\$BA\$6	Solution: p15	0	1.5	1.5	1E+30	1.5
\$BB\$6	Solution: p16	0	1.5	1.5	1E+30	1.5
\$BC\$6	Solution: p17	0	0.1	0.1	1E+30	0.1
\$BD\$6	Solution: p18	126.422185	0	1.5	1E+30	1.5
\$BE\$6	Solution: p19	126.4114206	0	0.7	1E+30	0.7
\$BF\$6	Solution: p20	126.422185	0	0.7	1E+30	0.7
\$BG\$6	Solution: p21	127.2791242	0	0.1	1E+30	0.1
\$BH\$6	Solution: p22	126.422185	0	0.1	1E+30	0.1
\$BI\$6	Solution: p23	112.8416969	0	0.1	1E+30	0.1
\$BJ\$6	Solution: p24	126.422185	0	3	1E+30	3
\$BK\$6	Solution: p25	126.3901349	0	0.7	1E+30	0.7
\$BL\$6	Solution: p26	0	3	3	1E+30	3
\$BM\$6	Solution: p27	0	3.5	3.5	1E+30	3.5
\$BN\$6	Solution: p28	0	1.5	1.5	1E+30	1.5

Constraints

Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
\$BQ\$12	Demand LHS	100.00	22.10	100	0.688128188	37.44354
\$BQ\$13	Safety (Occupational) LHS	100.00	0.00	100	1E+30	34.99406708
\$BQ\$14	Safety (Public) LHS	100.00	0.00	100	1E+30	93.3611517
\$BQ\$15	Economics LHS	100.00	0.00	100	1E+30	36.08510377
\$BQ\$16	PM10 (Morbidity) LHS	100.00	0.00	100	1E+30	98.83537091
\$BQ\$17	PM10 (Mortality) LHS	100.00	0.00	100	1E+30	98.83537091
\$BQ\$18	Ozone (Morbidity) LHS	100.00	0.00	100	1E+30	77.63912139
\$BQ\$19	Ozone (Mortality) LHS	100.00	0.00	100	1E+30	77.63912139
\$BQ\$20	Lead Damages LHS	100.00	0.00	100	5.62134E+17	89.19877594
\$BQ\$21	Mercury Damages LHS	100.00	0.00	100	1E+30	98.7693291
\$BQ\$22	Air Toxics LHS	100.00	0.00	100	1E+30	97.67074181
\$BQ\$23	Visibility Damages LHS	100.00	0.00	100	1E+30	99.70569343
\$BQ\$24	Materials Damages LHS	100.00	0.00	100	1E+30	98.83537091
\$BQ\$25	CO2 Damages LHS	100.00	0.00	100	1E+30	80.27616489
\$BQ\$26	Ash Radiation LHS	100.00	0.00	100	9.38587E+18	100
\$BQ\$27	I&E Damages LHS	100.00	0.00	100	1.9033E+17	3.320121556
\$BQ\$28	Thermal Discharge LHS	100.00	0.00	100	9.48925E+16	0.93303637
\$BQ\$29	C&M Discharge LHS	100.00	0.00	100	1E+30	100
\$BQ\$30	Normal Op (Fatal) LHS	100.00	-1.50	100	126.422185	1E+30
\$BQ\$31	Normal Op. (survived) LHS	100.00	-0.70	100	126.4114206	1E+30
\$BQ\$32	Accidents (Fatal) LHS	100.00	-0.70	100	126.422185	1E+30
\$BQ\$33	Accidents (Survived) LHS	100.00	-0.10	100	127.2791242	1E+30
\$BQ\$34	Waste (Fatal) LHS	100.00	-0.10	100	126.422185	1E+30
\$BQ\$35	Waste (Survived) LHS	100.00	-0.10	100	112.8416969	1E+30
\$BQ\$36	Fuel (Fatal) LHS	100.00	-3.00	100	126.422185	1.87717E+18
\$BQ\$37	Fuel (Survived) LHS	100.00	-0.70	100	126.3901349	1E+30
\$BQ\$38	Groundwater LHS	100.00	0.00	100	1E+30	100
\$BQ\$39	aesthetics LHS	100.00	0.00	100	1E+30	100
\$BQ\$42	SO2 LHS	0.00	0.00	100	1E+30	100
\$BQ\$41	NOx LHS	1.43	0.00	100	1E+30	98.57331111
\$BQ\$46	Reliability LHS	51.20	0.00	100	1E+30	48.80435293
\$BQ\$40	CO2 LHS	100.00	-1.70	100	347.2096189	13.10530901

Microsoft Excel 8.0 Sensitivity Report - Scenario 5
Worksheet: [Revised_Model3-normalize.xls]2020

Adjustable Cells

Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
\$C\$6	Solution: x1	0	0.004277826	0	1E+30	0.004277826
\$D\$6	Solution: x2	94652.99285	0	0	0.001465416	0.003322708
\$E\$6	Solution: x3	0	0.002096621	0	1E+30	0.002096621
\$F\$6	Solution: x4	62655.00715	0	0	0.003322708	0.001465416
\$I\$6	Solution: n1	51.98131857	0	0	3.119412712	0.1
\$J\$6	Solution: n2	95.33401503	0	0	1.409336748	0.1
\$K\$6	Solution: n3	42.01588741	0	0	19.57167766	0.1
\$L\$6	Solution: n4	92.86184937	0	0	0.712859546	10
\$M\$6	Solution: n5	92.86184937	0	0	0.712859546	10
\$N\$6	Solution: n6	0	0.1	0	1E+30	0.1
\$O\$6	Solution: n7	0	0.1	0	1E+30	0.1
\$P\$6	Solution: n8	33.79800939	0	0	0.321908808	2.095194579
\$Q\$6	Solution: n9	92.45707127	0	0	1.253755114	0.5
\$R\$6	Solution: n10	85.72369874	0	0	0.731619008	3.5
\$S\$6	Solution: n11	98.19615991	0	0	3.548906475	3.5
\$T\$6	Solution: n12	92.86184937	0	0	0.8968233	3.5
\$U\$6	Solution: n13	0	3.5	0	1E+30	3.5
\$V\$6	Solution: n14	100	0	0	0.12704714	0.1
\$W\$6	Solution: n15	16.3235041	0	0	4.618691097	1.5
\$X\$6	Solution: n16	37.44995352	0	0	3.178674291	1.5
\$Y\$6	Solution: n17	100	0	0	0.222892756	0.1
\$Z\$6	Solution: n18	-6.46235E-27	0	0	0.918156775	1.5
\$AA\$6	Solution: n19	0.004754125	0	0	0.918200428	0.7
\$AB\$6	Solution: n20	0	0.7	0	1E+30	0.7
\$AC\$6	Solution: n21	0	0.1	0	1E+30	0.1
\$AD\$6	Solution: n22	0	0.1	0	1E+30	0.1
\$AE\$6	Solution: n23	5.997861086	0	0	0.976740302	0.1
\$AF\$6	Solution: n24	0	2.081843225	0	1E+30	2.081843225
\$AG\$6	Solution: n25	0.014155013	0	0	0.918286759	0.7
\$AH\$6	Solution: n26	100	0	0	0.173060468	3
\$AI\$6	Solution: n27	100	0	0	0.898541858	3.5
\$AJ\$6	Solution: n28	0	0	0	1E+30	0
\$AM\$6	Solution: p1	0	0.1	0.1	1E+30	0.1
\$AN\$6	Solution: p2	0	0.1	0.1	1E+30	0.1
\$AO\$6	Solution: p3	0	0.1	0.1	1E+30	0.1
\$AP\$6	Solution: p4	0	10	10	1E+30	10
\$AQ\$6	Solution: p5	0	10	10	1E+30	10
\$AR\$6	Solution: p6	37.0524921	0	0.1	1.012065156	0.1
\$AS\$6	Solution: p7	37.0524921	0	0.1	1.012065156	0.1
\$AT\$6	Solution: p8	0	3.5	3.5	1E+30	3.5
\$AU\$6	Solution: p9	0	0.5	0.5	1E+30	0.5
\$AV\$6	Solution: p10	0	3.5	3.5	1E+30	3.5
\$AW\$6	Solution: p11	0	3.5	3.5	1E+30	3.5
\$AX\$6	Solution: p12	0	3.5	3.5	1E+30	3.5
\$AY\$6	Solution: p13	20.88973799	0	3.5	1.147376561	2.601579799

\$AZ\$6	Solution: p14	0	0.1	0.1	1E+30	0.1
\$BA\$6	Solution: p15	0	1.5	1.5	1E+30	1.5
\$BB\$6	Solution: p16	0	1.5	1.5	1E+30	1.5
\$BC\$6	Solution: p17	0	0.1	0.1	1E+30	0.1
\$BD\$6	Solution: p18	0	1.5	1.5	1E+30	1.5
\$BE\$6	Solution: p19	0	0.7	0.7	1E+30	0.7
\$BF\$6	Solution: p20	2.842E-14	0	0.7	2.081843225	0.7
\$BG\$6	Solution: p21	0.378469607	0	0.1	2.073993788	0.1
\$BH\$6	Solution: p22	1.42109E-14	0	0.1	2.081843225	0.1
\$BI\$6	Solution: p23	0	0.1	0.1	1E+30	0.1
\$BJ\$6	Solution: p24	0	0.918156775	3	1E+30	0.918156775
\$BK\$6	Solution: p25	0	0.7	0.7	1E+30	0.7
\$BL\$6	Solution: p26	0	3	3	1E+30	3
\$BM\$6	Solution: p27	0	3.5	3.5	1E+30	3.5
\$BN\$6	Solution: p28	0	1.5	1.5	1E+30	1.5

Constraints

Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
\$BQ\$12	Demand LHS	100.00	9.56	100	17.41853945	8.142675948
\$BQ\$13	Safety (Occupational) LHS	100.00	0.00	100	1E+30	51.98131857
\$BQ\$14	Safety (Public) LHS	100.00	0.00	100	1E+30	95.33401503
\$BQ\$15	Economics LHS	100.00	0.00	100	1E+30	42.01588741
\$BQ\$16	PM10 (Morbidity) LHS	100.00	0.00	100	1E+30	92.86184937
\$BQ\$17	PM10 (Mortality) LHS	100.00	0.00	100	1E+30	92.86184937
\$BQ\$18	Ozone (Morbidity) LHS	100.00	-0.10	100	37.0524921	1E+30
\$BQ\$19	Ozone (Mortality) LHS	100.00	-0.10	100	37.0524921	1E+30
\$BQ\$20	Lead Damages LHS	100.00	0.00	100	1E+30	33.79800939
\$BQ\$21	Mercury Damages LHS	100.00	0.00	100	6.12005E+17	92.45707127
\$BQ\$22	Air Toxics LHS	100.00	0.00	100	1E+30	85.72369874
\$BQ\$23	Visibility Damages LHS	100.00	0.00	100	1E+30	98.1961599
\$BQ\$24	Materials Damages LHS	100.00	0.00	100	1.38907E+16	92.86184937
\$BQ\$25	CO2 Damages LHS	100.00	-3.50	100	20.88973799	2.1392E+18
\$BQ\$26	Ash Radiation LHS	100.00	0.00	100	5.15217E+17	100
\$BQ\$27	I&E Damages LHS	100.00	0.00	100	1E+30	16.3235041
\$BQ\$28	Thermal Discharge LHS	100.00	0.00	100	1E+30	37.44995352
\$BQ\$29	C&M Discharge LHS	100.00	0.00	100	3.73451E+18	100
\$BQ\$30	Normal Op (Fatal) LHS	100.00	0.00	100	1E+30	0
\$BQ\$31	Normal Op. (survived) LHS	100.00	0.00	100	1E+30	0.004754125
\$BQ\$32	Accidents (Fatal) LHS	100.00	-0.70	100	0	1E+30
\$BQ\$33	Accidents (Survived) LHS	100.00	-0.10	100	0.378469607	1E+30
\$BQ\$34	Waste (Fatal) LHS	100.00	-0.10	100	0	1E+30
\$BQ\$35	Waste (Survived) LHS	100.00	0.00	100	1E+30	5.997861086
\$BQ\$36	Fuel (Fatal) LHS	100.00	-2.08	100	0	0
\$BQ\$37	Fuel (Survived) LHS	100.00	0.00	100	1E+30	0.014155013
\$BQ\$38	Groundwater LHS	100.00	0.00	100	1E+30	100
\$BQ\$39	aesthetics LHS	100.00	0.00	100	1E+30	100
\$BQ\$42	SO2 LHS	0.00	0.00	100	1E+30	100
\$BQ\$41	NOx LHS	8.74	0.00	100	1E+30	91.25565363
\$BQ\$46	Reliability LHS	49.50	0.00	100	1E+30	50.50261167