A LIFE-CYCLE BASED DECISION-MAKING FRAMEWORK FOR ELECTRICITY GENERATION SYSTEM PLANNING

by

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A thesis
presented to Ryerson University
in partial fulfillment of the
requirements for the degree of
Master of Applied Science
in the Program of
Environmental Applied Science and Management

Toronto, Ontario, Canada, 2006

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Abstract

This thesis proposed a decision-making framework to consider multiple objectives in long-term planning situations, and asserts that planning for power generation systems should consider relevant environmental and/or social objectives at the same decision level as traditional economic or reliability objectives. The framework was applied to the case study of long-term planning for Ontario's power generation system. The framework integrates life-cycle based information and decision-maker preferences toward multiple objectives in the context of sustainable development. Six decision criteria evaluated as measures of the objectives include life-cycle cost of electricity, a system flexibility indicator, demand reduction, land use requirements, greenhouse gas emissions, and air emissions. Stakeholder values were derived through questionnaires. Three hypothetical electricity generation scenarios were compared to test the decision-making framework. The results of the application indicated that the scenario which included aggressive renewable energy development and demand reduction was favourable, even given the tradeoffs of reliability and costs.

Acknowledgements

I would like to thank my supervisor, Dr. Liping Fang, for his knowledge, guidance and patience throughout the development of this thesis. Dr. Fang provided the resources and support that made completing this thesis possible. I would also like to thank my external supervisor, Dr. Jim McTaggart-Cowan, who inspired me in so many ways as an undergraduate student at Royal Roads University, and who graciously provided input and insight that was integral to this thesis.

A special thanks to Dr. Neil Freeman for his comments and contribution to this thesis, and whose experience, knowledge and mentorship has helped to shape this work. I thank my friend, Zhong Liu, for his inspiration and interest throughout this thesis. I also thank the many others who participated in the development of this thesis.

Dedication

To my mother and father, Denise and Donald Norrie, whose extreme patience and support over many years made this work possible.

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Chapter 1: Introduction

1.1 Electricity Generation Systems

Modern developed societies and economies have flourished by harnessing energy from the natural environment and converting it to higher quality forms. High quality energy carriers, such as electricity, have universal application making them arguably the single most important resource to an industrial society (Sen, 2004). Generating electricity has many costs and impacts, and much electricity provides lesser quality services (such as space heating) or is not used (wasted). In addition, line losses can reach 10% where system design locates power plants far from energy users. Large, central thermal power plants also reduce opportunities to maximize efficiencies by utilizing thermal energy for district heating systems.

Electric energy, assuming adequate ancillary services like voltage control, functions independent of its primary energy source. The electricity generation system is a complex system which can be designed to adapt to changing conditions, where the energy sources and conversion technologies change but energy carriers do not. The fundamental objectives of such complex, adaptive systems change over time (Hipel and Fang, 2005). During most of the 20th Century, the primary objective of Ontario's power generation system was to provide reliable power for the least cost. In recent decades, the system objectives have expanded to include social and environmental considerations, as well as the provision of multiple energy carriers (e.g. thermal energy). Assuming that cost-effectiveness will always be a consideration when designing a system paid for by humans, expanding the goals of power generation systems has introduced objectives that compete with the goal of minimizing costs.

Ontario's electric system is a grid-based, integrated system. It is among the world's oldest and well developed electricity systems, being over 100 years old and comprised of many mature generation assets. Much of Ontario's hydroelectric capacity has been in service since the early 1900s and Ontario's nuclear fleet has been in service for decades.

Ontario currently has just over 30,000 MW of installed capacity on the Independent Electricity System Operator (IESO) controlled grid, composed of 36% nuclear, 21% coal, 17% gas/oil, 26% hydroelectric and less than 1% renewable electricity (IESO, 2005).

Four main electricity supply functions of grid-based systems are described by Joskow (1997) as generation, transmission, distribution, and retailing. Generation is the conversion of primary energy to electricity; transmission is the transport of electricity along high-voltage wires to substations; and distribution is the transport of electricity along low-voltage wires to customers' meters. Retailing, the fourth function, includes arrangements for billing, on-site support, and demand management. This thesis focuses on planning for the long-term development of the generation function.

1.2 Electricity Generation Systems Planning

Until 1998, Ontario's electric system was owned and operated by Ontario Hydro (previously the *Hydro-electric Power Commission of Ontario*) as a government-granted, vertically-oriented monopoly which sold power to consumers through local municipal utilities. Even though some independent power producers existed, Ontario Hydro produced and transmitted the bulk of Ontario's electricity. This monopoly structure lasted until 1998, when Ontario Hydro was re-organized into several independent, crown corporations. The power generation function was transferred to Ontario Power Generation (OPG) and the transmission system became the control of Hydro One Networks Inc. (Hydro One). Even though a competing generation market was opened in 2002, OPG continues to own approximately 70% of the generation capacity on the IESO controlled grid.

With the former Ontario Hydro came the natural function of integrated planning. Determining system needs and then building the system to meet those needs, while coordinating the generation, transmission and distribution functions were integral to planning in the publicly owned utility model. Market restructuring in Ontario left a void where the central planning function previously existed. While the emerging free-market is intended to maximize efficient allocation of resources, uncertainty and risk associated with financing new electricity generation projects has resulted in little investment in new infrastructure following market opening.

A crown owned, statutory agency, the Ontario Power Authority (OPA), was created in 2004 to assume centrally integrated medium and long-term planning functions. The existence of central planning in Ontario led to a "hybrid" electricity market, where integrated generation and transmission planning, generation procurement and conservation would occur centrally, while competing generation, retail and possibly transmission markets would mature. The OPA is charged with developing a 20-year integrated power system plan (IPSP) for Ontario. In developing the IPSP, the OPA must forecast demand as well as adequacy and reliability of electricity resources over the medium to long-term and conduct independent planning for electricity generation, demand management, conservation and transmission. The IPSP is to be updated and re-approved every three years.

In Ontario, the *Environmental Assessment Act* applies to public sector plans, such as the IPSP. In addition, the Electricity Act outlines criteria by which the IPSP will be approved by the Ontario Energy Board (OEB), such as compliance with directives from the Minister of Energy and cost-effectiveness and economic prudence. Economic, socio-economic and environmental objectives are implicit parts of the approval processes of the plan even though they are evaluated in separate processes. The multiple objective nature of power systems planning is alluded to further in Ontario Regulation 424/04 which states that the OPA must "ensure that safety and economic and environmental sustainability and environmental protection are reflected in the plan" (Government of Ontario, 2004). This thesis argues that methods should be developed to systematically consider multiple objectives in making decisions for long-term planning, and proposes a framework for integrating multiple criteria into the decision-making processes used in planning.

Besides considering multiple objectives, the information by which options are evaluated should accurately describe the systems being compared. For multiple stage processes such as electricity generation, the full life-cycles of power plants and fuel cycles should be considered. Many life-cycle assessments of power plants have been published. A description of life-cycle assessment is provided in the following section.

1.3 Life-cycle Assessment

Life-cycle assessment (LCA) provides a way to more accurately and appropriately compare the characteristics of multiple stage products, processes or activities (Allen *et al.*, 1997). It allows for more complete, holistic views of the spectrum of benefits, costs, materials and energy inputs and outputs associated with processes whose impacts extend beyond their operation phases. Electricity generation plants are candidates for LCA because their construction, operation, maintenance and decommissioning occur over long time frames, can be spatially distributed, and can have environmental consequences at life-cycle phases other than the actual operation phase of the facility. Although the boundaries of LCA can change, the following stages of the power plant's life-cycle can be included if applicable to the technology:

- Extraction or collection of raw energy resources;
- Manufacturing and processing of desired energy form(s);
- Transportation and distribution of the energy to users;
- Energy storage (if applicable);
- Use of the energy to provide services and tasks;
- Recovery and reuse of output energy that would otherwise be wasted (e.g. waste heat recovery);
- Recycling of wastes from any of the above steps; and
- Disposal of final wastes (e.g. material such as stack gases and solid wastes including ash) (Rosen, 2001).

LCA gained prominence in the 1990s as an approach to evaluating and comparing products, processes and services, but little consistency is evident among LCAs for power generation systems. Appropriate modeling of environmental burdens has resulted from increasing environmental concern, and available LCA data for power generation systems can provide planners with a baseline for comparing performance in several dimensions. LCA is not limited to environmental aspects of electricity generation, as social and economic attributes can also be evaluated over plants' life-cycles. In general, LCA provides "a better understanding of the energy and environmental performance of electricity generation systems" (Meier, 2002).

However, LCA is not well understood by decision makers (Ross and Evans, 2002). Even though there is a demonstrated need for further development of LCA methodologies related to energy supply, LCA data can be adapted to support decision-making in the planning of electricity generation (Curran *et al.*, 2001). This thesis surveys available life-cycle environmental and cost information for electricity generation technologies, to provide inputs to the proposed decision-making framework and to evaluate the information in the context of multiple objectives.

1.4 Multiple-criteria Decision Making

Decision analysis has been evolving as a set of methodologies rooted in operations research and systems engineering for systematically examining complex and opaque decision situations, such as those faced in the energy sector (Huang *et al.*, 1995). Decisions concerning energy and the environment are made in an atmosphere of uncertain needs, difficult tradeoffs, and risk. Conditions external to the physical system, such as environmental impacts, fossil fuel availability, or drought, can affect the outcomes of prior decisions made by planners. These types of decisions can occur as series of irreversible decisions.

When making decisions concerning the resource mix of electricity generation systems, planners must consider economic objectives (e.g. cost-effectiveness), in addition to environmental and social goals. The multiple objectives involved in planning decisions for electricity generation systems are often conflicting and subject to public scrutiny. Therefore, more holistic methods of evaluating alternatives and making strategic development decisions have become a prominent application of decision analysis. For long-term planning several characteristics of electricity generation systems make decision-making particularly challenging:

- The heterogeneity of electricity supply systems;
- Technological progression of energy conversion, storage and supply technologies and techniques;
- Geographic diversity, demographic distribution and unpredictable nature of human behavior;
- Effects of dynamic energy markets;
- Uncertainty regarding fossil fuel prices, due to price volatility or fuel supply availability; and
- How changes in assumptions can result in different outcomes.

Even as electricity generation technologies become smaller, more diversified, and more cost-effective, the many technologies have different environmental and social impacts. At the same time, the parties interested in planning decisions have increased as a result of market restructuring. Decision-making that utilizes multiple objective methods can provide for diverse stakeholder involvement in evaluating optional strategies. These methods allow stakeholders to articulate tradeoffs and express value judgments to evaluate alternatives against multiple criteria in complex decision problems (Hobbs and Meier, 2000).

Many methods have been developed and proposed over the last 30 years to make decisions under multiple objectives. Combinations of methods have been utilized to evaluate complex energy planning decisions, as no single decision-making methodology has been applied (Hobbs and Meier, 2000). The choice of methods depends on time, budget, expertise, stakeholder interest, politics and the appropriateness for the decision problem. Decisions reflecting public policy interests with disparate, conflicting objectives warrant innovative methods of considering these objectives in decisions. In addition to stakeholder participation, multiple criteria decision-making methods are intended to be transparent and open, to explicate values, and to document the decision-making process.

Strategic planning should focus on the range of possible alternatives and identify opportunities to adapt to new information, changing assumptions or adverse situations. To address the problem of uncertainty in decisions with multiple criteria, alternatives should be built from ranges of varying assumptions over fixed predictions (based on trends extensions or 'forecasting'). Structuring complex decision problems to more clearly display values and tradeoffs between alternatives allows for uncertainties to be viewed in terms of plausible outcomes, rather than deterministic or probabilistic variables.

The challenges to planning power generation systems are not new phenomena, although the restructuring of Ontario's electricity market has added new variables to systems development, such as competing generating companies and consumer choices. The multiple objective nature of power systems planning in the contexts of uncertainty, technological change, social interests, environmental impacts, rising fuel costs and the omnipresent importance of supplying reliable energy to the economy have been well known in Ontario for over 25 years (Porter, 1980). These issues relating to energy and environment decisions unfold over long timeframes following capital-intensive investments in generation infrastructure, further necessitating multiple-criteria decision making methods (Huang *et al.*, 1995). Despite the prior recognition of these issues, few formal attempts have been made to address multiple objectives in power system planning applications.

In the Ontario context, it has been predicted that the power generation system will require a significant amount of new generation capacity after the next ten years (IESO, 2005; OPA, 2005a). A multitude of power generation technologies, energy sources and demand-side measures can contribute to filling this supply gap, with each potential resource having different operational characteristics, costs, benefits and risks.

Also, citizens, coalitions, non-governmental organizations, trade associations and labour unions have become increasingly knowledgeable as active stakeholders in Ontario's electric system development. Planning for electricity supply has not been an open and transparent process in the past, but major planning decisions have been made disjointedly by Ontario Hydro's board of directors, the Ontario Cabinet, the Ontario Energy Board, the Environmental Assessment Board and other organizations. This thesis maintains that the various objectives of electric power generation systems must be formally considered in planning decisions to consider the values of stakeholders and to promote openness, transparency and credibility in the planning process.

1.5 Objectives of the Research

The objectives of this research are threefold. The first objective is the review and compilation of life-cycle based attributes of power generation technologies, such as cost and environmental performance data. The second objective is to develop a framework for making decisions to guide planning decisions with multiple objectives. The decision-making framework is intended to allow planners to evaluate alternatives by comparing how well they meet the objectives. The third objective is to develop a method of quantifying stakeholder weights for the decision objectives to apply to the life-cycle based inputs in the decision-making framework.

The purposes of the decision-making framework include providing a systematic method to increase openness and transparency in the decision process, to display tradeoffs between alternatives, and to communicate the values of decision-makers. Planning for electricity generation in Ontario is selected as the test case for the decision-making framework because it provides a currently relevant case in which life-cycle information can be applied to a decision problem that inherently involves multiple objectives.

The life-cycle data for electricity generation technologies are compiled from published and non-published literature and life-cycle assessment reports, and are used to model the performance of three hypothetical future electricity generation scenarios. The decision-making framework evaluates the options against multiple objectives. Although the decision framework could be applied to a number of decision situations, the life-cycle data used in this thesis were limited to electricity generation technologies in the context of long-term planning for the electricity generation system in Ontario. The decision objectives are selected to indicate progress toward sustainable development and evaluate environmental, cost and system objectives over the life-cycles of power plants. Values-based information is applied to the objectives through the use of questionnaires, which weighted the objectives in terms of their relative worth to participants with some working knowledge of electricity generation systems. Six indicators (decision criteria) were selected as measurements of performance in meeting the objectives.

1.6 Organization of this Thesis

Chapter 2 presents an overview of the electricity generation system in Ontario and the stakeholders involved in decisions that shape the system's development. Chapter 2 also presents a summary of traditional criteria used to make electricity generation system planning decisions and how these methods have evolved under pressure to consider additional societal objectives. Chapter 3 describes the development of the decision-making framework to assist with making difficult planning decisions with multiple objectives, through its method of application to the electricity generation system in Ontario. The basic steps used to create the decision problem are outlined in Chapter 3 in addition to summaries of literature sources for the life-cycle information for electricity generation technologies.

Chapter 4 presents the alternative generation scenarios that were developed to apply the decision-making framework, as well as summarizes the assumptions that were made in creating the scenarios. Chapter 5 presents the results of the literature review of life-cycle environmental, cost and performance data for electricity generation technologies and the results of the application of the decision making framework scenarios. Chapter 5 also discusses the results of the thesis. Chapter 6 summarizes the conclusions and suggests future work that could make the decision making framework more usable and adaptable to changing contexts in planning for future electricity generation systems.

Chapter 2: Electricity in the Ontario Setting

This chapter introduces stakeholders in the development of Ontario's power generation system and discusses the modes by which these groups act to influence decision-making in the planning process. Secondly, this chapter discusses planning for Ontario's power generation systems, both traditionally and with respect to future modes of planning from which the decision-making framework outlined in Chapter 3 draws from.

2.1 Stakeholders in Electricity Generation

Ontario's electricity sector provides power for use by over 12.5 million people and has been in operation for over one hundred years. Even with this long history, more institutional and policy changes have occurred in the electricity sector since 1998 than in the prior 90 years (Winfield *et al.*, 2004). Since integrated long-term planning has become a public policy priority, individuals, associations, organizations, businesses and industries have become active in trying to influence planning decisions (OPA, 2005b; OPA, 2005c). Long-term planning decisions generally occur before facility locations or specific transmission routes are selected, where many parties are primarily motivated by local issues such as local economic development resulting from power plant construction or the impacts of power prices increases on industrial sectors. Other stakeholders have been motivated by regional and global issues, such as air pollution and greenhouse gas emissions.

The OPA reported a diverse group of stakeholders that expressed an interest in Ontario's future generation supply mix (OPA, 2005b). Table 2.1 presents a list of stakeholders and summarizes some modes by which these groups participate in the decision-making processes of electricity generation system planners.

Table 2.1: Stakeholder Influences on Decision-Making in Electricity Generation System Planning

Stakeholder groups	Categories or institutions	Mode(s) of participation
Government and regulatory agencies	Ministry of Energy, Ministry of the Environment; parliamentary bodies, committees and input processes, Ontario Energy Board (OEB)	Determine public policies, targets, standards, moratoriums, social programs, educational programs, taxation and rebates, environmental assessments and approvals. OEB sets rules and regulations, penalties, incentives, and approvals to operate.
System operator	Independent Electricity System Operator (IESO)	Responsible for sound operation of system, near term planning, generation dispatch, system monitoring and market operation.
Planning bodies	Ontario Power Authority (OPA)	Determine needs and anticipate risk, develop strategies to enact public policy goals. May offer fixed tariffs through contracts, financial support or risk guarantees to developers.
Consumers and non-governmental organizations (NGOs)	Consumer consortiums, better business bureaus, environmental and consumer advocates	Views represented in public forums, buying power and consumer choice, resistance through "not in my backyard" syndrome. NGOs influence public opinions, participate in stakeholder consultations, fund research, advocate narrow objectives or particular issues ("issue-based").
Generation, transmission and distribution companies	Individual companies, cooperatives and trusts, Hydro One, utilities	Communicate through associations, invest in and operate generating units, compete and experience conflict, cost recovery and profit structures, answerable to boards and/or shareholders, construct and operate wires and ancillary services.
Retail and energy services companies (ESCOs)	Mostly private companies	Increase range of options open to consumers, influence can be limited through restrictions set by regulatory board

Even though OPA invited and received comments from interested parties in preparing an evaluation and recommendation for Ontario's future supply mix, some issues are evident in reviewing the Supply Mix Advice Report. The range of options considered for the supply mix is limited and a formal process by which alternatives were screened out of the analysis is not documented. This is important because many interested parties asked OPA to consider a coal and nuclear-free future, as well as to consider higher success in demand-side management. Even if these outcomes were determined to be unlikely, the uncertainty associated with such futures could have been modeled using risk parameters or highlighted by adopting a scenario-based approach to creating alternatives. OPA considered economic, financial risk and environmental factors in describing its supply mix scenarios, but presented no documented process by which all three major objectives were used to arrive at the recommended scenario. No indication of preference toward each of these three objectives in evaluating the decision was present. A weighting scheme was applied to the environmental factors that comprised the environmental scorings, but these weights were not derived from stakeholders' preferences, but by extrapolating from a European report on the external costs of energy (ExternE (1997), cited in OPA (2005b).

2.2 Planning for Electricity Generation Systems

2.2.1 Planning Approaches and the Need for Planning

Planning is based on the practice of developing human systems to meet changing needs. Many systems require planning, such as urban and rural communities, transportation networks and power generation systems. Planning for the long-term is widely defined, but the main purpose is similar: developing strategies and tools to create systems to satisfy a set of societal objectives. Crow *et al.* (1978) acknowledged the lack of consensus regarding the definition of planning, but outlined four characteristics of planning activities, including:

- The establishment of ends or goals;
- An orientation to the future;
- A conscious, purposeful and systematic action; and
- Rational evaluation of facts, values and alternatives.

In the long-term context, planning for electricity generation systems is encumbered by uncertainties, wide ranging values that shift over time, and groups of stakeholders with disparate and often conflicting views. Market restructuring, emerging technologies and fuel availability represent additional challenges to power system planners. Creating long-term plans is further complicated by a lack of site and time specific information and heavy reliance on forecasts of key variables which are often inaccurate.

Centralized planning activities often express broader public policy or societal objectives. Policy objectives can be influenced by increasing awareness of environmental issues, and by the views of industries and businesses that bring economic and social benefits. Evidence of ecological damages or human health impacts resulting from economic activity can also determine public policy objectives. In part due to concerns of fuel supply uncertainty or price volatility, Ontario's policy agenda includes increasing the share of renewable energy sources. Effectively developing these newer energy sources should be based on different conceptions of energy planning procedures (Georgopoulou *et al.* (1998); Pohekar and Ramachandran (2004)).

Apart from the ecological consequences of electricity generation, electricity's critical role in other societal systems increases the risks involved in power system planning. Performance of the electricity generation system can directly affect the economy and impact the environment. To mitigate such risks, Manzini and Martinez (1999) describe a prospective approach to the future beginning with envisioning possible or desirable future conditions and then calculating the steps needed to achieve those conditions. The first stage develops ranges of plausible future scenarios and the second stage is known as backcasting, or working from prospective future systems back to the present. Prospective approaches to the future are not descriptive or normative, nor do they forecast or deduce the future from the present. Instead, prospective approaches assist in identifying both possible and/or desired future outcomes and the steps needed to reach them. Prospective studies start from the following general principles:

- The future is not predetermined, it is created;
- The future emerges from the present and is sustained by the past;
- The intention is not to reform the present, but rather to understand the possibilities and consequences of specific plans for the future;
- Planning is influenced by the values and beliefs of the planners; and

- The terms "better" and "desirable" have subjective connotations (Manzini and Martinez, 1999).

In addition to the above, the number of tools and models available to electricity system planners is immense. Some of these tools include forecasting models, econometric models, utility functions, probabilistic analyses, contingency analyses, and cost-benefit analyses. Methodologies that attempt to predict future states in order to strategically move systems toward a most desired or desirable state remain prominent in planning.

Traditionally, long-term planning for the electricity sector has worked by determining the least costly strategy to achieve the decision-maker's most favoured state. Even though the preferred alternative may consider social and environmental parameters as constraints (e.g. remaining below emissions limits), such approaches tend to use single-variant objectives such as economic performance to evaluate options. These approaches use net economic benefits as a measure of allocative efficiency, or "Pareto" improvement, in planning decisions (Greening and Bernow, 2004). In more recent planning activities, multiple economic objectives have been considered, such as financial risk, but these exercises simply considered multiple dimensions of an economic objective rather than attempting to comprehensively consider the planning exercise as a multiple objective decision problem (OPA, 2005b).

Traditional planning methods have also failed to explicate values in addition to information or knowledge-based variables. Decision-makers opted instead for the appearance of neutrality in considering future states and creating strategies for development. Traditional models of energy planning have ignored many factors that humans consider valuable because they are difficult to quantify on equal terms (i.e. monetary valuation). Energy planning in the past was dominated by the model of least-cost planning, with the main objective being the accurate estimation of future energy demand using the least cost criterion in "identifying" the most efficient supply options (Pohekar and Ramachandran (2004); Greening and Bernow (2004)). Such methods may give homage to environmental and/or social factors while they make decisions based on economic considerations.

In addition to ignoring values, traditional approaches to planning have been based heavily on the practice of forecasting. Forecasting is used to reduce the problem of uncertainty by making predictions of future states that can be adopted as assumptions in the planning process. One then looks for a least costly strategy to achieve a desired future state. The criticality of visioning future states in planning is, in part, why forecasting has grown into a multibillion-dollar industry. Much forecasting uses consolidative models, where many known facts are assembled into single indicators which are then used as surrogates for the entire system (Bankes (1993); cited in Smil (2003)). While seeming to work reasonably well, forecasting errors have increased in frequency and magnitude over time (Wack, 1985). When forecasts from the past are compared to the conditions of the present, the errors become obvious (Kleinpeter, 1995). When looking back at national or global energy demand, almost every institutional long-range projection published since the 1960s has badly missed its targets (Smil, 2003).

Smil (2003) states that "typical forecasts offer little else but more or less linear extensions of business as usual". Moving beyond agnostic, passive forecasting of possible outcomes toward more holistic definitions of fundamental goals may assist in merging the maintenance of human dignity and quality of life with protecting the biosphere's integrity (Smil, 2003). While this thesis is not arguing against the necessity of forecasting in planning, the basis by which the alternatives were developed questions the way decision-makers relate to forecasts. Forecasts should be developed so that they produce ranges of plausible futures, so that decision-makers can make value judgments regarding the objectives that drive the system forward and prepare for contingencies in case the future develops differently than predicted.

2.2.2 Changing Modes of Planning in the Ontario Setting

In the past, plans for Ontario's power generation and transmission infrastructure were completed by Ontario Hydro according to projected demand increases. In the late 1970s, it was contended that conceptual master plans seemed inappropriate for the "complex and uncertain electric power planning environment" (Porter, 1980). Several years later, Ontario Hydro invested heavily in such a master plan with the Demand/Supply Plan, later withdrawn from the environmental review process (Ontario Hydro, 1989). Beginning in the 1990s and lasting until 2005, Ontario's power generation system was devoid of long-term, integrated planning. More recently, the Ontario Power Authority (OPA) was charged with producing an integrated power system plan with a built in 3 year rolling, iterative regulatory review process.

In the current context, planning approaches must transparently and systematically consider multiple objectives and account for uncertainties inherent to electricity generation systems. Technology changes have made smaller power generation plants more cost effective and increasing fossil fuel and uranium prices have decreased the economic advantages of large thermal plants. As a result, opportunities for alternative energy production have grown (Kagiannas *et al.*, 2004).

Market restructuring has occurred because the electricity generation function is not a natural monopoly (Bogorad and Penn, 2001). Changing market structures and increased technology choices have also increased the complexity and risk associated with the results of planning decisions. In addition to planning for the development of power generation and transmission infrastructure, the central planning function of OPA must increase market opportunities for a naturally functioning generation market, which underpin the economic theories that support electricity market restructuring. It is not known whether a competitive market for electricity generation could result in adequate long-term development. Electricity generation itself is not a natural monopoly, but the creation of OPA is evidence that a central planning function is necessary.

The availability of electricity is considered a public good much like environmental quality or social benefits. Many of the key attributes of cleaner and renewable generation technologies are also public goods providing benefits to the whole and hence, are not readily evaluated by and on open markets. Therefore they are often excluded from system analyses (van den Bergh *et al.* (2000), cited in Greening and Bernow (2004)). The multiple criteria method of decision-making proposed in this thesis draws from a range of tools and mechanisms that allow for the evaluation of public goods that are valued by society but difficult to value accurately in discounted cash dollars.

Planning in such contexts requires a range of approaches that evaluate alternatives by considering ranges of criteria rather than least-cost or other economic considerations (such as price risk). While some method of determining future needs is necessary, relating to forecasts not as firm assumptions but possibilities spanning some range can assist in identifying strategic development paths and can increase the chances of identifying a "no regrets" solution to the planning exercise. In making decisions, scientific uncertainty regarding the future leaves predictions weak at best (Wismer *et al.* (1977) cited in CELA (2002)). In forecasting, only one set of assumptions is possible (Kleinpeter, 1995). Scenario-based planning (scenario planning) has emerged in recent decades as a method of organizational and public planning that presents a feasible way to move away from the heavy reliance on forecasting and making often flawed predictions of uncertain futures.

Scenario planning deals with critical uncertainties differently than basing plans on traditional forecasts. Scenario-based approaches avoid predictions about probable or "most certain" futures. Instead, they focus on plausible ranges of future states to address the risks associated with events that might otherwise be unforeseen. However, scenario planning is not consistently methodologically defined. It involves creating alternative scenarios about the future by identifying three elements: driving forces, predetermined elements and critical uncertainties. The current planning environment in Ontario is used as a test case for developing alternative electricity generation futures using a limited scenario-based approach. The alternative scenarios are described in Chapter 4.

Chapter 3: A Multi-Criteria Approach to Planning Decisions

Strategic thinkers have recognized the need to clarify values as being key to making smart decisions (Franklin, cited in Keeney, 2004).

This chapter presents the steps involved in developing the proposed decision-making framework. This chapter is presented as follows:

- Section 3.1 presents an overview of the decision-making framework tool;
- Section 3.2 introduces the sources of information used in the development and application of the decision-making framework;
- Section 3.3 describes the identification of objectives and definition of the criteria used in the decision-making framework;
- Section 3.4 describes the collection of life-cycle based data and operational characteristics of electricity generation technologies used as inputs to the decision-making framework;
- Section 3.5 presents the development of the decision alternatives as a set of electricity generation scenarios;
- Section 3.6 describes the weighting of the decision criteria used as proxy measures of the decision objectives; and
- Section 3.7 presents the methods used to rank the performance of the scenarios.

3.1 Overview of the Proposed Decision-Making Framework

The main purpose of this thesis is to present a framework for life-cycle based decision-making and to test the framework by applying it to a long-term planning process that considers multiple objectives. Thus, the focus of the decision-making framework is on the insights gained from evaluating multiple objectives in a complex decision situation, rather than answering the question of which electricity generation supply mix is optimal. The planning context for the electricity generation system is used as a test case due to its current relevance in the Ontario setting.

The integrated, multi-dimensional nature of sustainable development is a challenge to the development of innovative planning approaches. The first step in the development of the decision-making framework is to define the objectives with respect to sustainable development. Sustainable development involves the simultaneous evaluation of non-equivalent descriptive domains to study changes in relevant dimensions of systems (Giampietro *et al.*, 2002). To address the complexity inherent in measuring sustainable development objectives, the following common characteristics were assumed to comprise the decision-making framework. They are:

- A finite number of alternatives, which can be screened, prioritized, selected, and/or ranked against each other;
- A number of attributes which depend on the nature of the problem;
- Measurement units specific to each attribute; and
- Potential for characterization of the relative importance of each attribute, usually through an ordinal or cardinal scale (Keeney and Raiffa, 1976).

The inputs to the decision-making framework include information (knowledge or "facts") regarding electricity generation technologies, values or preference information regarding the decision objectives, and a prospective approach to developing options for analysis and comparison. The options are described as alternatives which describe future possibilities (referred to as scenarios). Figure 3.1 illustrates the components of the decision-making framework. Facts, information or knowledge are used to describe the degree to which future possibilities satisfy multiple objectives. Stakeholder values toward the objectives are used to apply relative weights to the objectives.

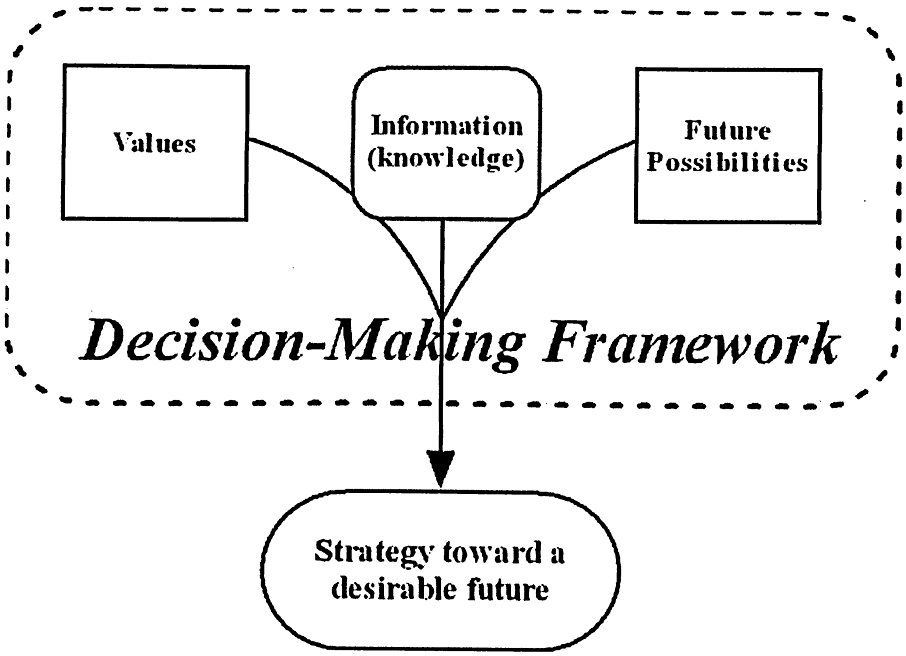

Figure 3.1: Schematic of the Proposed Decision-Making Framework

3.2 Sources of Information for the Decision-Making Framework

Developing the life-cycle based decision-making framework involved literature reviews in a number of subject areas. These sources are referenced throughout this thesis. The subject areas of the literature reviews include:

- The history of power system planning, general planning methods and scenario-based planning;
- Life-cycle environmental data, cost information and operational characteristics of electricity generation technologies; and
- Decision making methodologies which consider multiple objectives and methods used to apply weights to multiple criteria.

Scenario planning documents were surveyed in developing the optional configurations of power generation systems. These documents included industry reports, task force documents, books and journal articles. The articles and books were generally focused on the methodologies involved in scenario-based planning activities while the remaining sources documented the results of scenario planning exercises. Planning documents for Ontario's power systems were also reviewed to apply the decision-making framework to the Ontario test case.

A review of life-cycle based information for electricity generation technologies was completed. This part of the literature review focused on environmental characteristics (land use and environmental emissions), cost information, and technical and operational characteristics (typical plant sizes and capacity factors) of power generation plants. These sources included journal articles, independent research, national implementation reports, and electricity generation company and manufacturer reports.

In addition, the literature review surveyed published information regarding decision making methods specific to problems with multiple objectives and energy planning related activities. Most of these sources were peer-reviewed journal articles and academic textbooks. These sources were used to develop the decision-making framework.

3.3 *Identifying Objectives and Defining Criteria*

3.3.1 Objectives of the Decision Problem

The scope and boundaries of decision problems are central to multiple-criteria decision-making methods (Keeney (1992); Marshal and Oliver (1995); Hobbs and Meier (2000)). The objectives were selected to integrate environmental criteria into planning decisions for power generation systems. Sustainable development almost universally involves the simultaneous consideration of ecological, social and economic elements and the consideration of next generations (Spreng (2005); WCED (1987)). In this context, future sustainable power generation systems would consume natural resources slower than they are naturally replenished, would produce residual materials consistently slower than their assimilation rates into natural cycles, and would ensure the fair and equitable distribution of electricity's services.

A set of sub-objectives representing some of these dimensions of sustainable development were gleaned from the literature review and through conversations with energy-related professionals. Then they were organized into a hierarchy, with the main objective being the promotion of a sustainable electricity generation system and subsequent levels of the hierarchy working toward sustainable development. These objectives included availability, acceptability and accessibility (WEC, 2005). Availability relates to security and reliability of the system; acceptability to optimizing efficiency and limiting emissions; and accessibility is ensuring equitable distribution of service (WEC, 2005).

The literature review and conversations with energy professionals assisted in developing the objectives "wish list" summarized in Table 3.1. The wish list helps to identify and structure objectives in multiple objective problems (Keeney, 1992). The sub-objectives complementing the fundamental objectives (availability, acceptability and accessibility) are structured according to economic, social, and environmental objectives. The objectives wish list provided a basis for defining the criteria to be used in the decision-making framework.

Table 3.1: Objectives Wish List Used for Developing the Decision Problem Under the Fundamental Objectives of Availability, Acceptability and Accessibility

Economic Objectives:	Minimize (reduce) cost of production Maximize (increase) efficiency of generation plants Minimize (reduce) use of imported energy sources Maximize (increase) local wealth creation
Social Objectives:	Adequate capacity to meet demand Reduce or reverse demand growth Ensure equity of supply (minimize "fuel poverty") Maintain capacity for future generations Minimize (reduce) accidents, injuries and/or fatalities Maximize (provide) employment
Environmental Objectives:	Minimize (reduce) fossil fuel sources of energy Minimize (reduce) air emissions of greenhouse gases Minimize (reduce) other air pollutants Minimize (reduce) water use Minimize (reduce) production of toxic and radioactive wastes Minimize (reduce) land use/ habitat destruction Minimize (reduce) radiological or other recalcitrant wastes

Objectives are organized into the hierarchy shown in Figure 3.2. Fundamental objectives represent the goals of the decision-making framework at the top of the hierarchy while sub-objectives, at the bottom of the hierarchy, are goals that help achieve fundamental objectives. The fundamental objective to increase sustainability of the electric generation system can be decomposed into objectives that consider environmental, social and economic aspects of electricity generation systems. Sub-objectives are selected from the objectives wish list and are meant to indicate availability, accessibility and acceptability of the system as components of sustainable development. The six sub-objectives at the bottom of the hierarchy are called criteria in the proposed decision-making framework.

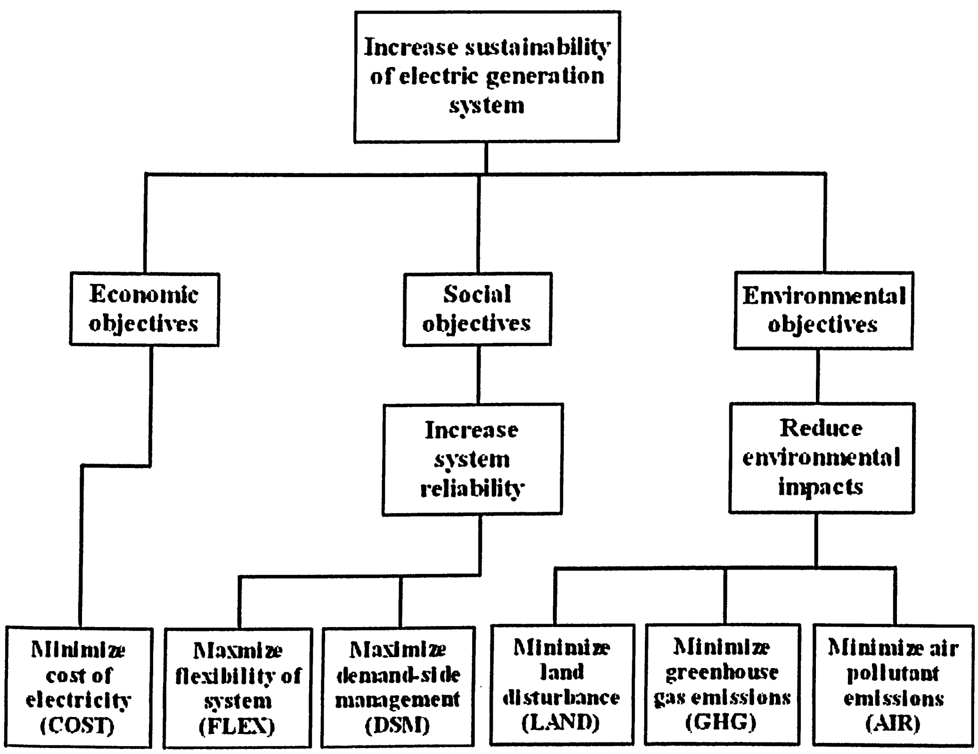

Figure 3.2: Fundamental Objectives Hierarchy for the Decision Problem

The six criteria are the basis by which options in the decision-making framework are evaluated using information available in the literature. In the test case used in this thesis, the criteria cannot be exhaustive in representing sustainable development objectives. The choice of criteria is a value judgment in itself, and other criteria exist or could emerge to assist in subsequent iterations of the decision-making framework. The six criteria selected for the test case in this thesis are described in the following subsection.

3.3.2 Overview of the Decision Criteria

The terms criteria, attributes and objectives are often used synonymously in the literature. Hobbs and Meier (2000) describe criteria or attributes as measures that can express planning objectives. The proposed decision-making framework was designed for long-term system planning which occurs prior to defining specific technological configurations of power plants or selecting locations for the plants. No attempt was made to quantify the impacts of environmental emissions such as local health effects, crop damage or ecosystem impacts resulting from habitat loss. Purely local impacts can be addressed by project level environmental assessments; however implementation of a strategy can be blocked through activism at the local level. The use of a decision-making framework to consider multiple objectives in an open, transparent manner is partly motivated by prospects for better acceptance of planning level decisions at the local implementation stage. This procedure is not intended to negate the need for environmental assessment of individual projects, because the criteria to measure system wide objectives utilize absolute emissions where possible to avoid introducing the uncertainty of estimating actual impacts at local or regional levels.

The selection of criteria is limited by the availability of data for environmental and social aspects of electricity generation systems. In narrowing the criteria further, conversations with energy and environmental professionals were conducted, which centered on values and objectives of power generation systems with a primary goal of sustainable development. The six decision criteria and their characteristics are described in detail as follows.

<u>Minimize the cost of electric energy (COST)</u>

The economic objective was to minimize the cost of generating electricity, measured in Canadian dollars per megawatt hour, and aggregated to account for the total amount of energy produced by the system. The COST criterion reflects the cost at the generating units rather than the price to consumers because estimating retail prices adds more uncertainty. These prices are subject to the influence of public policy (through regulation) and retail prices typically include additional charges for ancillary services, transmission and distribution, and in the Ontario case, nuclear debt retirement charges.

The costs of power generation technologies vary widely. The location and size of the generator, cost of construction materials (e.g. steel, concrete), interest rates, and emissions abatement equipment all can significantly affect the cost of power plants. The cost data proposed for the decision-making framework were derived from OECD (2005) *Projected Costs of Electricity Generation* and OPA (2005b) *Supply Mix Advice Report.* The costs were "levelized unit electricity costs" (LUECs), which include the 'upfront' construction costs, operation and maintenance costs, fuel costs, and debt service over the plant's lifetime. The costs from OECD (2005) were presented as 2003 dollars and converted to Canadian dollars at the average July 1, 2003 exchange rate (OECD, 2005).

The costs of transmission and/or distribution infrastructure and back-up generation are not accounted for in the COST criterion. In addition, externalities associated with electricity generation are not included. Externalities, or external costs, include those costs which are normally not factored into the price of electricity and include the costs of health care, environmental damage, or other impacts related to electricity generation.

Maximize the flexibility of the power generation system (FLEX)

Power generation systems comprised of many geographically dispersed plants that utilize a diverse set of fuel sources can have greater operational flexibility and more resistance to widespread disruptions than systems comprised of fewer, larger power plants with less diversity (Porter, 1980). Small-scale generation is commonly referred to as distributed generation, in which the electricity is generated by facilities sufficiently smaller than central generating plants as to allow interconnection at nearly any point in a power system. Distributed generation offers a system greater flexibility for adapting to changing requirements (OPA, 2005b).

The FLEX criterion is not an absolute measure of reliability, but it is intended to provide a relative index reflecting the number of fuel types, number of generating units and size distribution of the generation resources comprising a generation scenario. More fuel types and more, smaller sized power plants result in higher numeric values using the FLEX criterion. Use of the FLEX criterion does not consider grid reinforcement and ancillary services necessary to maintain power quality in scenarios with higher penetration of distributed generation resources.

Different types of generation resources are assigned a multiplier, or 'flexibility factor', based on their operational flexibility characteristics. Some electricity generation technologies have fast ramping capability while intermittent sources lack dispatch capability. The flexibility factor was used to weigh generation types according to their expected level of service, interpreted from Gagnon *et al.* (2002). In addition, typical generation plant sizes were assumed for the various resources. Expected levels of service and typical plant sizes for generation resources are shown in Table 3.2. Coal integrated gasification combined cycle (IGCC) and bio-fuelled technologies were added to the list in Table 3.2 because these technologies could make a contribution to electricity supply in Ontario in the future.

Table 3.2: Expected Level of Service and Typical Plant Sizes of Electricity Generation Systems

Electricity generation systems	Comments on reliability and flexibility of electricity production
	Systems capable of meeting base load and peak load (high flexibility)
Hydropower with reservoir and pumped storage	High reliability and flexibility, many run-of-river plants having an upstream reservoir can be considered as having reservoirs, assume 400 MW typical plant size for new installations.
Natural gas single cycle	High flexibility and high cost, normally run for very short periods of time, assume 250 MW typical plant size for new installations.
Coal IGCC	With gas storage capability, technology emerging at commercial scale but complex, assume 250 MW typical unit size for new installations.
Bio-fuelled technologies (biogas)	Anaerobic digesters and fuels from converted biomass, high flexibility and controllable generation using gas storage, assume 20 MW typical plant size for new installations.
	Base load systems with less flexibility
Natural gas combined cycle	Mostly base load with high technical flexibility, but high use factors are needed to buy gas at low price which reduces flexibility, assume 500 MW typical plant size for new installations.
Coal (thermal)	Can function as baseload, has some flexibility, environmental considerations have limited coal use to intermediate/peaking capacity, assume 500 MW typical unit size for new installations.
Gas/oil dual fired	Baseload/ intermediate resource with some flexibility, resource not considered in scenarios.
Hydropower run-of-river	Mostly base load with low flexibility, assume 20 MW typical plant size for new installations.
Biomass (thermal)	Mostly base load with low flexibility, includes wood waste and plantations, assume 100 MW typical plant size for new installations.
Nuclear	Base load only, almost no flexibility, assume 1000 MW typical unit size for new installations.
	Intermittent systems that need a backup production (no flexibility)
Wind power	Needs a backup system with immediate response, energy production coincident with winter peak, assume 20 MW typical plant size (cluster of turbines).
Solar photovoltaic	Needs a backup system with immediate response, energy production coincides with peak demand, assume 3 MW typical plant size (for collection of PV arrays in areas with high solar insolence).

Adapted from Gagnon *et al.* (2002).

The FLEX criterion assumes a typical generating unit size for each resource and a constant for the expected level of service. These assumptions can be modified to vary the outcome of the indicator. The formula used for calculating the FLEX criterion is as follows. Let:

FLEX denote an index representing the relative operational flexibility of an electricity generation scenario with higher values for systems with higher diversity of generation resources, fewer large generating plants, and more generation resources capable of meeting both base and peak loads;

R_i equal the total installed capacity (in MW) of resource i, $i = 1, 2, \ldots, I$;

U_i denote the typical generating unit size (in MW) for resource i, $i = 1, 2, \ldots, I$; and

f_i be the multiplier denoting the expected level of service for resource i, $i = 1, 2, \ldots, I$, where generation resources capable of meeting base load and peak loads with high flexibility are assigned a multiplier of 3; generation resources capable of meeting baseload with less flexibility are assigned a multiplier of 1; and generation resources with no flexibility are assigned a multiplier of 0.01.

Therefore:

$$FLEX = \sum_{i=1}^{I} \frac{R_i f_i}{U_i}$$

The use of a multiplier to confer more weight to generation resources using the FLEX index is a subjective judgment. While the three levels of operational flexibility selected for this thesis range from 0.01 to 3, the use of different multipliers is possible and would lead to different results.

<u>Maximize impact of demand-side management programs (DSM)</u>

Reducing the need for additional generation capacity through demand-side management (DSM) programs is a system wide objective. The DSM criterion is measured by the change in the system capacity requirement in megawatts (MW). This criterion was intended to allow decision-makers the opportunity to trade-off other criteria to construct fewer supply-side resources through a reduction in need. DSM was displayed on the supply side of the decision alternatives so it could be visualized and given equal opportunity to compete with new or refurbished supply capacity. This criterion did not, in itself, model the absolute success of all demand-side management initiatives, but was intended to display demand reduction in MW only.

The uncertainty in the success of DSM programs can be reflected in the decision-making framework by modifying the capacity factor of the capacity contribution of the DSM criterion. A less conservative approach was used in this thesis, expressed by an 80% capacity factor for DSM, reflecting a high confidence that demand reduction will offset the need for generating capacity. The decision-making framework is designed so that the capacity factor for DSM can be modified; for example it can be reduced to reflect less confidence in the results of demand-side management activities.

Minimize land disturbed by power generation systems (LAND)

The LAND criterion is used to indicate the land space utilized by electricity generation, expressed per unit energy produced by the system. The LAND criterion is intended to highlight optional systems likely to have greater land use impacts, and does not represent ecosystem impacts or habitat loss. Land occupied by transmission lines is not represented by the criterion.

Land use information for electricity generation technologies was sourced from life-cycle assessment literature, and was reported in km^2 per megawatt (MW) capacity and in km^2 per TWh. The units used in the decision-making framework are in km^2 per TWh.

Minimize greenhouse gas emissions (GHG)

The GHG criterion is an indicator of global warming potential. Three primary greenhouse gases, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), are normalized and aggregated into the GHG criterion and expressed in kg per MWh. Normalization is a common way of expressing indicator results relative to well-defined reference information. A numerical weighting factor is an expression of relative importance of the components of an indicator which are aggregated together. For the indicator GHG, emissions of three greenhouse gases are weighted according to global warming potential relative to carbon dioxide. These weights are presented in Table 3.3.

Table 3.3: Estimated Global Warming Potentials of Three Primary Greenhouse Gases (IPCC, 2001)

Greenhouse gas	**100-Year Global Warming Potential**
Carbon dioxide (CO_2)	1
Methane (CH_4)	23
Nitrous oxide (N_2O)	296

For each generation resource on the power system, the three greenhouse gases composing the GHG criterion are aggregated and measured in tonnes of CO_2 equivalents (tCO_2 eq.) per megawatt hour. The aggregated GHG emissions are summed for all of the generation resources comprising the candidate generation systems evaluated using the decision-making framework. The formula used to calculate the GHG criterion is as follows. Let:

GHG denote the total amount in kg of the three primary greenhouse gases released by a generation scenario per MWh of energy produced;

I be the number of generation resources in the generation scenarios;

E^i_{CO2} be kg of carbon dioxide emissions per MWh electricity generated by resource i, $i = 1, 2, \ldots, I$;

E^i_{CH4} be kg of methane emissions per MWh electricity generated by resource i, $i = 1, 2, \ldots, I$;

E^i_{N2O} be kg of nitrous oxide emissions per MWh electricity generated by resource i, $i = 1, 2, \ldots, I$; and

T_i denote electricity in megawatt hours (MWh) generated by resource i, $i = 1, 2, \ldots, I$.

Therefore:

$$GHG = \sum_{i=1}^{I} \left(E^i_{CO2} + 23\, E^i_{CH4} + 296\, E^i_{N2O} \right) T_i$$

Minimize air pollutant emissions (AIR)

The AIR criterion is a measure of emissions of three primary air pollutants subject to ambient air quality criteria in Ontario, including sulfur dioxide (SO_2), nitrogen oxides (NOx) and particulate matter (PM). The PM portion of this criterion is the ultra-fine particulate range ($PM_{2.5}$), but where data for $PM_{2.5}$ emissions were not found in the literature, the ultra-fine fraction is estimated from reported PM_{10} emissions. A multiplier of 0.1 is used to estimate the $PM_{2.5}$ fraction from the reported PM_{10} data, as described by Pace (2005). This multiplier is applied to all generation resources evaluated by the decision-making framework. Although no similar methods were found in the literature for estimating ultra-fine particulates from PM_{10} data, the decision-making framework is designed with the capacity to accommodate a higher multiplier because electricity generation produces particulates through mainly combustion processes and therefore a higher fraction of ultra-fine particles ($PM_{2.5}$) may be present in emissions.

The three compounds are selected to comprise the AIR criterion because air emissions information is available for the suite of electricity generation technologies and these substances have been linked to environmental and human health impacts. SO_2 has direct effects on public health and indirect impacts from sulfate aerosols, which are also $PM_{2.5}$. NOx damages include indirect effects on public health, mortality and morbidity, and losses in crop yields due to chemical transformations into nitrate aerosols ($PM_{2.5}$) and ozone species (Spadaro and Rabl, 1998). PM, particularly the $PM_{2.5}$ fraction, have direct effects on human health which can include mortality.

To determine a value for the AIR criterion, weighting factors are applied to the component air emissions using a normalization procedure. Normalization is applied because the three air emissions in the index are assumed to be unequal in their effects on the environment and/or human health. Without site specific data it is not possible to estimate actual impacts because generation resources are highly spatially distributed and predicting impacts solely from emissions data is uncertain. For the AIR criterion, 24 hour ambient air quality standards are used to weight the relative importance of the three components of the criterion. In Ontario, 24 hour ambient air quality standards for $PM_{2.5}$, NOx and SO_2 are listed as follows.

- Canada-Wide Standard for $PM_{2.5}$ is 30 μg/m^3;
- Ontario Ambient Air Quality Criteria for NOx (as NO_2) is 188 μg/m^3; and
- Ontario Ambient Air Quality Criteria for SO_2 is 261 μg/m^3 (CCME (2000); MOEnv (2001)).

Using the above 24 hour ambient air quality standards, the normalized emissions for components of the AIR criterion are presented as follows:

- SO_2 is assigned a weight of 1;
- NOx is assigned a weight of 1.4 (higher due to NO_2 only accounting for a portion of the NOx compounds as well as combined effects of eutrophication and acidification of nitrogen compounds); and
- $PM_{2.5}$ is assigned a weight of 8.7 due to its higher direct human health impacts.

For each generation resource on the power system, the three air emissions composing the AIR criterion are normalized and aggregated as kg of air emissions per megawatt hour. The aggregated AIR emissions were summed for all of the generation resources comprising the candidate generation systems evaluated using the decision-making framework. The formula used to calculate the AIR criterion is as follows. Let:

AIR denote the total amount in kg SO_2 equivalents of the three primary air pollutants released by a generation scenario per MWh of energy produced;

I be the number of generation resources in the generation scenarios;

E^i_{SO2} be kg of sulphur dioxide (SO_2) emissions per MWh electricity generated by resource i, $i = 1, 2, \ldots, I$;

E^i_{NOx} be kg of nitrogen oxides (NOx) emissions per MWh electricity generated by resource i, $i = 1, 2, \ldots, I$;

$E^i_{PM2.5}$ be kg of ultra-fine particulate matter ($PM_{2.5}$) emissions per MWh electricity generated by resource i, $i = 1, 2, \ldots, I$; and

T_i denote electricity in megawatt hours (MWh) generated by resource i, i = 1, 2, …, I.

Therefore:

$$AIR = \sum_{i=1}^{I} \left(E^{i}_{SO2} + 1.4\, E^{i}_{NOx} + 8.7\, E^{i}_{PM2.5} \right) T_i$$

3.4 Electricity Generation Technologies

A number of characteristics of electricity generation technologies are summarized from the available literature for use in the decision-making framework. Power generation systems are subject to constant change over time, therefore the analysis included only best available and some currently emerging commercial technologies. Characteristics included in the literature review include the decision criteria and operational characteristics of electricity generation technologies that can allow estimations of energy production in the optional scenarios considered using the decision-making framework.

3.4.1 Technical Characteristics of Electricity Generation

Information regarding technical characteristics of electricity generation technologies is limited to operational flexibility (summarized in Table 3.2), typical plant sizes and a capacity factor. The capacity factor is used to estimate the energy produced from the total capacity (in MW) of the various electricity generation technologies making up the system. The capacity factor is a percentage which denotes the time (in hours) that an electricity generation technology operates at full load per year (8760 hours). The assumptions for the capacity factors are based on several sources which are referenced in Table 3.4.

Table 3.4: Assumptions Regarding Generator Performance

Resource	Capacity Factor Estimates (%)			
	Vattenfall (1999)	NEI (2003)	EIA (2003)	Pollution Probe (2004)
Hydroelectric (large)	32	19-38	39.6	
Hydroelectric (small)	--	--	--	50
Nuclear	75	92	87.9	--
Biomass	50[1]	--	69.1	80
Wind turbine (onshore)	17	30	26.8	30
Solar photovoltaic	13	--	15.1	14
Oil	11	34	29.1[2]	--
Combined cycle gas turbine	86	15-50	See Oil	--
Fuel cell	92	--	--	--
Coal	80	--	71.0	--
Simple cycle gas turbine	1	--	See Oil	--

[1] Reported as biomass combined heat and power (CHP).
[2] Reported as "Oil & Gas".

3.4.2 Life-cycle Data for Electricity Generation Technologies

A large volume of life-cycle assessment reports and other accounts of environmental and cost information for electricity generation technologies are reported in this thesis. In the initial phase of the literature review, all available sources of life-cycle based information were collected and reviewed. Life-cycle information considered in the decision making framework was selected from the sources presented in Table 3.5. Several of the sources of life-cycle information cite previously published results. Life-cycle assessment reports which include only data sourced from the reports already summarized in Table 3.5 are not included in the data used as inputs to the decision-making framework.

The generation types included in the literature review included the following:

- Hydroelectric generation:
    - Impoundment reservoirs;
    - Run-of-river generation; and
    - Pumped storage generation;
- Natural gas technologies;
    - Single cycle;
    - Combined cycle; and
    - Combined heat and power;
- Nuclear generation;
- Coal-fired generation:
    - Integrated gasification combined cycle;
- Biomass and bio-fuels:
    - Wood waste (combustion);
    - Plantations;
    - Integrated gasification combined cycle and biogas; and
    - Combined heat and power;
- Wind turbines; and
- Solar photovoltaics.

Table 3.5: Sources of Life-Cycle Based Environmental and Cost Information for Electricity Generation Technologies

Author	Year	Title, comments
Dones *et al.*	2005	Life Cycle Inventories for the Nuclear and Natural Gas Energy Systems and Examples of Uncertainty Analysis
Dorland *et al.*	1997	ExternE National Implementation - Externalities of Electricity Production in the Netherlands
Gagnon *et al.*	2002	Life-cycle Assessment of Electricity Generation Options: The Status of Research in Year 2001
Gagnon	2004	Life Cycle Assessments Confirm The Need For Hydropower and Nuclear Energy
Greijer	2001	Cited in Pacca (2003)
Hydro-Quebec	2001	Hydro Quebec land use data, from annual sustainable development report. Also cited in Gagnon (2002)
Matthews	2000	Cited in Gagnon (2004)
Koch	2000	Hydropower: Internalised Costs and Externalised Benefits, Implementing Agreement for Hydropower Technologies and Programmes
Krewitt *et al.*	1998	ExternE: Externalities of Energy, National Implementation in Germany
OECD	2005	Projected Costs of Generating Electricity, 2005 Update: includes cost information, amalgamated of multiple OECD country specific experience, standardized questionnaire
Pacca	2003	Global Warming Effect Applied to Electricity Generation Technologies
Pingoud *et al.*	1997	ExternE: Externalities of Energy, National Implementation Finland, Final Report
Schleisner and Nielson	1997	ExternE: Externalities of Energy, National Implementation Denmark, Final Report
SENES	2005	Cited in OPA (2005b), based on published results and SENES consulting experience
Spadaro and Rabl	1998	ExternE – External Costs of Energy: Application of the ExternE Methodology in France
Spath and Mann	2000	National Renewable Energy Laboratory LCA for natural gas combined cycle generation
Spath *et al.*	2000	Life Cycle Assessment of Coal-fired Power Production
US NREL		Cited in Gagnon (2004)
Vattenfall	1999	Life Cycle Studies of Electricity
Wehowsky *et al.*	Unknown	Cited in Krewitt *et al.* (1998)
White	1999	Cited in Gagnon (2004)

Screening the LCA data involves judgments about the comparability of the data among the volume of published data and the ability to provide reasonable aggregated, or average, figures representative of the environmental and cost categories. Among the published results of LCAs, data varied significantly for the electricity generation technologies. In some cases, the results varied by several orders of magnitude. In determining suitable inputs to the decision-making framework, the outlying values for each criterion were excluded from the average values for each technology. In cases where three or fewer sources of information were found for a particular life-cycle category, the outliers were not excluded. A simple average was calculated to determine a representative value for these life-cycle categories.

3.5 Decision Alternatives: Developing the Scenarios

Following the literature review, the life-cycle based emissions, cost and performance data for the power generation technologies were assimilated to construct a set of hypothetical electricity scenarios. These scenarios are considered as the options, or possible futures, in the decision-making framework. The scenarios were developed through conversations with professionals in energy and related fields and members of the public with an interest in energy and environmental issues. Scenario development was initiated over the course of several conversations with attendees of four environmental education workshops held by the author between January 2005 and July 2005, and through conversations with professionals attending an energy-related conference in May 2005.

Several published documents on scenario planning were also used to guide the development of the scenarios. These documents traditionally describe elaborate narratives which provide the context for scenarios. The test case used to illustrate the decision-making framework focused on the makeup of electricity generation systems in the Ontario setting rather than on the narrative context of the scenarios. A summary of scenario planning reports and papers is provided in Table 3.6.

Table 3.6: Sources of Information for Creating Scenarios for the Decision-Making Framework

Author	Year	Title, comments
EIA	2004	Annual Energy Outlook 2004 with Projections to 2025
Eriksson	2003	Nordic Hydrogen Energy Foresight: Scenarios for Nordic H_2 Energy Introduction
Government of Germany	2004	Ecologically Optimized Extension of Renewable Energy Utilization in Germany
Hennicke	2004	Scenarios for a Robust Policy Mix: The Final Report of the German Study Commission on Sustainable Energy Supply
Fischedick and Hennicke	2004	Scenarios for the Transition to a Sustainable and Climate Protecting Energy System in Germany
IEA	1993	Shared Goals
Narvinger *et al.*	2003	Energy Foresight – Sweden in Europe: Synthesis and Summary
Schwartz	1991	The Art of the Long View
Soontornrangson *et al.*	2003	Scenario Planning for Electricity Supply

The scenario development exercise was initiated by first quantifying Ontario's current electricity generation mix and recording the end of service lifetimes for those generation resources due to expire within the planning period (up to 2030). A spreadsheet was created to illustrate a timeline and generation mix from 2006 to 2030. The decision-making framework is intended to be able to compare the performance of scenarios at any point within the planning time horizon. The years 2015 and 2030 were selected to compare the scenarios. The generation mix was compared across the scenarios at these two points in time.

A second spreadsheet was constructed to allow the comparison of the hypothetical generation scenarios by estimating the energy output of the various resources comprising the system using the capacity factors of the generation resources. This spreadsheet was constructed so that the main assumption used to estimate energy production is visible and modifiable. For example, if planned biomass capacity additions were intended to be run in a base load capacity, the capacity factor could be increased. The scenario comparison component of the decision-making framework is illustrated in Table 3.7.

Table 3.7: Scenario Comparison Component of the Decision-Making Framework (Example)

Generation Resource	*Installed Capacity*	Capacity	Capacity Factor	Energy Production
	%	MW	%	TWh
Hydro (reservoirs)	*1*	500	60	2.6
Hydro (run-of-river)	*18*	6390	85	47.6
Gas SCGT	*9*	3000	20	5.3
Gas CCGT	*0*	0	60	0.0
Gas CHP	*0*	0	85	0.0
Nuclear	*0*	0	90	0.0
Coal (thermal)	*0*	0	40	0.0
Coal IGCC	*0*	0	70	0.0
Biomass (wood residues)	*0*	0	70	0.0
Biomass (plantations)	*0*	0	70	0.0
Biogas	*13*	4441	70	27.2
Biomass CHP	*0*	0	85	0.0
Wind	*39*	13932	15	18.3
Solar PV	*8*	2877	15	3.8
DSM	*12*	4147	80	29.1
Total	**100**	**35286**		**133.8**
Requirement (MW):	**35286**			

In addition to estimating energy production of individual resources, the spreadsheet indicates whether a scenario produces enough energy to meet the demand load. The demand requirement is added by the user. Demand-side management (DSM) was added to the supply side, to allow for ease of incorporating its performance and cost features into the alternatives for equal consideration alongside supply side measures (generation capacity).

The scenario builder also displays how scenarios perform in each of the decision criteria, which depends on both the total capacity of each generation resources and the energy produced by the sum of the resources and DSM on the system. An example of an alternative scenario illustrates the performance of the above hypothetical scenario in Table 3.8. The bottom row of the spreadsheet displays the performance of the scenario in the criteria. These data are used to compare several scenarios in the decision-making framework.

Table 3.8: Criteria Performance for an Electricity Generation Scenario (Example)

Generation Resource	COST	FLEX	DSM	LAND	GHG	AIR
	($1000M)	(index)	(MW)	km2	tCO2eq.	$tSO_2eq.$
Hydro (reservoirs)	133	4	--	2.4E-01	3.9E-02	1.6E-02
Hydro (run-of-river)	4120	319	--	4.8E-05	3.8E-01	1.0E-03
Gas SCGT	690	36	--	9.5E-04	3.5E+00	1.0E-02
Gas CCGT	0	0	--	0.0E+00	0.0E+00	0.0E+00
Gas CHP	0	0	--	0.0E+00	0.0E+00	0.0E+00
Nuclear	0	0	--	0.0E+00	0.0E+00	0.0E+00
Coal (thermal)	0	0	--	0.0E+00	0.0E+00	0.0E+00
Coal IGCC	0	0	--	0.0E+00	0.0E+00	0.0E+00
Biomass (wood res.)	0	0	--	0.0E+00	0.0E+00	0.0E+00
Biomass (plantation)	0	0	--	0.0E+00	0.0E+00	0.0E+00
Biogas	2149	666	--	0.0E+00	0.0E+00	0.0E+00
Biomass CHP	0	0	--	0.0E+00	0.0E+00	0.0E+00
Wind	1930	7	--	2.7E-01	1.6E-01	1.8E-03
Solar PV	1774	10	--	0.0E+00	1.5E-01	3.4E-04
DSM	2	124	4147	0.0E+00	0.0E+00	0.0E+00
Total	**80.67**	**1166**	**4147**	**3.8E-09**	**3.1E-05**	**2.2E-10**
	$CDN /MWh	**Index**	**Total MW**	**km2/ TWh**	**tCO2eq/ MWh**	**$tSO_2eq.$/ MWh**

The decision-making framework is intended to compare multiple scenarios, therefore multiple iterations of Tables 3.7 and 3.8 are required by the decision-making framework. Once multiple scenarios are developed, the results of the criteria can be displayed in tabular format to allow for the ranges of criteria performance to be displayed for the decision situation. The range of values for several scenarios is displayed as an example in Table 3.9.

Table 3.9: Criteria for the Proposed Decision-Making Framework

Criteria			Range			
			At 2015		At 2030	
Description	Units	Abbreviation	Worst	Best	Worst	Best
Minimize the cost of electric energy	\$CDN/MWh	COST	67.55	65.97	85.92	64.84
Maximize the flexibility of the power generation system	Resource flexibility/size index	FLEX	382	411	455	687
Maximize impact of demand-side management programs	Change in peak capacity in MW	DSM	-1350	-2894	-1350	-6203
Minimize land disturbed by power generation systems	Km^2/TWh	LAND	0.0746	0.0594	0.1897	0.0509
Minimize greenhouse gas emissions	$kgCO_2$ eq./MWh	GHG	253.75	187.23	286.32	169.81
Minimize air pollutant emissions	$kgSO_2$eq./MWh	AIR	0.4058	0.3452	0.4248	0.3671

Applying the decision-making framework requires the criteria to be weighted. Weighting assigns values which denote measures of desirability or preference for certain objectives over others by decision makers. In the public policy arena, it is assumed that decision makers would engage stakeholders in determining weights for objectives in decision-making problems. The criteria weighting process used in this thesis utilized information derived from volunteers acting as stakeholders in the electricity generation system. Criteria weighting is described in the next section.

3.6 Criteria Weighting

Decision makers do not value objectives equally in their minds. These values are often subject to strongly held beliefs and change over time as new information emerges, but decision makers often strive for objectivity in evaluating large volumes of complex and interrelated data. Even when planning decisions are evaluated in an objective manner, inherent preferences for certain criteria or attributes can be present (Hobbs and Meier, 2000). The choice of criteria itself is a values-based judgment. To make such values more explicit and open, the proposed decision-making framework applies a method to derive relative preferences for the criteria.

Electricity generation system development is normally open to broad stakeholder input, so a method of deriving weights for the decision criteria must lend itself to input from groups with wide ranging values, as well it must average disparate views. Many methods have been developed for the quantitative determination of weights for criteria in decision problems. However, few methods allow for operational tradeoffs between criteria when multiple objectives are under consideration.

A questionnaire was developed to gauge stakeholder preferences toward each of the six criteria of the decision problem (attached as Appendix A). The questionnaire was distributed to 57 individuals identifying themselves as having at least "some knowledge" of power generation systems or generation technologies. The questionnaire urged stakeholders to think about how much they favor or disfavor each criterion when compared to each other systematically in a pair-wise fashion, in relation to the fundamental objectives of the decision problem. The structure of the fundamental objectives was illustrated in Figure 3.2. Even though participants were asked for their personal views, they were employed or experienced with the following organizations:

- Ontario Ministry of Energy;
- Ontario Ministry of Natural Resources;
- Ontario Ministry of the Environment;
- Ontario Power Authority;
- Natural Resources Canada;
- Environment Canada (co-op student);
- National Energy Board;
- Independent Electricity System Operator;
- Heating, ventilation and air conditioning specialist (independent);
- Electricity distribution and services companies;
- Parks Canada;
- Energy consulting firm;
- World Business Council for Sustainable Development;
- Energy Council of Canada;

- The Sierra Club of Canada; and
- Two graduate students enrolled at Ryerson University and University of Toronto.

The method selected to assign weights to the decision criteria is known as the analytic hierarchy process. The analytic hierarchy process (AHP) is used to derive the weights for the criteria. AHP is a decision making technique that was introduced in the mid-1970's and has since been applied in a variety of applications, including solving problems with multiple objectives (Saaty (1977), (1980), (1994); Mollaghasemi and Pet-Edwards (1997); Kablan (2004)). The AHP is a popular MCDM methodology due to its flexibility and ease of use (Mollaghasemi and Pet-Edwards, 1997).

AHP is based on three principles: decomposition, comparative judgments, and synthesis of priorities. The "decomposition" principle requires that the decision problem be structured in a hierarchy, wherein higher elements are more general objectives while lower elements are more specific attributes. The "comparative judgments" principle entails pair-wise comparisons using a scale of relative importance, between elements within a given level and with respect to their higher level objectives. The "synthesis of priorities" principle constructs a composite set of priorities for the elements at the lowest level of the hierarchy (attributes or criteria) from the derived ratio-scale priorities determined by the comparative judgments. These three principles are described further below.

First, the decomposition principle is satisfied by organizing the six criteria into a hierarchy with the fundamental objective at level one, decision criteria at level two, and alternatives at level three. Kablan (2004) describes such a hierarchy as an "AHP model" which is illustrated with respect to the present decision problem in Figure 3.3.

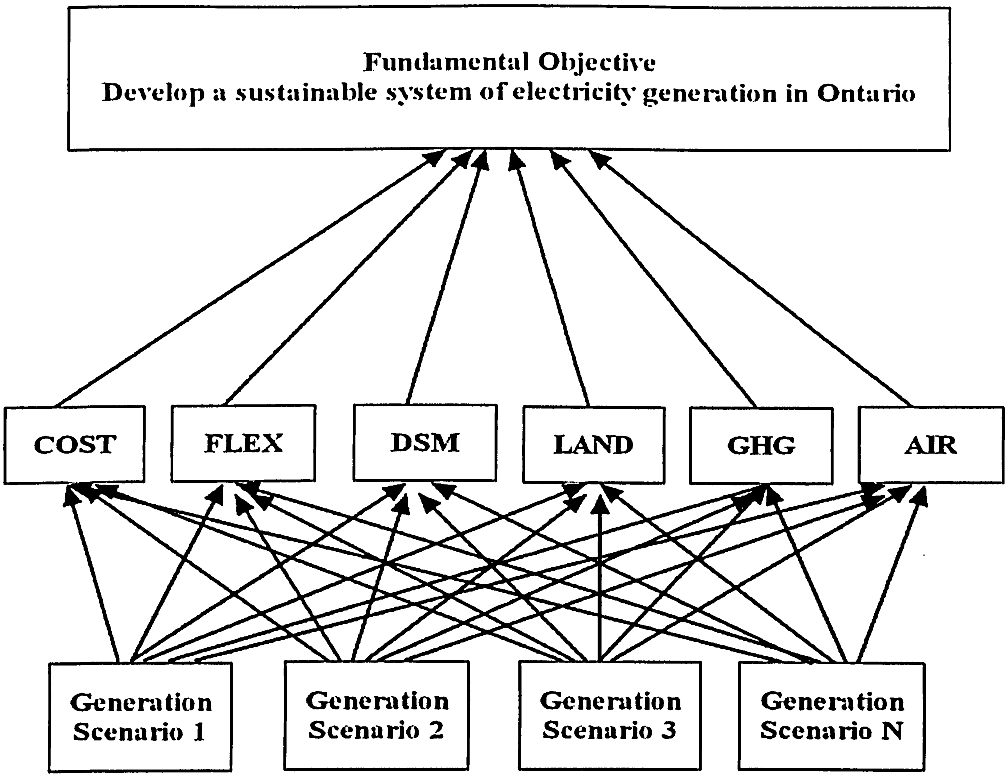

Figure 3.3: AHP Model for the Prioritization of Alternative Generation Scenarios

As previously described, the literature review and consultations with individuals, energy professionals and experts were used to develop the fundamental objectives to which the decision-making framework could be applied. The fundamental objectives were stated in the questionnaire as "meeting three conditions: providing an adequate supply of electricity to meet demand, maximizing the security and reliability of the system, and minimizing environmental and public health burdens of generation" (Appendix A). The decision criteria and their units of measurement were also presented and described to all potential participants.

Using AHP, a problem with n attributes will have $n(n-1)/2$ pair-wise comparisons to be made. When $n = 6$, 15 pair-wise comparisons are required. The quantitative judgments provided by participants between the different criteria (denoted as A, for attributes) can be illustrated in the $n \times n$ matrix given in Figure 3.4. The AHP matrix as presented to the participants in the application of the decision-making framework is displayed in Table 3.10 with the legend for making pair-wise comparisons. Because the top right of the AHP matrix is a mirror image of the bottom left, participants were asked to complete only the unshaded portion of the matrix.

$$A = \begin{array}{c} \\ A1 \\ A2 \\ . \\ . \\ An \end{array} \overset{\begin{array}{cccc} A1 & A2 & \ldots & An \end{array}}{\begin{bmatrix} a11 & a12 & \ldots & a1n \\ a21 & a22 & \ldots & a2n \\ . & . & \ldots & . \\ . & . & \ldots & . \\ an1 & an2 & \ldots & ann \end{bmatrix}}$$

Figure 3.4: Example Illustration of an AHP Matrix A (n x n)

Table 3.10: Analytic Hierarchy Process (AHP) Matrix for the Decision Problem: Multiple Criteria for Sustainable Electricity Generation System Planning (Reproduced from Questionnaire)

	COST	FLEX	DSM	LAND	GHG	AIR
→ COST	1					
→ FLEX		1				
→ DSM			1			
→ LAND				1		
→ GHG					1	
→ AIR						1

Legend for pair-wise ranking of criteria using AHP.		
Importance	**Numerical Rating**	**Inverse Relationship**
Equally important (indifferent)	1	1
Moderately important	3	1/3
Strongly important	5	1/5
Very strongly important	7	1/7
Extremely important	9	1/9
* Numerical values 2, 4, 6, 8 indicate intermediate values.		

Having entered the numerical pair-wise judgments into the matrix "A", the decision-maker recovers the numerical weights (W_1, W_2, .., W_n) of the criteria from the matrix. The numerical weights for each criterion derived using AHP always sum to a total of one.

After deriving criteria weights from participants using AHP, follow up conversations were conducted with some participants to gain insight regarding the selection of criteria and the use of the criteria weighting scheme. In some cases, the conversations were completed during or immediately following stakeholders' completion of the questionnaires. Some of the participants elected to revise their preferences toward the criteria in light of the decision alternatives. The AHP supports a degree of agreement in the decision-making process while not requiring consensus because it averages disparate viewpoints.

3.7 Ranking Alternatives

Once relative weights are determined for the criteria, the decision-making framework integrates the values-based information with the life-cycle based information pertaining to each electricity generation scenario. Two steps are involved in this process. First, the performance of each criterion for the scenarios is displayed on a linear scale from zero (worst) to one (best). This step is referred to as calculating linear value functions. Next, the linear value functions are amalgamated with the criteria weights for each criterion and an additive method is used to calculate a numerical "total value" for each scenario. These steps are described in the following subsections.

3.7.1 Linear Value Functions

The performance of each criterion for each alternative scenario is determined by calculating linear value functions for the criteria across the alternative scenarios. The linear value functions for criteria were calculated using the following formula:

$$V_i(x) = \frac{x_i - x_{i*}}{x_i^* - x_{i*}}$$

where $V_i(x)$ represents the value of alternative x on criterion i, x_i is the performance of alternative x on criterion i, x_i^* is the performance of the best alternative on criterion i and x_{i*} is the performance of the worst alternative on criterion i. The value is calculated for each criterion for every scenario, resulting in a linear scale of performance for all criteria. For each criterion, the worst performing alternative will have a value of zero, the best performing scenario will have a value of one, and intermediate values are displayed on the linear scale between zero and one.

3.7.2 Total Value of Alternative Scenarios

The total value of each scenario is calculated using the results from the criteria weighting exercise (AHP) and the results of the linear value functions. The decision-making framework utilizes an additive approach commonly referred to as the weighted sum method, which is described by the equation:

$$TV(x) = \sum_{i=1}^{n} w_i V_i(x)$$

where $TV(x)$ is the total value of alternative x, w_i represents the weight of criterion i, $V_i(x)$ is the value of alternative x on criterion i, and n is number of criteria. The total value for each alternative scenario is calculated, resulting in a numerical indication of how each scenario satisfies the fundamental objectives of the decision problem.

For the test case used to apply the decision-making framework, the total values of the electricity generation scenarios were compared at two points in the future: 2015 and 2030. The two years were compared to determine if tradeoffs made in the near term could be strategically traded-off in order to achieve a more desirable long-term outcome.

Chapter 4: Electricity Generation: Scenarios

4.1 Approach to Generation Scenario Development

Scenario-based planning involves developing ranges of plausible futures that describe possible outcomes for comparison, contrast and evaluation. Many published scenarios are described using narrative styles which often paint elaborate pictures of the future. Three elements of scenarios as described by Schwartz (1991) are used as a basis for soliciting insight regarding candidate generation resources to build the scenarios. The three elements of scenarios include driving forces, predetermined elements, and critical uncertainties. Driving forces are forces that influence the outcome of events, or the elements that move the plot of a scenario (determine a story's outcome). Predetermined elements do not depend on any particular chain of events. If an element seems certain, no matter which scenario comes to pass, then it is a predetermined element. Predetermined elements can be slow changing phenomena (i.e. population growth), constrained situations (i.e. electricity as a service of necessity, it must always be on), things that are "in the pipeline" (i.e. technology transfer), or inevitable collisions (i.e. the end of a power plant's service life). Critical uncertainties are ultimately related to driving forces and predetermined elements in that they are those elements that the decision-maker does not know or cannot predict. Unforeseen events, such as catastrophic failure at a power plant or the willingness of consumers to change their habits and choices regarding energy use, are examples of critical uncertainties (Schwartz, 1991).

4.2 Assumptions

Assumptions make it possible to limit the possibilities with regard to electricity generation systems, both in terms of technology choices and their individual prevalence on the systems described by the scenarios. The assumptions presented below are based on areas of general agreement among the participants in this study.

4.2.1 Best Available Technologies

It is assumed that, in the future, the range of available generation technologies will be constrained to best available technologies that conform to legislated standards for emissions limits and other environmental quality or efficiency standards. Environmental quality standards and emissions limits are not static, and generally become more restrictive as generation technologies and pollution control equipment improve and environmental pressure from development increases. Therefore it is assumed that any new electricity generation resources will be based on technologies that perform better than those operating today.

This assumption allows the life-cycle based information used in the decision-making framework to exclude technologies that would not likely be considered for development in the future. A wide range of life-cycle data is reported in the available literature, and general agreement is present among the participants that technologies developed in the future would exceed current technologies in environmental and operational performance. This assumption allows for data for technologies that would be outdated as the scenarios would develop to be culled from the analysis.

4.2.2 Speed of Technological Transitions

Experience in the development of civilizations, societies and industries has shown that it takes about 60 years for the world to transition from being primarily dependent on one energy resource to a new resource or set of resources (Aitken, 2003). This slow pace could be due to sunk costs and lack of political will to change, but it is likely to quicken with the advancement of information technology. Even with quickening technological change, the 25 year timeframe of this thesis did not make it possible to consider a fully renewable system among the scenarios. Several iterations of such a fully renewable system were constructed early in the scenario development exercise but ultimately they were not considered a feasible end state within the planning horizon. This is because of a lack of data for the types of generation technologies that might bring about such a system, and because the operational characteristics (capacity factor and flexibility) of available renewable power generation technologies did not produce enough energy to meet the projected demand in the future.

4.2.3 Demand-Side Management and Demand Load

Estimating future demand for electricity is a critical component in planning for the electricity generation system. The IESO established an annual projection of demand growth in its 10-Year Outlook (IESO, 2005), but future demand remains a critical uncertainty facing future generation systems. It is assumed that more investment in demand-side management would result in more demand reduction.

The success of demand-side management programs is displayed on the supply side of the decision-making framework, so that the current IESO demand projection could be extended to 2030 and demand reduction could be stacked with supply side resources. The IESO 10-year Outlook projections for high, medium and low peak demand and energy demand growth, extended to 2030, are illustrated in Figures 4.1 and 4.2 (IESO, 2005). The IESO's projection for median energy demand growth of 0.9% is assumed for the scenarios of the decision-making framework.

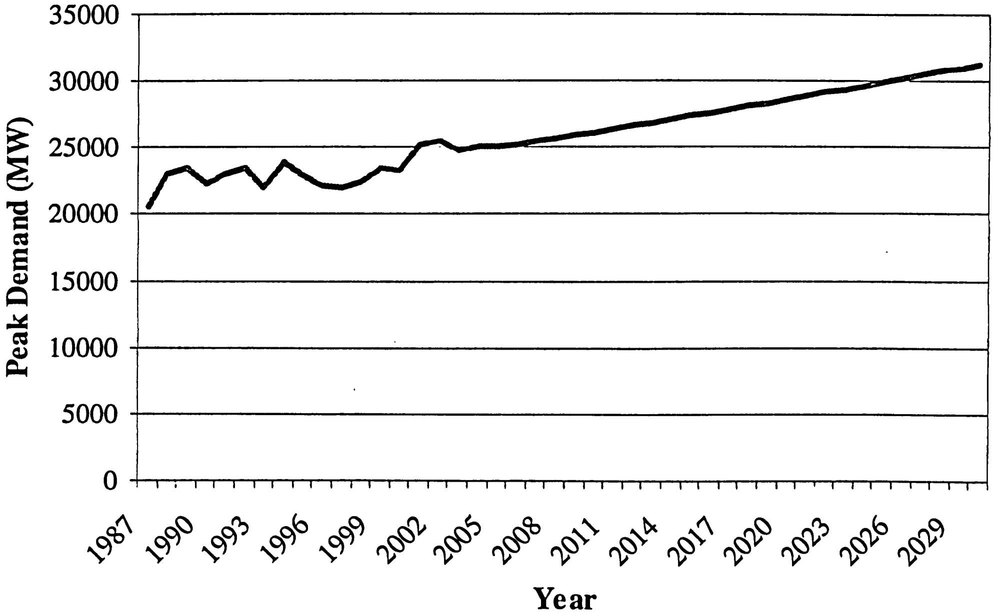

Figure 4.1: Ontario Peak Electrical Demand Projected to 2030
Adapted from IESO (2005)

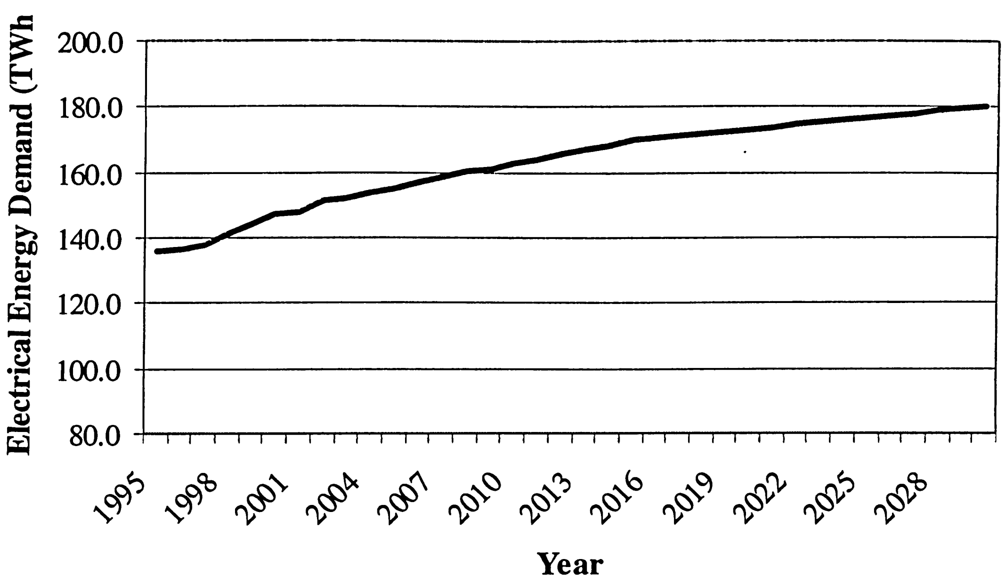

Figure 4.2: Ontario Electrical Energy Demand Projected to 2030
Adapted from IESO (2005)

4.2.4 Accidents

Contingencies associated with accidents, catastrophes and extreme weather are not considered in the scenarios. The decision-making framework is intended as a meta-planning decision tool, focused more on the process of planning rather than on the outcomes of planning activities. As a result, the logistics behind system dynamics and adaptability to emergencies, planned outages or other disruptions to electricity generation are not included in the analysis.

It is also envisioned that subsequent iterations of the decision-making framework could construct scenarios to display any combination of generation technologies to meet extreme demand scenarios, such as extreme weather effects.

4.2.5 Imports

All three scenarios are subject to the same speculations regarding future imports of electricity to Ontario. These imports could come either from the USA, Quebec, Manitoba or Labrador. Ontario currently receives imports as required from the USA and Quebec, and the possibility exists for additional import capacity from hydroelectric sources in Manitoba, Quebec and Labrador. For future imports, the costs and impacts of receiving power from Manitoba and Labrador are not known, and the feasibility of constructing such interconnections are uncertain. Because these conditions are equal across all future generation scenarios, imports are not considered in the decision-making framework.

4.2.6 The Starting Point

The baseline for the generation scenarios developed in this thesis is Ontario's current supply mix. Ontario's supply mix in 2005 was composed of about 50% base-load and 50% intermediate and peaking capacity and consisted of nuclear, coal, hydroelectric, natural gas, natural gas/oil dual fired, with a few other minor generation resources such as wood waste and wind. Ontario's 2005 generation supply mix is illustrated in Figure 4.3. Because all the hypothetical generation scenarios in this thesis are starting from the same base, the scenarios reflect only new generation assets as they are added to the system, except in cases of coal or nuclear generation where end-of-service lifetimes differ between the scenarios.

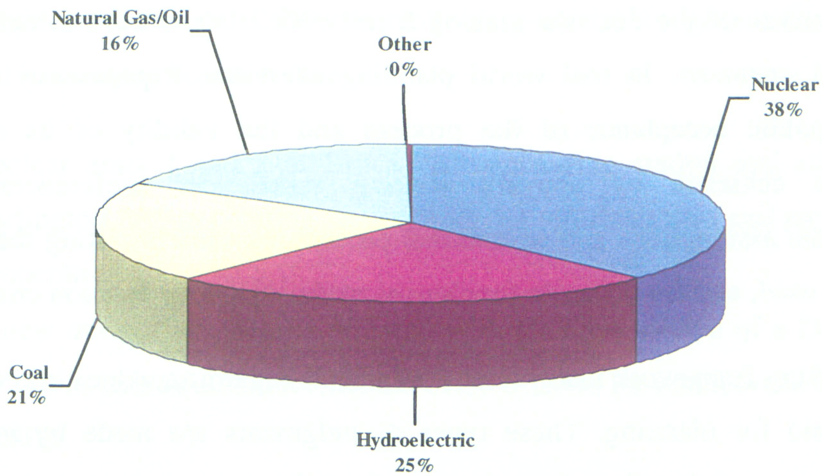

Figure 4.3: 2005 Generation Supply Mix in Ontario

The number of generation technologies available in Ontario becomes more complex in projecting hypothetical future systems, as the number of viable generation technologies has increased in the last several years. In addition, active research and development and experience with new and emerging energy conversion technologies is opening up a wide range of alternative futures. It is assumed that future electricity generation systems in Ontario will tend toward more diversity of energy production and conversion technologies.

4.2.7 Momentum for Change

After decades of neglect, a measurable increase in energy technology purchases in Ontario is imminent. However, it will not be "business as usual". Canin and Berst (2004) relate several trends in favour of an electricity system transformation. These trends include recent increased attention to deteriorating infrastructure, availability of cost-effective technologies, growing needs for high quality power for digital devices, a greater awareness of the risk of catastrophe at "single point of failure" central power plants, and a growing concern over climate change. These trends have resulted in more interest in efficiency and to approaches intended to reduce greenhouse gas emissions. Thus, it is these trends that serve to steer the development of the scenarios presented in Section 4.3.

4.2.8 Transparency of Analysis

One of the objectives of the decision-making framework is to achieve a high level of transparency and openness. In real world planning exercises, transparency would be critical to the public acceptance of the process and the validity of its outcomes. Transparency is achieved by actively seeking stakeholder preferences, openly communicating the assumptions and operational procedures, clearly stating the methods and data sources used, and the rationale for choices made regarding decision criteria.

The decision-making framework incorporates judgments regarding values into a science-based decision aid for planning. These types of judgments are made by individuals concerning measures of "goodness" or "badness" of the system. Such judgments are fundamentally non-scientific (Barnthouse *et al.*, 2003). While science-based life-cycle data can describe processes, analyze past actions or events, or assist in predicting future events, science is inherently incapable of determining whether these events are good or bad. Judgments regarding goodness or badness of environmental impacts of generation options, suitability of costs, or robustness of generation systems are expressions of values. This thesis focuses on describing such values quantitatively; therefore, a high degree of transparency is required to communicate the results.

By making value judgments explicit, rather than implicit inside the decision maker's mind, the decision making process is inherently more transparent. The values underlying decisions are on the table for discussion, and alternatives that compromise those values are highlighted so that tradeoffs could be made.

4.3 Alternative Scenarios

4.3.1 Scenario One

Scenario One is the closest to "business as usual" for Ontario's electricity generation system. Given the number of energy conversion technologies that are on the verge of commercialization or cost-effectiveness, an extension of business as usual could develop in many ways. Considering the assumptions described in Section 4.2, resources were added to the scenario builder to produce a scenario characterized by large, central power plants, utilizing conventional fuel types and where minimal demand-side management occurs. Between 2006 and 2030, the following electricity generation resources were considered in creating Scenario One:

- Nuclear units 1 and 2 at Bruce "A" generating station and all units at Darlington "A" generating station undergo refurbishment and are returned to operation.
- A new nuclear program is initiated with the construction of a Darlington "B" Unit, and an announcement is made in 2006 for commercial operation in 2016.
- Two additional new nuclear generating stations are built with four units each, and the initial units come online in 2017 and 2019, with all 8 units scheduled to come online by 2022.
- Four 1000 MW coal plants using integrated gasification combined cycle (IGCC) technology, with four 250 MW gasifiers each, commence operation in 2010, 2013, 2017 and 2020.
- A total of 6400 MW combined cycle gas turbine (CCGT) plants are brought into service between 2006 and 2027.
- 2400 MW of single cycle gas turbine (SCGT) peaking capacity is brought into service.
- Two new biomass 250 MW IGCC plants utilizing forestry wood residues come online in 2012 and 2013.
- A new small hydro development and grid-connection program starting between 2007 and 2010 adds several MW of small hydro to the grid between 2008 and 2017 (500 MW total).
- Some wind power is installed, with 150 MW of new wind capacity installed by 2008, followed by a modest annual growth rate (10%) for the planning horizon (1000 MW total).
- A small amount of solar PV (2 MW or 200-4.8 kW solar rooftop arrays) is installed by 2010 followed by a slow annual growth rate (5-10%).

- 500 MW of demand reduction is achieved through demand-side management programs.

A timeline illustrating the development of Scenario One for electricity generation is illustrated in Figure 4.4.

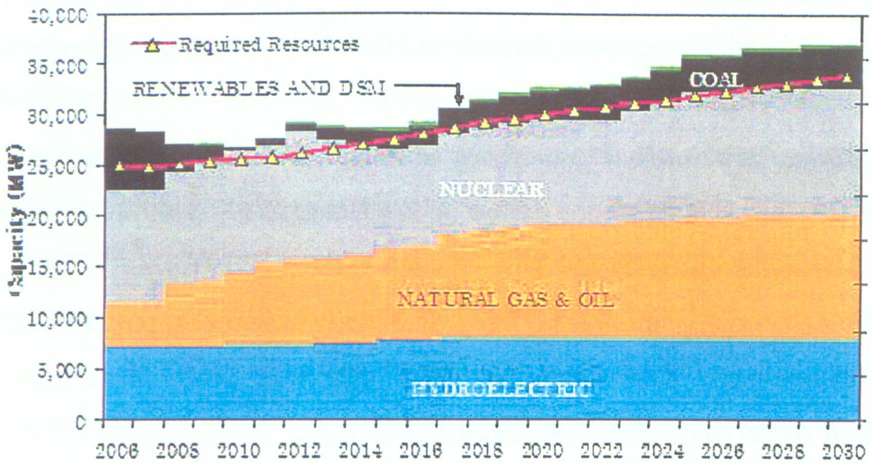

Figure 4.4: Electricity Generation Timeline for Scenario One

4.3.2 Scenario Two

Scenario Two represents a compromise between "business as usual" and the development of renewable energy sources and demand-side management in a future electricity generation system for Ontario. The number of renewable energy conversion technologies and advanced conventional generation technologies available means that such a scenario could develop in many ways into the future. Considering the assumptions described in Section 4.2, resources were added to the scenario builder to produce a scenario in which some large, central power plants co-exist with distributed generation, as well as advanced conventional fuel technologies and a phase out of nuclear power. Moderate success in demand-side management is achieved. Between 2006 and 2030, the following electricity generation resources were added to the alternative titled Scenario Two:

- 4000 MW of CCGT capacity is brought into service by 2025.

- 2000 MW of SCGT capacity is brought into service by 2011.
- 2000 MW of natural gas combined heat and power (CHP) capacity is installed over the 25 year time horizon: including 250 MW additions in 2008, 2010, 1013, and 2014, two-250 MW additions in 2012 and 2015.
- The service life of the coal-fired generation plants is extended beyond 2009, utilizing best available emissions control technologies to extend existing coal-fired generating capacity to the end of the current plants' operating lifetimes.
- 500 MW of hydroelectric run-of-river capacity is built.
- The Moose River basin hydroelectric reservoir is developed, adding 1300 MW of intermediate and peaking generation capacity.
- 1000 MW of pumped-storage hydroelectric capacity is developed.
- Aggressive biomass energy is developed, totaling 6500 MW by 2030.
- 50 MW of new wind capacity is installed by 2006, as some incentives for renewable energy development are put in place (e.g. Standard Offer Contracts), stimulating a moderate to fast annual growth rate (20%) in wind energy to 2025, followed by declining growth rates.
- 2 MW of solar PV capacity is installed by 2007, followed by demonstration projects to achieve an achievable potential of 41 MW by 2015 (CanSIA, 2005). Following 2015, Ontario sustains rapid growth (35%) in solar PV until 2020, due to established solar PV manufacturing and technical expertise in Ontario.
- Moderate demand-side management results in 2400 MW of peak demand reduction by 2030.

A timeline illustrating the development of Scenario Two for electricity generation is illustrated in Figure 4.5.

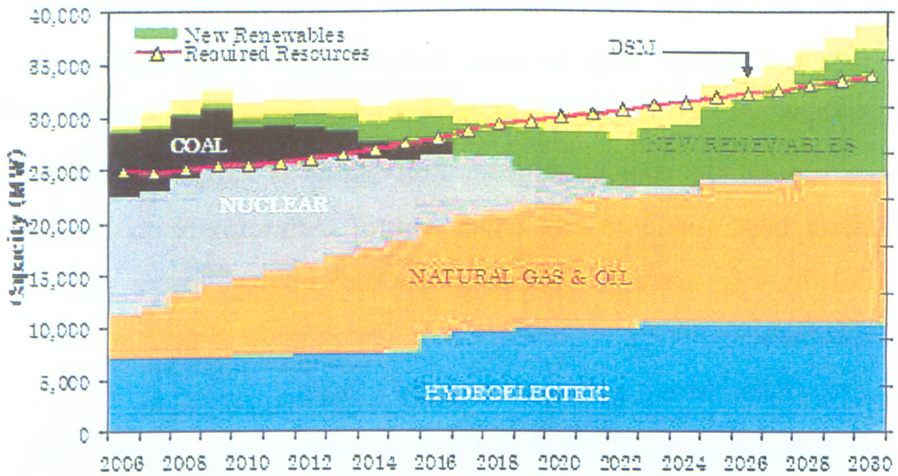

Figure 4.5: Electricity Generation Timeline for Scenario Two

4.3.3 Scenario Three

Scenario Three represents the furthest departure from a "business as usual" scenario in Ontario. This scenario represents a future in which the electricity generation system favours smaller scale distributed resources, renewable energy sources, a phase out of nuclear power and aggressive demand-side management. In Scenario Three, communities gain the greatest stake in their own energy supplies, as shifts toward local generation also foster responsible energy use. Given the possibilities for distributed energy conversion technologies that are close to or at commercial, cost-effective operation, such a scenario could develop in many ways. Between 2006 and 2030, the following electricity generation resources were added to the alternative titled Scenario Three:

- 100 MW of new wind capacity is installed by 2008 and incentives for renewable energy development are put in place (ARTs or SOCs), stimulating a rapid growth rate (30%) n wind capacity until 2025, which then declines from 2026 to 2030 (14,000 MW by 2030).
- Aggressive demand-side management results in 4,150 MW of peak demand reduction by 2030.

- 2 MW of new solar PV capacity is installed by 2008, followed by an increasing annual growth rate while a domestic solar PV industry mobilizes to install 2900 MW of solar PV capacity by 2030.
- Up to 8000 MW of SCGT capacity is built to meet the supply gap throughout the planning period. By 2030, the amount of SCGT capacity is reduced to 3000 MW.
- 4400 MW of biomass anaerobic digestion capacity is installed by 2030.
- Aggressive development of hydroelectric run-of-river capacity is developed to total 6400 MW by 2030.
- 500 MW of hydroelectric pumped-storage generation is developed.

A timeline illustrating the development of Scenario Three for electricity generation is illustrated in Figure 4.6.

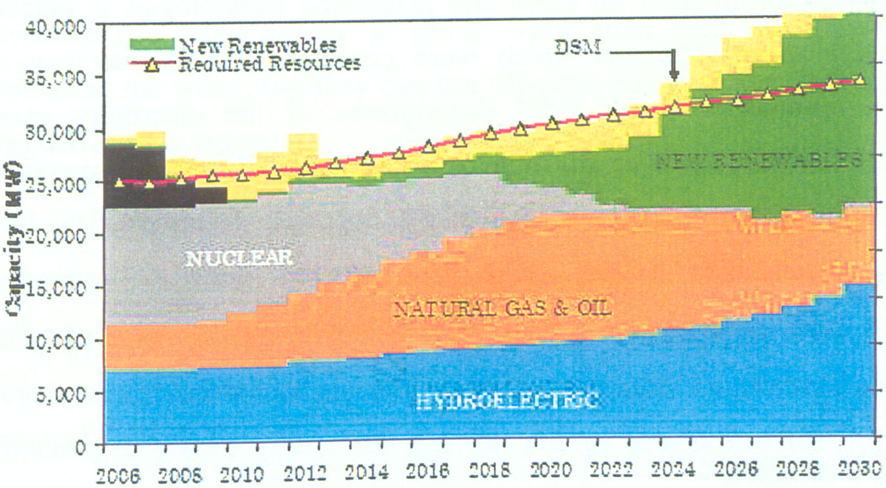

Figure 4.6: Electricity Generation Timeline for Scenario Three

Chapter 5: Application and Results of the Proposed Decision-Making Framework

This chapter discusses the application and results of the proposed decision-making framework, using the scenarios described in Chapter 4. The life-cycle based information collected from the literature review is summarized first, as these data were used as inputs to the decision-making framework. The results of the criteria weighting exercise is then described, followed by the actual application of the framework, in which the three scenarios described in Section 4.3 are ranked using the procedures described in Section 3.6. The latter half of this chapter describes and interprets the results of the application of the decision-making framework to the case of long-term planning for Ontario's power generation systems.

5.1 Application of the Decision-Making Framework

5.1.1 Life-Cycle Based Information

The life-cycle based information for electricity generation technologies is presented in this section. Only those attributes which were considered in the decision-making framework are summarized here. Brief descriptions of the electricity generation technologies are provided; however, for more detail regarding the technologies the reader is directed to the full life-cycle tables in Appendix B, the original sources of the life-cycle based information, and OPA (2005b). Cells filled with two dashes (--) indicate where fewer than three values were present in the literature for a life-cycle category to provide a range of values.

Hydroelectric Generation

Little life-cycle data for hydroelectric generation systems emerged from the literature review due to the heterogeneity and site specificity of hydroelectric installations. Worldwide, hydroelectric facilities have a large range in capacity and size, from one kW to 12,000 MW in capacity and from less than one metre head to 1500 m head (MIT, 2005). Therefore it was difficult to assign quantified, certain life-cycle cost and emissions data to hydroelectric developments.

Three basic types of hydroelectric generation systems were described in the literature, each varying widely in scale and performance, including impoundment, run-of-river and pumped storage systems.

- Impoundment systems involve constructing dams and creating reservoirs to flood tracts of land. Water is then released, utilizing the potential energy of water stored at higher elevations to drive generation turbines. Impoundment systems generate dispatchable electricity, but water may be released when the power is not needed to maintain downstream water levels.

- Run-of-river hydroelectric generation systems involve water that is diverted through a constructed channel which drives a generation turbine. They do not require the construction of reservoirs.

- Pumped storage systems pump water from a lower reservoir to a higher elevation, which may or may not involve an upper reservoir. These systems use more energy to pump water than they can generate by releasing the water, but they can use off-peak power to store energy until needed at peak times.

Tables 5.1 and 5.2 summarize life-cycle based emissions, land use and cost data for hydroelectric impoundment and run-of-river generation. No specific information is available for pumped storage generation; however, if reservoirs are located above ground the life-cycle characteristics of pumped storage generation are assumed to be similar to impoundment generation, except for less net energy production and higher costs. In general, the construction of hydroelectric reservoirs accounts for the largest use of resources and emissions of CO_2, SO_2, and NOx, which is attributed to the production of formwork timber, cement and steel (Vattenfall, 1999).

Table 5.1: Life-Cycle Based Emissions, Land Use and Cost Data for Hydroelectric Impoundment and Pumped Storage Generation

	Cost $/MWh	Land Use Km^2/TWh	GHG Emissions $kgCO_2eq./MWh$	AIR Emissions $kgSO_2eq./MWh$	SO_2 Emissions $kgSO_2/MWh$	NOx Emissions kgNOx/ MWh	$PM_{2.5}$ Emissions $kgPM_{2.5}/MWh$
Min	--	--	1.8	--	0.007	0.03	--
Max	--	--	33	--	0.59	1.57	--
Average	**50.70**	**152**	**15**	**0.006**	**0.21**	**0.8**	**0.003**

Sources: Larson (1993); Vattenfall (1999); Hydro-Quebec (2001); Gagnon *et al.* (2002); Hydro-Quebec, cited in Gagnon (2004); SENES (2005), cited in OPA (2005).

Notes:
It is assumed that pumped storage generation is similar to hydroelectric impoundment.

Table 5.2: Life-Cycle Based Emissions, Land Use and Cost Data for Hydroelectric Run-of-River Generation

	Cost $/MWh	Land Use Km^2/TWh	GHG Emissions $kgCO_2eq./MWh$	AIR Emissions $kgSO_2eq./MWh$	SO_2 Emissions $kgSO_2/MWh$	NOx Emissions kgNOx/ MWh	$PM_{2.5}$ Emissions $kgPM_{2.5}/MWh$
Min	50.70	--	2	--	0.001	--	--
Max	122.49	--	20	--	0.04	--	--
Average	**86.60**	**1**	**8**	**0.000022**	**0.02**	**0.03**	**0.003**

Sources: Koch, (2000); Gagnon *et al.*, (2002); SENES, (2005), cited in OPA (2005b); EIA, (2005); Hydro-Quebec, Vattenfall, Dones, cited in Gagnon, (2004).

Notes:
A high degree of variability is typical of hydroelectric run-of-river generation due to the site specific nature of these projects.

Natural Gas

There are three basic thermal generation technologies that utilize natural gas as a fuel source: single-cycle gas turbines (SCGT), combined-cycle gas turbines (CCGT) and cogeneration, or combined heat and power units (CHP). These modes of electricity generation using natural gas are summarized as follows.

- A SCGT utilizes technology similar to a jet engine, in which the hot combustion gases drive a turbine which spins an electrical generator.

- A CCGT utilizes a combination of gas and steam turbines to generate electricity using both a gas combustion cycle and a steam cycle, driven by exhaust gases from the gas turbine. Higher thermal efficiencies can be achieved using CCGT technologies than by using either the gas combustion or steam cycle alone.

- CHP applications capture surplus heat generated by the gas combustion cycle for utilization by a "steam host" either for space heating, water heating, or to drive industrial processes. Space and water heating applications can be utilized by residential developments, or for nearby industries or commercial developments. The highest thermal efficiencies for natural gas generation can be realized in CHP applications.

The life-cycle data for three modes of natural gas generation are summarized in Tables 5.3 to 5.5. In general, the majority of impacts from natural gas fired electricity generation results from the operation phase of gas turbines, which is attributed to the combustion of natural gas.

Table 5.3: Life-Cycle Based Emissions, Land Use and Cost Data for Natural Gas Single Cycle Generation

	Cost $/MWh	**Land Use** Km^2/TWh	**GHG Emissions** $kgCO_2eq./MWh$	**AIR Emissions** $kgSO_2eq./MWh$	**SO_2 Emissions** $kgSO_2/MWh$	**NOx Emissions** kgNOx/MWh	**$PM_{2.5}$ Emissions** $kgPM_{2.5}/MWh$
Min	--	--	--	--	0.011	0.38	--
Max	--	--	--	--	0.95	3.9	--
Average	**131.30**	**0.15**	**660**	**0.002**	**0.015**	**0.58**	**0.018**

Sources: Vattenfall (1999); SENES (2005), cited in OPA (2005b).

Table 5.4: Life-Cycle Based Emissions, Land Use and Cost Data for Natural Gas Combined Cycle Generation

	Cost $/MWh	**Land Use** Km^2/TWh	**GHG Emissions** $kgCO_2eq./MWh$	**AIR Emissions** $kgSO_2eq./MWh$	**SO_2 Emissions** $kgSO_2/MWh$	**NOx Emissions** kgNOx/MWh	**$PM_{2.5}$ Emissions** $kgPM_{2.5}/MWh$
Min	--	--	--	--	0.003	0.26	--
Max	--	--	--	--	0.314	0.71	--
Average	**70.30**	**0.15**	**435**	**0.011**	**0.164**	**0.44**	**0.012**

Sources: Koch (2000); Spath and Mann (2000); Krewitt *et al.* (1998); Spadaro and Rabl (1998); Gagnon *et al.* (2002); SENES (2005), cited in OPA (2005b).

Table 5.5: Life-Cycle Based Emissions, Land Use and Cost Data for Natural Gas Combined Heat and Power (CHP) Generation

	Cost $/MWh	Land Use Km^2/TWh	GHG Emissions $kgCO_2eq./MWh$	AIR Emissions $kgSO_2eq./MWh$	SO_2 Emissions $kgSO_2/MWh$	NOx Emissions kgNOx/MWh	$PM_{2.5}$ Emissions $kgPM_{2.5}/MWh$
Min	--	--	--	--	0.0028	0.22	--
Max	--	--	--	--	0.025	0.793	--
Average	**79.40**	**0.15**	**295**	**0.0009**	**0.014**	**0.507**	**0.01**

Sources: Schleisner and Nielson (1997); US NREL, cited in Gagnon (2004); OECD (2005); SENES (2005), cited in OPA (2005b).

Nuclear

Nuclear generation currently serves an important role in Ontario's electrical system. All nuclear generation in Ontario is provided using the Canada Deuterium Uranium (CANDU) technology, which uses unenriched (natural) uranium as the fuel source and heavy water as a moderator and coolant. Ontario's CANDU reactors utilize uranium fuel mined and milled in Saskatchewan and refined in Ontario.

Several other nuclear technologies are either commercially available or in various stages of development. Atomic Energy of Canada Ltd. (AECL) has developed an advanced CANDU reactor design (ACR), however, this technology remains conceptual. The ACR reactor would utilize a low enriched uranium fuel, similar to other nuclear reactor designs currently in use in other countries. Two types of light water reactors in use around the world are the pressurized water reactor (PWR) and boiling water reactor (BWR). These reactors use light water as both coolant and moderator and utilize enriched uranium as a fuel source.

If Ontario were to initiate a new nuclear build program, it is uncertain which technology would be utilized. The original CANDU design currently utilized in Ontario experienced problems such as exceeding budgets, construction time overruns and poorer than expected performance. The ACR design is currently in the design phase and its time to commercial deployment is also uncertain.

For the purpose of this thesis, it was assumed that all nuclear electricity generation technologies will exhibit similar performance characteristics, environmental emissions and levelized unit costs. The life-cycle data for nuclear electricity generation technologies are summarized in Table 5.6. For nuclear technologies, the largest consumption of resources and atmospheric emissions occur during the construction phase, resulting from construction activities and materials such as formwork timber, cement and steel. The second largest emissions into air and water occur during the production and transportation of the fuel, then the management of the spent fuel and the construction and operation of deep geological repositories (Vattenfall, 1999). Transport of the Uranium fuel is associated with fewer emissions in Canada than in other countries, because Canada sources its uranium domestically (i.e. unenriched uranium). Also, environmental and cost information for permanent nuclear waste handling or disposal facilities is not known in a Canadian context; therefore, any information regarding the final life-cycle phase for nuclear fuel in Canada is purely speculative, as these facilities have not been constructed yet.

Table 5.6: Life-Cycle Based Emissions, Land Use and Cost Data for Nuclear Generation

	Cost $/MWh	Land Use Km^2/TWh	GHG Emissions $kgCO_2eq./MWh$	AIR Emissions $kgSO_2eq./MWh$	SO_2 Emissions $kgSO_2/MWh$	NOx Emissions kgNOx/MWh	$PM_{2.5}$ Emissions $kgPM_{2.5}/MWh$
Min	$54.57	0.001	3	--	0.032	0.0324	0.005
Max	$79.30	0.5	40	--	0.05	0.100	0.009
Average	**66.94**	**0.113**	**19**	**0.00012**	**0.028**	**0.045**	**0.0076**

Sources: Wehowsky *et al.*, cited in Krewitt et al. (1998); Vattenfall (1999); Koch (2000); Gagnon *et al.* (2002); Vattenfall, Dones, cited in Gagnon (2004); Dones *et al.* (2005); OECD (2005); SENES (2005), cited in OPA (2005d).

Coal

Coal can be converted to electricity using a variety of technologies and specific designs. Similar technologies vary widely according to emissions control technologies and the quality of coals used. Ontario's current coal fleet consists of pulverized coal burners, which heat a boiler to produce steam to drive generation turbines. Coal is widely accepted as having the poorest environmental performance, especially in terms of air emissions, among electricity generation technologies. However, several techniques and technologies have been adapted to reduce emissions from coal.

Coal cleaning is a set of processes by which impurities such as sulfur, ash, and rock, are removed from the coal using either mechanical or chemical processes (EPA, 1995). Chemical coal cleaning processes use water or other solvents to "wash" most of the pyritic sulphur from the coal following coal crushing. Techniques that separate more sulphur from coal are currently being researched (DOE, 2005).

Flue gas desulphurization (FGD) is a process by which sulphates react with wet limestone in the flue gases from coal combustion to form calcium sulphate, or gypsum. FGD can remove from 70% to over 90% of all sulfur present by converting them to sulfates (Lunt and Cunic, 2000). FGD was reported to cost US$144.64 per kW to install on thermal power plants (EIA, 2005)

Selective catalytic reduction (SCR or DeNOx) is the catalytic elimination of NOx compounds from flue gases at thermal power plants, much like catalytic converters installed on internal combustion engine automobiles.

CO_2 recovery and CO_2 sequestration techniques currently under investigation are intended to remove CO_2 from thermal power plant emissions. The most promising technology is the pumping of CO_2 emissions into subsurface cavities or spent oil and gas fields. The utilization of CO_2 for secondary recovery of conventional hydrocarbons is currently being demonstrated in southeast Saskatchewan, using coal-fired power plant emissions from the US, transported via pipeline. The viability and cost-effectiveness of this technology is uncertain in Ontario, and the prospect of reducing greenhouse gas intensity for recovering additional hydrocarbons for combustion seems an oxymoron.

Fabric filters have been employed as a method of reducing large particulate matter (PM) emissions in wet and dry coal cleaning processes as well as those contained in fly ash (EPA, 1995). In addition, electrostatic precipitation has the ability to remove 99% of PM from coal plant emissions. It does not work well for fly ash resulting from the combustion of low sulfur coals (Holbert, 2003).

Coal can be burned by itself in a conventional thermal power generation plant. More advanced designs of these plants such as pulverized coal, circulating fluidized bed and pressurized fluidized bed combustion, supercritical steam cycles and IGCC technologies are likely the only candidates for future coal generation development due to the coal's environmental performance. Very little to no life-cycle information was available for these coal technologies due to the lack of experience in their utilization and development. Worldwide experience is also proving integrated gasification combined cycle (IGCC) technologies which convert coal to a combustible gas (syngas) to be a viable future electricity generation option. Very little information is available in the literature regarding coal IGCC technology.

The life-cycle data for coal-fired thermal and coal IGCC electricity generation are summarized in Tables 5.7 and 5.8.

Table 5.7: Life-Cycle Based Emissions, Land Use and Cost Data for Coal-Fired Thermal Generation

	Cost $/MWh	Land Use Km^2/TWh	GHG Emissions $kgCO_2eq./MWh$	AIR Emissions $kgSO_2eq./MWh$	SO_2 Emissions $kgSO_2/MWh$	NOx Emissions kgNOx/ MWh	$PM_{2.5}$ Emissions $kgPM_{2.5}/MWh$
Min	--	--	--	--	0.711	0.54	0.01
Max	--	--	--	--	2.53	2.9	0.025
Average	59.72	4	1.2	2.3	1.4	1.2	0.1

Sources: Dorland *et al.* (1997); Pingoud *et al.* (1997); Krewitt *et al.* (1998); Spadaro and Rabl, (1998); Spath *et al.* (2000); Gagnon *et al.* (2002); Dones (1999); cited in Gagnon (2004); SENES (2005), cited in OPA (2005d).

Table 5.8: Life-Cycle Based Emissions, Land Use and Cost Data for Coal Integrated Gasification Combined Cycle (IGCC) Generation

	Cost $/MWh	Land Use Km^2/TWh	GHG Emissions $kgCO_2eq./MWh$	AIR Emissions $kgSO_2eq./MWh$	SO_2 Emissions $kgSO_2/MWh$	NOx Emissions kgNOx/ MWh	$PM_{2.5}$ Emissions $kgPM_{2.5}/MWh$
Min	--	--	--	--	--	--	--
Max	--	--	--	--	--	--	--
Average	90.90	4	910	0.038	0.62	0.5	0.01

Sources: SENES (2005), cited in OPA (2005d).

Biomass

Biomass is energy stored in the form of plant material or organic matter and is considered a renewable resource. It is available in Ontario as forest industry and harvesting residues, agricultural residues, peat, gases from landfills and decaying sewage, municipal solid waste and dedicated energy crops. Biomass is the only carbon-based fuel source which has the capacity to be carbon neutral.

Biomass can be burned to provide heat for heating, cooking, or to create steam to drive a turbine. It can be fired in a thermal generation unit, similar to the technology currently used in Ontario's coal-fired power plants or it can be co-fired with coal as a means of reducing air emissions. The biomass source is dried and often compressed prior to being combusted. The energy in biomass can also be utilized to generate electricity by capturing the combustible gases produced when organic matter decays under anaerobic conditions. Many jurisdictions capture gases from landfills to generate power and agricultural applications are being used in Europe to produce combustible gases through anaerobic digestion of livestock manure, sewage treatment plants or composting facilities. Finally, biomass can also be converted to a combustible gas using IGCC technology. Heat and steam are applied to biomass in order to produce the syngas, using the same technology used to convert coal to gas in IGCC plants.

Biomass is best suited in applications where the source of biomass is close to the generating plant. Low heating values are characteristic to biomass, and surplus energy and environmental advantages of biomass could be compromised if the fuel must be transported appreciable distances to the power plant. Local opportunities for biomass energy include the capacity for combined heat and power (CHP) operation while providing base load power, common in the Nordic countries. Processes for increasing the energy density of biomass are currently being researched, but no environmental or cost information was available for these conversion technologies.

The Canadian Bioenergy Association (CanBIO) has estimated that Ontario has at least 1700 MW of incremental biomass fueled electricity generation capacity. This is a conservative value because several of the estimates of biomass capacity potential are based on developing 20% of previously published estimates of biomass potential in Ontario (BioCap (2003) and IPPSO (2003), cited in CanBIO (2003)). This capacity represents the sum of biomass residues, landfill/ bio-gas, municipal solid waste and dedicated energy crops. A summary of biomass sources and estimated incremental potentials for electricity generation are provided in Table 5.9. The total energy production capacity in Table 5.9 is based on 25% conversion efficiency assuming 80% net capacity factor. Because the figures below represent a conservative estimate, it is assumed that the actual potential of biomass energy in Ontario could be much larger than 1700 MW.

Table 5.9 Future Potential Ontario Biomass Generation Capacities (CanBIO Estimate)

Biomass source	Capacity (MW)	Energy (MWh/yr)
Forest industry residues	80	555,000[1]
Forest harvesting residues	560	3,890,000[2]
Agricultural residues	660	4,655,400[3]
Landfill gas/biogas	70	490,560[2]
Municipal solid waste	130	930,000
Energy Crops	200	1,401,600[4]
Total	**1700**	**11,922,560**

Notes:

1. Based on BioCap estimate in "A Canadian Biomass Inventory: Feedstocks for a Biobased Economy", May 2003.
2. Based on 20% of BioCap estimate. Agricultural residues estimate includes 50 MW of livestock waste anaerobic digestion.
3. Based on Environment Canada, (1999), Report on Potential for Additional Landfill Gas Utilization (as cited in CanBIO, 2003).
4. Based on 20% of IPPSO (1993) estimate (as cited in CanBIO (2003)).

The life-cycle data for several biomass electricity generation technologies are summarized in Tables 5.10 to 5.13. Most biomass technologies reported in the literature were less than 100 MW in capacity. The large land use requirement for biomass plantations, such as trees and shrubs, could be mitigated due to other uses being possible on the land used for growing biomass between harvesting, such as recreation.

Table 5.10: Life-Cycle Based Emissions, Land Use and Cost Data for Biomass Wood Waste Thermal Generation

	Cost $/MWh	Land Use Km^2/TWh	GHG Emissions $kgCO_2eq./MWh$	AIR Emissions $kgSO_2eq./MWh$	SO_2 Emissions $kgSO_2/MWh$	NOx Emissions kgNOx/MWh	$PM_{2.5}$ Emissions $kgPM_{2.5}/MWh$
Min	--	--	--	--	0.018	0.701	--
Max	--	--	--	--	0.026	1.29	--
Average	**101.49**	**1**	**33**	**0.003**	**0.022**	**0.891**	**0.014**

Sources: Krewitt *et al.* (1998); Koch (2000); Gagnon *et al.* (2002); OECD (2005); SENES (2005), cited in OPA (2005d).

Table 5.11: Life-Cycle Based Emissions, Land Use and Cost Data for Biomass Plantation Generation

	Cost $/MWh	Land Use Km^2/TWh	GHG Emissions $kgCO_2eq./MWh$	AIR Emissions $kgSO_2eq./MWh$	SO_2 Emissions $kgSO_2/MWh$	NOx Emissions kgNOx/MWh	$PM_{2.5}$ Emissions $kgPM_{2.5}/MWh$
Min	--	--	--	--	--	--	--
Max	--	--	--	--	--	--	--
Average	**114.10**	**1367**	**85**	**0.007**	**0.026**	**1.59**	**0.014**

Sources: Matthews (2000), cited in Gagnon (2004); Gagnon *et al.* (2002); OECD (2005).

Notes:
Assume $PM_{2.5}$ emissions similar to wood waste.

Table 5.12: Life-Cycle Based Emissions, Land Use and Cost Data for Biomass IGCC Generation

	Cost $/MWh	Land Use Km^2/TWh	GHG Emissions $kgCO_2eq./MWh$	AIR Emissions $kgSO_2eq./MWh$	SO_2 Emissions $kgSO_2/MWh$	NOx Emissions kgNOx/MWh	$PM_{2.5}$ Emissions $kgPM_{2.5}/MWh$
Min	61.70	--	--	--	0.04	0.35	0.033
Max	96.14	--	--	--	0.105	0.386	0.04
Average	**78.92**	**1**	**39**	**0.001**	**0.007**	**0.37**	**0.024**

Sources: Spadaro and Rabl (1998); Spath *et al.* (2000); OECD (2005); SENES (2005), cited in OPA (2005d).

Notes:
It is assumed that biogas generation using anaerobic digestion technology is similar to IGCC.

Table 5.13: Life-Cycle Based Emissions, Land Use and Cost Data for Biomass CHP Generation

	Cost $/MWh	Land Use Km^2/TWh	GHG Emissions $kgCO_2eq./MWh$	AIR Emissions $kgSO_2eq./MWh$	SO_2 Emissions $kgSO_2/MWh$	NOx Emissions kgNOx/MWh	$PM_{2.5}$ Emissions $kgPM_{2.5}/MWh$
Min	--	--	--	--	--	--	--
Max	--	--	--	--	--	--	--
Average	**114.10**	**1**	**8**	**0.001**	**0.018**	**0.492**	**0.013**

Sources: Krewitt *et al.* (1998), Gagnon *et al.* (2002); OECD (2005).

Wind

Installed wind generation capacities have been increasing rapidly worldwide, having grown to 48 GW in 2004 (REN21, 2005). Almost all wind generation technologies have utilized a three blade horizontal axis configuration, with on-shore turbine capacity ratings approaching 1.5 to 2.5 MW and off-shore ratings as high as 5 MW. Modern wind turbines can have blade diameters up to 90 m or greater, and wind farms can occupy large areas of land; however, most of this land is still available for other uses. A 50 MW wind farm can be composed of dozens of turbines.

Ontario has a large potential for wind generation capacity, however, most of this capacity is located appreciable distances from transmission and distribution infrastructure (OPA, 2005a). Wind is also an variable source of electricity, which means that turbines only produce electricity when the wind blows. Wind power may not be available when needed, and turbines may produce electricity when it is not needed. As a result of its intermittent nature, wind power is inflexible, not dispatchable and requires back-up generation for operational flexibility.

Air emissions from wind generation occur primarily during the construction, dismantling and maintenance stages. Other impacts of wind include landscape change, soil erosion, and local climactic effects. The life-cycle data for on-shore wind turbines are summarized in Table 5.14.

Table 5.14: Life-cycle Based Emissions, Land Use and Cost Data for On-Shore Wind Generation

	Cost $/MWh	Land Use Km^2/TWh	GHG Emissions $kgCO_2eq./MWh$	AIR Emissions $kgSO_2eq./MWh$	SO_2 Emissions $kgSO_2/MWh$	NOx Emissions kgNOx/ MWh	$PM_{2.5}$ Emissions $kgPM_{2.5}/MWh$
Min	$102.90	15	--	--	0.015	0.0151	--
Max	$107.92	72	--	--	0.032	0.042	--
Average	**105.41**	**44**	**9**	**0.0002**	**0.02**	**0.03**	**0.02**

Sources: Schleisner and Nielson (1997); Krewitt *et al.* (1998); Vattenfall (1999); Hydro-Quebec (2001); OECD (2005); SENES (2005), cited in OPA (2005d).

Notes:
Off-shore wind turbines were not considered in this thesis.

Solar Photovoltaics

Solar photovoltaics (PV) provide very little energy to grid-based electrical systems worldwide, however, they are currently the fastest growing generation technology. Solar PV achieved a growth rate of 60% in 2004 (REN21, 2005). Solar PV systems have small power capacities, with typical ratings for rooftop systems from three to four kW. Like wind, emissions to the environment from solar PV technologies occur during the life-cycle stages outside of generation, such as fabrication, construction, dismantling and maintenance stages. Solar PV power is also an intermittent resource and is non-dispatchable, but solar PV energy production coincides with peak demands for electricity (Rowlands, 2004). The life-cycle data for solar PV are summarized in Table 5.15.

Table 5.15: Life-Cycle Based Emissions, Land Use and Cost Data for Solar Photovoltaic (PV) Generation

	Cost $/MWh	Land Use Km^2/TWh	GHG Emissions $kgCO_2eq./MWh$	AIR Emissions $kgSO_2eq./MWh$	SO_2 Emissions $kgSO_2/MWh$	NOx Emissions kgNOx/MWh	$PM_{2.5}$ Emissions $kgPM_{2.5}/MWh$
Min	$299.40	0	29	--	0.104	0.063	--
Max	$639.35	45	127.6	--	0.143	0.1	--
Average	**469.38**	**0**	**41**	**0.00009**	**0.12**	**0.1**	**0.02**

Sources: Krewitt *et al.* (1998); Koch (2000); Greijer (2001), cited in Pacca (2003); Gagnon *et al.* (2002); Vattenfall, Dones, cited in Gagnon (2004); OECD (2005); SENES (2005), cited in OPA (2005d).

Notes:
It is assumed that building integrated technologies will be developed, therefore no land use requirements were included as inputs to the decision-making framework.

Fuel Cells

Fuel cells represent an emerging electricity generation technology for which little life-cycle data or experience has been documented. Midilli *et al.* (2005) stated that restructuring of the electric utility industry will present opportunities for hydrogen-powered fuel cells to provide on-site electricity generation as well as thermal energy for hot water, space heating, and industrial processes. In the intermediate term, hydrogen can be produced from coal and biomass using pyrolysis or gasification. In the longer term, hydrogen markets and hydrogen related infrastructure will create more opportunities for renewable hydrogen systems (Midilli *et al.*, 2005).

In addition to electricity generation, hydrogen fuel cells may emerge as alternatives to internal combustion engine (ICE) powered vehicles and could represent increased demand for electricity. As concerns regarding air quality increase and uncertainty regarding fossil fuel prices mount, the future of the ICE powered vehicle is unclear. If hybrid (electric plus ICE) and electric vehicles (EVs) gain market shares, the result would be increased electricity demand. The emergence of fuel cell powered vehicles as well as hybrid and EVs over the planning horizon of this thesis is uncertain.

As a potential load on the electric system, large numbers of hybrid and EVs could have significant effects. Ford (1995) compiled the results of six studies to conclude that the demand of an EV on the utility grid could range from 11.2 kWh to 37.4 kWh per day[1]. Ford also concluded that EV demands would tend to improve the overall shape of electricity demand, thus allowing utilities to operate more efficiently, as EV charging normally occurs at night, during periods of low electricity demand. As a potential source of supply to the electric system, Kempton and Letendre (1997) postulated that the dawning interaction between EVs and the electricity supply system will be far more significant than simply increased load. This is due to the fact that electric grids could receive power from EVs as well as provide power to them. The current fleet of mechanical drive ICEs, by contrast, offer no electric system interactions or benefits.

In addressing societal air quality objectives, it should be noted that in some urban areas, such as the Greater Toronto Area, transportation can account for two-thirds of emissions that cause smog (Environment Canada, 2005). In planning for future electricity generation systems, changes in the automobile fleet which could have impacts on the electric system should be considered. No life-cycle data for fuel cell technologies were encountered during the literature review.

5.1.2 Results of Criteria Weighting Exercise

The criteria weighting questionnaire intended to develop a set of weights (values or preferences) for the six decision criteria, which were used as proxy measures of the fundamental objectives. Of the 57 questionnaires distributed to individuals with a stated knowledge of electricity generation, 18 completed questionnaires were returned representing a 32% return rate. Despite the small sample size, enough information was retrieved to allow the calculation of a set of weights for the six criteria. A larger sample size would have been necessary to develop the criteria weights into values representative of the broad range of stakeholders in the case of Ontario's electricity generation system.

The AHP results define a set of relative weights to indicate preferential importance of the objectives of the decision-making framework. The results are summarized in Table 5.16.

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[1] Assume average daily travel distances. Kempton and Kubo (2000) list efficiencies of several commercially available EVs as ranging from 6.09 km/kWh to 10.48 km/kWh.

The sum of the weights for all criteria always totals one using the AHP method. The numerical weights indicate the relative value of each criterion (objective) with respect to the rest, averaging results of the questionnaires. Figure 5.1 illustrates the averaged weights, which show that across all participants, five of six of the objectives are highly valued by participants, and that trading off land used by electricity generation systems would be most acceptable to gain on most of the other objectives. Air emissions and system flexibility are preferred the most, while land use and cost are preferred the least among the objectives.

Table 5.16: Results of Stakeholder Preference Information for the Six Criteria Obtained during the AHP Exercise

Criteria	Average Value
COST	0.1601
FLEX	0.1855
DSM	0.1739
LAND	0.1122
GHG	0.1804
AIR	0.1880
Total	**1.000**

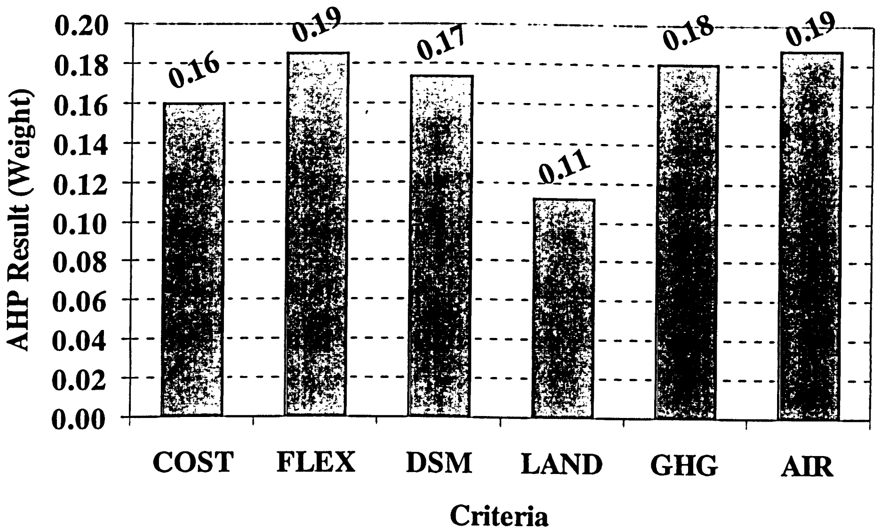

Figure 5.1: Illustration of Relative Stakeholder Values for the Six Criteria

The criteria weighting exercise (see Section 3.5 for details) illustrates one example of a process by which relative preferences for objectives can be quantified in formal decision-making problems with multiple objectives. Weighting exercises are important for comparing criteria that measure differing and often competing system objectives, that use different or otherwise incomparable measurement units, or cannot be described using monetary equivalents. For this decision problem, the actual weight of each criterion is less important than demonstrating an example of a methodology to apply quantitative and explicit value or preference information to the objectives. In a real world exercise, the actual criteria weights would require more consideration.

5.1.3 Results of Linear Value Function Calculations

The three scenarios were developed using the scenario builder component of the decision-making framework (see Section 3.4). Then the life-cycle based information was applied to the scenarios to estimate the performance of each scenario on the six decision criteria using the decision-making framework. The main assumptions affecting system performance in the framework are the capacity factors of the generation technologies. The capacity factor assumptions for the generation technologies directly influence the performance on the criteria, because the capacity factors affect the energy produced by each generation resource on the system. The performance of the three scenarios at 2015 and 2030 is summarized in Table 5.17.

Table 5.17: Performance of Three Generation Scenarios on Six Criteria

2015	COST	FLEX	DSM	LAND	GHG	AIR
Scenario One	72.73	96	490	2.8E-08	3.4E-04	2.0E-08
Scenario Two	70.12	256	1645	1.5E-07	3.3E-04	2.3E-07
Scenario Three	56.28	165	1995	8.4E-09	1.9E-04	1.1E-09

2030	COST	FLEX	DSM	LAND	GHG	AIR
Scenario One	72.22	172.16	496	2.2E-08	2.4E-04	1.5E-08
Scenario Two	78.74	715	2382	2.3E-07	1.9E-04	4.4E-09
Scenario Three	80.67	1166	4147	3.8E-09	3.1E-05	2.2E-10

The values in Table 5.17 are converted to a linear scale for all of the criteria in the next step. The linear value functions are calculated for both time periods: 2015 and 2030. The linear value scale displays each criterion as a cardinal ranking from worst performing (zero) to best performing (one) for each scenario. Table 5.18 summarizes the linear value functions for the six criteria at 2015 and 2030.

Table 5.18: Linear Value Functions of Three Generation Scenarios on Six Criteria

2015	COST	FLEX	DSM	LAND	GHG	AIR
Scenario One	0.0	0.0	0.0	0.9	0.0	0.9
Scenario Two	0.2	1.0	0.8	0.0	0.1	0.0
Scenario Three	1.0	0.4	1.0	1.0	1.0	1.0

2030	COST	FLEX	DSM	LAND	GHG	AIR
Scenario One	1.0	0.0	0.0	0.9	0.0	0.0
Scenario Two	0.2	0.5	0.5	0.0	0.3	0.7
Scenario Three	0.0	1.0	1.0	1.0	1.0	1.0

The linear value functions are illustrated using value plot diagrams, shown in Figures 5.2a and 5.2b. The y-axis of both value plots displays the performance of each scenario on the linear scale from worst performing to best performing. The value plot allows decision-makers to see which, if any, scenarios clearly perform better than others or where some criteria are inversely related in performance, prior to the weighting of the criteria using values-based information.

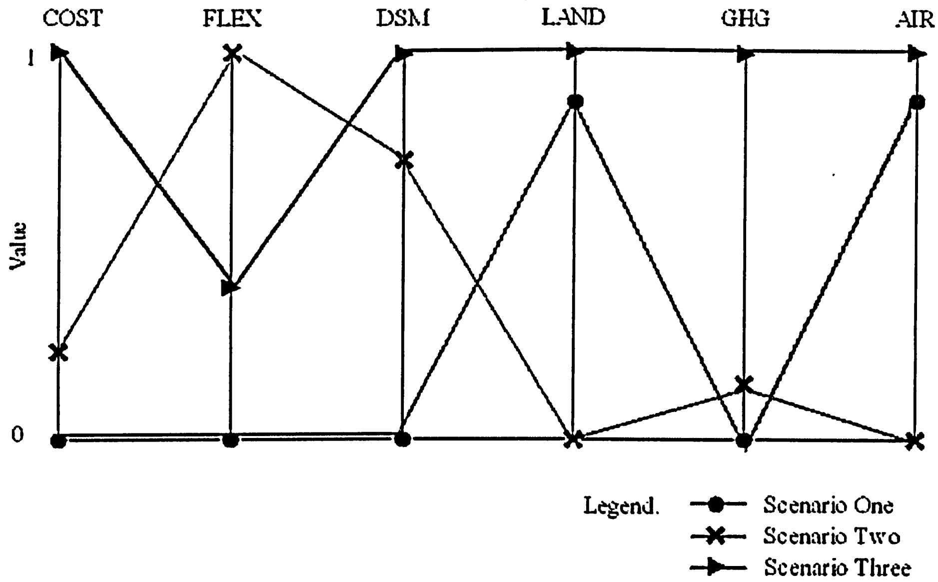

Figure 5.2a: Value Plots for Three Generation Scenarios: 2015

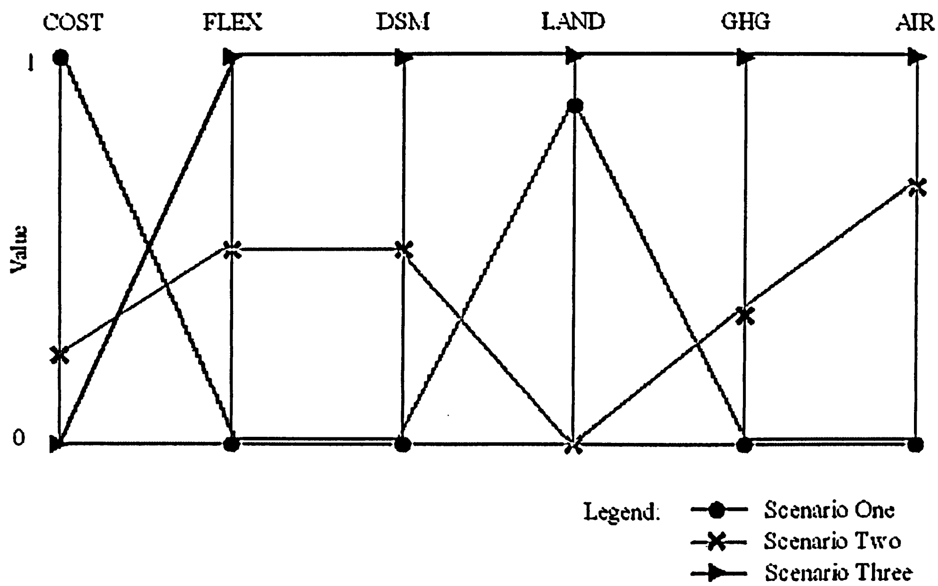

Figure 5.2b: Value Plots for Three Generation Scenarios: 2030

5.1.4 Results of Total Value Calculations

The final step in the decision-making framework calculates the total value of each scenario. The total value is derived by integrating the values-based preferential information obtained from the AHP with the performance of each scenario. A higher total value indicates a scenario that goes further in achieving the fundamental objectives (criteria are measures of the objectives), after performance on the decision criteria is weighted with values-based information. The results of the total value calculations are summarized in Table 5.19. The scenarios with the highest total value at 2015 and 2030 are bolded.

Table 5.19: Results of Total Value Calculations for Three Electricity Generation Scenarios at 2015 and 2030

Scenario	**2015**	**2030**
Scenario One	0.27	0.26
Scenario Two	0.36	0.41
Scenario Three	**0.89**	**0.84**

The results of the total value calculations indicate that at 2015 and 2030, Scenario Three was the closest to achieving the fundamental objectives, according to its performance on the decision criteria. Scenario One performed the worst, while Scenario Two was marginally better. There is a large range between the best performing scenario (Scenario Three) and the next best scenario.

5.2 Discussion of Life-Cycle Based Information

The literature shows that the results of life-cycle assessments for various power generation technologies span a wide range. Both the life-cycle environmental and cost performance information vary within technological categories (e.g. natural gas combined cycle), and for some technologies no such information is available. In some cases, LCA reports are not able to provide the data used to derive their results due to proprietary or confidential aspects of electricity generation technologies.

The methods and boundaries of the LCA are not always clearly stated in the LCA reports. Several studies also cite results from documents not available in the public domain. For example, several LCAs reference Vattenfall AB's *Life Cycle Studies of Electricity* (1999) but the data from which the charts in Vattenfall's final LCA report are not available.

Published LCA air emissions, greenhouse gas emissions and land use requirements vary widely between and among classes of power generation technologies. In some cases these data, when expressed in similar units, differ by orders of magnitude. This is due several factors, including the number of configurations of energy sources and conversion technologies, variable boundaries and assumptions between LCA exercises, and some location or country specific input parameters such as transport distances of fuel resources and power plant construction materials. The inconsistency and variability of LCA data increases the difficulty of utilizing such information in the decision-making framework.

Some LCA data have been culled from the decision-making framework because the subject technologies were dated, the data varied significantly from the rest (usually by orders of magnitude), or the values were from repeat sources. The average of the remaining data displays at least some consistency in results from certain LCA reports. The analysis of all available LCA data highlights the need for more standardized approaches to LCA for power generation technologies. Technological advancement of power generation technologies and emissions control equipment can account for much of the variability in LCA results, especially comparing recent studies to those a few to several years old. The majority of the LCA results were published between 1996 and 2000, from the European Commission's ExternE – *Externalities of Energy* national implementation reports. Following the same methodologies, several European countries published national implementation reports. Although the US Department of Energy collaborated in developing the methodologies for the ExternE project, the US had not published its own final report. The ExternE reports were able to provide a wealth of LCA results, but the range of technologies assessed was limited and the results are dated in 2005.

The LCA data suggest that power generation technologies have been improving in performance in recent years, with decreasing air emissions per unit of energy produced, reduced lifetime costs and improved operational performance. Despite these improvements however, additions of renewable energy resources to the generation system do not appear to result in improved system performance until they reach a certain threshold, due to the relatively low capacity factors of many renewable technologies. They do, however, have impacts to the cost of a generation system.

System performance is affected by the dynamic nature of the components making up the system. This is supported by experience in Ontario, where over the last several years, greenhouse gas and air emissions increased for the generation of electricity without additions of conventional thermal power plants to the system. The increased load placed on Ontario's coal-fired power plants was responsible for the increased emissions, following some nuclear units going out of service.

5.3 Need for Scenario-Based Planning in Ontario

No known instance of scenario-based planning has been applied in an open, transparent manner to planning Ontario's electricity generation systems; however, these methods have widely publicized in their use in private sector planning since the Royal Dutch/Shell Group developed the approach in the 1970s (Daum, 2001; Schwartz, 1991).

Ontario has specific resources, geographic and demographic regimes, and electrical demand requirements. Formal participatory exercises to develop scenario-based hypothetical futures for planning would be beneficial to Ontario's electricity generation systems in the long-term. The use of traditional forecasting and trend extension methods has not worked for Ontario, as Ontario has transitioned from having overbuilt capacity in the 1990s to a projected capacity shortage by 2014 (OPA, 2005), while creating a large legacy of debt over the last several decades. When long-range plans are based heavily in assumptions that forecast a particular set of future conditions, deviations from those assumptions in reality can render those plans irrelevant.

5.4 Interpreting Results of the Decision-Making Framework

The output variables of the decision-making framework are values that integrate the life-cycle based information measuring the performance of scenarios on the decision criteria and the values-based information regarding the objectives. The total value results are interpreted as denoting the relative worth of each scenario and indicating where divergence exists between scenarios. These results can enable the formal explication of the decision objectives, to make operational tradeoffs among the objectives in developing strategies, and to document both the basis by which decisions are made and the methods by which stakeholder input is accounted for in decisions.

The total values of the three scenarios are calculated in 2015 and at 2030 and displayed in Table 5.19. The same scenario scores the highest total value at 2015 and 2030: namely the renewables and conservation scenario (Scenario Three). This suggests that although there may be system reliability risks and higher cost associated with aggressively pursuing demand-side management and renewable energy sources, these risks should be explored further and mitigated in the short term in order to foster a more sustainable electricity generation system. It is interesting to note that the interpretation of the flexibility indicator changed during the course of this study. While initially meant to provide a positive measure of flexibility by ranking electricity generation systems according to the size and number of resources, further reading indicates that rapid expansion of small-scale and largely variable generation resources (such as wind) can require significant grid reinforcement and protection to operate reliably (E.on Netz, 2005).

The divergence of the total value results is similar at 2015 and 2030. According to the six criteria and decision-maker values toward the objectives (based on stakeholder input), a more desirable system is one that includes demand-side management and renewable energy sources, despite the higher costs.

5.5 Value of Multiple Objective Decision-Making in Generation Planning

The decision-making framework presented in this thesis describes a single methodology to incorporate the use of multiple criteria (multiple objectives) into complex decision-problems such as electricity generation planning. There are many more methodologies and techniques that have been developed to evaluate decisions with multiple objectives and to derive weights or preferential information for criteria under consideration.

The use of criteria is not constrained to those selected in this thesis. Multiple objective decision problems can be designed specifically to consider a broad range of criteria. The decision-making framework developed in this thesis is especially designed to be adaptable to new information and changing values regarding the decision objectives. Being a complex system, the problem of electricity generation development naturally encompasses a range of parameters which can serve as objective measures. A partial list of additional candidate criteria includes:

- Energy efficiency gains over time;
- Household electricity expenditures as share of disposable income;
- Production of radioactive air emissions or high-level waste;
- Water use; or
- Energy reserve life (given mixture of fuel sources).

The value of multiple objective decision-making is its ability to adapt to particular decision situations and in its use of values-based information. While traditional planning related activities tend to de-emphasize values-based information, it is the contention of this thesis that such values will always be prominent when solving difficult and complex problems, whether they are made explicit or not. If not made explicit and open by the decision-making processes employed, values information is not transparent and less opportunity exists for discussion and negotiation when the decision objectives conflict.

Multiple criteria methods of decision-making can assist in making planning processes more open and transparent. Hobbs and Meier (2000) state that one of the objectives of multiple criteria methods in energy and environmental decision-making is to help people understand the implications of their value judgments and to inspire confidence in the decision. In decisions considering multiple objectives, decision makers display inconsistency in their own subjective evaluations of the alternative options. Multiple criteria methods further facilitate negotiation by quantifying and communicating the priorities of the decision makers, move the discussion away from the alternatives themselves, and focus on the fundamental objectives and tradeoffs of the alternatives (Hobbs and Meier, 2000).

Chapter 6: Conclusions and Recommendations for Future Work

Traditional approaches to electricity generation system planning have relied principally on economic criteria such as least-cost planning or principles of economic prudence when evaluating alternatives. These approaches fail to consider the multivariate nature of these systems, specifically with regard to social and environmental objectives. Problems with using economic objectives as the main criteria arise when sustainable development is determined to be fundamental to system development. Planning with respect to sustainability should consider economic, environmental and social objectives at the same decision level in more open and transparent ways to increase the credibility of the outcomes. Because these objectives are not preferred equally by all, planners must systematically consider values or preferences for the different objectives, by eliciting judgments from stakeholders. In addition, data used to compare the performance of prospective futures should be more holistic by considering life-cycle based information capturing construction through decommissioning and full fuel-cycles of power plants.

This thesis first presented a framework for assisting decision makers considering multiple objectives in long-term planning. Inputs to the decision-making framework include life-cycle based information, preferences for the multiple system objectives, and an open and transparent method of evaluating options using this information. Life-cycle based information for environmental characteristics, costs, as well as the operational performance of generation technologies are used as indicators of the decision objectives. Secondly, this thesis used the case of the Ontario electricity generation system to demonstrate the application of the decision-making framework. The framework's application compares and evaluates alternative electricity generation scenarios against a set of sustainable development objectives.

A literature review compiled a set of life-cycle based environmental emissions and land-use data for electricity generation technologies that could comprise future electricity generation systems in Ontario. Operational characteristics of generation plants and levelized unit electricity costs (life-cycle costs) were also researched. A spreadsheet was developed to enable the creation of hypothetical electricity generation scenarios by entering percentage shares for individual generation technologies corresponding to two time periods (2015 and 2030). Based on a set of assumed capacity factors for power generation technologies (openly displayed and user definable), the spreadsheet estimated the energy produced by each technology (in TWh) in the scenario and the corresponding performance on six decision criteria. The criteria were selected to indicate the scenario's achievement of the set of sustainable development objectives. The criteria were then translated into linear value functions for each scenario.

Decision-makers' preferences (values-based information) were collected for the six criteria using a questionnaire. The Analytic Hierarchy Process (AHP) estimated quantitative numbers to weight the six criteria. The linear values of each scenario's performance on the decision criteria was then integrated with the values-based information to evaluate the three electricity generation scenarios at 2015 and 2030.

The results of the decision-making framework are total value estimations for three electricity generation scenarios, with respect to the degree that the scenarios satisfy the fundamental objectives for the decision problem. The total values are calculated by summing the weighted value of each criterion, and are expressed as a numeric total value for each scenario. This information denotes an estimation of desirability for each scenario and can further be used to highlight where tradeoffs might be feasible between optional futures. The results of the application showed that the scenario with high renewables and high demand-side management were preferred to the other scenarios at both 2015 and 2030. The results also indicated that in pursuing the highest valued scenario, system reliability would be traded off in the medium term (2015) and cost would be traded off in the longer term (2030).

The main contribution of this thesis is the decision-making framework itself, which included the compilation of life-cycle based data for power plants, application of a method for quantifying stakeholder preferences, and the testing of the framework against three hypothetical scenarios. This thesis demonstrates that values-based information can be integrated into complex decision problems which consider multiple objectives, and that alternatives can be evaluated using criteria that are not measured using common scales. Of significance is the open and transparent manner in which the decision-making framework allows assumptions and values inherent to complex decision problems to be communicated and explicated.

The decision-making framework serves to make explicit key assumptions and values regarding complex, human-made systems. It is designed to be adaptable to changing knowledge, assumptions or values. Decision-makers have the ability to add, subtract or modify objectives and criteria, as long as values, or weights, can be applied to account for the changes. AHP was the technique used to assign this preferential information to the objectives in this thesis, but other weighting methods could be applied. It may be useful to use more than one methodology to increase the consistency of the weights.

Further development of the decision-making framework for application in real world planning exercises is recommended, but work should first be completed in several areas. The literature review highlighted the wide range of data for the many electricity generation technologies and the inconsistent and evolving methodologies for LCA. Reliable, open databases of LCA information should be developed to lessen the impact of wide ranging datasets for electricity generation technologies. Currently, much LCA data is subject to interpretation and is questionable in accuracy and comparability. This deters the use of life-cycle information in real-world planning situations.

The decision-making framework requires an easier graphical interface in which the user-modifiable and explicit assumptions, preferences and scenarios can be easily visualized, to enable tradeoffs to be made in real time. The current spreadsheet version of the decision-making framework requires manual recording of scenario attributes and each component of the framework to be completed in separate, standalone steps. The majority of the decision-making framework could be designed to operate in the background of a simple, graphic-based program. This would allow decision-makers to more quickly and easily determine the impacts of new information, different value-sets, and alternate decision criteria on the desirability of the options under consideration.

The process by which stakeholder preferences are derived should be streamlined to allow for easier quantification of values-based information. Currently, if additional criteria are added to the decision-making framework, the AHP process would require the entire criteria weighting process to be repeated. Additional research should be completed regarding the derivation of relative weights for the objectives of multiple objective decision problems. Also, it is recommended that additional weighting schemes be tested and possibly applied using multiple methods to increase the consistency in weighting, both across stakeholder groups and for individual decision-makers.

Finally, the creation and documentation of alternative electricity generation scenarios should be formally conducted as a group based participatory exercise, possibly facilitated in a public forum. This could be completed through small, formal discussion groups, through workshops conducted using smaller numbers of experts, or through less formal web-based applications which could be open to anyone taking an interest in planning future electricity generation systems. Lending itself to broad stakeholder input, a planning process that implements open and transparent methods to clearly communicated objectives, integrates values-based information, and develops a set of decision alternatives that encompass the range of uncertainties inherent in long-term planning would increase the credibility of planning outcomes.

Appendix A: Participant Questionnaire

A Life-Cycle Based Decision-Making Framework for Electricity Generation System Planning

A Thesis being conducted in partial satisfaction of the requirements for the degree of *Master of Applied Science in Environmental Applied Science and Management* from the School of Gr[illegible] at Ryerson University, Ontario.

Principal Investigator:
Steven J. Norrie, B.Sc.

Thesis Supervisory Committee:
Dr. Liping Fang

Dr. Professor Jim McTaggart-Cowan (ret.)

Introduction

This Master's level thesis is designed to apply a method of coordinated science and values based decision-making to the strategic, long-range planning of Ontario's electricity generation system. With the phase out of Ontario's coal fired generating plants and ageing of current capacity, the IESO has stated that "a substantial amount of new supply, refurbished generation and demand side resources could be required by 2014" (IESO, 2004, 10 yr outlook). By 2014, approximately 12,850 MW of new or refurbished supply or demand side measures would be required to meet Ontario's forecasted peak capacity deficiency (ibid). Assuming that a significant amount of new generating capacity is needed to meet Ontario's long-term demand, this thesis intends to address the following questions.

How should Ontario's system of electricity generation be developed to match long-term demand for electricity?

Can the use of a MCDM framework assist in identifying feasible options for a sustainable[2] system of electricity generation in Ontario?

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[2]Sustainable development has been broadly defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Bruntland, 1987).

A sustainable system of electricity generation has been defined for the purpose of this study, as meeting three conditions: providing an adequate supply of electricity to meet demand, maximizing the security and reliability of the system, and minimizing environmental and public health burdens of generation. Six criteria, or attributes, have been selected to reflect the degree to which several hypothetical future generation scenarios meet the objective of a sustainable system.

The purpose of this questionnaire is to collect information regarding preferences for the decision criteria, in order to model tradeoffs between them in the decision situation. The boundaries of the current decision problem encompass the electricity generation function, using a life-cycle approach which includes the full fuel cycle, plant construction, fuel and materials transport, operation and decommissioning. The decision-making framework will be applied to generation scenarios in Ontario using long-range time horizons, *spanning over 25 years into the future.*

The chosen criteria are intended to indicate the degree to which the fundamental objectives may be satisfied between alternative courses of action (alternate generation scenarios). Additional system attributes either inherent to a specific resource type or for which reliable data are not available, such as radiological emissions from nuclear power or coal combustion, resource depletion or other toxic emissions, will also be presented as attributes of the generation scenarios but not included as decision criteria. The attributes selected as criteria for the decision-making framework are presented in Table A1. A brief explanation of each of the six criteria is provided as follows.

- **COST:** The cost of electricity generation, averaged across the generation portfolio, in Canadian dollars per unit Megawatt (MWh) produced.
- **FLEX:** System flexibility, as an indicator of system reliability, is a weighted index, reflecting the number and relative sizes of generation technologies comprising the system, and the distribution of those technologies based on their

contribution toward the total supply.

- **DSM**: Demand-side management reflects the degree to which reductions in demand growth avert the need to build additional generation capacity.
- **LAND**: Reflects the area of land used per unit electricity produced, aggregated for the generation system.
- **GHG**: Greenhouse gas production in CO_2 equivalents aggregated across the generation system over the life cycle of each generation technology in use.
- **AIR**: Other air pollutant emissions, based on an aggregated index of SO_2, NO_x and PM, averaged across the generation system and over the life cycle of the generation technologies used.

Table A-1. Proposed Criteria for Multicriteria Framework for Ontario Sustainable *Electricity Generation System Planning*

Criteria	Units	Abbreviation
Minimize costs of electricity generation	\$/MWh	COST
Maximize flexibility of generation system	Resource/ size scale	FLEX
Minimize or reverse demand growth	Change in electricity demand (MW)	DSM
Minimize land use requirements/habitat loss	km^2/MWh	LAND
Minimize greenhouse gas emissions	kg CO_2eq/MWh	GHG
Minimize other air pollutants (SO_2, NOx, PM)	kg SO_2eq/MWh	AIR

The Questionnaire

This questionnaire is aimed at stakeholders possessing some knowledge, expertise or interest in system wide aspects of electricity generation. Follow-up interviews will be completed with selected, willing participants.

Your participation in this study is greatly appreciated. You will have received a consent agreement, which you should have signed prior to your participation in this study. If you have any questions regarding this questionnaire or the nature of this study, you are invited to contact either the principal investigator or the thesis supervisor, using the contact information provided at the end of this document.

Please answer the following.

1. Do you agree, in principle, with the selection of criteria presented in Table A1? Please remember that other attributes of electricity generation systems can also be considered when comparing generation scenarios, however only the six criteria in Table A1 have been selected for the decision framework.

2. In order to model preferences and tradeoffs between the criteria in the decision-making framework, the criteria presented in Table A1 must be weighted using an empirical approach. The methodology that has been selected is known as the Analytical Hierarchy Process (AHP). AHP is an established method used to arrive at a ratio-scale cardinal ranking of alternatives for multiple criteria decision problems.

   The six criteria are displayed in a matrix in Table A2 followed by a legend for pair-wise ranking of the criteria. Only one relationship can exist for each pair of criteria, therefore the values in the upper-right half of Table A2 will be the inverse of the values in the lower-left half of the table. Working from left to right in the matrix, please compare each criterion down the left column, in a pair-wise fashion, to each corresponding criterion along the top row. Each pair-wise comparison should be considered independent of the rest of the criteria. The value entered into the box represents your opinion regarding the relative importance of one criterion to another criterion. The value corresponds to your preferential relationship between the criteria pairs as explained in the example below and in the legend. The corresponding inverse relationships (shaded boxes) will be automatically entered by the spreadsheet created by the principal investigator.

Example: Starting from the left column, COST is compared to FLEX (top row), and the preferential relationship is entered into the intersecting box. If you are indifferent between these two criteria, enter the value of 1. If you feel that COST is "very strongly important" compared to FLEX, enter 7 into the box. If you feel that FLEX is "very strongly important" compared to COST, enter 1/7 into the box.

Table A-2. Analytical Hierarchy Process (AHP) Matrix for the Decision Problem: Multiple Criteria for Sustainable Electricity Generation System Planning

	COST	FLEX	DSM	LAND	GHG	AIR
→ COST	1					
→ FLEX		1				
→ DSM			1			
→ LAND				1		
→ GHG					1	
→ AIR						1

Legend for pair-wise ranking of criteria using AHP.

Importance	Numerical Rating	Inverse Relationship
Equally important (indifferent)	1	1
Moderately important	3	1/3
Strongly important	5	1/5
Very strongly important	7	1/7
Extremely important	9	1/9
* Numerical values 2, 4, 6, 8 indicate intermediate values.		

3. Would you be willing to participate in an interview following the aggregation and analysis of the results from the present questionnaire regarding your views relating to the electricity generation system? If so, please provide your name and contact information in the space below.

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Please return completed questionnaires and consent forms to:

Steven Norrie c/o RSU

55 Gould Street, Room SCC-311

Toronto, Ontario M5B 1E9

If you are located near downtown Toronto, please contact Steven Norrie, the principal investigator if you would like the questionnaire to be picked up from your location. I also welcome any questions you may have regarding this study.

Steven Norrie:

Telephone: (416) 710-9107

E-mail: snorrie@ryerson.ca

Appendix B: Life-Cycle Based Emissions, Land-Use and Cost Information for Electricity Generation Technologies

Table B-1: Published Emissions and Life-cycle Data for Hydroelectric Generation Technologies

Author, year	Comments	Cost $C/MWh	Land Use km^2/TWh	$kgCO_2$ eq./ MWh	$kgSO_2$/ MWh	kgNOx/ MWh	PM_{10} kg/MWh	$PM_{2.5}$ kg/MWh
Impoundment/ Reservoir								
Gagnon *et al*. (2002)	Reservoir	--	152	15	0.007	--	--	--
Vattenfall (1999)	Based on three hydroelectric stations operating in Sweden (impoundment)	--	0.35	1.81	0.59	1.57	0.27	--
SENES (2005), cited in OPA (2005)	Reservoir/ impoundment	50.70	0.0935[2]	33	0.04	0.03	0.003	0.003
Hydro Quebec, cited in Gagnon (2004)	Reservoir, "best commercial technology"	--	$1x10^{-4}$	10	--	--	--	--
Average		50.70	152	15	0.21	0.8	0.14	0.003
Run-of-River								
Gagnon *et al*. (2002)	Run-of-river	--	1	2	0.001	--	--	--
SENES (2005), cited in OPA (2005)	Run-of-river	50.70	0	20	0.04	0.03	0.003	0.003
HydroQuebec; Vattenfall; Dones, cited in Gagnon (2004)	Run-of-river, "best commercial technology"	--	--	3	--	--	--	--
OECD (2005)	Based on eight hydro plants in six countries, small plants up to 120 MW capacity, CF ~50%, except two at 36.5% and 25%	122.49	--	--	--	--	--	--
Average		86.60	1	8	0.02	0.03	0.003	0.003
Other/ Unspecified								
Koch (2000)	Multiple participant international study from 1995 to 2000	--	--	2 - 48	0.005 – 0.060	0.003 – 0.042	0.005	--
HydroQuebec (2001)	Unspecified hydroelectric with reservoir	--	152	--	--	--	--	--

Notes:

[1]Levelized unit electricity cost, converted to 1993 CDN$ at 2003 exchange rate, median value in range presented at 10% discount rate.

[2] Stated units for land use: km2/MW

Table B-2a: Published Emissions and Life-cycle Data for Natural Gas Generation Technologies

Author, year	Comments	Cost \$C/MWh	Land Use km^2/TWh	$kgCO_2$ eq./MWh	$kgSO_2$/MWh	kgNOx/MWh	PM_{10} kg/MWh	$PM_{2.5}$ kg/MWh
Single Cycle Gas Turbine (SCGT)								
SENES (2005); cited in OPA (2005)	Single cycle gas Turbine (SSGT), dry gas, low NOx	131.30	0.00018[1]	440 - 880	0.011 – 0.018	0.38 – 0.77	0.020 – 0.034	0.018
Vattenfall (1999)	SCGT, operating as backup power, about 50 full load hours per year	--	0.15	1170	0.95	3.9	--	--
Average		**131.30**	**0.15**	**660**	**0.015**	**0.58**	**0.027**	**0.018**
Combined Cycle Gas Turbine (CCGT)								
Koch (2000)	CCGT	--	--	389 – 511 (450)	0.004 – 15+ (7.5)	0.0013 – 1.5 (0.75)	0.001 – 0.01+ (0.006)	--
Spath and Mann (2000)	CCGT	--	--	585.2	0.324	0.57	0.133	--
Spadaro and Rabl (1998)	CCGT, 250 MW, 39% efficiency, 1500 GWh energy	--	--	433	Negligible (SOx)	0.71	Negligible	--
Krewitt *et al.* (1998)	CCGT, 790.8 MW, 58% efficiency, 6500 full load hours/yr (75% capacity factor), 5054 GWh	--	--	402[2]	0.003	0.277	0.018	--
Vattenfall (1999)	Proposed 900 MW CCGT power plant	--	0.15	440	0.01	0.02	--	--
Gagnon et al. (2002)	CCGT	--	--	443	0.314	--	0.001 – 0.010	--
SENES (2005); cited in OPA (2005)	CCGT, 50% to 60% efficiency.	70.30	0.000184 [1]	290 – 350 (320)	0.008 – 0.009 (0.009)	0.26 – 0.31 (0.29)	0.015 – 0.017 (0.016)	0.012
Average		**70.30**	**0.15**	**435**	**0.164**	**0.44**	**0.056**	**0.012**

Notes:

[1] Stated units for land use: km2/MW.

[2] Based on CO2, CH4 and N2O emissions.

Table B-2b: Published Emissions and Life-cycle Data for Natural Gas Generation Technologies

Author, year	Comments	Cost \$C/MWh	Land Use km^2/TWh	$kgCO_2$ eq./ MWh	$kgSO_2$/ MWh	kgNOx/ MWh	PM_{10} kg/MWh	$PM_{2.5}$ kg/MWh
Combined Heat and Power (CHP)/ Cogeneration								
Schleisner and Nielson (1997)	Combined cycle CHP plant, 77 MW,300 GWh/yr (SK Energie; cited in Schleisner and Nielson, 1997)	--	--	662	0.0028	0.793	0.00004	--
US NREL; cited in Gagnon (2004)	"Best commercial technology", 58% plant efficiency, 4000 km transportation	--	--	422	--	--	--	--
SENES (2005); cited in OPA (2005)	Cogeneration	79.40	0.000184 [1]	250	0.02501	0.22024	--	0.01
Average		79.40	0.15 [2]	295 [3]	0.014	0.507	0.00004	0.01
Other/ Unspecified								
Dones et al. (2005)	Nine "average natural gas power plants operating around year 2000"	--	0.4 – 0.7	485-983[4]	0.020 - 0.54	0.53 - 1.1	--	0.011 – 0.022
OECD (2005)	10% discount rate levelized over plant life cycle, 2003 CDN dollars	68.65	--	--	--	--	--	--

Notes:
[1] Stated units for land use: km2/MW.
[2] Assume land use comparable to CCGT.
[3] Upper outlier was excluded from the average.
[4] Based on CO2 and CH4 emissions.

Table B-3: Published Emissions and Life-cycle Data for Nuclear Generation Technologies

Author, year	Comments	Cost \$C/MWh	Land Use km^2/TWh	$kgCO_2$ eq./ MWh	$kgSO_2$/ MWh	kgNOx/ MWh	PM_{10} kg/MWh	$PM_{2.5}$ kg/MWh
Wehowsky *et al.*, cited in Krewitt *et al.* (1998)	Pressurized water reactor (PWR), 1375 MW	--	--	40	0.032	0.007	0.039	--
Vattenfall, Dones; cited in Gagnon (2004)	"Best commercial technology" Nuclear technology not specified	--	--	3	--	--	--	--
Gagnon et al. (2002)	Unspecified: aggregate sources	--	0.5	15	0.003	--	--	--
SENES, (2005); cited in OPA, (2005)	CANDU 6 technology	79.3	0.001465	12	0.01	0.188	0.013	0.009
Vattenfall (1999)		--	0.22	6	0.026	--	0.00374	--
Dones et al. (2005)	Range over five nuclear cases (pressurized and boiling water reactors, PWR/BWR)	--	0.0056 – 0.0064[2]	5 - 11	0.0224 – 0.0609	0.0324 – 0.0470	--	0.00520 – 0.0072
Koch (2000)	Unspecified	--	--	2 – 59	0.003 – 0.050	0.002 – 0.100	0.002	--
OECD (2005)	13 nuclear plants in 12 countries	54.57	--	--	--	--	--	--
Average		66.94	0.113	19	0.028	0.045	0.008	0.0076

Notes:
[1] Not stated as carbon dioxide equivlents.
[2] Stated units for land use: m2a/kWh.

Table B-4: Published Emissions and Life-cycle Data for Coal Generation Technologies

Author, year	Comments	Cost $C/MWh	Land Use km^2/TWh	$kgCO_2$ eq./MWh	$kgSO_2$/MWh	kgNOx/MWh	PM_{10} kg/MWh	$PM_{2.5}$ kg/MWh
Krewitt *et al.* (1998)	Pulverized coal, 652 MW (600 Mw_{net}), 3900 GWh/yr, 43% efficiency, FGD, deNOX, dedusting, 6500 full load hours/yr (capacity factor 74%)	--	--	904	0.326	0.56	0.182	--
Dorland *et al.* (1997)	Conventional thermal	--	--	1023	0.4113	0.7176	0.0172	--
Pingoud *et al.*, (1997)	Conventional thermal	--	--	865	0.83	0.63	0.07	--
Spath *et al*. (2000)	Pulverized coal, low emission boiler system, surface mining	--	--	759	0.72	0.54	0.11	--
SENES (2005); cited in OPA (2005)	Conventional thermal		0.0057[1]	1020	0.711	0.408	0.071	0.025
Spadaro and Rabl (1998)	Pulverized fuel, 600 MW, 2100 GWh/yr, 38% efficiency, steam turbine, FGD	--	--	1085	1.36[2]	2.22	0.17	--
Spath *et al*. (2000)	Pulverized coal, meeting "new source performance standards", fuel transport 48 km by railcar + 434 km by barge, surface mining	--	--	962	2.53	2.34	9.78	--
Spath *et al*. (2000)	Pulverized coal, average system, surface mining	--	--	1044	6.7	3.35	9.21	--
Dones (1999); cited in Gagnon (2004)	Lignite coal	--	--	1340	--	--	--	--
Gagnon et al. (2002)	Modern plant using 2% S coal with SO2 scrubbing	--	--	960	0.104	2.9	--	--
SENES (2005); cited in OPA (2005b)	**IGCC without CO_2 removal**	**90.90**	**0.00138**	**910**	**0.62**	**0.5**	**0.02**	**0.01**
Koch (2000)	"Modern plant"	--	--	790 - 1182	0.700 – 32.321+	0.700 – 5.273+	0.030 – 0.663+	--
OECD (2005)	28 coal plants in 9 countries, wide range of technologies	59.72	--	--	--	--	--	--
Average		**59.72**	**4**	**975**	**0.9**	**1.0**	**1.1**	**0.1**

Notes:

[1] Stated units for land use: km2/MW.

[2] Reported as SOx.

[3] Stated units for land use: km2/TWh.

Table B-5: Published Emissions and Life-cycle Data for Biomass Generation Technologies

Author, year	Comments	Cost SC/MWh	Land Use km^2/TWh	$kgCO_2$ eq./ MWh	$kgSO_2$/ MWh	kgNOx/ MWh	PM_{10} kg/MWh	$PM_{2.5}$ kg/MWh
			Conventional Combustion					
Krewitt *et al.* (1998)	Circulating atmospheric fluidized bed combustion (AFBC), 20 MW CHP plant, 3.6 MWenet, 3000 full load hours/yr, 18% efficiency[1]	--	--	8	0.018	0.492	0.013	--
Koch (2000)	Biomass forestry waste, combustion	--	--	15 - 101	0.012 – 0.140	0.701 – 1.95	0.217 – 0.320	--
Gagnon *et al*. (2002)	Sawmill wastes	--	1	--	0.026	1.29	--	--
OECD (2005)	Non-CHP, 10% discount rate	101.49	--	--	--	--	--	--
Average		101.49	1	33	0.022	0.891	0.14	0.014
			Gasification					
SENES (2005); cited in OPA (2005)	Gasification to CCGT, various sources	61.70	0.00835	60	0.105	0.386	0.033	0.024
Spadaro and Rabl (1998)	Poplar wood gasifier with intercooled steam injected gas turbine, 40 MW, 245 GWh/yr, 38% efficiency	--	--	17.7	0.04[2]	0.35	0.04	--
OECD (2005)	European facilities, 10% discount rate	96.14	--	--	--	--	--	--
Average		78.92	85[3]	39	0.07	0.368	0.04	0.024
			Plantations					
Matthews (2000); cited in Gagnon (2004)	Short rotation coppice plantation, best commercial technology, 20 km biomass transport distance	--	--	51	--	--	--	--
Gagnon *et al*. (2002)	Biomass plantation	--	533 - 2200	118	0.026	1.59	--	--
Average		114.10	1367	85	0.026	1.59	--	0.014
			Other/ Unspecified/ CHP					
Vattenfall (1999)	Biofueled CHP, gasification with combined cycle and a conventional stem cycle with FGD, using forestry residues and willow plantations	--	85	--	--	--	--	--
OECD (2005)	CHP plant	114.10	--	--	--	--	--	--

Notes:
[1] Emissions data calculated using ExternE's annual emissions data, based on 138,240 GJ heat and 10.8 GW electricity produced annually (Total E=49.2 GWh).
[2] Reported as SOx.
[3] See Vattenfall (1999).

Table B-6: Published Emissions and Life-cycle Data for Wind Generation Technologies

Author, year	Comments	Cost SC/MWh	Land Use km^2/TWh	$kgCO_2$ eq./MWh	$kgSO_2$/MWh	kgNOx/MWh	PM_{10} kg/MWh	$PM_{2.5}$ kg/MWh
Onshore								
Krewitt *et al.* (1998)	Onshore	--	--	7	0.015	0.02	0.0046	--
Schleisner and Nielson (1997)	Onshore	--	--	15	0.032	0.048	--	--
OECD (2005)	Onshore	107.92	--	--	--	--	--	--
SENES (2005); cited in OPA (2005)	Various sources, onshore	102.90	0.125 km^2/MW	12	0.06	0.042	0.029	0.02
Vattenfall (1999)	500 kW onshore turbine, 1500 hours annual utilization time	--	15	6	0.0146	0.0151	--	--
White (1999); cited in Gagnon (2004)	"Best commercial technology," two sites in Wisconsin, average use factor 24%	--	--	9	--	--	--	--
Average		**105.41**	**44**	**9**	**0.02**	**0.03**	**0.017**	**0.02**
Offshore								
Schleisner and Nielson (1997)	Offshore	--	--	22	0.045	0.076	--	--
Unspecified								
Koch (2000)	Unspecified	--	--	1 - 124	0.021 – 0.087	0.014 – 0.050	0.005 – 0.035	--
Gagnon *et al.* (2002)	Unspecified	--	72	9	0.069	--	0.005 – 0.035	--

Table B-7: Published Emissions and Life-cycle Data for Solar PV Systems

Author, year	Comments	Cost $C/MWh	Land Use km²/TWh	$kgCO_2$ eq./ MWh	$kgSO_2$/ MWh	kgNOx/ MWh	PM_{10} kg/MWh	$PM_{2.5}$ kg/MWh
Greijer (2001), cited in Pacca (2003)	Nanocrystalline dye sensitized solar cell (ncDSC), 9% efficiency, 220 kWh.m2, 500 MW plant	--	--	29	0.143	0.063	--	--
Krewitt *et al.* (1998)	PV home application, CO2eq.	--	--	55.38	0.104	0.099	0.0061	--
Vattenfall (1999) and Dones (1999); cited in Gagnon (2004)	"Best commercial technology (very good sites for renewables)"	--	--	38	--	--	--	--
Gagnon *et al.* (2002)	Unspecified	--	45 (km²/TWh)	13	0.024	--	0.012-0.190	--
SENES (2005); cited in OPA (2005)	PV array, 30% capacity factor	299.40	0.0013 (km²/MW)	127.6	0.12	0.1		0.02
Koch (2000)	Unspecified	--	--	13 - 731	0.024 – 0.490	0.016 – 0.340	0.012 – 0.190	--
Vattenfall (1999)	On-grid solar PV	--	--		0.3	0.12	--	--
OECD (2005)	10% discount rate levelized over plant life cycle, 2003 CDN dollars	639.35	--	--	--	--	--	--
Average		469.38	45	41	0.12	0.1	0.0061	0.02

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