Environmental Predictions and the Energy Sector: A Canadian Perspective

Literature Review Report

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Executive Summary

The purpose of this research project is to gather information on the economic benefits of applying Environmental Prediction (EP) for the planning and management of the energy system. In particular, the economic benefit of EP across the whole energy value chain in Canada is investigated.

Environmental Prediction may be defined as "Developing and using knowledge of environmental and socio-economic sciences to project likely or conditional states of the natural world in order to assess future risks and opportunities that support decision-making regarding human health and safety, the environment, and socio-economic well being." (Cantwell, Heffernan and McCulloch 2007).

This report reviews the relevant literature and attempts to quantify the narrowly defined financial benefit of a variety of predictions about the natural world to the energy industry. These benefits may be considered as a subset of the aggregate benefits attributable to Environmental Prediction, which undoubtedly include societal benefits as well as private ones. A variety of classes of forecasts about the natural world are utilized in the studies summarized here, ranging from short-term predictions of dry bulb temperature to more complex multi-factor predictions of the natural world such as those relating to hydrology and to the formation of sea ice.

In this report, the economic benefits described are those applying to well defined classes of energy sector participants who use certain types of EP in their business. No attempt is made to obtain the important broader economic or societal benefits resulting from EP, because this report is building to individual case studies of how a certain type of EP helps a certain type of energy sector end user. Of course, the financial values obtained here may be taken as lower bounds to the broader societal economic value of EP. For a review of some of the broader issues involved see Katz & Murphy (1997).

This report constitutes the literature review phase of this research and it was designed with the intent of analyzing the impacts of EP on the energy sector in a structured and rigorous way. The research team has made a conscious effort to understand the priorities of EP, and reflect these in the literature review. The multidisciplinary and integrative nature of EP, and its relevance to energy are discussed as part of the review. Furthermore, the focus of the report is not only on the benefits of EP for risk reduction, but also on creating new opportunities.

We have identified a number of studies which quantify the financial benefits of various types of predictions about the natural world to various energy subsectors – this quantitative information is tabulated at the end of this Executive Summary.

In order to systematically evaluate the potential of various tools and approaches and to provide structure to our research efforts, a classification framework has been developed. This framework is used to categorize various case studies within the energy sector based on two main factors: their application area (strategic, tactical and operational) and their location on the value chain (demand, supply and financial markets).

One of the main objectives of this research project is to determine the economic value of forecasts for a variety of entities operating within the energy sector. Therefore, an overview of the related literature on decision theory, decision making under uncertainty and energy finance is presented. Additionally, various tools and approaches, which can be used for performing economic benefit analysis for the Canadian context, are identified.

With regard to the economic benefit analysis of forecasts, one of the most fundamental insights identified in this report relates to the use of the forecast information. For there to be any value, the information has to be "actionable". If the information cannot be used to take action, or the marginal impact of the decision is negligible, then no matter how accurate or long-term the forecast might be, the economic value is minimal.

On the other hand, if the forecast provides exclusive, timely or actionable information, then, in most cases, it has a positive value. However, it should be noted that the cost of acquiring this information is also part of the equation and not all forecasts with a positive economic value will prove to be worthwhile once the cost aspect is incorporated into the valuation.

With respect to the different segments of the energy sector are concerned, the literature review reveals some interesting facts and observations.

There is a high level of interaction between the electricity generation industry and various environmental conditions. Understanding the mechanics and dynamics of this interaction can pave the way for creating both environmental and economic value from EP. However, for weather forecasts to have a truly positive environmental impact, the load must no longer be considered simply as an external constraint imposed upon the electrical generating system, but as a variable to be managed in its own right.

Upstream oil and gas industry focuses on finding and extracting natural gas or oil from the Earth. Determining the value of EP and improved weather forecasts for this important industry is a challenging task. While natural gas markets, in particular, are very dependent on temperature over short time scales, the value of predicting this temperature dependence will mostly be captured by downstream players such as natural gas and pipeline operators. In addition to the operators, EP can provide multiple benefits for the upstream activities in the oil and gas industry. In particular, offshore oil production and exploration activities stand to gain significant benefits from EP.

Given the public perception of renewable energy sources as having a price premium over other forms of energy, any cost reductions would help with the wider adoption of such systems. Reliability is also a major concern for renewable energy systems. One of the findings of this review is that EP can play a very positive role to tackle both the cost and reliability issues by providing a wide range of tools to the renewable energy sector.

Although the space environment seems removed from our daily lives, in reality, space weather can pose significant risks to satellite operations, communications, navigation, electric power distribution grids and pipelines, systems we rely on everyday. Elements of space weather can interact with electricity transmission grids and oil pipelines, causing significant damage. One way of mitigating these risks is to achieve advances in space weather forecasting and to give operators of energy transmission networks sufficient time to react and protect their networks. Pipeline operations and oil and gas exploration efforts can also benefit from tools for monitoring space weather.

EP can create a variety of economic benefits for the financial markets as well. Increasingly, weather related events are affecting the performance of various financial instruments. From relatively infrequent events such as a devastating hurricane to daily events such as a temperature forecast, the environment is becoming an integral part of the financial markets. Emerging financial markets, such as climate exchanges, are further evidence of the important relationship between the economic and environmental realms.

As various cases presented in this report have demonstrated, EP has a rich set of applications in the energy sector, touching all levels of decision making and covering the whole energy value chain. Although this richness signals a significant potential for the use of EP in the energy industry, it also creates more responsibilities for both policy makers and the industry itself. Given the limited resources in both public and private sectors, the real challenge will be determining the optimal subset of EP applications to invest in.

Borrowing yet another financial concept, perhaps one could argue that a portfolio management approach would be an ideal candidate to address this issue. A portfolio in which the objective is not just to minimize the risks posed by the environment to the energy sector, but also to maximize the benefits of the environment to the energy industry and to the Canadian public.

Summary Table of Economic Benefits from Applications of Environmental Predictions

Description	Benefit	Type of Forecast	Use	Estimated Value
Spinning Reserve Electric Generation	▪ reduced dependence on spinning reserves and AGC ▪ economic savings through fuel savings ▪ reduction of emissions	▪ short-term forecasts	▪ incorporated into scheduling decisions	▪ US$366 million per year to the U.S. electrical industry (NOAA-NESDIS, 2002)
		▪ U.S. National Weather Service Forecast	▪ scheduling of US hydroelectric plants	▪ US$139 million per year (NOAA, 2004)
		▪ perfect weather forecast information	▪ incorporated into US scheduling decisions	▪ additional US$69 million per year (NOAA, 2004)
		▪ short-term demand based on weather variables	▪ in all applications of short-term load forecasting and spinning reserve management	▪ £66 million per year to the U.K. private sector (Teske & Robinson, 1994
		▪ 24 hour temperature forecasts	▪ improve US unit commitment decisions	▪ US$166 million annually (Teisberg, Weiner and Khotonozad 2005)
		▪ perfect 24 hour temperature forecasts	▪ improve US unit commitment decisions	▪ US$75 million annually (Teisberg, Weiner and Khotonozad 2005)
Hydroelectric Electric Generation	▪ optimal operation of hydroelectric plant	▪ long-range inflow forecasts	▪ flow rate projection use operations	▪ Columbia River watershed utilities case: US$161 million per year (Hamlet, Huppert & Lettenmaier 2002) ▪ Missouri river basin utilities case: US$10 million per year (Maurer & Lettenmaier 2004)
		▪ improved one-month to one-year stream flow forecasts	▪ flow rate projection use operations	▪ single reservoir system of the California State Water project case: US$0.4 to $0.8 million annually (William et. al 1982)
		▪ low water levels forecast	▪ flow rate projection use operations	▪ Manitoba case in spring of 1981: potential reduction of US$80 million loss (Philips 1986)

Peaker Units Electric Generation	▪ "shave" the peak and reduce the need for the peakers reduces photochemical smog	▪ short-term weather forecasts	▪ demand management	
Wind Energy Generation	▪ better site selection, site construction, and wind farm investment decisions for both on-shore and off-shore wind farms	▪ historical and predicted wind speed and direction ▪ sea-state and height forecasts	▪ wind data analysis and flow modelling	
	▪ enable large scale integration by decreasing uncertainty ▪ decrease backup generation sources ▪ more efficient use of energy generating assets ▪ more efficient utilization of transmission assets ▪ reduction of fossil fuel use	▪ day ahead wind speed and direction forecasts	▪ energy yield predictions ▪ uncertainty analyses ▪ unit commitment management	▪ \$10/MWh for state-of-the-art day ahead forecast in NYSBPS (Smith, 2007)
Solar Energy Generation	▪ make better site selection, site qualification, and solar farm investment decisions for both PV and CSP farms	▪ solar irradiance measurement ▪ cloud cover	▪ estimation of ground irradiance ▪ operational decision-making & plant efficiency management	
Biofuels and Ethanol	▪ improve harvest yields ▪ increase amount of fuel without increasing prices	▪ mid-term to long-term climate forecasts	▪ selection of harvest time and crop	
Storage & Transmission of Oil & Gas	▪ increase efficiency gains in the construction and operations of natural gas pipelines ▪ reduce "overbuilding cost" to facilitate natural gas storage ▪ shave peak pipeline usage ▪ profit from shorter time scale price fluctuations	▪ short-term temperature forecasts	▪ natural gas supply & demand management	
	▪ assessment of levels of corrosion	▪ space weather monitoring ▪ space weather nowcasting	▪ ex-post analysis of geomagnetic activity from which GICs can be modelled ▪ postpone tests of cathodic protection systems	▪ 10% of pipeline wall thickness loses to corrosion induced by GICs over a 14 year period (ISU, 2006)

Electricity Transmission	▪ more efficient use of resources	▪ windstorm & lighting forecasts	▪ allocation of resources to line maintenance crews	
	▪ increased transmission safety operations ▪ decreased environmental impact in emergency situations	▪ long term wind speed distribution trending trends	▪ influence transmission line installation codes relative to surroundings	
	▪ provision of sufficient time to react and protect transmission networks ▪ socio-economic loss prevention from service interruptions	▪ space weather forecast (including ex-post data of the temporal component of the magnetic field)	▪ energy transmission network management	▪ March 1989 incident: over US$30 million ($10 million of this amount attributed to Hydro Quebec's loss. Remaining amount includes loss suffered by Public Service Electric and Gas in New Jersey where transformers had to be replaced and replacement electricity had to be found at a total cost of more than $24 million to the company), (ISU, 2006) ▪ March 1989 incident: economic cost of approximately $6 billion from service outage, and $1.2 billion incurred by Hydro-Quebec for system hardening and upgrading (ESA, 2001)
Offshore Oil & Gas Operations	▪ increased crew and operations safety	▪ hurricane intensity and trajectory predictions	▪ manage various risks caused by hurricanes	▪ US$15 million for a 50% improvement in hurricane forecast accuracy (Considine et al., 2002)
	▪ increased crew and operations safety	▪ synoptic maps of sea-surface height	▪ tracking eddies in near-real time ▪ operational monitoring of offshore infrastructure	▪ prevention of $100 million, including lost production revenue (CBC, 2005) – based on 2005, evacuation assessment of two platforms due to rocket launch risk

	▪ increased crew and operations safety ▪ savings in transportation time and fuel costs ▪ prevention of environmental damage from ocean floor	▪ sea ice monitoring and prediction	▪ tracking sea ice and icebergs ▪ route planning ▪ iceberg towing or deflection	▪ prevention of $100 million, including lost production revenue (CBC, 2005) – based on 2005, evacuation assessment of two platforms due to rocket launch risk
	▪ efficiency in dynamic positioning (DP) systems	▪ Space weather monitoring and forecasting	▪ make necessary corrections to counter effects of ionospheric scintillations	
Exploration & Drilling Activities	▪ more accurate resource exploration, site construction, and environmental impact assessment and remediation activities	▪ atmospheric conditions (temperature, wind direction, wind speed, incident solar radiation, humidity, haze, or aerosols)	▪ image correction for conditions that interact with both the incoming solar illumination of the ground target and the reflected electromagnetic energy in hyperspectral imaging	
	▪ more accurate and less costly surveys & drilling operations	▪ space weather forecast (including forecasts of geomagnetic disturbances and ex-post data of the temporal component of the magnetic field)	▪ corrections to magnetic surveys generating contour map of magnetic intensity for determining subsurface properties ▪ better scheduling of surveying activities ▪ correction of drilling direction	
Financial Markets	▪ financial gains by trading companies ▪ prevention of financial losses by trading companies ▪ strengthening of weather-based financial markets such as catastrophe bonds ▪ social benefits of more efficient and transparent risk transfer in insurance sector	▪ various EP applications (including weather forecasts, climate forecasts, hurricane forecasts, space weather forecasts, etc.)	▪ information to support trading decisions	▪ 2006 Amaranth LLP loss of US$3.5 billion on trades based on published US natural gas storage levels and expectation that a hurricane would hit the Gulf of Mexico drilling platforms again, as had happened in the fall of 2005 (Amaranth Advisors; Wikipedia article, 2007)

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List of Acronyms

AGC Automatic Generation Control
CDD Cooling Degree Days
CHU Corn Heat Unit
CSA Canadian Space Agency
CSP Concentrating Solar Power
ENSO El Nino Southern Oscillation
EP Environmental Predictions
ERS Earth Resource Satellite
ESA European Space Agency
GIC Geomagnetically-induced Currents
GPS Geographical Positioning System
HDD Heating Degree Days
IEA International Energy Agency
HDD Heating Degree Days
IEA International Energy Agency
IESO Independent Electricity System Operator
JPL Jet Propulsion Laboratory
kWh Kilowatt hour
MWh Megawatt hour
NASA National Aeronautics and Space Administration
NOAA National Oceanic and Atmospheric Administration
SAR Synthetic Aperture Radar
WMO World Meteorological Organisation

Note: Unless otherwise noted, all currency figures in this report are in Canadian dollars.

1. Introduction

The purpose of this research project is to gather information on the economic benefits of applying Environmental Prediction (EP) for the planning and management of the energy system. In particular, the economic benefit of EP across the whole energy value chain in Canada is investigated.

In this report, the economic benefits described are those applying to well defined classes of energy sector participants who use certain types of EP in their business. No attempt is made to obtain the important broader economic or societal benefits resulting from EP, because this report is building to individual case studies of how a certain type of EP helps a certain type of energy sector end user. Of course, the financial values obtained here may be taken as lower bounds to the broader societal economic value of EP. For a review of some of the broader issues involved see Katz & Murphy (1997).

This report constitutes the literature review phase of the study being conducted for Environment Canada. Based on the findings of this literature review and the guidance of Environment Canada, some of the topics discussed in this report will be selected for further study with the aim of quantifying the economic benefits associated with these case studies.

The research team has targeted a comprehensive approach for demonstrating the primary economic benefits of EP within the energy value chain. However, the underlying philosophy of this report is not to strive for exhaustiveness, but rather to present a structured approach shedding light on the "big picture" while focusing on certain case study candidates.

Environmental Prediction may be defined as:

"Developing and using knowledge of environmental and socio-economic sciences to project likely or conditional states of the natural world in order to assess future risks and opportunities that support decision-making regarding human health and safety, the environment, and socio-economic well being." (Cantwell, Heffernan and McCulloch 2007)

The research team has made a conscious effort to understand the priorities of EP, and reflect these in the literature review. The multidisciplinary and integrative nature of EP, and its relevance to energy are discussed as part of the review. Furthermore, the focus of the report is not only on the benefits of EP for risk reduction, but also on creating new opportunities.

1.1. Research Objectives

The primary objective of this literature review is to provide the foundation of the economic benefit analyses which will be conducted in the subsequent phases of this research project.

The following topics have been identified as specific research objectives:

- ☑ To understand the nature of Environmental Predictions, and its significance for the energy value chain in Canada

- ☑ To create a solid, multidisciplinary framework for quantifying economic benefits of EP, based on energy finance, economics, earth observation, and other disciplines

- ☑ To identify various case studies which demonstrate the interaction between EP and energy, by focusing on four priority areas: electricity generation, electricity transmission, renewable energy, and upstream oil and gas. This report covers each of these priority areas in Sections 5-8.

- ☑ To create a framework for classifying these case studies based on different criteria, including their relative position on the value chain and the nature of the decisions involved.

1.2. Report Outline

The Introduction of this report is comprised of both Section 1 and Section 2, which summarizes the current Canadian energy outlook. Section 3 describes methodological aspects of this work, including a primer on the fundamentals of economic benefit analysis as well as the classification framework developed for this project. In order to determine where and how environmental forecasts can bring value to the electricity generation sector, it is important to understand some of the intricacies of this industry. To this end, the fundamentals of electricity generation are discussed in Section 4. The rest of the literature review is devoted to the analysis of various segments of the energy value chain. Section 5 outlines the relevance of EP for electricity generation while Section 6 describes its impact on energy transmission. Section 7 focuses on the upstream oil and gas industry. Sections 8 and 9 are devoted to renewable energy and space weather, respectively. Section 10 discusses the implications of EP on the financial markets. Following Section 11, Conclusions, various appendices are presented which provide more detail for selected topics.

2. The Current Energy Outlook in Canada

This section provides a synopsis of electricity generation in Canada. As it can be seen in Figure 1, generation capacity and the shares of generation types show considerable difference across the provinces.

In certain provinces, such as Quebec, Manitoba, British Columbia and Newfoundland and Labrador, a single generation type (in this case, hydroelectricity) clearly dominates. Other provinces have very diverse electricity generation capabilities. For instance, in Ontario, coal, nuclear and hydro seem to have comparable shares in the generation pie, with natural gas, oil and other generation types accounting for the remaining 15% of this province's electricity supply.

Overall, hydroelectricity provides approximately 60% of Canada's total electricity supply. Fossil fuels, including coal, natural gas and oil, provide about a quarter of the generation capacity. In the aggregate statistics, nuclear energy accounts for 10.5% of the generation capacity, although its share is as high as 47.2% in certain provinces. The role of renewable energy sources in electricity generation is very modest, and they are all grouped under the "other" category in the current statistics. Nevertheless, certain types of renewables, particularly wind power, are prominent in some of the provinces, such as Prince Edward Island.

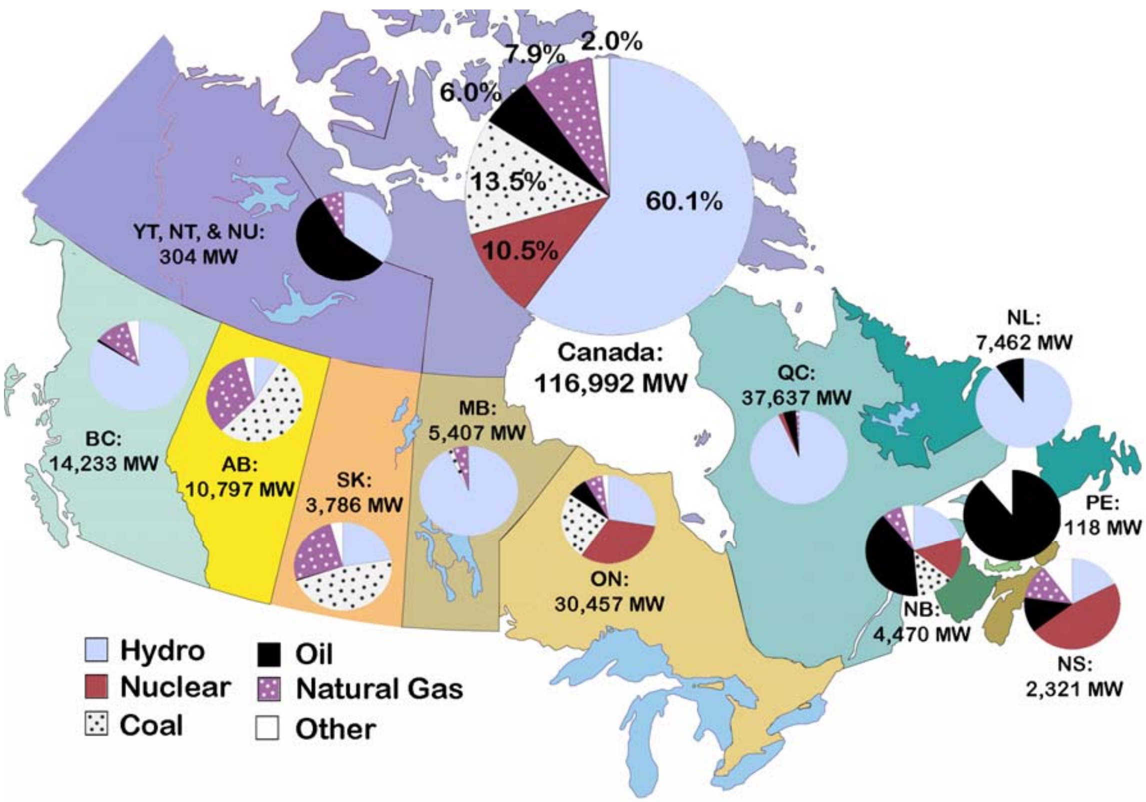

Figure 1: Electricity Generation by Province and Fuel Type (2003 figures)
Data Source: National Energy Board (2005)

3. Methodology of the Research Project

The project team has developed a research framework with a solid scientific background and a special emphasis on practicality and relevance in a real-world setting. One of the challenges of the literature review is to cover a wide variety of tools and approaches with applications across the whole energy value chain while creating a common evaluation framework. This framework will be used in the subsequent phases of the research effort, following the literature review. This section explains the methodology developed for tackling the research objectives.

There are two main parts of this evaluation framework: a method for classifying various EP applications in the energy sector and the methodological approach for quantifying economic benefits.

3.1. Classification Framework

In order to evaluate the economic benefits of various tools and approaches systematically and to provide structure to our research efforts, a classification framework has been developed. This framework is used to categorize various case studies within the energy sector based on two main factors: their application area (strategic, tactical and operational) and their location on the value chain (demand, supply and financial markets).

a) Application Area Axis:
One practical way to categorize various EP cases in the energy sector is to consider their area of application. While noting that actual decisions cut across a continuum of time scales, our research team nonetheless finds it useful to consider three categories:

- ☑ Strategic Applications: This category covers applications and tools used for making long-term, infrequent, irreversible decisions as well as early warning systems. An important subset of this category is infrastructure purchase and siting decisions.

- ☑ Tactical Applications: This category includes applications and tools used for medium-term, relatively frequent, and repetitive decisions.

- ☑ Operational Applications: This category covers applications and tools used for day-to-day management of energy systems.

b) Value Chain Location Axis:
In order to assess the economic benefits of EP, both the supply and demand sides of the energy markets need to be studied in detail. As in any market, the interaction between supply and demand is also a critical issue, and needs to be studied as well. This category axis extends through the totality of the energy value chain, covering the steps of energy generation, storage, distribution and consumption [1]. Figure 2 presents a conceptual overview of the value chain.

[1] For a more detailed look at the energy value chain, see Gurtuna (2005).

For the literature review, energy generation, storage and distribution steps have been collapsed into a single category, labelled "supply". All applications and tools relevant to the consumers have been classified under "demand". Depending on research needs, a finer resolution can also be obtained by breaking supply and demand categories further down.

Moreover, given the increasing integration of financial markets into the energy sector, a third category, "Financial Markets", was also included in the value chain. As it can be seen in Figure 2, these markets interact with almost all parts of the energy value chain.

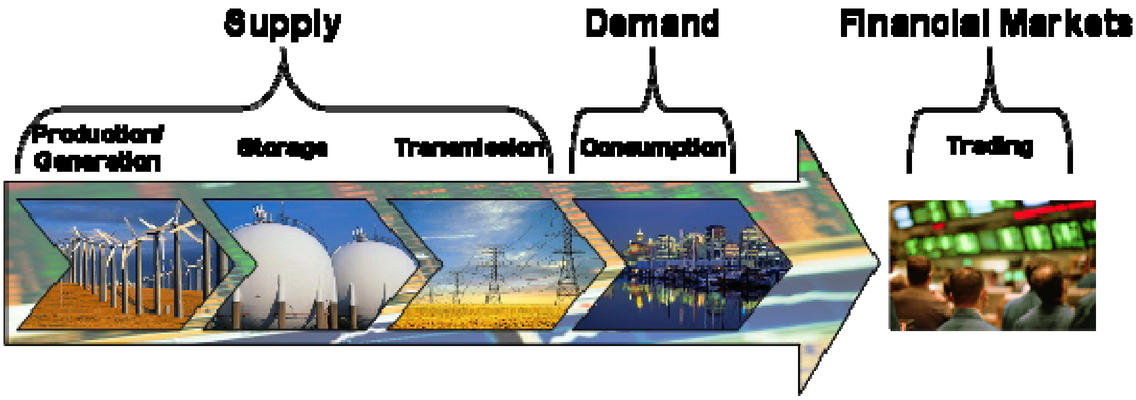

Figure 2: The Energy Value Chain

Table 1 provides a summary of the cases explored as part of the literature review. It can also be used as a "report map", and readers interested in specific parts of the literature review can find the corresponding section numbers for each of the cases considered.

	Strategic Level	Tactical Level	Operational Level
Supply Side	√ Site selection for natural gas storage facilities (Section 6.1) √ Site selection for a new wind turbine (Section 8.1) √ Site selection for solar power plants (Section 8.2) √ Space weather early warning system for electricity grids (Section 9.1)	√ Incorporating wind forecasts into power line maintenance (Section 3.2.3) √ Optimal scheduling of power plant maintenance (Section 3.2.4) √ Inflow monitoring for hydroelectricity plants, including the incorporation of snow pack thickness (Section 5.2) √ Hurricane forecasts for offshore oil production (Section 7.1) √ Sea ice and iceberg now- and forecasts for offshore oil exploration and production (Section 7.1) √ Corn variant selection for biofuel production (Section 8.3)	√ Plant scheduling based on load forecasts (Section 5.1) √ Plant scheduling based on smog forecasts (Section 5.3) √ Performance monitoring for solar power plants (Section 8.2) √ Space weather impact assessment on pipelines and oil & gas exploration efforts (Section 9.2)
Demand Side	√ Design of demand-management programs which allow the incorporation of weather forecasts (Section 5.4)	√ Predicting El Nino – Southern Oscillation events for improved seasonal weather prediction: Impacts on hydroelectric system (Section 5.2), Impacts on natural gas markets (Section 7.2)	√ Electricity load forecasting based on weather parameters (Section 5.1)
Financial Markets	√ Design of novel financial markets for emissions trading, weather derivatives, and catastrophe bonds (Section 10, Appendix 3)	√ Designing financial market trades based on climate-based demand trends (Section 10)	√ Energy trades depending on short term information such as hurricane impacts on oil & gas production (Section 10)

Table 1: Classification Framework

3.2. Valuation of Various Forecasts: General Conceptual Framework

One of the main objectives of this research project is to determine the economic value of a forecast to a variety of entities operating within the energy sector. A forecast is a special form of information – one which reduces uncertainty about future events. From the point of view of this general methodology section, the forecast might be a weather forecast (for temperature, precipitation, wind, etc), a longer range "climate" forecast, or a multi-factor "environmental" forecast. Taking into account their prior beliefs, this information may allow the entities to make better decisions. The value of the forecast can be quantified by determining the added financial value of these decisions[2]. As Stewart et al. (2004) point out, attention must be paid not only to the forecast quality but also to the process by which users are able to utilize this forecast for optimal value extraction to occur.

This section draws heavily on two recent reports written to meet similar research objectives: Macauley (2005) provides an excellent literature review on the early efforts to quantify the value of weather information, also shedding light on the cost/benefit decision of purchasing additional pieces of information. The latter decision problem is also described in a report written by the Danish Ministry of Transport and Energy (2006). Other works adopting similar methodological frameworks include WMO (2007) and NAV Canada (2002). All of these works are based on the seminal papers of Baquet, Halter & Conklin (1976) and Hilton (1981). Since customizing this research project to the Canadian context is a priority, the guiding principle of this section is to build on these earlier works by adding new elements and approaches.

The rest of this section expands, elucidates, and quantifies the first paragraph of the section. Since accurate forecasts allow better decisions to be made by reducing uncertainty, the first topic covered is a review of the classical decision science approach to making decisions under uncertainty. Following this introduction, methods for quantifying the value of information which can be used to reduce uncertainty are examined. These methods are then expanded to cover cases for which the information a forecast will yield is not know in advance. All of these valuation steps are best suited for irrevocable decisions. However, some decisions (especially strategic ones) require evaluation of multiple decision "paths" in which the decision maker can have or actively create flexibility. "Real options" theory, another topic of discussion in this section, provides certain tools to capture the value of this flexibility. The section ends with the discussion of certain facts related to valuation unearthed during the literature review.

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[2] Following the project requirements, the societal or public benefits of such forecasts will not be examined as part of this project. Nevertheless, this aspect of the problem cannot be ignored completely: for a discussion about the general concepts related to the public good nature of forecasting services, please see Appendix 4.

3.2.1. Decision Making Under Uncertainty: Basic Concepts

Table 2 outlines the basic concepts of decision making under uncertainty. Assume that a decision maker can take either Action 1 or Action 2. The decision maker has no control on the outcomes and independent of her choice of action, either A or B can happen. A has a probability of p and B has a probability of q = 1 - p. For each action - outcome pair, there is an associated "payoff" (i.e., a loss or a benefit) denoted by the payoff function P().

Probabilistic Thinking

Making good decisions under any type of uncertainty requires a good understanding of **probabilities**. However, decision makers are not only interested in the chances of an event occurring, they are also very interested in the associated outcomes. Therefore when decisions are based on uncertain future events, both the probability and outcome of such events need to be considered. A very frequent mistake in problem analysis is to think that these two main problem elements are separable.

	Outcome A (prob p)	**Outcome B (prob q = 1-p)**
Action 1	P(A1)	P(B1)
Action 2	P(A2)	P(B2)

Table 2: Actions and Outcomes in a Tabular Format

This approach can be used to "map" a myriad of decision problems. For instance, an investor faced with the problem of investing in a stock versus purchasing a bond might construct a table like this:

	Outcome A: Stock rises (probability 50%)	**Outcome B: Stock falls (probability 50%)**
Action 1: Buy the stock	Investor owns the stock and makes $10	Investor owns the stock and loses $5
Action 2: Buy a Canada Savings Bond	Investor makes $1 in interest (the stock still rises without any impact on the investor's payoff)	Investor makes $1 in interest (the stock still falls without any impact on the investor's payoff)

Table 3: Stock vs. Bond Decision

There are several ways to evaluate this decision. Two of the simplest are expected value decision making and minimax (or maximin) decision making.

An expected value decision maker computes the expected value of each course of action. For the stock vs. bond decision, the expected profit when buying the stock is 0.5($10) +0.5(-$5) = $2.50, while the expected profit when buying the bond is 0.5($1) + 0.5($1) = $1. An expected value decision maker would therefore buy the stock.

Not all decision makers base their choices on expected values. A risk averse decision maker might agree on all the probabilities and outcomes in the stock vs. bond problem and yet analyze it differently. Risk averse decision makers might be more interested in minimizing their downside. Therefore their reasoning could work as follows: the worst that can happen with Action 2 is to make a dollar, whereas if they adopt Action 1 they run a reasonable chance of losing 5 dollars. Therefore they would decide to buy the bond. Such a decision maker is called a minimax[3] decision maker because they minimize the probability of the worst case occurring.

The expected value decision process is most appropriate to decisions which are made repeatedly and in which the worst case scenario is acceptable. For instance, the daily choice made by an electricity generation utility of how to bid the output of their various plants within a deregulated market will be better modelled using expected value decision making.

The minimax decision process is appropriate to decisions which are made just once and/or in which the worst case scenario is unacceptable because it involves catastrophic risk (e.g., loss of life). For these types of decisions, the priority is to cover the worst case. An example of a minimax approach is the evacuation decision faced by offshore oil production companies in the presence of a significant risk to one of their oil platforms.

This decision problem (with fictitious numbers) is shown in Table 4.

	Hurricane hits the oil rig (probability 1%)	**Hurricane misses the oil rig (probability 99%)**
Action 1: Evacuate Rig	Oil company pays $200,000 in evacuation and lost production costs.	Oil company pays $200,000 in evacuation and lost production costs.
Action 2: Business as Usual	Company pays $10 million compensation to the families of the drowned rig workers as well as $500,000 in (more costly) evacuation and lost production costs.	The company pays nothing.

Table 4: Oil Rig Evacuation Problem

A minimax decision maker would evacuate the rig, and lock in a cost of $200,000. Note that the expected value decision maker would select business as usual, with an expected cost of (0.01)*($10.5 million) or $105,000.

[3] In this particular case, technically a "minimin" decision maker.

It is also interesting to note that in the oil rig evacuation case, the minimax and the expected value decision makers are actually not too far apart. If the cost of the loss-of-life disaster were instead judged at $100 million (because of punitive costs imposed by a jury, for instance), or if the probability of the hurricane were 10% rather than 1%, the minimax and the expected value decision makers would agree on the same course of action.

Defining Risk and Uncertainty

Risk is one of the key concepts in finance, economics and decision sciences. It is also the substance of many financial products and services (classic example is insurance). Risk can be defined as the likelihood and magnitude (impact) of an unfavourable event. **Uncertainty**, on the other hand, is a more neutral concept and it refers to the variability of future conditions. Therefore, risk can also be seen as "adverse consequences of exposure to uncertainty". Not all uncertainty is bad, however. If the downside risks are properly managed, uncertainty can be leveraged to increase positive payoffs on the "upside".

Finally, an additional insight from this case is that, the minimax decision maker will choose to evacuate the oil platform no matter how low the perceived probability of a hurricane would be, provided that risk is nonzero. Since it is impossible to reduce the probability of most outcomes to zero, minimax decision makers are usually unable to act unless some kind of special concepts like a "threshold of materiality" are employed.

These two insights prepare the groundwork for the introduction of the final type of decision maker, the expected utility decision maker. Such a decision maker computes the utility of every possible outcome and uses those utilities, rather than the dollar values, in his computation of the expected values. A utility function is an economic concept designed around the insight that people prefer more money to less money, but with diminishing returns (e.g., the millionth dollar a person owns isn't as valuable to her as the first). Expressed in mathematical terms, a utility function U(x) associates a real number to every amount of wealth x. In fact, given appropriate choices for U(x), both expected value and the minimax decision makers are special cases of expected utility decision makers.

Since people prefer more wealth to less, the utility function has a positive slope: $U'(x) > 0$. Due to the diminishing returns, the size of this slope decreases with increasing wealth, flattening out the function U(x) in the process: $U''(x) < 0$. Figure 3 shows a utility function which represents this shape. A typical example of a utility function in the literature is $U(x) = \log(x)$.

Different types of utility functions can be described; Hilton (1981) and Bosch and Eidman (1987) analyze the impact of different utility specifications on the problem of valuing information.

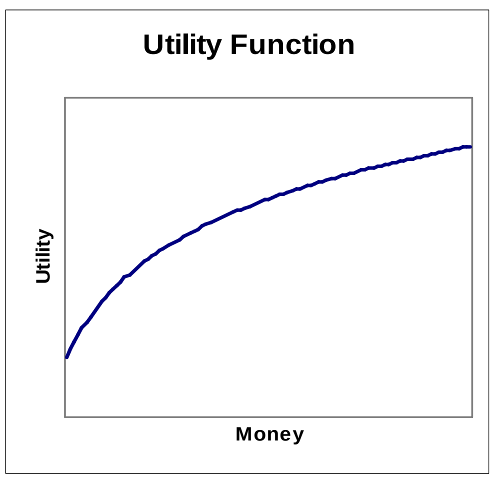

Figure 3: A Typical Shape for a Utility Function

Such expected utility decision makers are more risk-averse than expected value decision makers without being terrified of extreme events with tiny probabilities. However, it is difficult to choose a utility for a decision maker in a straightforward and defensible way.

The rest of this section will be centred around expected value decision makers with occasional discussions of minimax decision makers. Naturally, in real life decision makers face decision problems with many choices, not just two, as presented in the previous examples. However this is certainly not a limitation for the framework: one can simply choose the alternative with the best expected value. The same generalization applies to the number of possible outcomes. In most real cases, multiple, even an infinite number of, outcomes may be possible. This can also be dealt with: the only requirement is being able to define the set of possible outcomes and their corresponding probabilities[4].

To generalise this approach, the range of possible outcomes can be characterised by X, the probability density function of a given member x of X occurring as $p(x)$, the consequence of outcome x given decision k as $C_k(x)$, where $C_k > 0$ is a good outcome and $C_k < 0$ a bad outcome. Then the integral $\int C_k(x)p(x)\,dx$ can be computed, and the value of k which maximizes this integral is chosen as the course of action.

In the rest of this section, the insight-rich two-outcome, two-alternative conceptual model will be used, knowing that it can easily be generalized to more complicated scenarios.

3.2.2. A Framework for Valuing a Single Piece of Information (ex post)

The question of how to value information is of great theoretical and practical interest. Information is different from physical commodities. For example, although it is often very difficult to obtain or invent information, it can be shared at little or no incremental cost using various dissemination tools at our disposal. Forecast data is characterised by another feature: it must be used immediately or it loses most of its value (e.g., How much is the weather forecast for last week worth?).

A variety of approaches has been developed for the valuation of information, Baquet, Halter, and Conklin (1976) and Hilton (1981) being early examples. This section of the report will describe the framework considered to be the most conceptually appealing by the research team. In a nutshell, the value of a given piece of information to a given user can be computed by:

(i) Finding the value of the actions taken by the user based on that information, and
(ii) Subtracting the value of the actions taken by the same user in otherwise identical circumstances without this piece of information.

[4] The arsenal of quantitative analysis tools is diverse and powerful enough to tackle even problems with infinite number of outcomes: a probability density function can be used to describe these outcomes.

For a well written illustration of this ex post framework see Kite-Powell (2005) which analyzes a nowcasting[5] application of ocean environmental data.

Consider the following examples, which illustrate this valuation approach. A power company has to decide how to bid tomorrow's production from their various generation assets into tomorrow's market. This company is likely to use expected value decision making, since they go through this process every day and even a decision which is (in hindsight at least) a poor one is unlikely to have extremely serious financial outcomes.

Small improvements in the ability to predict the future can have significant values for such decision makers. For instance, suppose an investor could purchase a tool that allowed her, on a daily basis, to pick from the entire market a single stock which was more likely to increase than to decrease. For ease of exposition, it is assumed that a stock which can be purchased for $10 today (net of all trading costs) can either be sold for $9.50 or for $10.50 tomorrow (again, net of all costs). The usual model for daily moves in stock prices stipulates that, on average, tomorrow's price will be the same as today's price (although stocks tend to rise in the long run, over a one day time horizon the random variation completely dominates this upward drift). In this scenario, what is the value of a stock picking tool that can find a stock that is 60% likely to rise and only 40% likely to fall?

Each day you could invest $10 into the market, 60% of the time selling for the next day at $10.50 and 40% of the time selling for the next day at $9.50. Thus, the expected value of the sale price of the stock is 0.6($10.5) + 0.4($9.5) = $10.10, so every day an expected trading profit of 1% could be realized. Since, in this example, this trade can be performed every day, the annual profits would be around 250%, a huge value. Therefore, although the impact of the slight increase in the accuracy of the probabilistic forecast is marginal per trade, its incremental value over a long time period is very substantial.

However, not all of the literature confirms such a result. Considine et al. (2002) present a study of the value of hurricane forecasts to drilling rig operators in the Gulf of Mexico. This study suggests that, unless a forecast brings near certainty, it is worth quite little.

A simplified example derived from their study is as follows. Suppose an oil company has a forecast indicating that a hurricane will miss their oil platform by a 50% chance. But it is 50% likely that the same hurricane will damage the platform and possibly kill or injure some or all of the workers. The oil company will evacuate the rig; either because minimax decision making is being employed or because the costs of a missed evacuation are staggeringly large compared with that of an unnecessary evacuation. An incremental improvement in the accuracy of the forecast, such as raising the quality of the forecast to 40/60 is unlikely to change this decision. In this case, a similar improvement in accuracy has no real impact as it does not change decisions.

[5] Please see Appendix 2 for the definition of nowcasting.

3.2.3. Valuing an Entire Forecast

As long as a method for valuing a piece of information is available, this method can be used to value an entire forecast in advance[6]. This can be done simply by calculating the value of every possible forecast and then combining these values, using the probability of obtaining each forecast.

Perhaps an example is the best way to illustrate this approach. High winds often bring down trees, damaging transmission lines and causing local power blackouts. While at the tactical level decision makers can act to minimize the cost of this event by keeping tree branches well trimmed, at the operational level little can be done except to clean up after a storm. However, if reliable forecasts indicate that high winds are coming, a decision theoretic process (as discussed above) can be used to achieve some operational savings by preparing the work crew ahead of time.

For the sake of argument, assume that wind forecasting is performed on a daily basis and the forecasters can correctly predict high winds 1% of the time and harmless levels of wind the remaining 99% of the time. If high winds are forecast, then the power utility can take some mitigating preventative action and save $100,000. In this simple example the value of the wind forecast is therefore, 0.01($100,000) + 0.99($0) = $1000. For a simple dice game expanding the intuition on this topic, please see Appendix 1.

3.2.4. Incorporating Prior Information: Bayesian Approach

Up until this point, the decision maker has been portrayed as someone who is able to objectively assess probabilistic information. But in real life, many decision makers have prior beliefs that may be hard to switch. Most people's personal experience suggests that if we believe something is true, we tend to assess the data we receive in light of this assumption. In such a case, overwhelming evidence contradicting our prior belief is needed to shift our prior assumption.

Bayesian decision analysis provides a framework for discussing the impact of incorrect priors on future decisions. Since it has been shown that the average U.S. decision maker does not possess accurate prior information about climate variables (see for example Sherrick, Lamb & Mazzoco (2000)), the capability to assess the impact of incorrect priors is especially valuable within the Environmental Predictions context. The application of Bayesian decision making to valuing forecasts dates back to Baquet, Halter & Conklin (1976), who used this framework to quantify the value of frost forecasts to orchard operators who could decide whether or not to run heaters.

Bayesian decision making is a large and complicated subject used in many settings extending from the decision science setting (described here) to pattern classification and many other areas.

In order to illustrate the basic idea of Bayesian decision making, some simple examples will be used. The first example relates to evaluating a new piece of evidence in a forecast. Suppose that the state of the world is either A or B and an observation x is made. What does that tell us about the state of the world?

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[6] In the literature, "in advance" is often written as "a priori" or "ex ante".

If the world is in state A then observation *x* is made with probability p(*x*|A), if the world is in state B then observation *x* is made with probability p(*x*|B). The core question is, does observing *x* support that the world is in state A or in state B? For the sake of argument, suppose that it is 10 times more likely that *x* occur given state A than it occur given state B. Does this mean that the observation of *x* implies the existence of state A? Not necessarily. If state B is 100 times more likely than state A, 10 times as many *x* will be observed in state B than in state A.

To clarify this last observation, consider an example from medical diagnosis. The patient is either suffering from the early stages of a rare but dangerous disease (state A) or he has the common cold (state B). If the disease is present the patient is 100% likely to have an ache in his leg (observation *x*); p(*x*|A) = 1. If the patient is simply suffering from a cold then he is also somewhat (say 10%) likely to have the aching leg. So p(*x*|B) = 0.1. Just based on this information, we could not conclude that a patient with a leg ache has the dangerous disease. The reason is that, at any given time, say 5% of the population has the common cold, and say 0.01% of the population has the dangerous disease. If the only way a person could have an aching leg is by having a cold or by having the disease, and nobody has both a cold and the disease, then at any given time 5%(10%) or 0.5% of the population has aching legs due to having the cold and 0.01%(100%) or 0.01% of the population has the aching legs because of the disease. Therefore 50 times as many people have aching legs and just a cold than aching legs and the disease (it is for essentially this reason that most beginning medical students apparently believe they have terrible diseases).

The way to combine this information into a forecast is by using "Bayes decision rule":

First compute:

$$p(A|x) = \frac{p(x|A)p(A)}{p(x|A)p(A) + p(x|B)p(B)}$$

and then compute:

$$p(B|x) = \frac{p(x|B)p(B)}{p(x|A)p(A) + p(x|B)p(B)}$$

These equations arise from Bayes' theorem. The "Bayes decision rule" states that it should be assumed that the world is in state A if p(A|*x*) > p(B|*x*) and vice versa. For the aching leg example p(A|*x*) = 0.001/0.051 = 1/51 while p(B|*x*) = 50/51, therefore the proper conclusion to draw is that the aching legs weren't in and of themselves great cause for concern.

It is important to note that this diagnosis was based on the relative frequencies of the common cold and the disease in the population. In some cases it can be difficult to determine these prior probabilities and they can be determined in quite subjective and idiosyncratic ways. In the above example if the frequency of the disease were 1% rather than 0.01%, then the same Bayes decision rule process suggests that 2/3 of the time patients presenting with aching legs had the disease. So the same observation and the same understanding of how the ailments work (100% of people with the disease but only 10% of cold sufferers having aching legs) can lead to quite different results based on different prior probabilities.

Similar challenges arise when a new piece of information, such as a weather forecast, needs to be incorporated into a complex decision within the energy sector, as illustrated in the following example:

Suppose it is May and a power generator has to decide whether or not to take a coal plant down for maintenance. The coal plant has been working hard all winter to meet winter peak electricity demand and, in June, it has to work hard again to meet the demand for summer air conditioning. In April and May, however, the demand for power is expected to be rather low and the company can do without the output of this given plant. However, once the power plant is taken down for maintenance it must remain offline for at least two weeks. If there is a power shortage, during this period, prices will rise and the idled coal plant will not make the high profits it could have made. However, if the power plant is not maintained there is a certain cost in lost efficiency and higher probability of failure later. Note that the problem of optimal maintenance planning is not new, and it has been studied as early as the 1960s, as part of a British study (Mason, 1966). The study concluded that better climate forecasts could result in savings of £200,000 per year (1966 values).

The corresponding decision matrix for this problem looks like this:

	No power shortage	Power shortage
Maintain Plant	**0**	**-2**
Leave Plant running	**-1**	**-1**

Table 5: Decision Matrix for the Maintenance Problem

There could be a power shortage for a number of reasons. Other companies could decide to take down their plants for maintenance (in most markets considerable coordination is done, but for this example, it is assumed that this is not the case), a large nuclear unit could trip offline, the temperatures could be well above the seasonal average during the period. Since it is May, this "heat wave" will only drive up demand a small amount, and will not lead to a power shortage unless one or more of the other factors are also in place.

How does a probabilistic long-range weather forecast influence the plant maintenance decision? The answer likely depends not only on what the forecast indicates and with what certainty, but also on a lot of other factors that can be difficult to disentangle. Bayesian decision analysis based on prior beliefs might be helpful to provide an answer to the valuation question. The difficulty with this approach is the very challenging task of obtaining reliable estimates for the prior beliefs of key decision makers. Therefore, although in principle Bayesian analysis can improve the valuation framework, it is also prone to many issues related to practicality.

3.2.5. Valuation Incorporating Flexibility: Real Options

Many decisions can be deferred until more or better information is available, and this ability to defer decisions can be of great value. Alternatively, the impact of a decision taken today can be mitigated in the face of new information by taking other decisions tomorrow. There are robust and proven methodologies for valuing this managerial flexibility. This theory is called the "theory of real options" (Dixit and Pindyck, 1994). An application of real options to the electricity generation industry has been performed by Thompson, Davison & Rasmussen (2004). The International Energy Agency (IEA) has also published a working paper recently, discussing the use of real options theory for quantifying the impacts of climate change policy uncertainties over energy investment decisions (Yang and Blyth, 2007).

Several of the case studies in this survey depend implicitly or explicitly on managerial flexibility, for instance, management of a watershed with partially predictable inflows and prices described in Section 5.2 and management of a gas storage facility described in Section 6.1. In the watershed management decision problem, in order for hydroelectric operators to make optimal decisions, future streams of information obtained through forecasts are critical. By not committing to a course of action at the beginning of the time period and creating strategic options, hydroelectric operators can change their course of action as new information arrives, thereby leveraging their managerial flexibility. For a simple dice game illustrating some of the conceptual foundations of real options, please see Appendix 1.

Where appropriate, the research team will use a customized real options methodology to quantify the economic benefit of environmental forecasts, while recognizing that the underlying theory for applying real options to quantifying the economic value of environmental forecasts is not yet fully developed. An interesting follow on project from this one might be to develop such a comprehensive theory.

3.2.6. Comment on Second Order Effects

As Macauley (2005) points out, better use of forecasts can lead to second order effects. For instance, better scheduling of electricity generation to match forecast load might lead to lower prices, which might in turn lead to higher overall demand, which in turn leads to higher prices. Given the complexity of the feedback mechanisms in the electricity markets, it will be very difficult to capture such second order effects particularly in a quantitative way.

3.2.7. Comment on Sectoral Sensitivity Calculations

"Everyone always talks about the weather but nobody ever does anything about it."

How much is an improved weather forecast worth to a given sector of the economy? One point of departure for this question is to calculate the sensitivity of this sector to a given weather or climate time series. For a very thorough study example, which reports the sensitivity of the U.S. Economy to climate variables, see Larsen (2006). For instance, it is a fact of the industry that on a summer day both the demand for and the price of electrical power increase with the temperature (for a detailed discussion of this phenomenon and related figures see Section 4).

The state of the art in modelling this relationship enables us to estimate the expected cost of the additional power needed at a future date. For instance, if the average temperature in Toronto on 3 August 2007 were to be 27 rather than 26 Celsius degrees, the impact of this increase on the demand for, and consequently the price of, electrical power can be estimated. However, the exact cost/benefit impact of this increase on various sectors of economic activity is not clear, and depending on who is asking the cost/benefit question, one can get many different answers.

The basis for the sectoral cost/benefit discussion already stimulates a number of interesting questions. First and foremost, the cost and benefit related to which sector is of concern: the Canadian economy overall, the power producers, the power consumers, or a given power producer? But this might fundamentally be the wrong question. Even if it is known in advance that the temperature would be high on August 3rd, most of these costs would remain. These costs arise for the simple reason that people prefer to air condition their homes and workplaces to a comfortable level, and the energetic cost of reaching that level increases with the ambient outside temperature.

To illustrate this point, consider the following example. It is expected that next summer is going to be hot and humid in Toronto. This heat will lead the population to turn on their air conditioning units, indirectly consuming large amounts of fuel in the process. What would be the value of a very detailed and precise forecast which could give us hour-by-hour temperature readings in Toronto 3-6 months in advance? How can this information be used? It might be surprising to reveal that such a forecast would actually not have a very significant value. Plans are already in place to use power generation capacity to the limit and all the power plants are expected to be operational during that time. Therefore there is limited managerial flexibility no matter how accurate the forecast may be.

On the other hand, such a detailed forecast would be rather useful in the "shoulder" months of fall and spring. During these seasons, power companies could make financially and technically better decisions if they have accurate information about upcoming peaks. As this example demonstrates, the value of information depends not just on the quality of the forecast but also on the actual ways the information can be put to use.

3.2.8. Other Valuation Methods Found in the Literature

For the sake of completeness, a short survey of other means for estimating the value of weather and climate forecasts is included in this section. In addition to the topics surveyed here, the economic techniques of rent valuation/return to factor approach, replacement cost approach, residual value approach, deriving market demand curve approach, benefits transfer approach, and alternative cost approaches could all be used in this context, although each would have to be adjusted for a probability of outcomes factor to be used in studies of this type.

3.2.9a Survey Approaches

In this approach, people are surveyed and asked what value they associate with weather services. An example of this approach is found in Lazo & Chestnut (2002), who use a survey methodology to determine the value of weather forecasts to ordinary American citizens. Rollins & Shaykewitch (2003) report a survey-based technique for valuing an Automated Telephone Answering Device offered by the Meteorological Service of Canada, while ARC (2003) uses surveys to value a new Canadian weather radar. A critical review of the application of survey methodologies to valuing forecasts is provided by Brown (2002).

A survey-based research method targeting the general public is not a very good fit for the current research project. Instead, the focus of the research effort should be on the economic impact of decisions taken by a small number of key decision makers within the energy industry and on how EP can have an impact on these decisions. Nevertheless, certain aspects of survey-based methods can help structure better interviews, a key part of the research effort for the next phase of this project.

3.2.9b Hedonic Pricing Studies

In this econometric approach, wage and housing prices are used to infer the value of weather information. The underlying assumption of this method is that these wages and prices somehow incorporate the value of weather services. This "hedonic approach" is typically used to price the value of incremental improvements (e.g., the value of another bedroom in a house). Preliminary research suggests that little or no work has been done on applying this approach to the particular problem of determining the value of various forecasts to the energy industry. Macauley (2005) provides a summary of this technique in a forecast-valuation setting.

4. How Electricity Markets Work: A Primer

Improved weather and climate forecasts are particularly valuable to the electrical power industry. Given that, for reasons that will emerge in this section, the electrical power industry already incorporates weather forecasts into their operational and tactical decision making processes, it is also possible to utilize the valuation framework described in Section 3 to quantify the economic benefits of forecasts for this sector.

The electrical power sector is a complex industry harbouring many intricacies, several of which must be understood to obtain a full appreciation of the value of forecasts. The intricacies occur at the level of engineering and operational considerations common to all electrical power generation and supply networks, as well as at the level of business organization. The latter is largely caused by the deregulation of electricity markets, a shift that is becoming increasingly common around the world, including Canada.

This section starts with an introduction to the features of power systems, beginning with operational and engineering features common to all power systems, and then focusing on some special features of deregulated markets. This is followed by examples of ways in which forecasts can add economic value to the power industry, and where possible, Canadian examples are provided.

4.1. Generation of Electricity

From the perspective of physics, electricity is generated in two main ways – by converting the mechanical energy of water or wind into electricity or by using a fuel to boil water and run a steam turbine[7]. The water can be boiled by burning coal or natural gas (and, in rare cases, oil), or by generating heat through a nuclear reaction. The conversion of mechanical to electrical energy is very efficient while the conversion of thermal to electrical energy is ultimately constrained by the Second Law of Thermodynamics and is relatively inefficient energetically.

Thermal electricity generation is the leading conversion method worldwide, but in Canada, hydroelectric power plays a very significant role in the energy value chain. Hydroelectricity supplies the overwhelming majority of power generated in Quebec, Manitoba, British Columbia, and the Yukon, while it provides a significant fraction in Ontario, and nontrivial amounts in nearly every other province and territory.

The economic and engineering features of the commonly used generation sources are very important both for operational and financial aspects of power systems. These features, together with environmental issues of each generation type, are summarized in the following table, which lists the generators in rough order of increasing variable cost per MWh[8].

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[7] Photovoltaic technology, currently a relatively negligible contributor to the Canadian energy supply, works in a third way, by direct conversion of electromagnetic radiation into electrical current.

[8] Note that the consumption of electrical energy is measured in the hybrid unit of Megawatt-hours (MWh) or, for residential customers, Kilowatt-hours (kWh).

Generation Plant Type	Cost[9]	Flexibility	Reliability	Environmental Impact
Hydroelectric	Variable cost essentially zero, unless water rights must be purchased. Annualized fixed costs low as dams last a long time	Very flexible; water can be stored (if possible) or spilled over the dam to meet load variations	Dependent on water inflows but typically quite reliable. Power can be "stored" if large reservoirs exist or via pump-storage	Minimal for run of the river hydro; however facilities with large reservoirs can cause considerable flooding and loss of land
Wind	Variable cost zero, fixed cost high but falling quickly	Turbines can be feathered to reduce power generation	Various reliability concerns exist (e.g., intermittent nature of wind)	Some cite aesthetic and noise related concerns, impact on wildlife (e.g., bird and bat mortality) also a concern
Nuclear	Variable cost very low despite recent dramatic increase in Uranium prices, fixed construction cost extremely high	Inflexible, delivers a nearly constant supply of electricity	Failures are infrequent but take a long time to repair	Nuclear waste disposal issues
Coal	Variable cost higher than for nuclear but still low; fixed cost fairly low	Very flexible, can be left in "spinning reserve" for quick response to load variation	Quite reliable	Emits large quantities of CO_2, NOx and SOx
Natural Gas	Rely on expensive natural gas so variable cost is quite high; fixed cost fairly low	Very flexible	Quite reliable	Cleaner than coal; can be used in combined cycle mode to utilize waste heat
Peaker Unit	Variable cost very expensive. Fixed cost very high per MWh actually generated	Very flexible (can be fired up on short notice)	Mechanically very unreliable	Can be quite inefficient and create significant emissions

Table 6: Summary of Power Generation Types

Other generation types, such as solar thermal, are not included in the table since they are at very early stages of adoption in Canada, however some of these generation methods are discussed in Section 8.

[9] The fixed costs considered in Table 6 include not only the cost of constructing the facility but also the costs of staffing it, since wages paid are not dependent on power generated.

4.2. Consumption of Electricity

Electricity is consumed by three main user groups: residential, industrial and other (including commercial, educational and governmental establishments). In households electricity is often used for heating, almost always used for cooling, and always used to power a range of electrical appliances and electronic equipment. It is used by large industrial establishments to power machinery and various production processes. Finally, it is used by commercial, educational, and governmental establishments for cooling, sometimes for heating, and to power electronic machines. Very roughly speaking, each of these broad sectors consumes about 1/3 of the electricity generated in Canada, which is a typical breakdown worldwide.

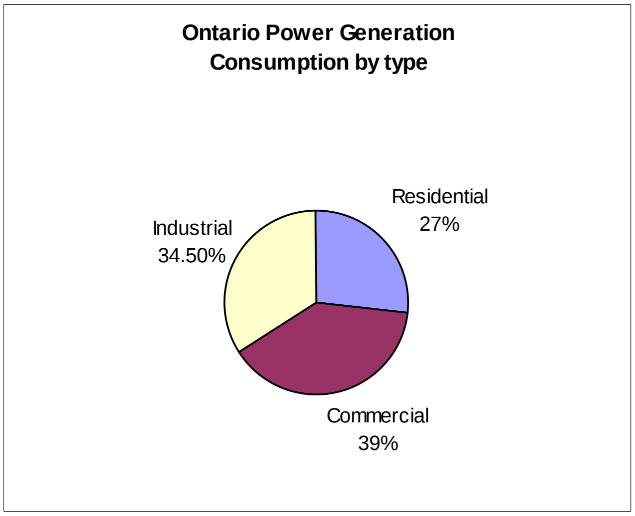


Figure 4: Ontario Electricity Consumption in 2002
Source: Ontario Power Generation

The demand for electricity is quite variable, both within a day and over the course of the year.

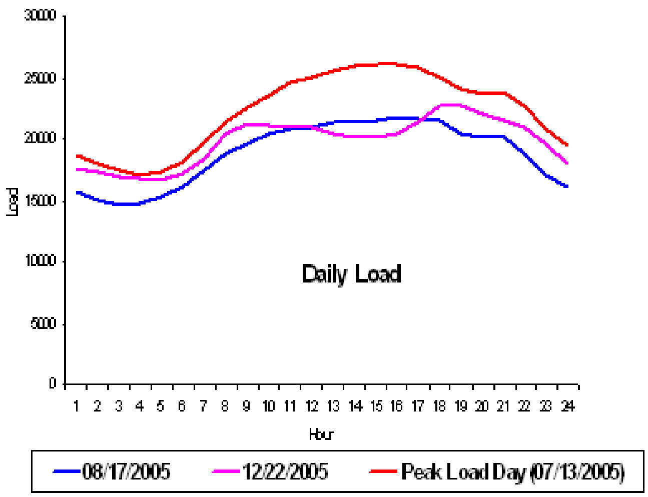


Figure 5: Daily Ontario Load Shape: Actual Plots of Hourly Loads (in MW)
Data Source: Ontario IESO as archived by Dydex

Within a day, power demand is low in the middle of the night when most residential and commercial establishments, and even many industrial establishments, are using little power. This daily variation in electricity use is called the "load shape" and it is quite predictable (see Figure 5).

Over the course of a week, there are also predictable patterns in electricity consumption, with weekend and holiday use being lower than work day use (Figures 6 and 7).

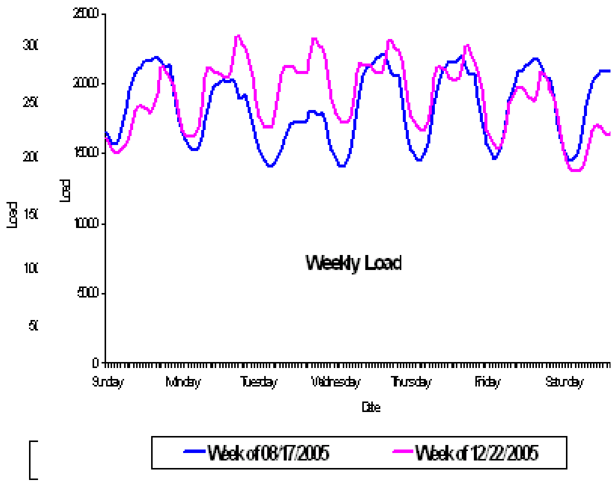


Figure 6: Ontario Weekly Load Shape; Load in MW
Data Source: Ontario IESO as archived by Dydex

Because of this weekly and daily variation in power demand, the week is often divided into peak (Monday to Friday, 7 AM to 11PM) and off-peak (the rest of the week) classifications, to denote the different demand regimes.

Over and above this weekly variation, electricity consumption varies a great deal over the course of a year. This annual variation arises for two main reasons – the differing lighting requirements corresponding to variations in daylight hours and, most importantly, the different requirements for heating and cooling arising from the different seasons (Figure 7).

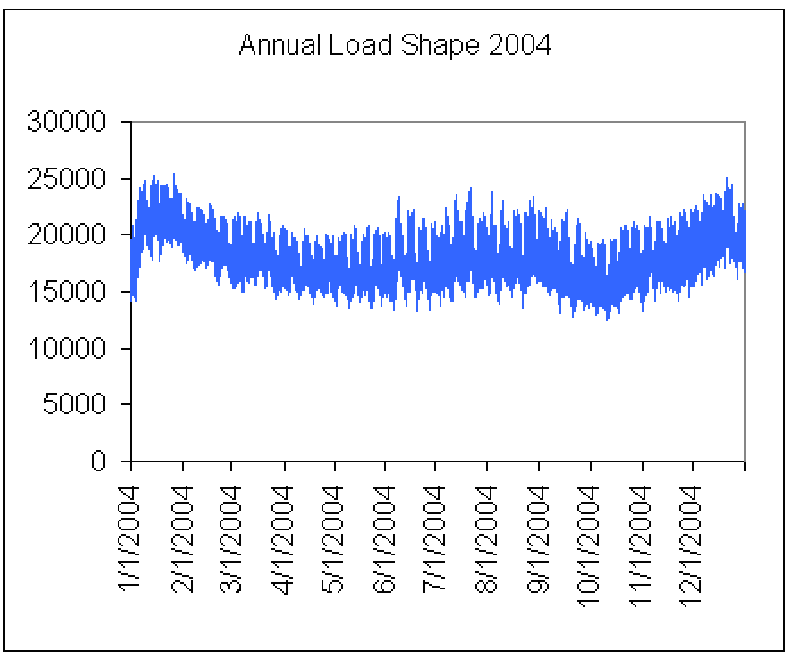


Figure 7: 2004 Load (in MW) for the Province of Ontario
Data Source: Ontario IESO as archived by Dydex

As is already becoming clear, for the use of electricity in heating and, even more important, in cooling, the exterior temperature is a big determinant of power use. Previous work conducted by one of the research team members of this report has demonstrated this link by plotting the realized Ontario load vs. realized dry bulb temperature measured at the Pearson Airport.

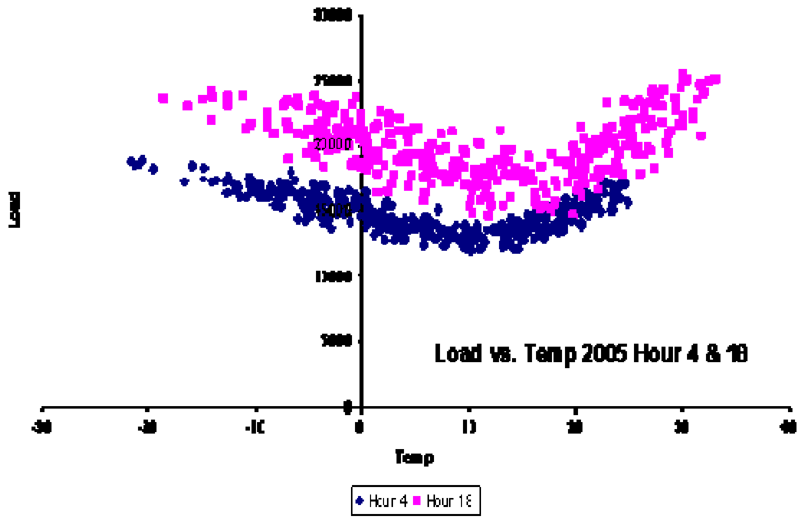


Figure 8 Data Sources: Ontario IESO as archived by Dydex (load); Environment Canada (2006,2007) for temperature data. Aggregate Ontario load data is plotted against Toronto (Pearson airport) climate data.

Figure 8: Load (in MW) vs. Temperature (Ontario)

It is interesting to see that adding a humidity correction does not tighten the display of this data (Figure 9).

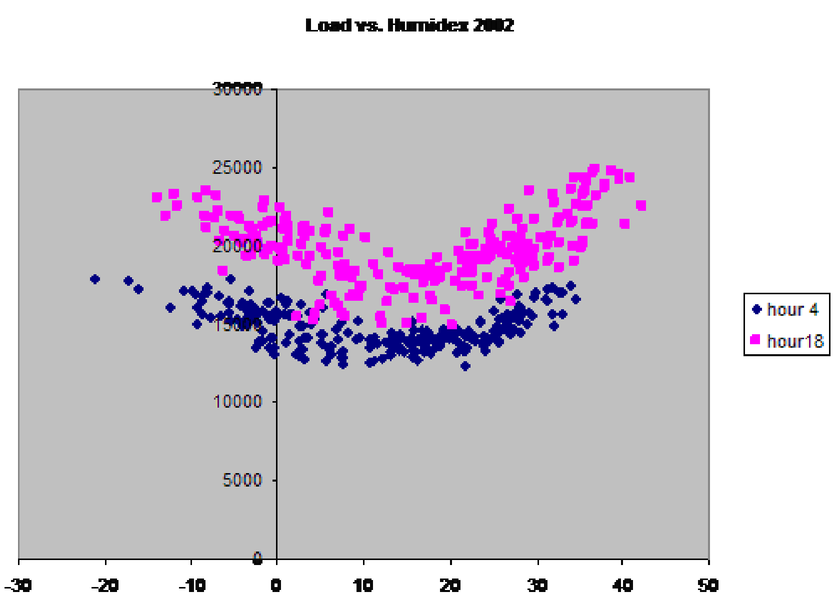


Figure 9 Data Sources: Ontario IESO as archived by Dydex (load); Environment Canada (2006,2007) for temperature and humidity data. Ontario load data is plotted against Toronto (Pearson airport) climate data.

Figure 9: Load (in MW) vs. Humidex (Ontario)

The following example gives a good indication about the variation in energy consumption. During 2006, in Ontario, hourly electricity consumption varied from 27,005 MWh (on Aug 1 between 4 and 5 PM) to 11,621 MWh (on Oct 9 between 4 and 5 AM). The extreme variability in electricity demand combined with the fact that electricity cannot be stored in any appreciable quantities makes the problem of matching generation with consumption a crucial one, which is addressed in the next subsection.

4.3. Matching Generation with Consumption

Although it is relatively easy to store electricity for the consumption of a single electronic device (in a battery or even in a capacitor), storage becomes a big challenge at higher scales of consumption. It is very difficult to store the huge amounts of electricity required by a modern industrial society, even for a single hour. Consider the AA battery: one of the most ubiquitous forms of energy storage in use today. A standard AA battery can store about 0.1 Watt-hours. Therefore it would require 10 billion AA batteries to store 1000 MWh, approximately six minutes of Alberta's hourly electricity requirement.

As discussed in the previous section, the demand for electricity is quite variable even within a single day. It has also been shown that a typical electrical system has a wide variety of generating technologies with varying marginal costs of production. Given this variety in supply, the first order of business is to make a generation plan that, for a given level of production, uses the cheapest sources of power first. At the level of analysis of this report, the only relevant difference between a traditional command and control monopoly and a deregulated market is the way in which the generation plans are made: in the former, by a central optimizer; in the latter by a competitive market or auction process.

In the case of a central optimizer, the problem at hand is to decide which plants to use (or "dispatch") to meet a single known and constant load over time. The relatively simple concept behind this decision process is known as the "stack". The available generation is listed in increasing order of marginal cost (variable cost of production). For instance, at a given time a market might have 10,000 MW of low marginal cost Hydro, 8,000 MW of next lower marginal cost Nuclear, 5,000 MW of next higher coal, and 2,000 MW of highest cost natural gas generation. If the provider has to meet a load of 20,000 MW, all hydro and nuclear supply would be dispatched, as well as 2,000 MW of coal generation. This stacking procedure is shown graphically in Figure 10:

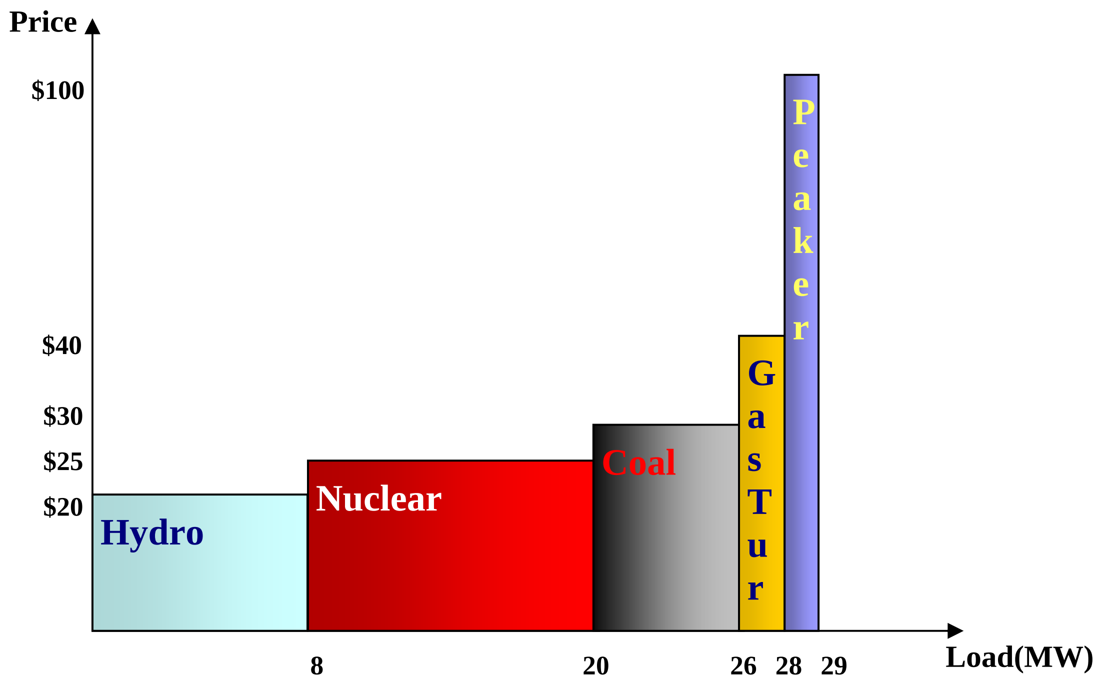


Figure 10: A Representative "Power Stack"

Note: Numbers are indicative of fuel costs for the year of 2005. Other renewables such as wind and solar are typically dispatched first (i.e., are located on the left side of the stack). This stack location is achieved by pricing them at $0 (for dispatch purposes only). Since the current supply of renewables in Canada is minimal, they are not shown in this conceptual stack diagram.

Over the course of a day, the load varies. Therefore, the stacking procedure needs to be performed repeatedly to find the best variable generation mix over the course of the day. The dynamic nature of this process creates a complication since many generation types are quite inflexible and their output cannot be adjusted quickly, if at all. For instance, although CANDU reactor technology allows some variation in fuel rate, due to various operational issues, nuclear plants are usually run at a constant power output (Ron Stark, 2005).

The need to take these flexibility characteristics into account might result in plans which no longer use the absolute low-cost producer, as measured by the stack. Nuclear power must typically always be dispatched. This requirement has led, on occasion, to the financially odd outcome of negative power prices. Electricity, once dispatched, must be consumed (Davison et al., 2002) and it is cheaper to pay an industry with the ability to "soak up" more power to consume an hour of electricity than it is to take a nuclear power plant off line.

Finally, the demand for electrical power is not completely predictable. There are no models which can be used to forecast the consumption pattern of an individual consumer or give precise information on the shifts in power consumption, for instance when the consumer will decide to turn off a table lamp and turn on the television. However, once the analysis is moved from the individual level to the collective one, patterns start to emerge. Naturally, over a large grid the aggregate impact of many individual behaviour patterns will average out to a great extent, but some random variations will remain.

In previous sections, it has also been shown that the electrical load is highly temperature dependent. Extremely detailed, short-term temperature forecasts are available, but they are still not 100% accurate.

In light of these two factors, diversity of generation systems as well as the variations in consumption, it is clear that generation plans need to be varied over the course of the day. In order to enable the variation of these plans effectively, very responsive plants are required. Two main methods can be used for this purpose: spinning reserve and Automatic Generation Control (AGC). A unit is said to be part of the spinning reserve if it is not generating any power but it is in standby mode. Plants running in AGC surrender operational control to the system operator, which operates them to balance system load rather than to optimize their efficiency.

An excellent review of the technical and environmental issues surrounding spinning reserve and AGC can be found in the NOAA-NESDIS report (2002). This description can be summarised as follows. Units operating under AGC are able to rapidly increase or decrease their output, as commanded, to respond to load changes. The price to pay for this flexibility is that the generator cannot simultaneously be managed to maximize efficiency. Thermal power plants operating in spinning reserves still consume enough fuel to "keep their boilers hot". Therefore improvements in temperature (and hence load) forecast accuracy that enable plants to be taken off spinning reserve will be both economically and environmentally advantageous, in ways examined in Section 5.1.

4.4. Deregulated Markets: An Overview

From a technological point of view, deregulated markets function in a very similar fashion to regulated markets. However, instead of a single decision-maker, the stacking process is performed through competitive bidding. The bidding process can create extreme price volatility, with occasional "price spikes" of up to 20 times the average prevailing power price. For more details on deregulated power markets in a Canadian setting, see Stabins (2004), Davison et al. (2002), Wellenius & Adamson (2003).

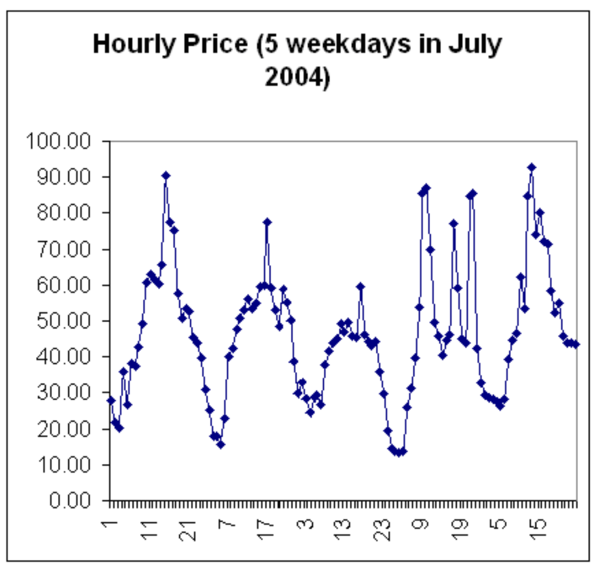


Figure 11: Variation in Hourly Ontario Electricity Prices: An Example
Data Source: Ontario IESO as archived by Dydex

Figures 11 and 12 demonstrate the extreme variability of electricity prices which has been observed in the past.

These price spikes can provide strong economic signals to consumers and generators, causing them to make new decisions and act in order to protect their interests. For this reason, in certain circumstances, Environmental Predictions can have very substantial economic value, in ways discussed in Sections 5 and 6.

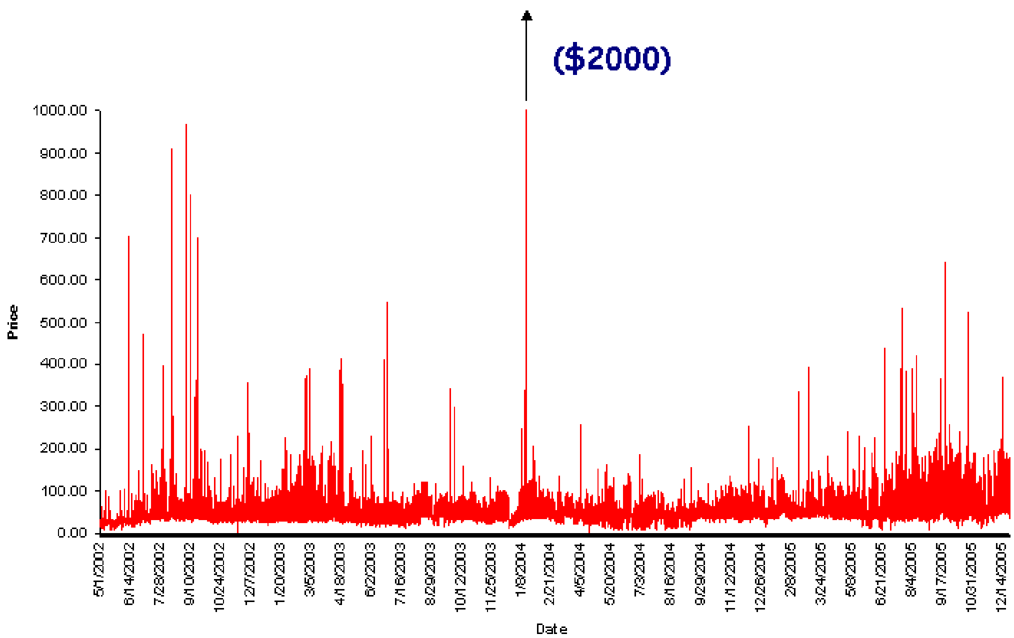


Figure 12: Variation in Ontario Electricity Prices Over Multiple Years, Showing Price Spikes
Data Source: Ontario IESO as archived by Dydex

5. Electricity Generation

There is a high level of interaction between the electricity generation industry and various environmental conditions. Understanding the mechanics and dynamics of this interaction can pave the way for creating both environmental and economic value from EP and quantifying the economic benefits of improved forecasting capabilities.

Following the review of operational and financial aspects of the electricity generation industry in Section 4, the value of improved forecasts for different segments of the electricity generation value chain will be elaborated in this section. Given the prominence of hydroelectric generation in Canada, hydroelectricity will be covered in this section. Other renewables will be analyzed separately in Section 8.

5.1. Using Short-Term Load Forecasts to Reduce the Dependence on Spinning Reserve

Incorporating better short-term temperature forecasts in an operational setting allows the amount of generating capacity devoted to spinning reserve and Automatic Generation Control (AGC) to be minimized (The technical details of this problem have already been surveyed in Sections 4.2 and 4.3 above). Minimizing spinning reserve requirements through better load forecasting can not only create a direct economic incentive by saving fuel, but also create environmental benefits by reducing emissions – without any loss in the actual amount of electricity generated. Most research quantifying the economic benefit of forecasts in this setting comes from a U.S. or U.K. setting, and the numbers obtained vary quite widely. In a recent report (NOAA-NESDIS, 2002), the value of a new space-based imager and sounder for this exact area of application was estimated to be US$366 million per year to the U.S. electrical industry. On the other hand, NOAA (2004, pg. 33) estimates the value of the official U.S. National Weather Service forecast to all scheduling of hydroelectric plants as US$139 million per year, and suggests that additional benefit of US$69 million per year could be obtained by incorporating perfect weather forecast information into the scheduling decision. The NOAA (2004) report goes on to assert that "the incremental benefit of a one-percent improvement in forecast accuracy for the U.S. as a whole is about $1.2 million per annum". The Ph.D. dissertation of Tribble (2003) suggests that improved weather forecasts can save even a small power utility about $0.5 million annually. In a U.K. setting, Teske & Robinson (1994) estimate that predictions of short-term demand based on weather variables are worth £66 million per year to the private sector, although this work covers all applications of short-term load forecasts, not only spinning reserve management. In a related study, Teisberg and his co-authors (Teisberg, Weiner and Khotonozad, 2005) quantify the annual cost savings by US electrical power generators by using 24-hour temperature forecasts to improve their unit commitment decisions. They estimate that these savings are US$166 million annually, and that an improvement of forecasting skill to make perfect 24-hour temperature forecasts would save an additional US$75 million annually. Their study makes heavy use of a methodology developed by Hobbs et al. (1997) for quantifying the value of load (power demand) forecasts in the same setting.

The methodologies employed by these studies differ considerably or, in the case of the NOAA figures, are not revealed. Existing literature in this field suggests that performing a similar study in a Canadian context can provide a rich set of findings.

5.2. Optimal Operation of Hydroelectric Plant Given Flow Rate Projections

Although globally hydropower accounts only for 16% of total electricity production, in water-rich countries, it constitutes a major portion of the energy mix. Hydroelectricity accounts for 60% of Canada's generation capacity. In Quebec, Manitoba, Newfoundland and Labrador, the share of hydroelectricity in generation capacity is over 90% (NEB, 2005).

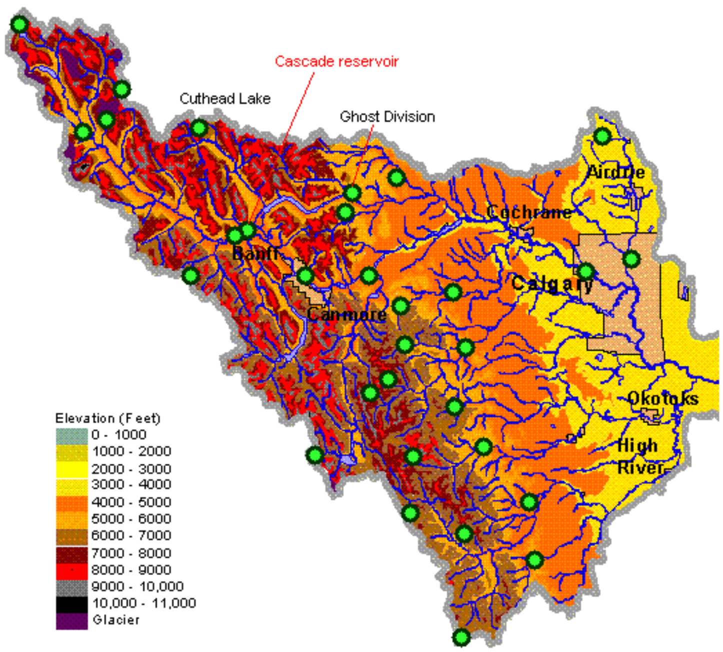
Obtaining accurate estimates of water flow into the watershed of a reservoir is key in managing the production of hydroelectric power more efficiently. Hamlet, Huppert & Lettenmaier (2002) estimate a value of US$161 million per year in 2004 dollars of better long-range inflow forecasts for Columbia River watershed utilities. Maurer & Lettenmaier (2004) estimate the value of improved inflow forecasts to Missouri river basin utilities at US$10 million per year. William et. al (1982) considered the value of improved one-month to one-year stream flow forecasts for the operation of a single reservoir system of the California State Water project as between US$0.4 and $0.8 million annually (1982 dollars). Bill Coley, President of Duke Power, is quoted in (NOAA,2004, pg. 34) as stating "By effectively using accurate rainfall forecasts in our hydro operations, Duke Power can save several million dollars annually in preventing 'wasted' water – water moved past the hydro station but not used for hydroelectric generation". In a Canadian context, Philips (1986) suggest that advance knowledge of low water levels could have reduced a US$80 million loss to Manitoba in the spring of 1981.

Hydroelectric facilities come in two main varieties: some facilities (for instance Niagara Falls) are "run of the river" facilities in which there is no dam or in which little or no water can be stored behind the dam. The second group of facilities have large dams or containment structures capable of storing large amounts of water. For both classes of facilities, accurate predictions of future water inflows will be economically valuable.

For run of the river dams, these forecasts, in conjunction with the short-term temperature forecasts described in Section 4, would be required for better decision making regarding spinning reserve and Automatic Generation Control issues.

Facilities with water storage possibilities give their operators flexibility to generate power immediately or to store water for use in generating power later. The decision of which course of action to adopt depends on a variety of inputs, including forecasts of future water inflow, reservoir levels (neither too high nor too low are desirable) and, for deregulated markets or operators able to sell into deregulated markets, forecasts of future power prices. For an introduction to some of the modelling and optimization issues related to this problem, see Thompson, Davison & Rasmussen (2004). In the Hamlet, Huppert & Lettenmaier (2002) study cited above, the large added value arose from using El Niño–Southern Oscillation based long-range climate forecasts for better decision making on the optimal level of late-summer and fall energy sales.

The problem of inflow forecasting is a very suitable area of application for EP, in which several forecast data series must be integrated (together with recent historical data) in a nontrivial way to obtain a flow forecast. As can be seen in Figure 13, stream flow at a given point depends on current water levels upstream of that point, in addition to forecast precipitation levels across the whole watershed. Other factors, such as current soil moisture levels are also important. For watersheds including mountainous or cold-climate regions, the thickness of the winter snowpack is a crucial factor in predicting water inflows for the entire year (Adams, Houston & Weiher, 2004). Kevin Cross, of Pacific Gas & Electric, is quoted in Williamson, Hertzfeld & Sen (2004) as suggesting that a finer resolution model of snow depth and runoff would be valuable to hydroelectric dam operators.



A recent thesis work completed by Lin Li (2007) provides some interesting insight into the current state of the art in inflow forecasting for power applications. Li completed her thesis by working closely with TransAlta (her current employer), which operates hydroelectric facilities in the province of Alberta. In her thesis she notes that:

"Currently, TransAlta does not use any inflow forecasting model for the inflows to Cascade Reservoir. Instead, they just trend the calculated inflows, [obtained] from known outflow and change in reservoir storage."

Figure 13: Forecasting the Flow for Hydroelectricity
Watershed map courtesy of Lin Li (Transalta Corp)

The reason for this seeming oversight is described later in the thesis:

".. hydrological models have been used to simulate rainfall-runoff processes for many years. However, a … hydrological model requires an extensive knowledge of the geographical and physiographical aspects of a watershed, [and] hydrological knowledge…. To forecast inflows, the hydrologists need to be familiar with basin-specific hydrological information and ..[calibration of the model].. is usually a lengthy process that must be repeated on a regular basis."

The stream forecasting application is likely to be of interest to hydro operators ranging from behemoths like BC Hydro and Hydro Quebec, who need to forecast inflows on mighty rivers draining huge watersheds, to much smaller players such as microhydro operators with a small dam and generator on a small creek draining a tiny watershed.

In northern latitudes, snow coverage, snow thickness, and ground temperature are the main determinants of how much power can be generated from hydroelectric systems. To this end, European Space Agency (ESA) has started a new initiative to combine optical and Synthetic Aperture Radar (SAR) data in order to obtain the required data regardless of the presence of clouds (ESA, 2003). Modern developments in the modelling of deregulated electricity markets allow the value of these improved forecasts to be quantified.

Based on the classification framework discussed in Section 3.1, the inflow forecasting application can be described as a tactical one in the supply side of the energy value chain.

5.3. Operation of Peaker Units: Impact of Smog Day Forecasts

When electrical load is very high, small and flexible generation units known as "peakers" can be employed to meet this load. These peakers are expensive, unreliable, and often responsible for a disproportionate amount of pollution when compared to the electricity they generate. Access to highly accurate short-term weather forecasts along with the capability to act on these can enable the electricity markets to "shave" the peak and reduce the need for the peakers. Some alternatives enabled by more accurate forecasts include demand management programs (see Section 5.4) and hydroelectric pump storage facilities (Thompson Davison & Rasmussen, 2004). Both of these load-avoidance mechanisms are quite expensive, but they may be advantageous from an environmental benefit perspective especially when photochemical smog is also forecast along with higher loads.

This potential application can be classified as both strategic and operational. Strategic in the sense that, structural changes in the market structures would be necessary to implement it; operational in the sense that, once the market structures are in place, the decision itself becomes an operational matter. Particularly at the strategic level, it is important to consider the link between EP and demand management programs, which are reviewed in the next section.

5.4. Opportunities for Demand Size Management Programs

For weather forecasts to have a truly positive environmental impact the load must no longer be considered simply as an external constraint imposed upon the electrical generating system but as a variable to be managed in its own right. Amory Lovins has been proposing this approach since the seminal paper (Lovins, 1976), suggesting that people are not really interested in purchasing electricity but rather in purchasing the services it provides.

To understand the premise of this approach, consider the following scenario. Consumers and businesses are interested in lighting, heating, and cooling their houses and in running their electronic equipment; manufacturers have additional needs such as powering their machinery or their chemical processes. Some of these services, particularly cooling, can be postponed for short periods of time. For instance, if the air conditioning is turned off on a well insulated building for a few hours, the building will remain cool. Therefore, in the presence of a summer heat wave in which extremely high temperatures are expected around 3PM, it would make sense to encourage consumers, particularly in offices, to shut off their air conditioning units at 3PM, turning them back on at a later time (e.g., 8PM) when the power demand has fallen. If supported by proper financial and other incentives, this kind of program can work even in the absence of a forecast: consumers could simply turn down their air conditioning in response to an external signal in exchange for a form of rebate on their power bills. In the presence of an accurate forecast, the system can work even better – consumers could turn up their air conditioner ahead of the signal to "bank some cold". Although such a strategy might not save any energy, it has the potential to shift the peak demand from high load times to lower load times. At the minimum, this shift would ensure that electricity is generated by lower cost and comparatively clean natural gas (or even coal plants) instead of expensive and dirty peaking units.

Demand size management applications can be grouped under operational applications within the demand side of the value chain with a very strong connection to supply side decisions, however the design of such demand management applications is strategic by nature.

6. Energy Transmission

Moving further on the supply side of the value chain, this section will discuss the possible impacts of Environmental Predictions on energy transmission networks.

6.1. Role of Storage in Optimizing Natural Gas Transmission

Similar to electricity load, the demand for natural gas is quite variable during the course of the year. However, in contrast to electricity load, the demand for natural gas tends to peak during the coldest months, when it is most required for heating. North America constitutes a special case in this pattern: here, gas usage also climbs in the summer, as gas is used for the peak electricity generation required for air conditioning equipment. This effect is less pronounced in Western Europe.

Although storing natural gas is expensive, it is more practical than storing large amounts of electricity. The common practice in the industry is to deliver the gas to consumers as it is used. This practice, combined with the high demand fluctuations implies that gas distribution networks (pipelines) must be sized to satisfy the peak demand, although they rarely operate at peak levels. Given the extremely capital intensive nature of pipelines, any efficiency gains in the construction and operations of these networks could result in substantial cost savings for the society in general, and pipeline operators in particular.

In Germany (Sven Duve, personal communication, 2007), this “overbuilding cost” is passed on to the companies and municipalities who purchase the gas, using the following calculation method. Their annual bill for pipeline and transmission costs is computed by multiplying a fixed use rate factor by their largest hourly draw of gas from the network, which is then multiplied by the number of hours in the year. As this calculation demonstrates, achieving cost-efficient storage practices can have clear benefits to the consumers as well.

An engineering economics analysis of spinning reserves on natural gas pipelines was conducted by NOAA-NESDIS (2002). The study reported relatively small benefits from spinning reserves.

The cost associated with the current gas distribution practice suggests a good business case for the construction of natural gas storage facilities and their operation in conjunction with short-term temperature forecasts, which can be used to predict the demand. Storage facilities can be used across seasons to substitute the purchase of cheap gas for the purchase of expensive gas. They can also be used over shorter time scales (i.e., weekly or even daily) for the purpose of shaving peak pipeline usage as well as for profiting from shorter time scale price fluctuations. Different types of storage facilities are required for each purpose.

Broadly speaking, there are two types of natural gas storage facilities: below-ground and above ground.

In the "below-ground" category, natural gas is injected into natural geological features such as an existing, but depleted, gas field or a salt dome structure. The details of maximum injection and withdrawal rates and loss functions will differ from structure to structure, but all of these structures are characterized by a relatively long time scale operation, large storage capacities and their predetermined location. These features make them very suitable for shifting gas use across seasons, but unsuitable for shifting gas use from day to day or from hour to hour. Salt domes typically allow slightly faster cycling than depleted fields, where one might allow monthly load shifting (depleted fields only allow for seasonal load shifting). These facilities may still require pipeline use, since their location is predetermined and linked to the location of existing features.

In the "above-ground" category, there are two main methods: the ability to change pipeline pressure (and implicitly storing gas) and above ground storage facilities (known in Germany as "storage cubes"). A detailed discussion on changing pipeline pressure is outside the scope of this research project, however various EP applications can be envisioned based on demand management programs similar to the ones discussed in Section 5.4. Above ground facilities have properties diametrically opposite to the below-ground storage options described above. There is a very high level of flexibility in choosing their location: for instance at the access point to the pipeline, allowing their use as pipeline load shifting tools. They can be quickly charged and depleted, allowing their use for shifting load over hourly, daily, and monthly time scales. However, on a per-storage-unit basis, they are quite expensive.

Figure 14: Above-Ground Natural Gas Storage Facilities
Source: U.S. Energy Information Administration, "The Global Liquified Natural Gas Market: Status and Outlook", December 2003

As such, a complete strategy for managing the volumetric uncertainty of consumers while minimizing their expected annual cost of gas (including pipeline charges), might reasonably be expected to include a portfolio of gas storage facilities. The decision of which facilities to include in the portfolio, and whether to include them by buying them or by leasing space in them will require mathematical tools for computing the value of each storage facility. Extracting maximum economic value from this portfolio will also require operating protocols telling the user when to inject or withdraw gas and from which facility. These operating protocols must be constructed in terms of trigger points for injection or withdrawal, depending on various factors such as the spot price, existing fill level, and time of the year. In fact, the mathematical determination of the facility values requires optimal operation protocols, as discussed in the simple "dice game" example in Appendix 1.

In broad terms, the seasonal patterns of gas consumption of different classes of users are well understood. For instance, a municipal energy utility will require large amounts of gas in the winter and much less in the spring. But fluctuating temperatures can make dramatic changes in these consumption patterns. This is precisely where EP and improved weather and climate forecasts can add value. The corresponding economic benefits can be quantified by using the proposed framework (Section 3.1) for a variety of time ranges.

A mathematical model for valuing (and determining optimal exercise strategies for) a single underground natural gas storage facility is contained in (Thompson, Davison & Rasmussen, 2007), which presents an algorithm for optimally operating and valuing this single storage facility in the face of price uncertainty. The storage facility is modelled including a loss rate function and finite injection and withdrawal rates. These rates are assumed to depend on the current fill level of the facility, with the functional dependence obtained from basic thermodynamic and fluid mechanical properties of gas. The operation problem reduces to deciding when it is best to inject gas into the facility, when it is best to extract gas from the facility, and when it is best to do neither. This decision is based on two variables – the existing fill level of the facility and the (random) spot price of gas. Very broadly speaking, the result of the paper is not surprising: it states that gas should be injected when the facility is nearly empty and the gas price is low and it should be withdrawn when the facility is nearly full and the gas price is high. In between these two extremes, when both prices and fill levels are moderate, the frictions modelled in the storage facility imply that it is best to do nothing. Of course, the real research interest is based on the exact quantitative behaviour of these rules.

Natural gas storage applications have the characteristics of both strategic and tactical decision problems. Site selection for storage facilities and designing the new market mechanisms can be seen as strategic problems, while the injection and extraction decisions can be evaluated within a tactical decision making framework. All the natural gas applications discussed in this subsection fall under the supply side of the value chain.

6.2. Electricity Transmission

Electricity transmission networks are another important area where EP can play a significant role. Please see Section 9.1 for a discussion of EP within the context of electricity transmission networks.

Wind storms create costs for local transmission line operators, and better forecasts of these storms can be used to allocate resources to line maintenance crews on a tactical basis (Blackmore 2007). In addition, longer term trends in wind speed distributions can impact codes on, for instance, how far vegetation must be cut back from power lines.

Transmission line operators are also strongly affected by lightning strikes, and the environmental forecast capability provided by, for instance, the Canadian Lightning Detection Network (CLDN) would have financial value in that sector. Moreover, the capacity of transmission lines is strongly dependent on temperature. On a very hot day the ability of a transmission line to transmit electricity is significantly degraded (Milbourne, 2007) leading to an interesting link between temperature forecasting and transmission planning.

7. Upstream Oil and Gas

Upstream oil and gas industry focuses on finding and extracting natural gas or oil from the Earth. Determining the value of EP and improved weather forecasts to this important industry is a challenging task. While natural gas markets, in particular, are very dependent on temperature over short time scales, the value of predicting this temperature dependence will mostly be captured by downstream players such as natural gas and pipeline operators. The operators supply natural gas to the consumers, operate natural gas storage facilities and maintain the pipelines. The value propositions for these two actors were described earlier in this literature review.

Beyond temperature forecasts, EP can provide multiple benefits for the upstream activities in the oil and gas industry. In particular, offshore oil production and exploration activities stand to gain significant benefits from EP. Three such applications were examined as part of the literature review: oil rig evacuation decisions, monitoring of sea ice and icebergs, and finally, monitoring of oil spills. In addition to offshore operations, new generation space-based and airborne instruments are starting to provide very useful environmental information which can help companies improve their exploration practices. It remains to be seen whether this new stream of environmental data will provide radical or incremental benefits.

7.1. Offshore Operations

EP can provide a very useful set of tools for maritime operations of the energy industry. Oil and gas exploration drillers require precise positioning of their ships and equipment, and they need to be able to stay on location for long periods of time (JPL, 2007a). An early report on the economic benefits of ice predictions to offshore navigation is provided by Pavskiy (1973)

One of the challenges for offshore operations in the oil and gas industry is to manage various risks caused by hurricanes and eddies (eddies are the marine equivalent of hurricanes caused by sea currents).

In the aftermath of Hurricane Katrina (2005), the risk caused by hurricanes to oil and gas infrastructure became crystal clear: more than 30 oil platforms were damaged or destroyed and nine refineries were damaged and/or shut down for weeks following the hurricane, resulting in economic losses on the order of hundreds of billions of dollars (U.S. DoC, 2006). Increased accuracy of hurricane intensity and trajectory predictions can create significant benefits for the oil and gas industry (please see Section 3.2.1 for a decision theoretic discussion of this case). Several papers estimate the value of improved Environmental Predictions to this problem, including Williamson et al., (2001) and Considine et al., (2002). The latter reference provides a thorough analysis of the oil rig evacuation example and obtains an annual value of US$15 million for a 50% improvement in hurricane forecast accuracy.

In addition to the hurricanes, the strong ocean currents generated by eddies can cause significant problems in offshore exploration, construction and production efforts as well (Mathieu, 2006). The oil and gas infrastructure in the Gulf of Mexico is one of the high-risk regions in the world, where eddies are a relatively common phenomenon and require operational monitoring. Traditionally, this monitoring was conducted by using surface drifters. In recent years, the industry has started to use earth observation tools to complement the traditional methods. Satellites carrying altimeters can measure height of the ocean with an accuracy of a few centimetres. Synoptic maps of sea-surface height can be generated by combining altimeter measurements with advanced hydrodynamic modelling techniques. Such maps are very useful in tracking eddies in near-real time (Mathieu, 2006).

EP can also provide significant benefits in tracking sea ice and icebergs, a potential risk for Canadian shipping and oil and gas exploration activities.

Sea ice formation is a natural occurrence in the northern shipping lanes. A personal communication with a mariner employed on the Newfoundland-Greenland route (Kirby, 2007) suggests that the main problem with sea ice is not danger to crew safety but simply slowing the speed of the ship. This suggests that EP can provide value for maritime operations by providing improved sea ice monitoring and prediction tools. The economic benefits of such tools can be determined by using the evaluation methods described in Section 3.2, if this application is modelled as a value of information problem within an expected value decision making framework. Kirby also revealed that current navigational practice involves plotting a route based on historical sea ice locations. Therefore it is highly likely that access to satellite-derived sea ice maps might allow for better route planning, with the attendant savings in time and fuel. This problem is described in thumbnail form in Danish Ministry of Transport and Energy (2006).

Another personal communication (Foster, 2007) resulted in a similar finding. The Centre for Cold Oceans Research and Engineering (C-CORE) is a company associated with the Memorial University of Newfoundland. Recently the company provided consulting services for a team sailing a yacht on a round-the-world race. The company's role was using near real-time satellite imagery together with their expertise in ice modelling, to plot a sea ice and iceberg-avoiding route for the yacht as it rounded Cape Horn off South America. It is interesting to note that the yacht supported by C-CORE won the race, in part because of the large amount of time it saved in the far southern waters.

Sea ice and icebergs are also a big concern for offshore oil and gas infrastructure. Hibernia and Terra Nova platforms on the Grand Banks region off the East Coast are an integral part of Canadian oil production. Icebergs pose a significant risk to these operations. They can damage well infrastructure on the ocean floor, cause environmental damage as well as costly production interruptions (Mathieu, 2006). For this reason, operational monitoring of icebergs around this region is crucial to ensure safety. If the potential threat cannot be detected in time to enable effective towing or deflection of the icebergs, the last resort is to put oil production on hold or, in extreme cases, evacuate the platform. Platform evacuations are high-risk operations with very high cost. In 2005, evacuation of these two platforms was considered due to a different risk (U.S. rocket launch operations from Cape Canaveral in Florida, with a northward trajectory), and the evacuation cost was estimated to be around $100 million, including lost production revenue (CBC, 2005).

Space-based Synthetic Aperture Radar instruments play a significant role in the detection of iceberg movements. These systems can provide data regardless of the atmospheric conditions (e.g., fog, rain, etc). Using both space-based and airborne surveillance, future paths of icebergs can be estimated with higher accuracy using a steady stream of data, enabling monitoring in all weather conditions (Mathieu, 2006).

Personal communication with another prominent Canadian academic (Marshall, 2007) suggests that there is a wealth of expertise on the sea ice modelling and prediction problem that could be accessed should this be an area of priority for Environment Canada and other stakeholders in maritime operations.

Hurricane and iceberg monitoring can be classified under strategic and tactical categories, based on their link to emergency evacuations and medium-range decision horizons. Sea ice monitoring seems to have a weaker link to the energy sector, with more repercussions on the operational realm. All three applications are at the supply side of the value chain.

7.2. The Impact of El Nino on Natural Gas Markets

The El Nino Southern Oscillation (ENSO) phenomenon is a global ocean-atmosphere coupling which has the effect of allowing long-range climate forecasts to be made. The ability to extract economic value from the resulting ENSO-based climate forecasts has been studied in agriculture (see Section 8.3) and in the annual operation of hydroelectric facilities (see Section 5.2).

Extensive anecdotal evidence linking the warming and cooling cycles produced by El Niño to natural gas and, to a lesser extent, crude oil prices is contained in, for example Klann (1997) and Gabrielski (2007). Such a predictable trend in natural gas prices should give gas buyers and sellers information about how best to conduct their sale and purchase of the commodity, as described in Changnon et al. (2000). Various financial theories stipulate that such information should be part of the pricing process in the natural gas futures and options markets. Therefore, further research in this area should be able to reveal such a link. To our knowledge, no properly constructed econometric study of this effect has been conducted in the Canadian setting. If, however, the effect can be shown to exist, it would have a major impact on the financial risk management activities of Canadian upstream oil & gas producers.

7.3. Exploration Activities

EP and related tools can provide new ways to plan and execute oil and gas exploration activities. Hyperspectral imaging, a new generation remote sensing technique, and its relationship with exploration activities will be discussed in this section. High-precision positioning and drilling applications and the impact of space weather on these applications will be discussed in Section 9.3.

Currently, almost all of remote sensing satellites in orbit have either panchromatic or multispectral imagers, collecting data from a few spectral bands and with limited resolution. In contrast, hyperspectral imagers can collect data in contiguous narrow bands simultaneously (up to several hundred bands) in the electromagnetic spectrum. It is expected that hyperspectral imagers can provide much more detailed data about the physical and chemical properties of surface features, a capability that can improve the current practices of oil and gas exploration (Gurtuna, 2005).
Hyperspectral imaging is defined as, "The simultaneous acquisition of images of the same area in many (usually 100 or more), narrow, contiguous, spectral bands." (NRC, 2005). Hyperspectral imaging is also known as imaging spectroscopy. All objects reflect, absorb, or emit electromagnetic radiation based on their composition and as such, have a unique spectra, or 'spectral signature'. As a result, objects can be identified and their material composition quantified by using a hyperspectral sensor that measure the intensity of solar energy reflected from the materials over hundreds of wavelengths. Hyperspectral imaging can be conducted from both airborne and space based sensors.

Among the various users of hyperspectral maps are oil, gas and mining companies, and government authorities. Its use in lithological mapping helps geologists decipher the overall lithologic and structural history of a region, and helps to define potential exploration targets. This application is of particular interest in areas where either no maps or generalized maps exist, such as in arctic environments, and can also assist in the detection of hydrocarbon micro-seepage (CSA, 2003). Its use in geobotanical mapping provides images identifying element-specific geobotanical anomalies and variations on the basis of absorption features or changes in the continuum of vegetation spectra. This application can shed vital information regarding geobotanical anomalies associated with ore bodies that may also be expressed as abrupt changes from one plant community to another, as a function of the underlying surficial geology, and not necessarily due to stress induced physiological changes in plants (CSA, 2003). This makes hyperspectral imaging an important tool for the energy sector in mapping for land development, pollution abatement, and mineral and hydrocarbon exploration.

Hyperspectral imaging can be used to monitor oceanic and coastal zone regions for oil spills. It can predict how oil spills disseminate in a body of water under current environmental conditions, and where it might affect sensitive sites. It can identify shoreline features and the severity of oil spills in environmentally sensitive areas such as coastal wetlands. It is also capable of determining the pollutant type. In the case of oil spills, it can determine if the spill is composed of crude or light oil. This information is important in helping cleanup crews identify the best cleanup method, the environmental impact of burning oil, and to predict the flow path, dispersion rates, and the time before a slick hits the shoreline (Salem, 2001).

Hyperspectral imaging is also used by the oil and gas and mining industries in environmental monitoring and operations planning. The ChevronTexaco Corporate Responsibility Report (2002) outlines the use of this technology in its operations in the Niger Delta. This area of operations is a delicate environment comprised of salty and freshwater swamps. Oil and gas activities can disrupt this environment. For example, pipeline construction or dredging activities that cross vegetation types can introduce salt water into freshwater zones causing damage to the freshwater habitats. Chevron Nigeria started to use hyperspectral data to conduct "environmental baseline" surveys to better monitor its operations' impacts on the environment over time. One of the objectives of the survey was to create a detailed map to accurately depict the different vegetation types of the region. By using this detailed map, the company can plan its construction activities to avoid sensitive areas and help preserve the balance of the ecosystem. Other operational activities, such as facilities planning, dredging, restoring impacted sites and developing environmental sensitivity index maps to aid in oil spill response are also part of this effort (ChevronTexaco, 2002).

Weather conditions influence the quality of the data collected. Knowledge of atmospheric conditions of temperature, wind direction, wind speed, incident solar radiation, humidity, haze, or aerosols are important to the collection and processing of hyperspectral images. This information is used to make image corrections for conditions in the atmosphere that interact with both the incoming solar illumination of the ground target and the reflected electromagnetic energy. Hyperspectral images are usually collected at or near solar noon, with the window being from about 2 hours prior to 2 hours after noon, ideally in clear weather (Gomez, 2002).

Considering that surveying can cost between $150 and $500 per square kilometre (CSA, 2003) and that there could be a number of other incremental costs resulting from the underestimation of resources leading to the decision to abandon a project, the underestimation of environmental damage in a pre-purchase audit, or reclamation costs that could haunt a company years after a site has been closed, hyperspectral imaging can provide concrete economic benefits.

Satellite derived data can play a significant role in new oil and gas exploration projects. Improved hyperspectral capability of remote sensing is particularly promising for exploration. OECD reports that, in addition to exploration efforts, space assets are also used extensively to monitor pipelines and to assist in major energy infrastructure projects (OECD 2005).

8. Renewable Energy

In the global energy mix, renewable energy sources and technologies play a modest role. With the exception of hydro, renewable energy sources provide only 2% of the total energy supply for electricity generation (IEA, 2006a). This figure includes almost all types of renewable energy sources, including geothermal, solar, wind, marine (wave and tidal), heat as well as combustible renewables and waste. In Canada, the percentage of electricity generated from renewables (other than hydroelectricity) is less than the global average, and is currently 1.4% of the total (McCarthy, 2007).

Although the adoption rate and installed capacity of renewable energy systems (especially wind and solar) are increasing at a rapid pace, the cost of electricity generated by such systems is still not competitive compared to more traditional, fossil-fuel based energy generation systems. Wind energy is arguably at the threshold of being cost competitive.

The cost of electricity produced by solar photovoltaic technology ranges between 35 to 45 U.S. cents per kWh (IEA, 2006b). The cost of generation using concentrating solar power (CSP) is in the range of 10 to 15 U.S. cents per kWh (Abboud, 2006; IEA, 2006b).

Wind energy systems, on the other hand, can generate electricity for as low as 3 U.S. cents per kWh (IEA, 2006b). However, depending on actual contract values, this figure can vary significantly. For instance, a recent contract signed by Hydro-Quebec pegs the cost of wind energy at 8.5 CDN cents per kWh, including transmission and other charges (Yakabuski, 2006).

For comparison, the cost of electricity generated from coal is 4-6 cents per kWh and the cost for natural gas generated electricity is 5-7 cents per kWh (Kammen, 2006; Roberts, 2004).

European countries have been systematically investing in renewable energy systems in the last decade, and they are beginning to reap some significant rewards. Their investment was not solely in the development of new renewable energy systems, but also in finding innovative solutions for resource assessment, design, grid integration and operational monitoring of these systems using multiple streams of environmental data. These streams include in-situ as well as remotely sensed data from airborne and space-based platforms.

Beyond the cost issue, other aspects, such as reliability and continuity of service, also need further improvements to achieve a wider diffusion of renewable energy systems. Most renewable energy sources are based on natural processes which fluctuate on different time scales, including daily and seasonal changes in the expected energy yield. Therefore, being able to predict these fluctuations and developing the necessary mitigation mechanisms are critical to ensure overall system security and reliability. There are numerous ways to achieve this objective where EP can play a key role, as discussed in the rest of this section.

8.1. Wind Energy

Wind generated power is being integrated into the energy grids in North America, Europe and other regions of the world at an increasing rate. Fuelled by the promise of an abundant, clean, and low-cost energy source, wind energy has provided up to 20% of electricity needs in some European countries such as Denmark and Germany (Mulholland, 2007). However, currently wind power accounts for only 0.7% of Canada's energy generation mix as of the end of 2006 (EER, 2007). Canada currently has almost 1,050 MW of installed wind capacity. In contrast, Germany and Spain have more than 18,000 MW and 10,000 MW in production, respectively (Blackwell, 2006a). Even with Canada's ambitious plans to increase its wind energy generating capacity over the next decade, current plans show that wind energy will encompass an average of only 5.5% of Canada's electricity generating capacity by 2015 (EER, 2007).

Integration of wind energy at a large scale into the Canadian electricity grid has resulted in some "growing pains". Critics argue that for certain wind farms, initial resource estimates, at the feasibility analysis stage, were overly optimistic and in certain cases, the margin of error in production capacity estimates was around 40% (Reguly, 2006; Yakabuski, 2006). Coupled with the intermittent nature of wind, such claims create an unfavourable image for wind energy and raise concerns regarding the reliability of wind energy. Recently, particularly in Alberta, the overall reliability of wind power was questioned as the share of wind power continues to increase in the overall supply of electricity in this province (Blackwell, 2006b).

As it will be discussed in this section, advances in wind forecasting can create multiple economic benefits, and help establish wind as a secure and reliable power source.

Wind turbines have been criticized as noisy, destructive to the aesthetics of the natural landscape, and dangerous to birds (Mulholland, 2007). However, the main factor impeding the large-scale integration of wind energy into the electricity grid is the concern that current methods of forecasting wind energy are unreliable. The sporadic nature of wind energy is problematic because energy suppliers must be able to meet demands for energy with an acceptably low probability of failure. The impact of failing to provide adequate capacity to meet demand can be so great, economically, socially and politically, that energy suppliers have traditionally been reluctant to rely on intermittent resources for capacity.

Therefore, the integration of wind to serve contractually obligated loads requires the ability to forecast wind within a certain level of confidence and in the planning horizons needed by the generation side of the energy value chain. From an operational perspective, some of these horizons include the following timeframes: 1, 2, 4, 6, 12, and 24 to 48 hours in advance (AESO, 2006). From a planning perspective, relatively accurate forecasts would be required anywhere from a week to 25 years in advance. A study conducted by the National Renewable Energy Laboratory (NREL) demonstrated that the goal of a wind forecasting project should not be achieving 100% accuracy, but balancing the degree of accuracy with the degree of benefit derived by that level of accuracy (NREL, 1995).

Wind power forecasting continues to be an area of research worldwide. Depending on the geographical, technical, and commercial nature of the various energy-related jurisdictions, different types of wind power forecasting platforms are being used. Most platforms incorporate a certain level of mesoscale [10] modelling to generate wind forecasts. Models include in-situ measurements, such as wind speed and direction, meteorological data, and other topographical data to generate wind data analysis and flow models, energy yield predictions and uncertainty analyses (Campbell, 2004).

In Europe, there are numerous initiatives using EP to support the development and operations of wind energy systems. For instance, satellite data is increasingly used for estimating the energy yield of prospective offshore wind farm sites. Compared to traditional methods (e.g., using an offshore meteorological mast to take wind measurements), satellite data not only provides cost-efficiency, but it also enables the analysis of multiple sites in a relatively short amount of time. Similarly, satellite data has also been used to measure topography and terrain roughness, important determinants of yield for onshore wind farms.

Given the size of Canada, using only traditional means (such as anemometers) for wind yield calculations can be prohibitively expensive. An alternative approach, as described by Choisnard et al. (2003), is to use satellite information. RADARSAT-1, a satellite designed and manufactured in Canada, provides such data using Synthetic Aperture Radar (SAR). Although traditional methods are still needed for data validation and accuracy, using "intermediate approaches" such as RADARSAT-1 data can result in significant cost savings (particularly when a high-level analysis over a wide geographic area is required).

Recently, the utilization of space-based assets, such as SAR and GPS, has proven useful in wind farm prospecting. For example, using numerical models that incorporate real-time data from satellites such as ERS-2, Météo-France generates daily sea-state forecasts. In addition to being broadcast as marine forecast bulletins this meteorological data is also used to validate derived geophysical data such as wind speed and wave height (Lefèvre, 2007).

Having the advantage of offering almost global coverage, with sufficient accuracy for most applications, the arrival of real-time altimetric data has encouraged the development of methods to extrapolate ocean surface observations in time and space. Many weather centres use wind and wave data from ERS-2 to estimate wave heights at any point (Lefèvre, 2007). Offshore wind power suppliers could use this information in both power potential prospecting and in offshore wind farm construction endeavours (Schneiderhan, 2004).

Denmark has emerged as a world leader in the field of wind energy. The Danish Meteorological Institute (DMI) reports that there are more than 5,000 wind turbines producing around 20% of the total electricity supply in the country. DMI's services have resulted in significant savings for the Danish energy sector, by providing wind forecasts

[10] Mesoscale refers to weather systems smaller than synoptic scale systems but larger than individual thunderstorm scale systems. Synoptic scale refers to a horizontal length scale of 1000 kilometres or more.

with a range of up to a week. These forecasts are used in the planning activities of the utilities that need to determine the amount of energy to purchase, in order to offset any significant drops in wind power (Danish Ministry of Transportation and Energy, 2006).

In recent years, the use of satellite derived information has been gaining importance in wind forecasting. Utilizing satellites for wind energy system planning, design and operations has multiple benefits:

- ☑ increased accuracy in statistical analyses through existing, publicly accessible databases containing decades of data
- ☑ a synoptic overview of wind fields
- ☑ improved forecasting algorithms from complementary in-situ measurements
- ☑ improved mesoscale models for short-term power generation forecasting
- ☑ environmental footprint analysis for offshore wind farms

More accurate wind forecasting can pave the way for larger scale integration of wind power into energy grids by decreasing the overall technical and economic uncertainties. Economic benefits can be realized on several fronts. At the operational and tactical levels, more accurate wind power forecasts will decrease the need for backup generation sources to compensate for the possibility of unanticipated outages as a result of low- or no-wind conditions (NREL, 1995). This translates into more efficient use of other energy generating assets, and more efficient utilization of transmission assets particularly in light of transmission congestion and redispatch issues (BPA, 2006).

Canadian utilities are starting to realise the importance of wind forecasting. Blackwell (2006b), quotes Don Tench, director of planning and assessments for Ontario's Independent Electricity System Operator, as stating "If we have a few hours notice of a significant wind change, we can make plans to deal with it". Furthermore, the economic benefits of more accurate wind forecasts increase through the reduction of fossil fuel use, particularly if the producer is accountable for emissions (NREL, 1995; Roulston et al., 2003; see also Section 5.1 on spinning reserves).

At the strategic level, better wind forecasting will assist in finding ideal sites for wind farms and optimizing the position of wind turbines within a wind farm. This can not only increase the generation capacity of an individual wind farm, but also result in economies of scale, if wind generators can be concentrated in regions where wind forecasts are maximized for accuracy. This could also result in targeted, cost-effective forecasts (NREL, 1995). These benefits can be compounded if the use of space-based assets for wind power forecasting proves to decrease the need for ground-based measurements.

One significant advantage of wind energy systems is their limited environmental footprint. Governments around the world support wind power for a number of reasons. Investments in such systems are generally perceived as concrete policy steps for increasing air quality and taking action against climate change. Wind power can also be seen as a new competitive element in electricity markets. For this reason, governments have often encouraged wind power production by giving wind producers a high guaranteed rate for their generated power. For example, in Ontario wind producers receive 13 cents per kWh generated in a market which, on average, rewards other producers with about 6-7 cents per kWh. Even in jurisdictions where there are no special treatments, environmentally conscious consumers can sometimes be persuaded to pay a premium for "wind generated electricity", which is marketed along much the same lines as fair trade products, such as coffee.

Photo: Turquoise Technology Solutions Inc. © 2006

Figure 15: A Wind Farm in Spain

However, as wind turbines provide an increasing share of generating capacity, they will need to participate in the electricity market without special financial protection. Electricity markets have recently been deregulated in many jurisdictions worldwide including, in Canada, the provinces of Alberta and Ontario, where wind energy is becoming increasingly important. As described in Section 4.3, in most deregulated markets, electricity is priced according to a daily auction of blocks of power running 24 hours in advance. This presents problems for wind power producers; unless the wind can be reliably forecast 24 hours in advance, it is possible that bids will be made and accepted on blocks of power that are not, in the end, available.

Even if this uncertainty regarding the availability of wind power cannot be fully resolved, it must still be incorporated into any meaningful engineering economic analysis of wind power. Such an engineering economic analysis would need to incorporate well-validated spot price models for electrical power (see for instance Davison et. al 2002 and Anderson & Davison 2005), as well as bidding algorithms designed to incorporate flexible operational decisions (see for instance Thompson Davison & Rasmussen 2004 and 2007, and Anderson Davison & Rasmussen 2005).

Increasing the overall reliability of wind power systems and ensuring their continued presence in the electricity markets can be achieved through a combination of methods:

- ☑ New engineering solutions can be developed to enable wind energy storage, such as pump storage systems or microhydro facilities. The optimal design of such facilities requires extensive engineering economic analysis, and will draw on the same references as above.
- ☑ The rules of power markets could conceivably be rewritten to give wind producers some additional flexibility.
- ☑ Financial contracts could be purchased to hedge the risk to the wind producer.
- ☑ Significant improvements can be targeted in the accuracy and range of wind forecasts, reducing uncertainty both at the individual producer and the overall market levels.

Clearly, forecasting can play an important role in managing the impact of wind energy on system operations and costs. However, the impact is directly tied into its appropriate use in the control room. The value of wind forecasting was shown very clearly in a study that General Electric (GE) conducted for New York Independent System Operator (NYISO) with primary support from the New York State Energy Research and Development Authority (NYSERDA). The study looked at the implications of integrating 3,300 MW of wind generation capacity (10% of NY State peak load) on the reliability of the New York State Bulk Power System (NYSBPS). The study also examined the variable cost reductions of market operations costs, such as the costs of dispatch, the unit commitment costs and the start-up costs.

The GE study simulated the hourly operation of the NYSBPS for several years. Simulations were run with and without wind generation into NYISO's unit commitment and day-ahead market, and with and without day-ahead wind generation forecasts. The operating cost impacts are summarized in Table 8. The simulation results also indicated a $1.80/MWh average reduction in the spot price in New York State (Piwko, 2005).

Without a forecast, the variable cost reduction of integrating 3,300 MW wind generation (10% of NY State peak load) was US$335M. With a state-of-the-art day-ahead forecast, there was an additional variable cost reduction of about US$95M which equated to a value difference of about $10/MWh for wind energy (Smith, 2007).

8.2. Solar Energy

In recent years, the installed capacity of solar energy systems has been increasing at a rapid pace, and many new solar energy products have been introduced into the global marketplace. The diversity of solar energy products is astonishing: from individual units generating a few watts to provide lighting inside a tent, to solar power plants in the megawatt-class providing electricity to thousands of households.

Broadly speaking, there are two kinds of solar power systems: solar photovoltaic (PV) and concentrating solar power (CSP). As explained in Section 4.1, solar PV technology generates electricity by direct conversion of electromagnetic radiation into electrical current. CSP, on the other hand, relies on the thermal conversion principle discussed in Section 4.1, where the solar radiation is focused on a single point (or a small area) to heat a liquid (e.g., liquid sodium) which also stores the energy. This energy is then used to create steam to power a turbine. In addition to electricity generation, the same principle can also be used to heat water for residential or industrial use. The latter application of CSP technology is scaleable and it delivers a cost-efficient substitute to other fuel types for heating water, such as natural gas. Both PV and CSP forms of solar power can be used in centralized as well as decentralized power system architectures.

Environmental Predictions can play a key role in the evolution of the solar energy market, and provide benefits at multiple levels of decision-making over different timescales.

At the strategic decision-making level, one particular area of EP application is the estimation of ground irradiance for solar energy plants, a critical parameter for site selection. For this purpose, meteorological satellite data for solar irradiance is used in combination with other earth observation capabilities such as Digital Elevation Models and cloud cover measurements (Schillings et al., 2004; Gurtuna, 2006). For site selection analysis, having access to long-term time series is highly desirable, since it can dramatically increase the accuracy of solar irradiance estimates for a given site (Mathieu, 2005).

This capability can also be used to support operational decision-making: plant managers can compare the actual energy production with the estimates from satellites on a continual basis. A wide spread between these two values can help identify potential problems with the performance of solar plants.

Photo: Turquoise Technology Solutions Inc. © 2006

Figure 16: An Experimental CSP System (Almeria, Spain)

Recently, the interest in satellite-derived solar energy information has spread to many different sectors, including financial institutions. Today, such information is being used for strategic decisions such as site selection (e.g., map products), as well as site qualification (e.g., time-series products). ESA reports that time-series of at least 10 years are required by the banks in Spain as part of the due diligence for extending loans to solar energy investments (ESA, 2006). Given that the scale of such investments has reached the level of 200 million euros for a single project, the economic importance of EP becomes clear. ESA indicates that for most places in the world this due diligence process can only be achieved through the use of operational meteorological satellite data.

European research institutes and industry have joined forces to build capacity in extracting and disseminating environmental data for managing solar energy investments. One such effort, the ESA-ENVISOLAR project, was designed to retrieve solar irradiance data from European Meteosat and Meteosat Second Generation Satellites, at time scales ranging from near-real-time observations to datasets spanning more than 10 years of historical data (Scroedter-Homscheidt et al., 2004).

This temporal resolution, as well as the corresponding know-how in extracting solar irradiance data from multiple streams of satellite data, has made a number of innovative applications possible. These applications can be used both at the strategic level of decision making (such as determining the optimal location for solar power plants), and at the operational level (such as plant management services including operational monitoring and fault detection). These applications fall under the supply side of the value chain and they can be used for both solar thermal and photovoltaic power plants.

8.3. Biofuels and Ethanol

The use of biofuels for transportation is of increasing interest for countries around the world. In Brazil, an emerging leader in this field, automobiles are fuelled by a mix with a large component of sugar-cane-waste-derived ethanol. In North America, the focus is on ethanol derived from corn. The Government of Canada has, in the recent 2007 budget, indicated strong support for ethanol programs: "Over the next seven years, another $1.5 billion will be used to provide incentives to business to develop renewable fuel alternatives to gasoline and diesel. The government is aiming for a 5% renewable fuel content in gasoline by 2010 and will now subsidize production to the tune of $0.10 per litre for gasoline alternatives and $0.20 per litre for biodiesels." (Conference Board of Canada, 2007)

Although ethanol proponents emphasize its various environmental and economic benefits, ethanol production has been a controversial topic for a number of reasons. The first argument against ethanol is based on the "energy equation": critics argue that the amount of energy required to create the ethanol is comparable to, or even more than, the amount of energy contained in the ethanol fuel; see for instance Seungdo & Dale (2005), Patzek et al. (2005), and Shapoori, Duffield, & Wang (2002). It should be noted that, depending on where the energy input is obtained, this may not necessarily be a deterrent, for instance if electricity derived from wind power can be used along with corn as a production input, then one could obtain a substitute for gasoline through wind power, which could be worthwhile even if energetically inefficient. The second concern is that, as the ethanol demand grows, it will consume an ever-increasing fraction of the North American corn harvest, bringing up the price of corn in the process.

Recent surge in corn prices seems to highlight this link between demand for ethanol and corn prices. It is possible that this link can evolve into a coupling between weather-dependent corn markets and gasoline markets. It is interesting to note that, a significant amount of research work has already been done linking climate variables (Corn Heat Units) with corn production. In a comprehensive survey of the economic value of meteorological services, Gunasekera (2003) quantifies the value of ENSO-based long range forecasts to the agricultural services.

At planting time each year, corn farmers select a particular hybrid, or variant, of corn. These hybrids are bred to work best for a given soil type and a given temperature regime, characterized by a so-called Corn Heat Unit (CHU) forecast for the region. The CHU forecast is obtained by combining the daily temperature over an entire growing season, stopping at first frost. Maps detailing the historically obtained CHUs for a given geographic location are produced by government agriculture agencies. For an Ontario example see Brown & Bootsma (1993).

The decision problem of a farmer can be summarized as follows. The farmer faces a trade off in her selection of hybrid. This trade off can be described in the following table, where the yield numbers are for indication only.

	Cool weather hybrid	Hot weather hybrid
Climate is cool	Yield of 12	Yield of 10
Climate is warm	Yield of 8	Yield of 15

Table 7: Corn Farmer's Decision Problem

Thus selecting a cooler weather hybrid is safer but does not allow for an optimal harvest if the weather is warm. If improved climate forecasts are available, both for secular changes caused by climate change and for year to year variation, such forecasts can also help farmers to optimize their selection of corn hybrids. All other factors remaining the same, better hybrid choices can help improve the corn yields, allowing for more use of corn to produce ethanol without increasing the market prices. The chain of reasoning for this decision problem is fairly long, and there are many uncertainties at each link of the chain. However, quantifying the improved value of a seasonal forecast on the ethanol market seems to be feasible.

8.4. Other Renewables

There are other types of renewable energy sources which are at the beginning of their development cycle, such as wave and tidal energy systems. There are also more established renewable energy sources elsewhere in the world, such as geothermal, which are not common in Canada. For these reasons these renewable energy sources will not be discussed in detail in this report.

9. The Impact of Space Weather on Energy Systems

Space weather is defined as "Conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health" (NSWC, 1995).

Although the space environment seems removed from our daily lives, in reality, space weather can pose significant risks to satellite operations, communications, navigation, electric power distribution grids and pipelines, systems we rely on everyday. Elements of space weather, such as solar flares and coronal mass ejections, can interact with electricity transmission grids and oil pipelines, causing significant damage. One way of mitigating these risks is to achieve advances in space weather forecasting and to give operators of energy transmission networks sufficient time to react and protect their networks. Avoiding these risks and corresponding socioeconomic losses can only be possible through a better understanding of the Sun-Earth system and by building early warning systems.

Canada is actively involved in various space weather research projects. One such project is a NASA-led mission called THEMIS (Time History of Events and Macroscale Interactions during Substorms). This mission will help scientists better understand the Earth's magnetosphere and determine where and why solar wind energy is released, causing the Aurora Borealis, "Northern Lights" (McIlroy, 2007). The total budget of this mission is US$ 200 million. Canada's contribution includes 16 automated terrestrial observatories across the country to monitor the sky for Aurora Borealis, at a cost of $1.4 million.

9.1. Electricity Grids

One of the most cited space weather incidents occurred in March 1989 in Canada. A solar storm caused the Hydro-Quebec power grid to collapse for over nine hours affecting 6 million customers. The economic consequences of the 1989 space weather incident have been summarized in a recent report (ISU, 2006). The total estimated loss was over US$30 million ($10 million of this amount is attributed to Hydro Quebec's loss). The remaining amount includes the loss suffered by Public Service Electric and Gas in New Jersey where the transformers had to be replaced and replacement electricity had to be found (at a total cost of more than $24 million to the company). This estimate does not include the costs incurred by the customer due to loss of business and other activities. There are no accurate estimates of this loss. However, NOAA indicates that the losses were "in the tens — if not hundreds — of millions of dollars" (NOAA, 2004)[11].

[11] Space weather is not the only natural phenomenon which can adversely affect transmission networks. Danish Ministry of Transport and Energy (2006) reports that lightning strikes can also pose a serious risk. Environmental data can be helpful in locating the reported errors across the system and speeding up the repair efforts.

Among the lessons learned from the 1989 incident, NOAA indicates that "comprehensive real-time protective space weather prediction services could have significantly reduced damages and costs". In the case of Hydro Quebec, the company opted to solve the problem by installing devices to block the entry of geomagnetically-induced currents (GICs) into its transmission network.

It is interesting to note that there is no consensus on the estimates for the total economic loss from the 1989 space weather incidence. A European Space Agency (ESA) publication cites an estimated economic cost of approximately $6 billion as a result of the service outage, and a further $1.2 billion incurred by Hydro-Quebec for system hardening and upgrading (ESA, 2001).

9.2. Pipelines

Another area where space weather can cause adverse effects is the oil and gas pipeline systems, particularly at higher latitudes. Due to the conducting nature of the pipeline material, GICs can cause a potential difference between the pipeline and the surrounding soil (ISU, 2006). This difference, in turn, can cause corrosion on the pipelines.

Contrary to its lightning fast impact on the electricity grid, space weather affects the pipelines over a much longer time scale. Therefore, it is difficult to estimate the exact economic losses incurred on pipelines that are attributable to space weather events. However, as an indication, a study has demonstrated that approximately 10% of the pipeline wall thickness was lost to corrosion induced by GICs over a period of 14 years (ISU, 2006).

The timescale for corrosion is also related to the coating material used on the pipeline and it can range from a period of months for uncoated systems to years for coated systems (ESA, 2001). It is estimated that in the U.S. and Canada, there are about 6,000 km of pipelines at an average cost of US$1 million per kilometre. The cost of a cathodic protection system ranges from 0.1% to 0.2% of project budgets. For very large projects, this additional cost translates into expenses on the order of hundreds of millions of dollars.

The benefit of space weather monitoring for pipeline operations comes principally from the ex-post analysis of geomagnetic activity from which GICs can be modelled. These models, in turn, can be used to assess possible levels of corrosion. Nowcasting would also benefit operators and allow them to postpone tests of cathodic protection systems (Rodgers, 2002).

9.3. High-precision Positioning and Drilling Applications

Resource prospecting and extraction are two areas that are directly impacted by space weather and could benefit from a comprehensive space weather forecast, nowcast, and post-event assessment service. Space weather events can cause errors in magnetic surveying results, drilling accuracy, and navigation of offshore oil rigs utilizing Dynamic Positioning (DP) systems (ISU, 2006).

Magnetic surveys are an essential tool in determining subsurface properties and are typically used in mineral and petroleum exploration and earthquake fault analysis (Rodgers, 2002). Satellites, aircraft, and ships carrying magnetometers are used to generate a contour map of magnetic intensity. These maps can be compared with other information to make inferences about the underlying rocks. Variations in the Earth's magnetic field, as a result of space weather, corrupt the generated data. Corrections can and must be made before the data is useful. This is extremely relevant to drilling operations that use models of the Earth's magnetic field to steer the drill bit in the required direction.

The importance of space weather forecasting to the oil and mineral extraction industries is echoed through the extensive geomagnetic measurements carried out by national authorities, such as the British Geological Survey (BGS) through their Commercial Geomagnetism Information and Forecast Service, and by international collaborations, such as INTERMAGNET (Rodgers, 2002). The economic value of space weather information comes from the accurate ex-post data of the temporal component of the magnetic field. This allows correction of both survey data and drilling direction. Forecasts of geomagnetic disturbances are of lower importance, but could influence scheduling of survey measurements (Rodgers, 2002).

In addition to the geomagnetic effects, space weather events can cause ionospheric scintillations. The National Space Weather Program (NSWP) lists ionospheric scintillation as one of the key components of space weather that require monitoring, nowcasting, and forecasting (JPL, 2007b). These are signals that present random temporal fluctuations in both amplitude and phase when received at an antenna. There is a higher occurrence of ionospheric scintillations during space weather events (JPL, 2007b). Ionospheric scintillation causes signal power fading, phase cycle slips, receiver loss of lock, and degradation of satellite navigation data.

The offshore oil industry is vulnerable to ionospheric scintillation because it corrupts the operation of Dynamic Positioning (DP) systems. DP uses onboard computer-controlled propellers and satellite navigation technology to maintain a vessel's exact position without using conventional moorings. This allows operations at sea where mooring or anchoring is not feasible due to deep water, or congestion on the sea bottom from pipelines or templates. It is estimated that, as of 2002, there are more than one thousand oil industry related DP ships in the North Sea, Persian Gulf, Gulf of Mexico, West Africa and off the coast of Brazil (IMCA, 2007). Space weather monitoring and forecasting could provide data that would be used to make the necessary corrections to counter the effects of ionospheric scintillations.

10. EP and the Financial Markets

Environmental Predictions can create a variety of economic benefits for the financial markets. Increasingly, weather related events are affecting the performance of various financial instruments. From relatively infrequent events such as a devastating hurricane to daily events such as a temperature forecast, the environment is becoming an integral part of the financial markets. Emerging financial markets, such as climate exchanges[12], are further evidence of the important relationship between the economic and environmental realms.

However, not being able to understand the full extent of this relationship, or using incomplete information for betting decisions can prove disastrous as evidenced by the recent experience of Amaranth LLP (Amaranth Advisors; Wikipedia article, 2007). Amaranth LLP was a hedge fund headquartered in Connecticut. Their star trader, Calgary-based Brian Hunter, had been making increasingly large and very successful natural gas trades which net the company literally billions of dollars. During the early fall of 2006, Hunter put on a trade on the spread between September expiry and October expiry natural gas futures. At its simplest, this was essentially a bet that a hurricane would hit the Gulf of Mexico drilling platforms again, as had happened in the fall of 2005. Mr. Hunter's bet incorporated more than just the hurricane prediction: his bet has also cleverly incorporated published US natural gas storage levels (see Section 6.1 for more details on natural gas storage). However, the expected hurricane did not materialize and Mr. Hunter's bet went awry. Amaranth ended up losing US$3.5 billion on the trade, bringing the whole hedge fund down with it.

The Amaranth case is an interesting counterpoint to the evaluation framework presented in Section 3, specifically to the idea that information is only typically worth some small fraction of the related sensitivity of the sector to the forecast event. The nature of the financial markets could provide an explanation: today, the markets allow greatly levered bets to be placed on information, sometimes even allowing the financial impact of a forecast to be greater than the underlying asset or commodity. This is despite well accepted financial markets research such as contained in (Roll, 1984) which suggest that commodity price volatility cannot be explained by news (such as that provided by weather forecasts) alone.

10.1. Weather Derivatives

Weather derivatives are another interesting case at the intersection of environment and financial markets. Weather derivatives are financial derivatives which depend on the measured value of some meteorological variable, typically temperature (cast in the form of heating- or cooling-degree days, HDDs or CDDs). See Bah (2002) for an excellent overview of these together a data intensive bootstrap-based pricing methodology for valuing them. See Jewson & Penzer (2006) for a trend-based technique for incorporating temperature forecasts into the pricing of these securities. For links between weather

[12] For more information on climate exchanges, emissions trading and Environmental Predictions, please see Appendix 3.

derivatives with the valuation of environmental forecasts see Hertzfeld, Williamson & Sen (2003) and Williamson, Hertzfeld & Cordes (2002).

10.2. Catastrophe Bonds

Another financial product with strong links to environmental prediction is the so-called "catastrophe bond". Catastrophe bonds are designed to provide a financial market based alternative to the reinsurance market and they are issued by very creditworthy companies. Typically they are structured in the following way: if insurance claims arising from a particular type of catastrophe (for instance a hurricane) are less than a certain threshold, they pay a high rate of interest (or coupon) to their holders. If, on the other hand, an economically damaging hurricane does occur, the bond holders only get their principal back, with no interest. The issuer of the bonds, typically an insurance company, can afford to pay the higher-than-normal coupon when insurance claims are low. The impact of catastrophic events is partially offset by the low coupon in the years when insurance claims are high. These bonds are theoretically also appealing to investors, because they provide a source of risk (and corresponding return) which is largely uncorrelated with the broader financial markets.

In light of the arguments provided in this literature review, one would expect a very strong interest in weather derivatives and catastrophe bonds. Energy traders, whose commodities of choice are so dependent on the weather (especially the temperature), should have an immense appetite to trade in these contracts. The surprising fact is that, so far, the interested has been very limited for weather derivatives and catastrophe bonds. It is possible that one reason for this lack of interest is a shortage of well understood, well validated data, provided by trusted data providers such as national meteorological offices. One impact of better environmental prediction of all types might be the strengthening of weather-based financial markets, with the attendant social benefits of more efficient and transparent risk transfer.

It is possible that in the future, not only atmospheric events, but also space weather phenomena can be incorporated into financial markets, and new financial products can be designed to better manage risk associated with space weather. Catastrophe bonds could be an ideal candidate to absorb the risks of companies exposed to risks caused by space weather. These companies could transfer this risk to the financial markets. In such a scenario, space weather forecasting could have significant value to market participants, including the insurance companies

11. Conclusions

This literature review was designed with the intent of analyzing the impacts of Environmental Predictions on the energy sector in a structured and rigorous way. It is the hope of the research team that the findings presented in this report will be put to practical use, and prepare the groundwork for more detailed analyses in the future.

With regards to the economic benefit analysis of forecasts, one of the most fundamental insights identified in this report relates to the use of the forecast information. For there to be any value, the information has to be "actionable". If the information cannot be used to take action, or the marginal impact of the decision is negligible, then no matter how accurate or long-term the forecast might be, the economic value is minimal.

On the other hand, if the forecast provides exclusive, timely or actionable information, then, in most cases, it has a positive value. However, it should be noted that the cost of acquiring this information is also part of the equation and not all forecasts with a positive economic value will prove to be worthwhile once the cost aspect is incorporated into the valuation.

As various cases presented in this report have demonstrated, EP has a rich set of applications in the energy sector, touching all levels of decision making and covering the whole energy value chain. Although this richness signals a significant potential for the use of EP in the energy industry, it also creates more responsibilities for both policy makers and the industry itself. Given the limited resources in both public and private sectors, the real challenge will be determining the optimal subset of EP applications to invest in.

Borrowing yet another financial concept, perhaps one could argue that a portfolio management approach would be an ideal candidate to address this issue. A portfolio in which the objective is not just to minimize the risks posed by the environment to the energy sector, but also to maximize the benefits of the environment to the energy industry and to the Canadian public.

11.1. Summary of Economic Benefits of Environmental Predictions in the Energy Sector

As discussed in the previous sections, various applications of Environmental Predictions already generate a significant amount of economic benefits in the energy sector. Table 8 provides a summary of these benefits.

Description	Benefit	Type of Forecast	Use	Estimated Value
Spinning Reserve Electric Generation	▪ reduced dependence on spinning reserves and AGC ▪ economic savings through fuel savings ▪ reduction of emissions	▪ short-term forecasts	▪ incorporated into scheduling decisions	▪ US$366 million per year to the U.S. electrical industry (NOAA-NESDIS, 2002)
		▪ U.S. National Weather Service Forecast	▪ scheduling of US hydroelectric plants	▪ US$139 million per year (NOAA, 2004)
		▪ perfect weather forecast information	▪ incorporated into US scheduling decisions	▪ additional US$69 million per year (NOAA, 2004)
		▪ short-term demand based on weather variables	▪ in all applications of short-term load forecasting and spinning reserve management	▪ £66 million per year to the U.K. private sector (Teske & Robinson, 1994
		▪ 24 hour temperature forecasts	▪ improve US unit commitment decisions	▪ US$166 million annually (Teisberg, Weiner and Khotonozad 2005)
		▪ perfect 24 hour temperature forecasts	▪ improve US unit commitment decisions	▪ US$75 million annually (Teisberg, Weiner and Khotonozad 2005)
Hydroelectric Electric Generation	▪ optimal operation of hydroelectric plant	▪ long-range inflow forecasts	▪ flow rate projection use operations	▪ Columbia River watershed utilities case: US$161 million per year (Hamlet, Huppert & Lettenmaier 2002) ▪ Missouri river basin utilities case: US$10 million per year (Maurer & Lettenmaier 2004)
		▪ improved one-month to one-year stream flow forecasts	▪ flow rate projection use operations	▪ single reservoir system of the California State Water project case: US$0.4 to $0.8 million annually (William et. al 1982)
		▪ low water levels forecast	▪ flow rate projection use operations	▪ Manitoba case in spring of 1981: potential reduction of US$80 million loss (Philips 1986)

Peaker Units Electric Generation	▪ "shave" the peak and reduce the need for the peakers reduces photochemical smog	▪ short-term weather forecasts	▪ demand management	
Wind Energy Generation	▪ better site selection, site construction, and wind farm investment decisions for both on-shore and off-shore wind farms	▪ historical and predicted wind speed and direction ▪ sea-state and height forecasts	▪ wind data analysis and flow modelling	
	▪ enable large scale integration by decreasing uncertainty ▪ decrease backup generation sources ▪ more efficient use of energy generating assets ▪ more efficient utilization of transmission assets ▪ reduction of fossil fuel use	▪ day ahead wind speed and direction forecasts	▪ energy yield predictions ▪ uncertainty analyses ▪ unit commitment management	▪ $10/MWh for state-of-the-art day ahead forecast in NYSBPS (Smith, 2007)
Solar Energy Generation	▪ make better site selection, site qualification, and solar farm investment decisions for both PV and CSP farms	▪ solar irradiance measurement ▪ cloud cover	▪ estimation of ground irradiance ▪ operational decision-making & plant efficiency management	
Biofuels and Ethanol	▪ improve harvest yields ▪ increase amount of fuel without increasing prices	▪ mid-term to long-term climate forecasts	▪ selection of harvest time and crop	
Storage & Transmission of Oil & Gas	▪ increase efficiency gains in the construction and operations of natural gas pipelines ▪ reduce "overbuilding cost" to facilitate natural gas storage ▪ shave peak pipeline usage ▪ profit from shorter time scale price fluctuations	▪ short-term temperature forecasts	▪ natural gas supply & demand management	
	▪ assessment of levels of corrosion	▪ space weather monitoring ▪ space weather nowcasting	▪ ex-post analysis of geomagnetic activity from which GICs can be modelled ▪ postpone tests of cathodic protection systems	▪ 10% of pipeline wall thickness loses to corrosion induced by GICs over a 14 year period (ISU, 2006)

Electricity Transmission	▪ more efficient use of resources	▪ windstorm & lighting forecasts	▪ allocation of resources to line maintenance crews	
	▪ increased transmission safety operations ▪ decreased environmental impact in emergency situations	▪ long term wind speed distribution trending trends	▪ influence transmission line installation codes relative to surroundings	
	▪ provision of sufficient time to react and protect transmission networks ▪ socio-economic loss prevention from service interruptions	▪ space weather forecast (including ex-post data of the temporal component of the magnetic field)	▪ energy transmission network management	▪ March 1989 incident: over US$30 million ($10 million of this amount attributed to Hydro Quebec's loss. Remaining amount includes loss suffered by Public Service Electric and Gas in New Jersey where transformers had to be replaced and replacement electricity had to be found at a total cost of more than $24 million to the company), (ISU, 2006) ▪ March 1989 incident: economic cost of approximately $6 billion from service outage, and $1.2 billion incurred by Hydro-Quebec for system hardening and upgrading (ESA, 2001)
Offshore Oil & Gas Operations	▪ increased crew and operations safety	▪ hurricane intensity and trajectory predictions	▪ manage various risks caused by hurricanes	▪ US$15 million for a 50% improvement in hurricane forecast accuracy (Considine et al., 2002)
	▪ increased crew and operations safety	▪ synoptic maps of sea-surface height	▪ tracking eddies in near-real time ▪ operational monitoring of offshore infrastructure	▪ prevention of $100 million, including lost production revenue (CBC, 2005) – based on 2005, evacuation assessment of two platforms due to rocket launch risk

	▪ increased crew and operations safety ▪ savings in transportation time and fuel costs ▪ prevention of environmental damage from ocean floor	▪ sea ice monitoring and prediction	▪ tracking sea ice and icebergs ▪ route planning ▪ iceberg towing or deflection	▪ prevention of $100 million, including lost production revenue (CBC, 2005) – based on 2005, evacuation assessment of two platforms due to rocket launch risk
	▪ efficiency in dynamic positioning (DP) systems	▪ Space weather monitoring and forecasting	▪ make necessary corrections to counter effects of ionospheric scintillations	
Exploration & Drilling Activities	▪ more accurate resource exploration, site construction, and environmental impact assessment and remediation activities	▪ atmospheric conditions (temperature, wind direction, wind speed, incident solar radiation, humidity, haze, or aerosols)	▪ image correction for conditions that interact with both the incoming solar illumination of the ground target and the reflected electromagnetic energy in hyperspectral imaging	
	▪ more accurate and less costly surveys & drilling operations	▪ space weather forecast (including forecasts of geomagnetic disturbances and ex-post data of the temporal component of the magnetic field)	▪ corrections to magnetic surveys generating contour map of magnetic intensity for determining subsurface properties ▪ better scheduling of surveying activities ▪ correction of drilling direction	
Financial Markets	▪ financial gains by trading companies ▪ prevention of financial losses by trading companies ▪ strengthening of weather-based financial markets such as catastrophe bonds ▪ social benefits of more efficient and transparent risk transfer in insurance sector	▪ environmental prediction (including weather forecasts, climate forecasts, hurricane forecasts, space weather forecasts, etc.)	▪ information to support trading decisions	▪ 2006 Amaranth LLP loss of US$3.5 billion on trades based on published US natural gas storage levels and expectation that a hurricane would hit the Gulf of Mexico drilling platforms again, as had happened in the fall of 2005 (Amaranth Advisors; Wikipedia article, 2007)

Table 8: Benefits of EP Applications - Summary

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Appendices

Appendix 1 Building Intuition: Dice Games

Although quantifying the economic benefit of Environmental Predictions is a complex undertaking, the building blocks of valuation are actually quite intuitive and can be explained by the following games.

Dice Game I: Illustrating the Value of a Weather Forecast

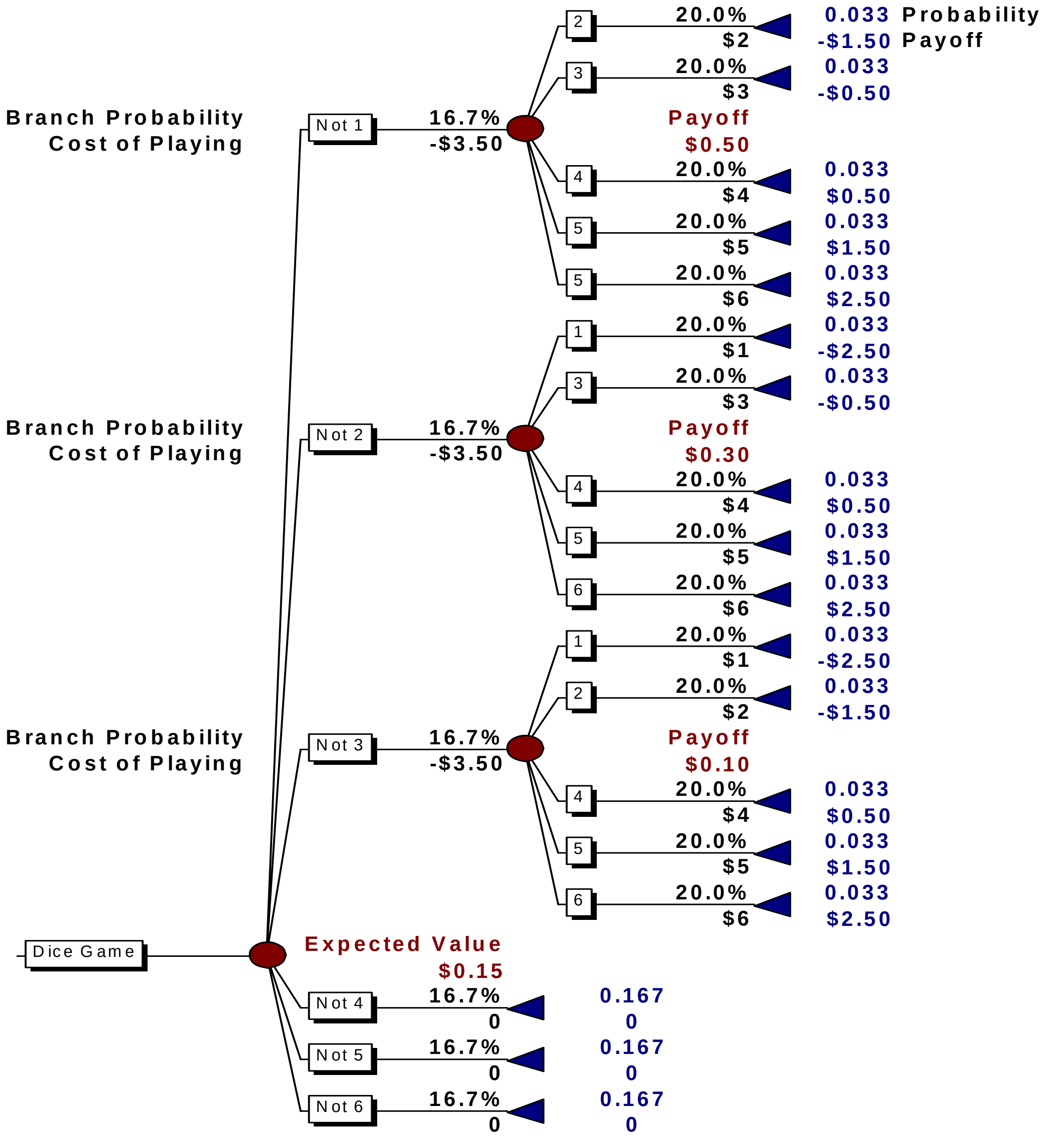
Assume you can buy the chance to roll a dice, and that you get paid $1 per spot. If the chance to roll the dice costs $3.50 and you were an expected value decision maker you would be indifferent between buying and not buying.

What if you could perfectly predict whether the dice roll would be even or odd? Then you could make on average $0.25 per roll from this. How? If you know it will be odd, then the expected dice roll will be 1/3(1+3+5) = $3, so you would not buy in at $3.50. On the other hand, if you know it will be even, then the expected dice roll will be 1/3(2+4+6) = $4, so you will buy at $3.50 and sell at an average of $4, making 50 cents. Given this ability to predict, half the time you can make 50 cents, and the other half the time you choose not to play and lose nothing.

An extension to this scenario is one in which you don't get any indication of the rolled values, except that you will know what the value will not be (cost to play is again $3.5). What if, for instance, there is a 1/6 chance you know it will not be 1, but it is uniformly likely to be any integer from 2 to 6? How much would a forecast of this kind be worth?

Half the time such a forecast tells you not to bet (if you know that the dice will not roll 4,5, or 6). The other half the time it gives you an edge.

If you know it won't be 1, the expected value is 0.2(2+3+4+5+6) = 0.2(20) = $4, so you make $0.50.



If you know it won't be 2, the expected value is 0.2(1+3+4+5+6) = 0.2(19) = $3.8 so you make $0.30.

If you know it won't be 3 the expected value is 0.2(1+2+4+5+6) = 0.2(18) = $3.6 so you make $0.10.

Therefore, on average, you make 30 cents half the time and you do not enter the game (and hence lose nothing) half the time. So your expected value of this information is 15 cents.

Armed with this information, you can also decide to create alternative strategies. For instance, you can decide to significantly lower your downside: if you use it to bet only when 1 has been removed from the suite of options (top branch in the figure above, with 1/6 probability), you make 50/6 cents on average, but the most you ever lose to do this is $1.50. ($3.50 – $2).

Real Options Theory: A Gentle Introduction

Real options theory provides a new perspective on strategic decisions and the value of flexibility. Another dice game illustrates some features of real options and shows that value and optimal operation are jointly determined.

In the game, as a player you get to roll a regular die three times. After each roll you are entitled to the same number of dollars shown on the dice. But once you take the money, the game ends. As soon as you roll a 6, it is optimal to take the money and end the game (there is no point in waiting for a better roll). However, in other cases, such as rolling a 5, the decision rule is not as clear, you need an “operation strategy”. The value of the game will depend on this operation strategy. As in the previous dice game, we assume that we can value the game by computing its expected value.

This problem can be solved using a technique called stochastic dynamic programming.
As in all other types of solutions based on dynamic programming, we start our calculations at the end of the game when the uncertainty is resolved and roll back our calculation until we hit “time zero” (the point in time where we roll the die).

We will assume that the game will end at the end of the third roll and begin our analysis at this point. In this case the operation strategy is simple – no matter what you roll, take the money.

Now we can progress “back in time” to the second (equally, second-last) roll. You can expect to get (on the average) 1/6($1) + 1/6($2) + … + 1/6($6) = $3.5, by waiting for the last roll, so you will only take the money at the end of the second roll if you get a 4, 5, or 6.

Taking one more step back in time, we now analyze the strategy for the first roll. We start by computing the expected value of waiting for the second roll: if, at the second roll, you get a 4, 5, or 6 you take the money and end the game. If, however, you roll 1, 2, or 3 you wait until the third roll, choosing an expected value of $3.5. Thus, from the vantage point of the first roll, by deciding to proceed to round two, half the time you will get $3.5, 1/6 of the time you will get $4, 1/6 of the time $5 and 1/6 of the time $6. Combining these values gives $3.5/2 + 1/6($4+$5+$6) = $1.75 + $2.5 = $4.25. Therefore, as an expected value decision maker, you should proceed to the second round if you roll 1, 2, 3 or 4 on the first roll, ending the game only if you get $5 or $6.

Following these steps, and rolling back the calculations, we now have an optimal “operation strategy”: on the first roll, take the money if you roll a 5 or a 6, otherwise proceed to the second roll. On the second roll, take the money if you roll a 4, 5 or 6, otherwise proceed to the third roll. On the third (and final) roll, take the money no matter what the realized value on the die is.

Once we have determined this operation strategy, computing the value of the whole game is relatively easy:

V = (2/3)*($4.25) + (1/6)*($5+$6) = $4.66

The first part of the value calculation is based on the fact that 2/3 of the time you proceed to roll two (and, depending on the outcome of roll two, possibly you proceed to roll three). We have already computed the value of these last two rolls assuming optimal operation at the second roll: this value is $4.25. Finally, the second part of the calculation is based on the decision rule for roll one: there is 1/3 chance that you will take the money at the first roll and end the game.

Appendix 2: Meteorology and Climatology: Some Basic Concepts

Weather is defined as the state of the atmosphere at some place and time, described in terms of such quantitative variables as temperature, humidity, cloudiness, precipitation, and wind speed and direction. Meteorology, in turn, is the study of the atmosphere and the processes that cause weather (Moran, 2006).

Climate is defined by IPCC (Intergovernmental Panel on Climate Change) as the "average weather" or more rigorously as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period is 30 years, as defined by the World Meteorological Organization (WMO). These relevant quantities are most often surface variables such as temperature, precipitation, and wind (IPCC, 2001). Climatology is defined as the study of climate, its controls, and spatial and temporal variability (Moran, 2006).

The term "forecast" was coined by Admiral Robert Fitzroy in the 19th century who was the head of the first meteorological office in history, established in Britain (Orrell, 2007). Admiral Fitzroy created this term so as to distance weather studies from the domain of astrologers. He was convinced that "the term forecast is strictly applicable to such an opinion as is the result of a scientific combination and calculation". Today, the term "prediction" is being used to describe weather and climate forecasts as well, and the distinction between forecasts and predictions seems to be disappearing. Many other terms have appeared over time to describe various forecasting activities, for example "nowcasting" refers to weather forecasting within the 0-12 hour timeframe.

Today, almost all major weather services are trying to increase the accuracy and range of their forecasts. In the U.S., NASA and NOAA are aiming to improve the accuracy of a 7-10 day weather forecast from 62% to 75% by 2010 while pushing the accuracy of a 5-day forecast to over the 90% level (Hertzfeld et al, 2003). In addition to developing a new generation of satellite instruments, these improvements will be achieved by integrating existing data streams, and, more importantly, by developing new models which can bridge the gap between data and insight.

An emerging trend in forecasting is the increasing use of probabilities to describe future weather and climatic events. For instance, instead of producing a single-point estimate for temperature tomorrow, a forecaster can use a probability distribution which would also reflect the level of uncertainty associated with the forecast. Therefore, one distinguishing feature of probability forecasts is that there is no clear sense of "right" or "wrong" forecasts, and if correctly used, a probability distribution can actually capture much more information than a single-point estimate (Doswell and Brooks, 2007).

Appendix 3: EP and Emissions Trading

Tackling climate change is a very complex challenge which requires an interdisciplinary approach at the global scale. One part of the answer is developing new energy technologies which generate minimal emissions (such as renewable energy systems) or help run fossil-fuel plants in a more environmentally friendly way (such as carbon sequestration).

Another part of the answer is creating economic incentives and/or penalties by putting a price on emitting greenhouse gases. For this purpose, two main types of economic tools are carbon taxes and cap-and-trade systems (Economist, 2006). Carbon tax is seen as a more stable policy tool given the minimal uncertainty regarding the price of emissions (once established by the government).

Cap-and-trade systems (also called emissions trading) is defined by IPCC as "a market-based approach to achieving environmental objectives that allows, those reducing greenhouse gas emissions below what is required, to use or trade the excess reductions to offset emissions at another source inside or outside the country" (IPCC, 2001). Trading can occur between companies, as well as at domestic and international levels. Compared to carbon taxes, cap-and-trade systems offer additional incentives for companies since decreasing carbon emissions or investing in renewable energy can translate into credits and corresponding revenues. However, cap-and-trade systems are much more volatile policy tools, as recently experienced by the European Emissions Trading Scheme (ETS).

In January 2005, Europe launched ETS, with the primary aim of cutting emissions from the five dirtiest industries of the EU. ETS created interested worldwide as one of the first initiatives at this scale to tackle greenhouse gas emissions. In April 2006, the price of permits that allow for extra emissions dropped from 31 euros to around 12 euros, when it was revealed by national governments that power producers and other energy-intensive European industries were 44 million tonnes under the permitted limit for 2005, significantly below the expected level (Schiermeier, 2006). As this experience demonstrates, ETS is driven by political and regulatory risks to a certain extent. However, market fundamentals are also playing an important role. Currently, CO2 output constitutes the main price driver for permits, which in turn is a function of parameters like weather, fuel prices and economic growth (European Climate Exchange, 2007). Therefore, monitoring the level of CO2 output and incorporating EP into trading decisions can give a competitive edge to the informed traders in this market.

It is interesting to note that, continuous monitoring of CO2 output and understanding the carbon cycle are priority areas identified by the Committee on Earth Observation Satellites (CEOS) as stated in their *Earth Observation Handbook*: "Since the dominant influence on future greenhouse gas trends is widely agreed to be the emission of CO2 from fossil fuel burning, an improved understanding of the global carbon cycle has become a policy imperative for the forthcoming decades, both globally and for individual countries." Furthermore, CEOS also argues that although global observing systems for climate will involve multiple terrestrial instruments, earth observation satellites will become the single most important contribution to global observations for climate (ESA, 2005).

In light of the scientific, political and economic interest in greenhouse emissions, the integrative nature of EP can be particularly valuable.

Appendix 4: Public vs. Private Goods Debate

A literature review of EP would be incomplete without a discussion of public and private good concepts.

As in most concepts in economics, scarcity and rivalry are at the core of the difference between private and public goods. Private goods are based on exclusivity and apply to goods whose consumption by one user will diminish consumption by others (the rivalry aspect). In contrast, public goods do not suffer from rivalry. Once the investment is made and a public good is provided, the marginal cost to additional users is very low, if not zero. In other words, the consumption by additional users will not diminish the consumption by others. A classic example for a public good is national defence.

Another distinguishing character of private vs. public goods is the cost of exclusion. In most cases, it is technically and economically feasible to identify and protect private goods. However, it may be very costly and technically challenging to exclude additional users from access to public goods.

There are also "hybrid" economic goods, mixed goods, sharing some characteristics of both public and private goods. Mixed goods can be non-rival, but exclusive or non-exclusive, but rival. Brown (2002) notes that in the case of mixed goods, the public and private good characteristics cannot be separated without an increased cost or decreased benefit to the society.

Gunasekara and Zillman (2004) argue that most meteorological infrastructure, science and services display the non-rivalrous and non-excludability characteristics of public goods. They provide a very useful conceptual framework for mapping various EP applications along the rivalry and excludability axes (Table A).

Another classification scheme was proposed by Peeters et al. (2005) for classifying investments in the space sector. Although this framework was not specifically developed for EP, it may still prove to be a useful tool. This framework is based on the concepts of private and social returns on investment. Social benefits include secondary (or external) benefits that are generated with an investment (in addition to the private benefits). Likewise, social costs include the opportunity cost to society of investing in a project (in addition to the costs just to one firm or individual).

Social return can be defined as the ratio of social benefits gained to social costs incurred by the whole society as a result of an activity or project. Social benefits include labor rents, consumer surplus and social external benefits. They exclude transfer payments. Private return, on the other hand, can be defined as the ratio of after tax and depreciation profits gained to costs incurred by the investing individual/firm from an activity or project.

Based on the private and social returns from a project, various funding mechanisms can be developed as shown in the diagram below (based on Peeters et al., 2005).

Non-Rival	**Mixed Goods** -Tailored forecasts for agricultural cooperatives -Access to official data networks and data banks -Weather information on pay TV -Weather information for aviation through World Aviation Forecast System or domestic equivalent -Weather information for air traffic management -Processed weather satellite images	**Pure Public Goods** -Freely exchanged basic data and products -Basic public forecasts and warnings through the news media -World wide weather conditions on the Web -Basic weather information for general aviation -Forecasts and warnings for safety of life at sea -The global climatological data base -The common body of fundamental knowledge of atmospheric science
Rival	**Pure Private Goods** -Tailored forecasts for competing energy utilities -Course-specific forecasts for competitive yachting -Design wind or rainfall studies for competitive tendering -Licensed weather presentation software -Flight planning services for individual airlines	**Mixed Goods** -New methods of weather forecast presentation using radar images and graphics
	Excludable	**Non-Excludable**

Table A: Public vs. Private Goods (Gunasekara and Zillman, 2004)