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Optimizing Ontario's Power Generation

Abstract: This project presents an optimization model for minimizing electricity generation costs in Ontario while advancing sustainability goals. Using reliable data, the model incorporates costs like fuel, health, and operations, along with constraints such as emissions caps and reserve margins. The results demonstrate a 35.38% reduction in daily costs, prioritizing renewable energy for 88.3% of power generation and aligning with Ontario's carbon neutrality goals under the Paris Agreement. Despite computational challenges, the model provides a strategic framework for cost-effective, sustainable energy planning.

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Chapter I – Introduction

As global temperatures rise and the impacts of climate change intensify, reducing greenhouse gas emissions has become an urgent priority. The global push towards sustainability has placed the **energy sector** at **the forefront of efforts to combat climate change**. International agreements like the Kyoto Protocol and the Paris Agreement have set ambitious targets for carbon neutrality, urging countries worldwide to align their energy policies with environmental goals.

Canada, as a signatory of the Paris Agreement, has pledged to achieve carbon neutrality by 2050 (Canadian Climate Institute, 2023; Leach, et al., 2021). However, despite Canada's commitment to reducing greenhouse gas (GHG) emissions, the nation continues to face significant challenges in achieving its target of 30% GHG decrease below 2005 levels by 2030. In 2022, Canada's GHG emissions were 708 megatonnes of carbon dioxide equivalent (Mt CO_2 eq), a decrease of 7.1% from 2005 levels. However, this represents a 1.3% increase from 2021, indicating a reversal in the downward trend (Government of Canada, 2024).

Ontario, one of Canada's largest provinces, relies on a mix of renewable and non-renewable energy sources to meet its electricity demands (Ontario Energy Board, 2024). Non-renewable power plants, while essential for grid stability, are major contributors to carbon emissions and incur high operational, fuel, and societal health costs. This dual challenge creates an opportunity to align economic efficiency with environmental stewardship.

Our project, *Optimizing Power Generation in Ontario,* focuses on addressing these dual challenges of cost effectiveness and sustainability. To tackle this, the focus of this project is to develop a mixed integer optimization model that minimizes the total cost of electricity generation while ensuring that Ontario's hourly energy demand is reliably met. By prioritizing renewable energy sources, which are cost efficient, and reducing reliance on high-emission, high-cost power plants, the model significantly lowers carbon emissions. This aligns Ontario's energy system with interim Paris Agreement targets while highlighting the economic benefits of sustainability.

What sets this project apart is its ability to demonstrate that cost-effectiveness and environmental stewardship are not mutually exclusive but can reinforce each other. The model optimizes which power plants to activate, the specific hours they should operate, and the precise amount of power they should generate to meet the demand and satisfy sustainability constraints. It incorporates fuel costs, operational expenses, health-related costs due to pollution, and sustainability constraints, creating a comprehensive solution.

Ultimately, the project's significance lies in this synergy – tackling the dual imperatives of economic efficiency and climate action **through a single objective**. This framework is a practical solution to one of the most pressing challenges of our times, it's not only a step forward in energy optimization but also a valuable case study for other regions who are also aiming to balance costs and ecological priorities worldwide.

Chapter II – Problem Formulation and Description

Ontario's power generation system is characterized by a diverse energy portfolio that includes nuclear (53%), hydro (25%), natural gas (13%), wind (8%), solar (< 1%), and biofuel (< 1%) plants (IESO, 2024). While this diversity provides flexibility, the province's electricity supply remains heavily reliant on nuclear, natural gas, and hydro plants, which dominate its electricity capacity (Ontario Energy Board, 2024). This reliance presents several challenges:

- **Nuclear Plants:** Ontario's nuclear power plants provide stable, low-carbon energy but face challenges in transitioning to renewables. In fact, they rely on finite uranium resources, contribute to environmental degradation, and generate costly radioactive waste[1] with long-term storage posing risks to human health and the environment (Lee, 2024; Clarke et al., 2022). Therefore, they have have high operational and societal health costs. Their limited flexibility in adjusting output makes them less suitable for fluctuating demand compared to renewables.
- **Natural Gas Plants:** These are critical for meeting peak demands due to their operational flexibility (Yauch, 2020). However, they are among the most pollutive and costly to operate, contributing to societal health risks (e.g., fine particulate matter, PM2.5), and environmental degradation (Government of Canada, 2021).
- **Hydro Plants:** A cleaner, renewable energy source, hydro plants face constraints due to geographic and seasonal factors. Although Ontario has abundant water resources due to seasonal snowmelt, it's been facing higher temperatures due to climate change posing risks to water availability and challenging their long-term reliability (Yauch, 2020)**.**

Although Ontario has made strides in integrating renewable energy sources like wind and solar, their intermittency and limited capacity to meet peak demand continue to constrain their impact. Addressing these challenges is critical for aligning with Canada's commitment to achieving carbon neutrality by 2050 under the Paris Agreement. In addition to the reliance on pollutive energy sources, Ontario's energy landscape is further complicated by operational constraints, including **ramp rates**, which are restrictions on the speed at which power plants can adjust their generation levels, **startup and shutdown costs**, which are high costs associated with cycling plants on and off, particularly for natural gas and biofuel facilities and **emission caps**, which are regulatory and environmental limits on greenhouse gas emissions to meet climate targets.

2.1. Approach and Methodology

To address these challenges, this project utilizes a **mixed-integer optimization model** designed to determine the most cost-effective and sustainable power generation schedule for Ontario. This advanced framework captures the discrete decisions of turning power plants on or off, alongside continuous variables that represent the generation levels of each plant. By reducing reliance on high-cost, high-emission plants and optimizing the utilization of cleaner energy sources, the model aligns with Ontario's economic and environmental objectives.

2.2.1. Model Formulation

Objective Function: The objective of the optimization model is to minimize the total cost of power generation across Ontario's power plants while meeting hourly demand and adhering to operational and sustainability constraints. The following costs associated with power generation were considered:

1 *For instance, the United States' Nuclear Waste Fund has accumulated over $40 billion, reflecting the substantial financial resources needed for safe disposal solutions* (Feldman, 2018).

- **Fuel Costs**: The cost associated with the fuel consumed by each generator to produce one unit of power (MWh).
- **Health Costs**: Costs representing the societal impact of air pollution caused by emissions from generators relying on polluting fuels[2].
- **Operational Costs**: The fixed costs incurred to keep a generator active, regardless of the amount of power it produces. These costs include routine maintenance, labor, and administrative expenses.
- **Startup Costs**: Costs incurred when transitioning a generator from an *off* state to an *on* state. These costs reflect the energy and resources required to initiate operations.
- **Shutdown Costs**: Costs incurred when transitioning a generator from an *on* state to an *off* state.

These cost categories were carefully selected as they are integral to Ontario's power generation landscape and directly influence the operational efficiency, sustainability, and economic viability of Ontario's power plants (see Appendix A). By incorporating them into the objective function, the model aims to provide a comprehensive framework for optimizing power generation in Ontario[3].

Mathematical Formulation:

Objective: Minimize Total Cost (TC)

$$\boldsymbol{Minimize} \sum_{\boldsymbol{i \in G}} \sum_{\boldsymbol{t \in T}} (\boldsymbol{f_i \cdot p_{i,t} + e_{i,t} \cdot p_{i,t} + o_i \cdot x_{i,t} + l_i \cdot y_{i,t} + q_i \cdot z_{i,t}})$$

Where:

Decision Variables

- $p_{i,t}$: Power generated by generator *i* at hour *t* (MWh).
- $x_{i,t}$: Binary variable indicating if generator *i* is active at hour *t* (1 if active, 0 otherwise).
- $y_{i,t}$: Binary variable indicating if generator *i* starts up at hour *t* (1 if startup, 0 otherwise).
- $z_{i,t}$: Binary variable indicating if generator *i* shuts down at hour *t* (1 if shutdown, 0 otherwise).

Sets

- G: Set of all generators.
- G_N: Set of all nuclear generators.
- T: Set of all hours in a day (T={1, 2, …, 24})

Parameters – Costs (in CAD)

- f_i: Fuel cost per MWh for generator *i*
- $e_{i,t}$: Health cost per MWh for generator *i* during time period *t*
- o_i: Operational cost per hour for generator *i*
- l_i: Startup cost for generator *i*
- q_i: Shutdown cost for generator *i*

Parameters – Others

- d_t: Power demand for each hour *t*
- c_i: Maximum power generation capability/ total capacity for power plant *i*
- m_i: Minimum percentage of power that must be generated from power plant *i*
- r_i: Ramp up/ ramp down speed for power plant *i*
- E_i: Emission factor for generator *i* (tonnes CO_2/ MWh)

With this, the model has 17,280 decision variables.

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2 *These costs account for public health effects, such as respiratory diseases and premature deaths, due to pollutants like particulate matter (PM2.5) and greenhouse gases (Government of Canada, 2021)*

3 *For details on costs' data collection, refer to Numerical implementation and results. Additional costs related to Ontario's power generation will be considered in Problem Extensions.*

Constraints:

1. **Demand Satisfaction Constraint:** Ensures that the total power generated by all generators in each time period meets the power demand for that period. This constraint is vital for ensuring that we meet the electricity demand for each time period *t*.

$$\sum_{i \in G} p_{i,t} = d_t \qquad \forall t \in T$$

2. **Nuclear Plants are Always On:** Nuclear power plants have operational constraints due to their design and safety requirements (Iurshina, Karpov, Kirkegaard, & Semenov, 2019). Frequent startups and shutdowns are impractical because they incur significant costs and require extended preparation times (Comstock, 2020). Once active, they must remain operational at a baseline capacity, producing at least 75% of their maximum output[4] to ensure grid stability and efficiency. Incorporating this constraint ensures that the model does not unrealistically shut down nuclear plants for short-term cost savings, which would be infeasible in practice.

$$p_{i,t} \geq m_i \cdot c_i \qquad \forall i \in G_N, \forall t \in T$$

3. **Maximum and Minimum Power Generation Constraint:** Ensures that generators operate within their permissible ranges during each time period. The power generated by a generator cannot exceed its maximum capacity c_i. Additionally, certain generators such as nuclear plants need to operate above a certain threshold m_i. This constraint also ensures that when there is no power generated ($p_{i,t} = 0$), then the plant is turned off ($x_{i,t} = 0$).

$$m_i \cdot c_i \cdot x_{i,t} \leq p_{i,t} \leq c_i \cdot x_{i,t} \qquad \forall i \in G, \forall t \in T$$

4. **Ramp-Up and Ramp-Down Rate Constraint:** Power plants adjust generation levels gradually to avoid machinery stress and inefficiencies from rapid output changes (Kumar et al., 2012). To reflect this, we impose ramp-up (increasing power generation) and ramp-down (decreasing power generation) constraints, limiting hourly power changes to a percentage of the generator's maximum capacity c_i, defined by its ramp rate r_i[5]. This ensures stable and efficient operations. For a generator *i*, the change in power generation between hour *h* and *h* − *1* is constrained by:

$$-r_i \cdot c_i \leq p_{i,h} - p_{i,h-1} \leq r_i \cdot c_i \qquad \forall i \in G, h > 1$$

5. **Logical Consistency of On / Off Transitions:** Ensures that when a generator is switched on during a specific time period, it is actively on, and when it is switched *off*, it is not. Hence, a generator can only start up or shut down if it is changing its online status. This helps maintain the logical consistency of the model. If the generator is switched *on* $y_{i,t} = 1$, it must also be *on* $x_{i,t} = 1$. If the generator is switched *off* $z_{i,t} = 0$, it must also be *off* $x_{i,t} = 0$.

$$y_{i,t} \leq x_{i,t}, \qquad z_{i,t} \leq 1 - x_{i,t} \qquad \forall i \in G, \forall t \in T$$

6. **Linking Start up and Shutdown variables to On / Off Variables Constraint:** This constraint links the startup, $y_{i,t}$, and shutdown, $z_{i,t}$, binary variables to the *online*, $x_{i,t}$, variable. It ensures consistency between the state of a generator in consecutive time periods. Specifically, if a generator is turned *off* at hour *t*−*1* and turned *on* at hour *t*, the startup variable $y_{i,t}$ is set to 1. If a generator is turned *on* at hour

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[4] *Refer to Numerical implementation and results*

[5] *Refer to Numerical implementation and results*

$t-1$ and turned *off* at hour t, the shutdown variable $z_{i,t}$ is set to 1. If there is no change in the generator's state, both $y_{i,t}$ and $z_{i,t}$ are set to 0.

$$y_{i,t} - z_{i,t} = x_{i,t} - x_{i,t-1} \qquad \forall i \in G, \forall t > 1$$

This constraint is crucial for modeling the operational dynamics of generators, ensuring that startups and shutdowns are correctly captured and penalized through their associated costs in the objective function.

7. **Carbon Emission Limit Constraint:** To ensure that the total carbon emissions from all generators across a 24-hour period in Ontario does not exceed the daily carbon cap (Paris Agreement). It incentivizes the use of low-emission generators and supports the transition toward a cleaner, more sustainable energy system. Ontario aims to reduce emissions by 30% below 2005 levels by 2030, which translates to a daily *Cap* of ≈ 57,534 tonnes of CO_2[6] for the electricity sector[7] (Ivey Business School, 2017).

$$\sum_{i \in G} \sum_{t \in T} E_i . p_{i,t} \leq Cap$$

Where *Cap* denotes the maximum allowable emissions in tonnes CO_2.

8. **Reserve Margin Requirements Constraint:** The reserve margin represents the extra power capacity above the expected peak demand that must be maintained to ensure the grid's reliability. This margin accounts for (1) unexpected surges in demand (e.g. during extreme weather), (2) unplanned outages or failures of power plants and (3) potential grid reliability requirements, if defined by regulatory authorities. This constraint ensures that the total power generated by all plants at any given hour is greater than or equal to the hourly demand, plus a reserve margin. The reserve margin[8] acts as a buffer to guarantee a reliable electricity supply. Based on historical North American practices, a 15% reserve margin R is standard (EIA, 2014).

$$\sum_{i \in G} p_{i,t} \geq (1 + r_m) \cdot d_t \qquad \forall t \in T$$

Where r_m is the reserve margin.

Chapter III – Numerical Implementation and Results

3.1. Setting and Data Collection

Generators Data Collection Procedure:

To optimize electricity generation in Ontario, the problem was formulated using real-world data combined with synthesized estimates to ensure accuracy and relevance. The primary data source was Ontario's Independent Electricity System Operator (IESO) publicly available dataset, which provided information on the generators operating across the province. **It is important to note that the dataset contained only the generators which have a capacity of at least 20 MW of electricity**. This dataset comprises of 180 generators from six distinct types – biofuel, wind, solar, nuclear, hydro and gas. Hourly capacities for

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[6] Assumption: the cap per day is a fixed amount

[7] Refer to *Numerical Implementation* for carbon cap calculation details

[8] According to the IESO's Ontario Reserve Margin Requirements for 2024 to 2028, the reserve margin is calculated to ensure that the Loss of Load Expectation (LOLE) does not exceed 0.1 days per year, aligning with reliability standards (IESO, 2023). Historical reliability studies conducted by system operators (including IESO) have shown that achieving a LOLE of 0.1 days/year typically requires a reserve margin of 15% (IESO, 2023; SPP Resource Adequacy Team, 2024).

January 1, 2024, were extracted from the dataset, with capacities recorded under the "Capability" column. Based on the dataset description, "Capability" and "Total Capacity" overlap as Capability represents each generator's maximum potential output under normal operating conditions. Unlike nonrenewable sources, total capacity was represented as capability for renewable generators. Hence, capability was utilized as the total capacity for the latter. The dataset focused solely on a 24-hour period to capture temporal variations in demand within a day.

Costs Data Collection Procedure:

To accurately incorporate **fuel costs** into our optimization model, we used a comprehensive report provided by the Independent Electricity System Operator (IESO), offering a breakdown of costs per fuel type category. These reported costs served as the foundation for our analysis. In cases where data was unavailable or missing, we got the costs using averages from comparable regions such as the U.S (Ivey Business School, 2017).

To account for **health costs** in our optimization model, we addressed the lack of Ontario-specific data by logically synthesizing a dataset based on informed research. Health costs represent the societal and environmental impacts of air pollutants, such as particulate matter (PM), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and greenhouse gases (GHGs), which are emitted during electricity generation. These pollutants contribute significantly to respiratory illnesses, cardiovascular diseases, and environmental degradation. Incorporating these costs into our model promotes sustainability and reflects the true societal costs of power generation. Power plants such as natural gas and biofuel facilities were assigned health costs due to their emissions, with ranges of \$1–\$15 per unit of electricity generated, based on their relative environmental impacts. Emission-free sources like nuclear, hydro, wind, and solar plants incur no health costs. To synthesize this data, we consulted sources including the Ontario Ministry of Energy's cost-benefit analysis of coal replacement, Health Canada's air pollution impact reports, the National Pollutant Release Inventory (NPRI), and the Air Quality Benefits Assessment Tool (AQBAT). These resources provided insights into emissions and their health impacts, which were translated into logical cost estimates for different fuel types. The synthesized dataset spanned 31 days and 24 hours per day, but our project specifically used data for January 1st, 2024, to align with the scope of the analysis.

For the **operational costs** of our model, we also synthesized data through a systematic approach, as Ontario-specific data was unavailable. To gather our data, we conducted extensive research on Statista datasets, which provided costs for U.S. power plants. They were used given it's a comparable region for electricity costs, as previously stated. By aggregating this data, we calculated the average operational cost per fuel type, ensuring it aligned with realistic assumptions. These costs vary depending on the type of generator (Statista, 2023). For instance, nuclear plants were assigned higher operational costs due to their rigorous safety protocols and complex infrastructure, while renewable sources like wind and solar had lower costs reflecting simpler operational requirements. Although the synthesized values were not specific to Ontario, the methodology ensured they were reasonable and representative of typical generator operations.

For **startup and shutdown costs**, we synthesized the data by researching average costs across various sources and estimating values for each generator type (Kumar, Besuner, Lefton, Agan, & Hilleman, 2012). These costs vary depending on the types of generators and fuel. With research from National Renewable Energy Laboratory (NREL), we calculated average startup costs for each fuel type as follows: **Hydro, Wind, and Solar** generators were assigned low startup costs of \$10 per event due to their straightforward operation; **Gas and Biofuel** generators were assigned higher costs of \$120, reflecting fuel requirements and operational complexity; and **Nuclear** generators were assumed to have negligible startup costs due to their continuous operation and inability to ramp on and off frequently. To simplify the modeling process and avoid additional complexity, we assumed that startup and shutdown costs were symmetrical, i.e., the cost of turning a plant on was equal to the cost of turning it off.

All of the costs accounted for in the optimization problem are tabulated in Table 1.

Type of Plant	Fuel costs	Health Costs	Operational Costs	Startup/ Shutdown Costs
Hydro	50	0	5.61	10
Biofuel	120	1 – 15	11.21	120
Wind	50	0	1.4	10
Solar	40	0	1.4	10
Nuclear	80	0 [9]	26.19	0
Gas	63	1 – 15	7.4	120

Table 1. *Fuel Costs per Category (in CAD)*

Demand Data Collection Procedure:

For the demand data, we utilized publicly available hourly electricity demand data provided by Ontario's **Independent Electricity System Operator (IESO)**. Further, we focused on **January 1, 2024**, selecting this date to analyze a period with high winter electricity demand due to heating requirements. This choice was strategic, as it presented a challenging test case for our model, with demand expected to fluctuate throughout the day.

Emissions Data Collection Procedure:

We assigned emission factors to each fuel type to integrate it into our model, representing the amount of carbon dioxide (CO_2) emitted per megawatt-hour (MWh) of electricity generated. These emission factors were sourced from NREL and depict 0.011 tonnes CO_2/MWh for Wind, 0.024 tonnes CO_2/MWh for Hydro, 0.045 tonnes CO_2/MWh for Solar, 0.450 tonnes CO_2/MWh for Gas, 0.050 tonnes CO_2/MWh for Biofuel and 0.012 tonnes CO_2/MWh for Nuclear.

Parameter Development for Model Constraints:

Minimum Power Generation Threshold (m_i): In our model, we introduced a minimum power generation threshold parameter to reflect operational and economic constraints. For nuclear plants, a threshold of 75% of their maximum capacity was set, based on their design for steady-state operation. Operating below 50% capacity can compromise reactor stability and increase costs per unit of electricity due to high capital investments and low fuel costs. Additionally, nuclear plants provide critical base load power for grid reliability, making consistent operation essential (Nuclear Energy Agency, 2011). For non-nuclear plants, such as gas, hydro, wind, solar, and biofuel, a minimum threshold of 1% was set.

Ramp Rate Limits (r_i): The ramp rate limits constraint ensures that power plants adjust their generation levels gradually. Ramp rates, defined as the maximum percentage change in power output per hour, vary based on the type of plant due to differences in technology and flexibility. For nuclear plants, a 60% per hour limit was set to reflect their limited ramping capability and safety requirements. Gas, hydro, and

[9] Nuclear power plants do not produce air pollution or carbon dioxide while operating, hence they incur 0 health costs

biofuel plants, known for their high flexibility, were assigned no strict limits (100% per hour) due to their ability to rapidly adjust output. Wind plants, influenced by natural wind variability, were set to 80% per hour, while solar plants, affected by changes in sunlight, were capped at 50% per hour to account for weather-induced fluctuations (Joshi, et al., 2020; Nuclear Energy Agency, 2011).

Carbon Cap Computation: To compute the daily carbon cap for Ontario's electricity sector, we followed a systematic approach based on Ontario's greenhouse gas (GHG) reduction targets under the Paris Agreement. As requested by the Paris Agreement, using 2005 as the baseline year, Ontario’s total GHG emissions were approximately 200 Mt CO_2e. The province has committed to reducing these emissions by 30% by 2030, leading to a target of 140 Mt CO_2e/year (Office of the Auditor General of Ontario, 2019). Since the electricity sector contributes about 15% of Ontario’s total emissions, its share of the target becomes 21 Mt CO_2e/year. Assuming emissions are evenly distributed across the year, the annual cap for the electricity sector is converted into a daily carbon cap of approximately 57,534 tonnes CO_2/day.

3.2. Implementation

After building all 17,280 decision variables, and collecting the data, we incorporated it into our constraints and objective function, as described in *Problem Formulation*. The optimization model was implemented in Python using the Gurobi solver. Gurobi was selected for its efficiency in solving large-scale optimization problems, especially mixed-integer programs.

3.3. Results and Discussion

3.3.1. Optimal Operating Schedule

The optimization model successfully produced a detailed power supply schedule for Ontario's generators over a 24-hour period, capturing hourly variations in demand while minimizing total electricity generation costs as shown in Figure 1 of the Appendix. Figure 1 offers insights into the allocation of power generation among the available 180 generators. From these, 120 were selected as part of the optimal solution, with 106 being renewable generators and 14 non-renewable generators, all of which were nuclear plants. Therefore, renewables accounted for 88.3% of the total generation, while non-renewables contributed only 11.7%, as shown in Figure 2 of the Appendix. Notably, nuclear plants were utilized carefully, primarily to address surges in demand when renewable resources alone could not provide power cost-efficiently. This is justified by their very low health costs and start up, shut down costs.

Hydroelectric plants played an important role in managing demand fluctuations due to their operational flexibility. For instance, hydro generators like *DECEWND1* and *NAGAGAMI* dynamically adjusted their output during the day to meet changing demand levels. *DECEWND1*, for example, was activated during hour 18 to handle a demand surge and deactivated by hour 20 when the demand subsided. This shows the model’s ability to efficiently manage fluctuations in demand while focusing on renewable resources. Generators operating on costly and emission-intensive fuels, such as biofuel and natural gas, were entirely excluded from the solution, further underscoring the model’s alignment with cost minimization and sustainability objectives. Additionally, the model identified *Beck2 Hydro* and *Saunders* as key contributors to the optimal power schedule, drawing heavily from their capacity due to their low costs and high reliability.

The results also highlight the model’s nuanced approach to balancing cost, operational feasibility, and environmental considerations. The penalization of high-cost generators and prioritization of renewables ensured that periods of peak demand, such as hours 18 and 19, were met predominantly through renewable sources like *LongSaulte*, as shown in Figure 3 of the Appendix, which was activated specifically during these hours to cover additional demand in an environmentally sustainable manner.

3.3.2. How Our Model Empowers Ontario's Energy Sector: Reporting Optimal Costs

Ontario's annual electricity system costs are approximately $23.1 billion, with electricity generation accounting for about 60% of this total, equating to $13.86 billion (Ontario Energy Board, 2023). As mentioned previously, health-related costs due to emissions from electricity generation are significant and it resulted in annual health benefits valued at approximately $3 billion (Luft, 2016). Given that coal has been phased out and natural gas remains a substantial contributor to emissions, we estimated current health costs at around $1 billion annually. Combining direct generation costs and health-related expenses, the total annual cost of Ontario's electricity generation is approximately **$14.86 billion**. Assuming a conservative scenario, where all of the costs are fixed per year, the total daily cost of power generation is approximately **$40.7 million**. Our optimization model offers a solution by minimizing electricity generation costs and prioritizing renewable energy sources. Over a 24-hour period, the model achieved a total cost of **$26.3 million**, as shown in Figure 4 of the Appendix, inclusive of fuel, operational, startup, shutdown, and health costs.

This major decrease in cost is explained by the following. Our model prioritizes renewable generators like hydro, wind, and solar, which have **minimal to no fuel costs**, over costly and emission-intensive options such as natural gas and biofuel plants. By eliminating reliance on these pollutive generators, the model effectively reduces health costs associated with emissions. Operational costs are also optimized by selectively activating generators with high efficiency and minimal maintenance requirements, while startup and shutdown costs are minimized through stable reliance on continuous renewable energy generation.

By implementing this framework, Ontario could realize savings of approximately **35.38% of its current generation and health-related expenses** per day. Beyond the financial benefits, the model aligns with Ontario's commitment to sustainability, helping the province meet its **30% emissions reduction target by 2030**, consistent with the Paris Agreement.

Ontario is likely aware of the substantial cost-saving potential presented by optimizing its energy mix. However, what might be constraining the province from fully realizing these savings is the significant upfront investment required to transition from traditional power plants to renewable energy sources. Decommissioning non-renewable power plants, such as natural gas facilities, incurs high demolition costs, including dismantling infrastructure, and addressing environmental contamination. Additionally, the startup costs for renewable energy plants, such as wind and solar, are substantial. For wind power, costs include purchasing and installing turbines, acquiring land, and integrating with the grid, while solar power involves expenses for photovoltaic cells, storage systems, and labor. Our model demonstrates that renewable plants are more cost-efficient in the long run, offering savings on operational, fuel, and health-related costs. Based on our analysis, Ontario could achieve daily cost savings of approximately $14.4 million, equivalent to $5.256 billion annually, by reducing reliance on non-renewable plants. For example, let's assume Ontario invests $1 billion in wind or solar power, this would yield a payback period of just 2.3 months, emphasizing the financial viability of transitioning to renewables. While initial costs may seem prohibitive, they are offset by long-term savings and the additional benefits of reduced carbon emissions and improved public health.

3.3.3. Sensitivity Analysis: Reserve Margin Impact on Total Costs

A sensitivity analysis was computed for the reserve margin parameter, as shown in Figure 5 of the Appendix. The reserve margin serves as a buffer for unexpected demand surges or generator outages, directly influencing operational decisions and costs. Given the analysis, at lower reserve margins (5% to 20%), the total cost remains relatively stable ($26 million), indicating that Ontario's current generation mix can reliably meet demand and reserve requirements without significant additional costs. However, as the reserve margin increases beyond 20%, costs escalate sharply, reaching approximately $34 million at a 50% reserve margin. This rise is driven by the activation of higher-cost generators, particularly non-renewable plants like gas, nuclear, and biofuel, which incur greater fuel and operational expenses. While higher reserve margins enhance grid reliability, they contradict Ontario's sustainability goals by increasing reliance on emission-intensive power plants. The findings suggest that a reserve margin of 15-20% is optimal, aligning with industry standards such as IESO guidelines, minimizing costs and emissions, and ensuring reliability.

Chapter IV – Problem Extensions

For the problem extensions, we can propose several directions to further improve or adapt the optimization model for Ontario's power generation system. The optimization model offers significant opportunities for enhancement, primarily focused on improving environmental sustainability and economic efficiency.

1. Enhancing the Objective Function

A. Incorporating additional cost components to make it more representative of real-world scenarios. For example, including transmission losses would account for inefficiencies as electricity is transported from power plants to end users. Maintenance costs could also be integrated to reflect the wear and tear associated with varying levels of generator usage. Moreover, adding environmental restoration costs and regulatory compliance penalties would align the model with stricter sustainability requirements. Mathematically, the new objective function would look like this:

$$Minimize \sum_{i \in G} \sum_{t \in T} \left(f_i * p_{i,t} + e_{i,t} * p_{i,t} + o_i * x_{i,t} + l_i * y_{i,t} + q_i * z_{i,t} \right) + \sum_{i \in G} \left(TransLoss_i + Maint_i + EnvRest_i + RegComp_i \right)$$

B. Including a carbon tax on non-renewable energy generation could simulate the economic impact of transitioning to cleaner energy sources. By modeling tax rates on emissions, the optimization process would favor lower-carbon options, promoting adherence to the Paris Agreement goals. This extension aligns with global trends toward carbon neutrality and can serve as a valuable policy planning tool for governments.

$$Minimize \sum_{i \in G} \sum_{t \in T} \left(f_i * p_{i,t} + e_{i,t} * p_{i,t} + o_i * x_{i,t} + l_i * y_{i,t} + q_i * z_{i,t} \right) + \sum_{i \in G} \sum_{t \in T} \tau * E_i * p_{i,t}$$

Where:

$\tau = Carbon\ tax\ rate\ (\$/tonnes\ CO2)$

C. Revenue maximization for renewable energy sources: by prioritizing green energy, the model could optimize for both cost efficiency and increased revenue through incentives or market-based energy pricing. This would encourage investments in renewable resources such as wind, solar, and hydro.

$$Maximize \sum_{i \in Gr} \sum_{t \in T} R_i * p_{i,t} - \sum_{i \in G} \sum_{t \in T} \left(f_i * p_{i,t} + e_{i,t} * p_{i,t} + o_i * x_{i,t} + l_i * y_{i,t} + q_i * z_{i,t} \right)$$

Where:

$R_i = Revenue\ per\ MWh\ of\ power\ generated\ by\ renewable\ generator\ i\ (\$/MWh)$

$Gr = Set\ of\ renewable\ generators\ (wind, hydro, solar)$

2. Integrating Sustainability Incentives

To further promote sustainable practices, the model could simulate the effects of tax rebates or subsidies for renewable energy plants. These incentives could lower operational costs for green energy sources, making them more competitive against fossil-fuel-based generators.

$$Minimize \sum_{i\in G}\sum_{t\in T}\left(f_i * p_{i,t} + e_{i,t} * p_{i,t} + o_i * x_{i,t} + l_i * y_{i,t} + q_i * z_{i,t}\right) - \sum_{i\in Gr}\sum_{t\in T} S_i * p_{i,t}$$

Where:

$S_i = Tax\ rebate\ or\ subsidy\ for\ renewable\ generator\ i$ ($\$/MWh$)

$Gr = Set\ of\ renewable\ generators\ (wind, hydro, solar)$

Additionally, introducing pollution penalties for exceeding emission caps or thresholds would enforce stricter compliance with environmental standards.

$$Minimize \sum_{i\in G}\sum_{t\in T}\left(f_i * p_{i,t} + e_{i,t} * p_{i,t} + o_i * x_{i,t} + l_i * y_{i,t} + q_i * z_{i,t}\right) + P * \max\left(0, \sum_{i\in Gr}\sum_{t\in T} E_i * p_{i,t} - Cap\right)$$

Where:

$P = Penalty\ rate\ for\ exceeding\ the\ pollution\ cap$ ($\$/tonnes\ CO2$)

$Cap = Pollution\ cap\ for\ the\ system\ (tonnes\ CO2\ /day)$

Chapter V – Recommendations and Conclusions

As consultants for this project, we recommend Ontario adopt the optimization model to achieve significant cost savings while advancing sustainability goals. The model demonstrates that integrating renewable energy sources and optimizing power generation schedules can reduce daily electricity generation costs by 35.38%, translating to substantial annual savings. By prioritizing renewable energy and minimizing reliance on costly, emission-intensive generators, Ontario can align its energy strategy with its commitment to carbon neutrality under the Paris Agreement. However, it's important to note that these annual savings were calculated based on **assumptions** mentioned previously, such as the estimation of $1 billion health costs and our assumption that all costs are fixed per year, which led to daily costs computed approximately. In reality, costs vary per day, but that data was not publicly available.

Reflecting on the project, it became evident that optimizing power generation involves trade-offs between cost, environmental impact, and grid reliability. Certain challenges arose during the analysis, such as the computational complexity of scaling the model to accommodate larger datasets. The analysis was conducted for only one day and it requires a significant computational power for larger datasets, such as a whole month or year. Additionally, the IESO dataset selected power generation plants that produce at least 20 megawatts, narrowing the number of total power plants to 180. In reality, there are more power plants in Ontario, and accounting for these in future implementations may affect the actual results.

If we were to redo the project, we would prioritize the inclusion of more accurate data, such as health, startup, and operational costs, to enhance model precision. Additionally, integrating dynamic weather data would help account for fluctuations in renewable energy availability, improving real-time applicability.

By refining the model to address these bottlenecks and continuing to align it with Ontario's energy and environmental goals, we believe this approach can serve as a blueprint for broader energy optimization projects across Canada and beyond.

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Appendices

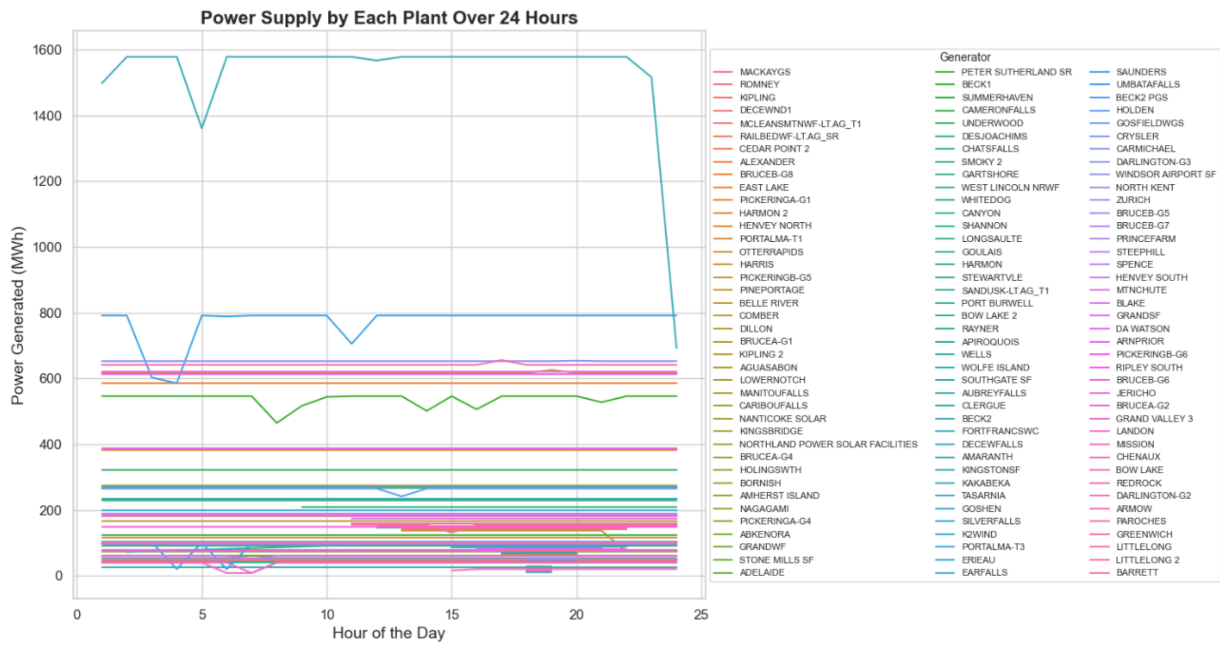

Figure 1. *Power Supply by Each Plant Over 24 Hours*

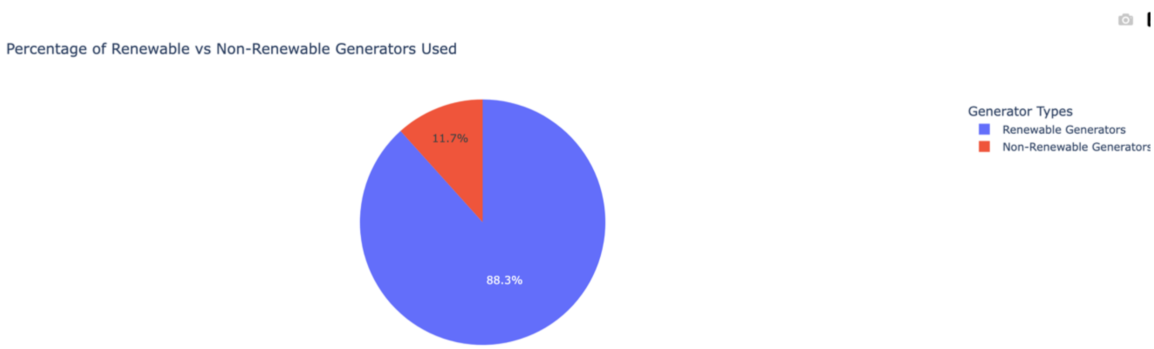

Figure 2. *Percentage of Renewables vs Non-Renewable Generators Used*

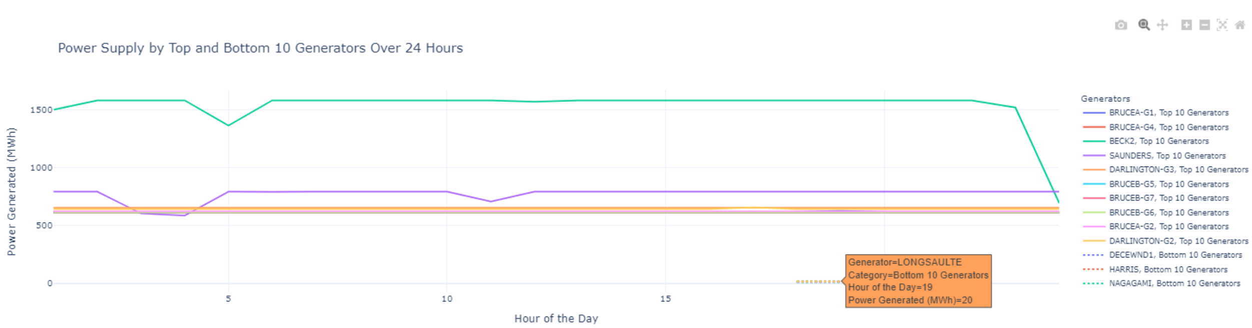

Figure 3 3. *Extra Power Supply During Demand Surges*

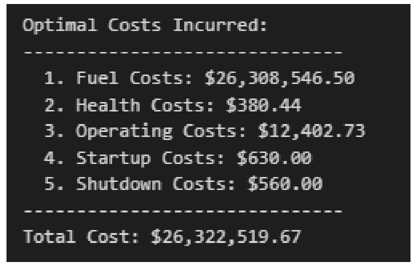
```
Optimal Costs Incurred:
------------------------------
  1. Fuel Costs: $26,308,546.50
  2. Health Costs: $380.44
  3. Operating Costs: $12,402.73
  4. Startup Costs: $630.00
  5. Shutdown Costs: $560.00
------------------------------
Total Cost: $26,322,519.67
```

Figure 4 4. *Optimal Reported Costs*

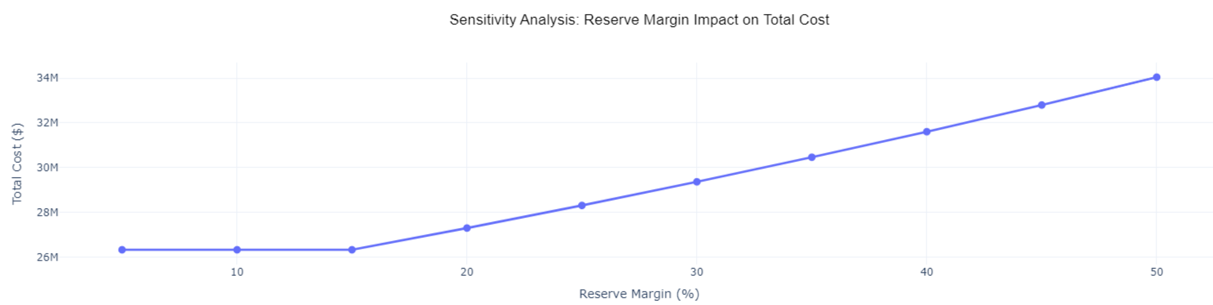

Figure 5 5. *Sensitivity Analysis: Reserve Margin Impact on Total Cost*

Appendix A – Cost inclusion justification

The costs used in our objective function and analysis were considered due to the following reasons:

- **Fuel Costs:** In Ontario, natural gas-fired power plants play a pivotal role in meeting electricity demand, especially during peak periods. The cost of natural gas directly influences the operational expenses of these plants, affecting overall electricity pricing. Ontario Power Generation (OPG) utilizes natural gas as part of its energy mix, and fluctuations in natural gas prices can impact generation costs (OPG, 2024).
- **Operational Costs**: Operational costs are inherent to all power generation facilities and are essential for ensuring a reliable electricity supply. For instance, OPG manages operational costs across its diverse portfolio, which includes nuclear, hydroelectric, and thermal (natural gas) plants.
- **Startup and Shutdown Costs**: Frequent cycling of power plants to match demand fluctuations can lead to increased maintenance requirements and reduced equipment lifespan, thereby elevating operational costs (EPRI, 2013; Kumar, Besuner, Lefton, Agan, & Hilleman, 2012). Analyzing these costs is vital for optimizing generation schedules and minimizing unnecessary expenditures.
- **Health Costs**: Historically, emissions from coal-fired power plants in Ontario were responsible for up to 668 premature deaths, 928 hospital admissions, and 1,100 emergency room visits annually. The associated health-related costs were projected to be approximately $3 billion per year. Although coal plants have been phased out, natural gas and biofuel plants still emit pollutants that contribute to health risks, making it imperative to account for these costs in the objective function (Luft, 2016; Ontario, 2017).