Chemical Engineering 4A: Work Report 400

Reducing Greenhouse Gas Emissions and Increasing Power Generation in the Toronto Area Utilizing New or Existing Technologies

Submitted by

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Date of submission: May 10, 2016

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May 10, 2016

Eric Croiset (Chemical Engineering Chair)
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Dear Professor Croiset:

This report, “Reducing Greenhouse Gas Emissions and Increasing Power Generation in the Toronto Area Utilizing New or Existing Technologies" was prepared as my 4A Work Report 400. This is my third and final work term report. Having worked as a WEEF TA for first year engineering calculus courses during my most recent coop job, I felt it was necessary to do my own research into a topic of interest since it was not relatable to a suitable work term report.

The purpose of this report is to evaluate a potential proposal/implementation of an increased power generation scheme for the GTA to keep up with problems like increasing population densities and global warming from non-renewable energy sources.

Because this report is based on a topic that I had interest on and not my work duties, all the data represented in the report was taken from government reports, contracted companies in charge of current energy production plants, and other journal sources cited and referenced.

This report was written entirely by me and has not received any previous academic credit at this or any other institution. I received no other assistance other than the references listed.

Sincerely,

Ryan Jung
20367412

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Abstract

There is growing global concern over topics like climate change and energy dependence. One of the main points of contention is when will fossil fuels or other dirty fuel sources be phased out in favor of cleaner energies that produce much less greenhouse gas emissions. This is a difficult topic since fossil fuels like oil and gas are much cheaper than their clean counterparts, so it makes it hard to adopt any new energy source. However, Ontario is expanding its role as a leader of clean energy, as it aims to produce most of its energy from renewable/clean sources (where energy from coal fired plants has already been phased out).

Ontario's current energy mix is very good. The supply comes from many different sources ranging from nuclear, wind farms, to even biofuels. However, Ontario's population will only become bigger and the population density situated around the GTA will continue to grow at a rapid pace which means that there could be a greater demand for energy. What this report aims to do is provide a scenario in which the increasing population and demand for energy could be apportioned using green/clean energies because of growing concerns of climate change.

It was found in this report that greener/cleaner energy supplies like nuclear, hydro and biofuels can meet GTA's growing energy demands in the future if:

- A balanced approach at slowly repurposing gas fired plants into biofuel sources is done, which will help combat the emission of GHG's as well as make up any potential power capacity lost from the gas plants.
- Biofuel plants can be used for temporary/reliable intermittent energy peaks during extreme weather events.
- Refurbishment or construction of nuclear plants can help with baseload power generation and will meet future energy demands projected past the year 2030.
- Adoption of electrical vehicles was also found to be a good idea in meeting energy demand criterion and curbing emissions.

The cost of undertaking all of these projects would be substantial, however, GHG emissions can become a significant problem in terms of global warming and the many problems that follow; therefore, looking at different alternatives using renewable/clean sources might present a huge opportunity for Ontario to become a global leader in green energy.

1.0 Introduction

The world population is growing at an overwhelming rate, usually accompanied by fast economic/technological growth. Immediate evidence of this can be found in the large mega cities that have started to emerge in China, where thousands of vacated buildings and infrastructure is being built in anticipation of a large population boom [1]. This phenomenon is not exclusive to China. Even developed countries like Canada are observing rapid population growth rates, where the Ontario Ministry of Finance projects that the population will increase by 31.3 percent from 2013 to 2041 [2]. With rapid population growths, even bigger problems arise: how will the increasing demand for energy be met, and how do we reduce the carbon footprint associated with producing or using this energy. Large metropolitan cities like the Greater Toronto Area (GTA) will have to deal with these problems in the near future, as issues like enhanced greenhouse gas (GHG) emissions and particulate/smog pollution will concentrate as the population density continues to grow at a rapid pace.

There are some common approaches on how to deal with the problem of rapid population growth accompanied by increasing energy demands and the pollution that follows:

- The Ontario government opts for a stance on mitigation, that is, reducing/stabilizing the levels of greenhouse gases emitted into the atmosphere that cause the enhanced greenhouse effect [3]. This can be done through either strict regulation/policy introduced by governments worldwide, improving energy technologies for better emissions standards, or the creation of sinks for the gases (like CO_2 enhanced oil recovery/ sequestration in deep oil well formations) [4].
- Society in general adapts to climate change, which might mean massive migration patterns for people living in coastal regions or those already in hot climates that won't be able to farm and grow food/live comfortably [5]. In either case, it will probably require a combination of both mitigation and adaptation practices in order for humans to cope with the problems associated with increasing surface temperatures.

In anticipation of the growing population and increasing global concerns on climate change, the Government of Ontario is currently planning to install 10,700 MW power capacity from renewable energies like wind, solar and bio-energies by a target date of 2018 [6]. On top of this, the Ontarian Government introduced the Green Energy and Economies Act in 2009 which states that the province is committed to growing more renewable/clean energy projects and reducing overall energy consumption [7]. However, even with these recent developments, it will be hard to meet the increasing demand and supply of energy if nothing is done to change the energy infrastructure in the GTA. This report will primarily focus on the GTA region aggregate in Ontario since it is representative of the majority of the population.

2.0 Future Global Climate and Pollution Concerns

The Intergovernmental Panel on Climate Change (IPCC), created by the United Nations, is the foremost international body for assessing climate change patterns, future projections of average surface temperatures and how it will affect human populations [8]. This is of considerable importance to a growing, dense urban population located on a shoreline like Toronto, since an increase in average global surface temperatures implies that polar ice caps will eventually become non-existent and sea levels will rise to problematic levels [5]. It was found in the most recent IPCC

Fifth Assessment Climate Report (*AR5, 2014*) that the evidence for man-made climate change was strong, and that global surface temperatures will continue to rise at an unsustainable rate unless both mitigation and adaptation policies are adopted [9]. This evidence is presented in Figure 1, where average surface temperatures were measured over a period of 1850-2012 using historical and satellite meteorological climate data [9]:

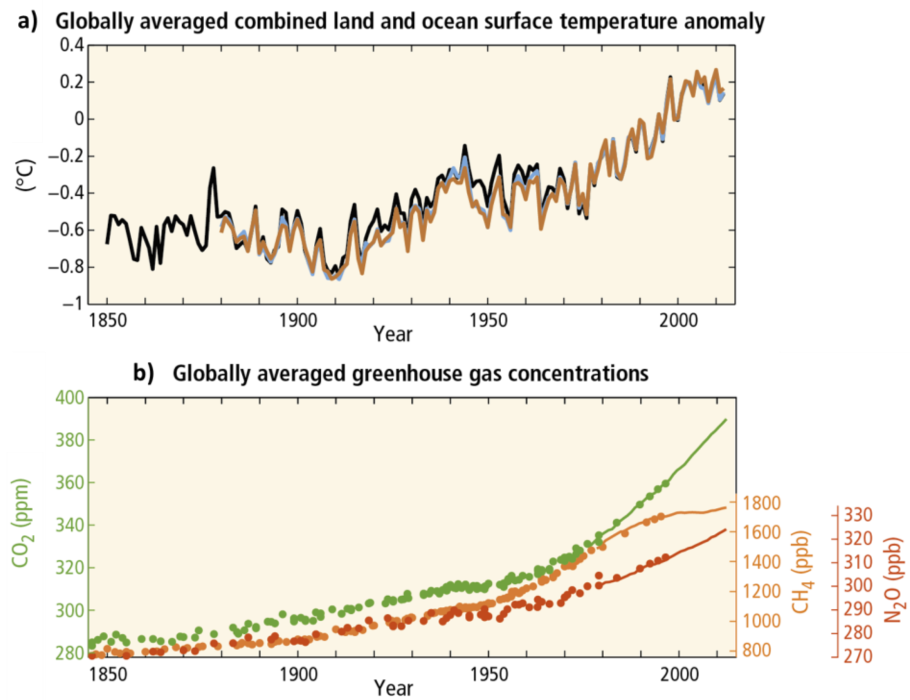


Figure 1: a) Global surface temperature trends from the IPCC. b) Global average greenhouse gas concentrations in the atmosphere over time (taken from ice core samples drilled in the Antarctic) (from the IPCC Fifth Assessment Report) [9].

It has been suggested that the leading proponent of this spike in climate change is the increase in greenhouse gases present in the troposphere (lower atmosphere) - carbon dioxide (CO_2), methane/natural gas (CH_4), nitrous oxides (N_2O), and ozone (O_3) - which leads to an enhanced greenhouse/trapping phenomena of the sun's radiation [5]. As observed in Figure 1-a), the global surface temperatures appear to anomalously increase at a rapid pace which happens to coincide with the findings in Figure 1-b) (which show that atmospheric concentration of these greenhouse gases has increased drastically over a short period of a few decades). There is strong evidence that the correlation between the two trends in both plots is not a mere coincidence: the IPCC has been trying to convince the general public that the increase in greenhouse gas pollution from the out-of-control utilization of non-renewable energies like coal/oil and gas is one of the direct causes of rapidly increasing surface temperatures [9].

Another topic of concern is the particulate matter and urban air pollution/smog that is generated from burning these non-renewable fuels. Of particular concern is the breathable air quality. As observed in China (which is synonymous with poor air quality), the rapid population growth was supported by coal fired plants that heats up water into steam, which is used to spin giant turbine/generators for energy. In 2005 alone, China burned the equivalent of 2.2 billion tons of coal to support this operation [1]. The problem with the dependence on coal and other non-renewable, carbonaceous fuels is that they generate unwanted pollutants like sulfates (which contributes to acid rain), nitrates (smog formation), and small particulates in the 2.5 to 10 micron range (PM_{10} and $PM_{2.5}$) which can irreparably damage human lungs if consistently inhaled on a daily basis [1].

Now, relating all of this to a rapidly growing urban population center like the GTA, it is important to note that negligible amounts of Ontario's power is generated from coal in relation to other energy types [10]; however, this does not mean that Ontario should be content with its current energy infrastructure. The influx of migrants to the region means a greater demand for energy, and an increase in pollution that generally follows the usage of energy. Therefore, it is useful to study the current power generation mix and analyze the potential for areas of improvement in the current system.

3.0 Background of Ontario's Power Generation Mix

As of March 22, 2016, Ontario power generation supply makeup is shown in Table 1 using data tabulated by the Ontario Independent Electricity System Operator (IESO) [10]:

Table 1: Current Ontario Power Generation Supply Mix Capacity and Actual Yearly Energy Production (from IESO Data as of March 22, 2016) [10].

Power Generation Supply Type	Power Generation Capacity [MW]	Capacity % of Total	Actual Yearly Energy Production			
			2014 Production [TWh]	% of Total (2014)	2015 Production [TWh]	% of Total (2015)
Nuclear	12,978	36%	94.9	62%	92.3	60%
Gas/Oil	9,942	28%	14.8	10%	15.4	10%
Hydro	8,432	24%	37.1	24%	36.3	24%
Wind	3,504	10%	6.8	4%	9.0	6%
Biofuels	495	1%	0.3	<1%	0.45	<1%
Solar	240	1%	0.0185	<1%	0.25	<1%
Coal	n/a	n/a	0.1	<1%	n/a	n/a
Total:	*35,591*		*154.0*		*153.7*	

From Table 1 Most of the current energy available to the GTA is from nuclear, which has a 36% capacity share (12,978 MW). In 2015, the total nuclear energy production in Ontario was 92.3 TWh, which accounted for over 60% of the energy produced in Ontario (in both 2014 and 2015). This implies that for the smaller power capacity share of the overall mix in Ontario, nuclear provides most of Ontario's energy and might be stretched thin/running close to capacity in comparison with the other energy types. In order to compare each energy type's production to its available capacity, a conversion must be made from energy to power (sample calculations are shown in the Appendix, with the assumption of constant energy usage per hour for each 24 hour/day period) as shown in Table 2:

Table 2: Average power produced in Ontario compared with available power capacity (using Table 1 data).

Power Generation Supply Type	Power Generation Capacity [MW]	Average Power Production in Ontario (Assuming constant energy usage per hour, see Appendix for sample calculations)			
		2014 Power Production on Average [MW]	% of Capacity Utilized	2015 Power Production on Average [MW]	% of Capacity Utilized
Nuclear	12,978	10833.33	83.47%	10536.53	81.19%
Gas/Oil	9,942	1689.50	16.99%	1757.99	17.68%
Hydro	8,432	4235.16	50.23%	4143.84	49.14%
Wind	3,504	776.26	22.15%	1027.40	29.32%
Biofuels	495	34.25	6.92%	51.37	10.38%
Solar	240	2.11	0.88%	28.54	11.89%
Coal	n/a	11.42	n/a	n/a	n/a

Again, the assumption in Table 2 is that the power production is constant/averaged per hour over the year. From the table, it is observed that in both 2014 and 2015, the average power production using nuclear required >80% of the available capacity/nuclear infrastructure in Ontario. This may indicate that even though most of the energy produced in Ontario is nuclear (>60%), the potential growth/capacity to increase nuclear output is very limited in comparison to other energy types like gas/oil (with only ~18% capacity in use). If the GTA is to have a nuclear future, more reactors or nuclear power plants must be built/maintained in order to supply future demands.

Another thing Table 1 also indicates is that all energy types have some type of associated usage problem/supply caveat which implies that there needs to be a variety/mix of different energy types instead of reliance on a single source. Dependence on a single energy source is not ideal, and to list a few problems:

- Coal and gas/oil energies are notorious for generating GHG's and urban air pollutants like smog. A life cycle analysis (LCA) of the total carbon dioxide emitted to produce a certain energy type was done by Jacobson (Table 3) [11]:

Table 3: LCA analysis of the equivalent CO_2 emitted (g CO_2/kWh) for different energy producing technologies done by Jacobson [11].

Technology Type	General Lifecycle [g CO_2/kWh]	Opportunity cost emissions due to delays [g CO_2/kWh]	War/terrorism (nuclear) or 500 yr leakage of CCS [g CO_2/kWh]	Total [g CO_2/kWh]
Solar Photovoltaic	19 - 59	0	0	19 – 59
Solar Thermal	8.5 – 11.3	0	0	8.5 – 11.3
Wind	2.8 – 7.4	0	0	2.8 – 7.4
Geothermal	15.1 – 55	1 – 6	0	16.1 – 61
Hydroelectric	17 – 22	31 – 49	0	48 – 71
Wave	21.7	20 – 41	0	41.7 – 62.7
Tidal	14	20 – 41	0	34 – 55
Nuclear	9 – 70	59 – 106	0 – 4.1	68 – 180.1
Coal – with carbon capture storage (CCS)	225 – 442	51 – 87	1.8 – 42	307.8 - 571

LCA's are useful for observing overall emissions of certain pollutants like CO_2 since they consider every aspect of how the fuel/energy was created; for example, emissions from vehicles transporting raw materials or goods, wastes/releases associated with manufacturing/ industrial processes, etc. Observing Table 3, it is immediately clear that even with a carbon capture storage solution, coal is by far the biggest polluter. All other energy types presented in Table 3 show that they are relatively clean options in relation to coal (this includes wind, solar, hydro, nuclear etc.).

- Hydroelectric energy produced from large dams can often lead to: loss of biodiversity because of water diversion and loss of habitable areas, large area requirements for the holding reservoir/basin, release of carbon dioxide from decaying plant material that was washed by the dam [9], and leaching of harmful toxins from the soils like mercury, PCB's, heavy metals among others where the water flow is diverted [5].
- Solar power benefits from maximal exposure to the sun year round. Unfortunately, Canada in general receives very minimal sunlight during winter months, and adverse precipitants like snow/hail could damage solar panels or might require constant cleaning/maintenance. As with solar, wind energy is also intermittent as it is dependent on an uncontrollable source. Intermittent energies (as a single source) might not be the best idea for dense urban populations like the GTA because they would not be able to ramp up energy supplies during peak usage hours [12].
- Nuclear energy has negative connotations in terms of public perception. Meltdown events like Chernobyl, Three Mile Island, and Fukushima were large catastrophes and have had an unfavorable effect on the public's perception of the safety of nuclear operation (because of the long half-lives/degradation of nuclear wastes). Also, nuclear is mainly used for baseload/steady generation and not for peak loads or ramping [13].

Therefore, it is useful to consider the benefits/disadvantages with using certain energy generation types in various situations when deciding on a supply mix. Currently, hydroelectric and nuclear are used for the baseload generation (constant supply of energy over 24 hour period) [13]. For peak generation, hydroelectric and natural gas are used. In the case of the GTA, the metropolitan area is located on Lake Ontario, which provides an interesting opportunity to expand into energy types that might require large water throughputs like nuclear reactor cooling for example which could play a bigger role in baseload generation.

3.1 Nuclear Energy Sources

The GTA has three main nuclear fission power plants that feed into its grid listed in Table 4 and shown in Figure 2 [13], [14]:

Table 4: Current Ontario Nuclear Power Plants and Operating Capacities (from IESO) [13].

Power Plant Site/Location	Operator	Power Generation Capacity [MW]	Number of Reactor Units	Projected Operation/Major Maintenance Dates
Bruce [Kincardine]	Bruce Power	6,300	8	- Two units refurbished on 2012, - Remaining units scheduled for refurbishment in 2020
Darlington [Clarington]	Ontario Power Generation (Government)	3,500	4	- All 4 units scheduled for refurbishment in 2016 (2026 completion)
Pickering [Pickering]		3,100	6	- All 6 units will be shut down by 2024

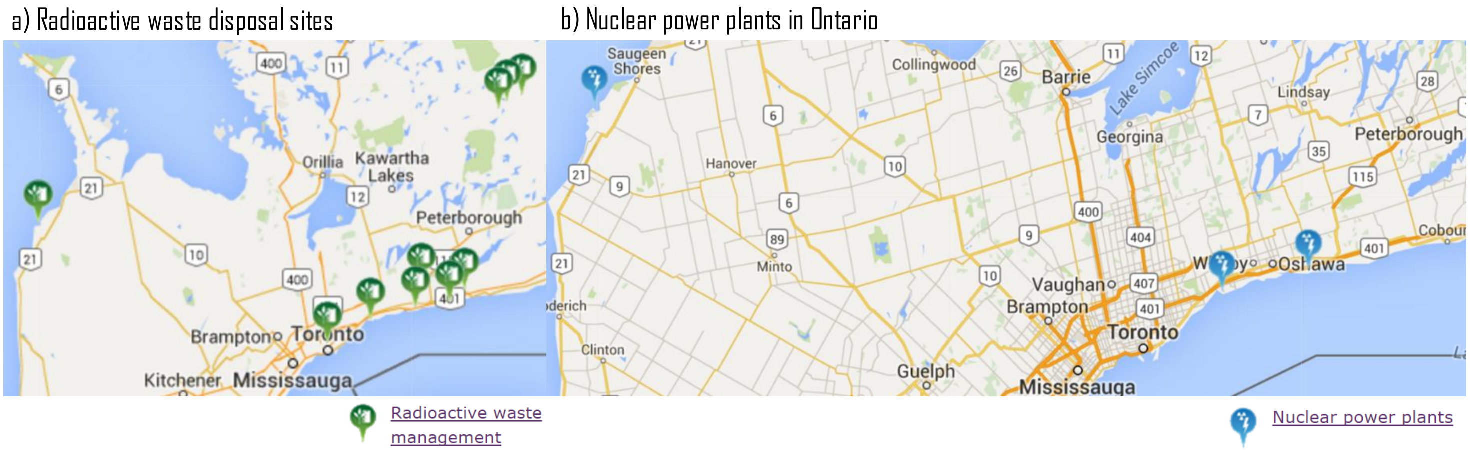


Figure 2: a) Location of radioactive waste disposal facilities in Ontario, b) Location of all nuclear power plants in Ontario (from the Canadian Nuclear Safety Commission) [14].

Figure 2 shows that the current nuclear power plants are located in areas of: lower population density, and close proximity to a generous water source (like Lakes Ontario or Michigan). Another important detail is that all of the current plants have a radioactive waste management sites located relatively close (to treat waste streams). This indicates that nuclear plants can operate when: there are water and waste treatment resources nearby, and the surrounding population is smaller and accepting of the nuclear culture as long as safety is emphasized. Another important thing to note from Table 4 is that there are efforts to refurbish older plants like Darlington in terms of equipment replacement/new boilers, which is estimated to cost $12.8 billion [15]. Although this might seem like a lot of money, it will help preserve around 3,000 jobs and is estimated to continue power generation operations over 30 years [15]. The Bruce power plant will also be undergoing a refurbishment scheduled in 2020 to the tune of $8 billion for six reactors, including an additional $5 billion for other life extending equipment [16]. The fact that the Ontario government is spending the money on these clean projects shows that they are committed to taking the right steps to reduce their climate impact.

Although nuclear power is not a renewable energy (as it requires certain nuclear isotopic fuels that have limited quantity), it can be considered a clean process – since it does not emit air pollutants when in operation [8]. Current nuclear plants in Ontario are used for baseload generation and not temporary/ramping use, this means that if there is a peak power surge in the GTA during a potential heat wave, nuclear power will not be able to deal with this individually and will require help from a secondary generator like hydroelectric or gas fired plants [10].

3.2 Natural Gas and Oil

Ontario has slowly phased out coal as a source of energy generation because of its impacts on climate change. In fact, the last coal plant running in Ontario began its phase out period in 2014 (according to the Ontario Ministry of Energy) [17]. This is where natural gas has come in and secured a larger share in power production in Ontario. Although the use of natural gas produces emissions, it is by far the cleanest energy source out of all conventional carbon fuels that pack the most energy-to-density ratio [17]. Natural gas is also the cheapest and most reliable option in regards to providing temporary power during peak demands. What is implied here is that natural gas is often used for quick ramping scenarios to increasee/decrease electrical output. It accomplishes this feat by controlling the mass flow rate of a hot gas/air mixture to the turbines using valves/air foils [12]. Once the hot gas mixture passes through the turbine generator, the waste heat can be used to boil water into steam, where it will be used on a secondary steam turbine for additional generation. This process is what is called a "combined-cycle" where it can increase the efficiency of a natural gas plant [18].

One of the biggest reasons that natural gas is still used today and not completely phased out like coal is because the amount of pollution it generates is tolerable in comparison to the reliability and very small cost to produce electricity in regards to other renewable/clean energy sources. As a point of comparison, Chu reports that the US Energy Information Administration did a projection study in 2010 on the average 2016 cost/MWh of the most common energy sources; it was found that natural gas was by far the cheapest energy source at around \$60/MWh compared to the next cheapest being hydroelectric at around \$80/MWh [12].

Considering that natural gas is very cheap, and is used in a niche area of reliable peak power supply or during intermittent periods, it has to be asked at what point the public's perception of its pollution problems outweighs the cost benefits. The US Energy Information Administration has studied the amount of CO_2 emitted of different carbon fuel types, where it was found that coal released roughly 210.20/117 times (or 1.8X) more CO_2 per million BTU of energy than natural gas [19]. Because natural gas emits way less pollution than coal, the point of phasing it out should begin when renewables/clean sources reach a point where they are cheaper such that cost incentives are met (that is, clean technologies should aim for costs less than \$60/MWh). This problem is compounded by the fact that gas prices have plummeted very recently (from \$5.00 in 2014 to less than \$2.50 per million BTU), which implies that there are now little incentives to leave natural gas since it is even cheaper to produce than before .

Another point of contention is the use of oil products. Since most vehicles on the road use gasoline or diesel (which are derivatives of oil), the short term dependence on this fuel will not go away. Potential alternatives for transportation might use future battery technology or hydrogen fuel cells (provided infrastructure like refueling stations are built in support). However, the adoption process up to this point has been slow and the dependence on traditional vehicles looks to remain steady in the foreseeable short-term future [17].

3.3 Hydroelectric Generation

The hydroelectric power generated in Ontario is produced in different river locations like the St. Lawrence and Niagara (which accounts for the most generation) [13]. In terms of the Niagara diversion, water flows out of Lake Erie and into Lake Ontario, where there is an international border between the United States and Canada. Because of this border, the amount of water that can be diverted from the river and into hydro generation tunnels is shared between the two countries based on the 1950 Niagara Treaty, where on average [6]: a third of the flow goes over the falls for tourism, and the rest of the two-thirds is split evenly between Canada and the US for diversion into large tunnels with water turbines. Most recently (2013), a third tunnel on the Canadian side was built to utilize more of the river flow diversion (Figure 3).

Figure 3: The third tunnel built to utilize the Niagara River diversion for hydro (From Niagara Frontier) [20].

Previously the Niagara River diversion available to Ontario for hydropower exceeded the generation site quotas about 65% of the time; however, with this new third tunnel, the time of overflow waste is reduced to around 15% [20]. This implies that there is still room to grow in terms of building an additional tunnel to reduce the waste time of 15% down to 0. The cost of building this most recent tunnel (as well as the additional costs associated with upgrading retired generation stations like the Ontario and Toronto power stations) was found to be in the excess of $1.6 billion.

Hydroelectric energy can be used for both baseload generation and intermittent/short term supply. This is done by utilizing a “pumped hydro storage” solution where potential energy can be stored by pumping water into an elevated reservoir when it is not needed, and delivered to a turbine during peak periods [17]. This flexibility means that future focus on baseload generation can involve different energy types while hydro can help with peak load needs.

3.4 Wind Energy

A wind farm and wind speed map are shown in Figure 4 for the entire province of Ontario:

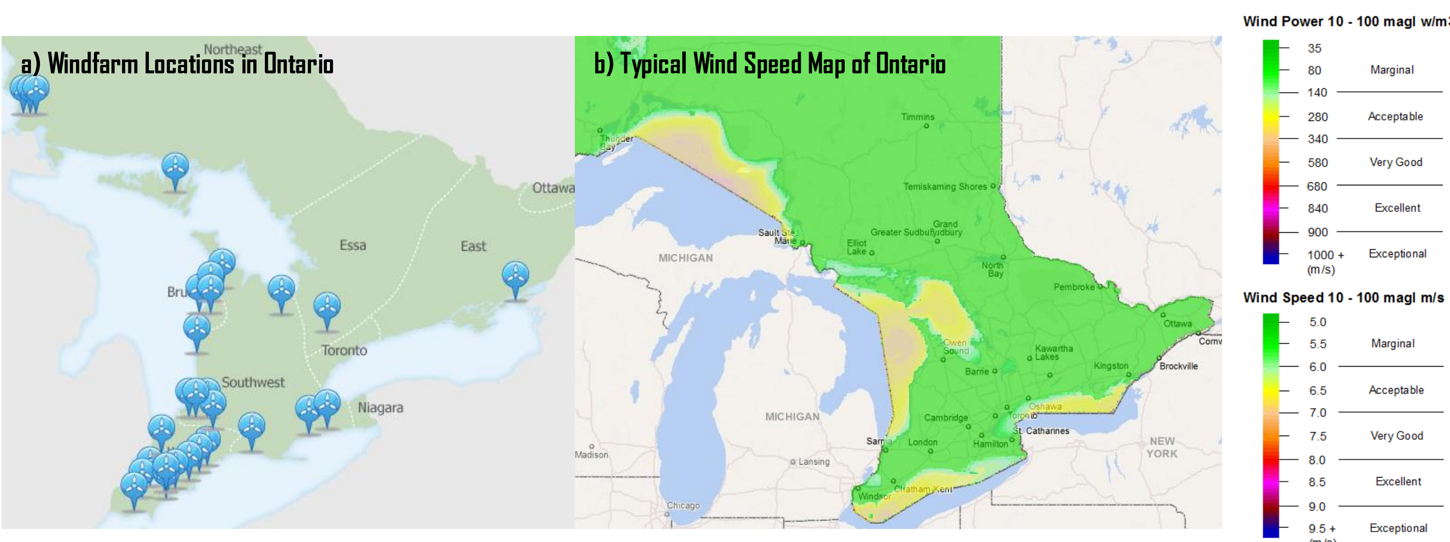


Figure 4: a) Location map of significant windfarms in Ontario (From IESO) [21]. b) GIS wind resource map showing typical wind speeds in the Region of Ontarian (from the Renewable Energy Atlas Map) [22].

As observed from Figure 4-a), most of the current wind farms are located around areas near the great lakes. Figure 4-b) shows that this is to be expected since the wind speed around the lake shore regions (deemed acceptable speed) are about 1-2 m/s faster than inland (marginal speed). Unfortunately, comparing the two maps shows that most of the acceptable wind area is already saturated with wind farms except for the GTA region and the area above Sault St. Marie. Because of this, a possible alternative is the use of offshore wind farms. Offshore wind farms can also be utilized (in Lake Ontario) but require stable marine platforms for the turbines that do not have to be periodically checked/maintained (which is problematic since marine environments are typically more harsh than building structures on land). Mark Jacobson suggested that most turbines being installed in 2012 had a capacity of 1.5 ∼ 2 MW, and the alternating current electrical power generated from the turbine rotation requires large amounts of rare earth magnets for the generators [11]. However, overlooking all of this, wind energy is an extremely enticing source since it is renewable and clean (produces negligible emissions).

One problem with wind energy is that it is intermittent (turbine speed is entirely dependent on the wind speed in the region of the wind farm, and is therefore never constant). This implies that if there is a large electricity demand/draw during peak hours, it might not be able to ramp up the supply to meet this demand. A worst-case scenario looking at Table 1 is if some electricity user was entirely dependent on the wind capacity of 3,504 MW, a heat wave hits the GTA region and everyone is off work and requires air conditioning/using electronic devices at home. In this scenario, an energy storage scheme or another source would be required with sufficient ramping capabilities to make up for wind energy deficiencies. Typically, large capacitor banks with ample storage/discharge capabilities or natural gas-fired plants with ramping capabilities of ∼50 MW/min solves this issue (but is obviously non-ideal since it is a pollutant producing process) [11].

3.5 Biofuels, Solar and Other Alternative Energies

Biofuels and solar energy each only account for <1% of Ontario's current power generation (Table 1). This is understandable, since solar is more prevalent in areas closer to the equator (with year-round exposure to the sun). Although biofuels and solar are not suitable for baseload generation (since they currently provide little capacity to Ontario's grid), they can still be used as secondary sources when demand increases during peak hours. With coal slowly being phased out as an energy source, generation stations are being converted to use biofuels instead [17]. Biomass and biogas systems have adjustment capabilities where they can increase their output for peak demands (which might mean it is a viable candidate to supplant natural gas systems). This fuel type is unique as it is produced from organic wastes and is a cleaner source of energy that might be suitable for smaller communities with less overall energy demands [17]. Ontario Power Generation states that biomass generation in Ontario is beneficial because: the harvested wood pellets burned into wood ash instead of gases produce 75% less NOx gases than coal, no SO_2's, and reduces GHG emissions by 80% compared to combined-cycle natural gas plants [23].

Other potential future energy sources include tidal and wave energies that utilize the natural movements/waves of large bodies of water to generate electricity. However, these technologies are still in infancy and current costs make the incentive to build them very low.

3.6 Cost Estimates Summary

The Ontarian Government has planned to upgrade transformer and switching stations around GTA in anticipation of the growing energy demands. The total cost of these stations/transmission lines is estimated to come in at around $816.2 million (see Appendix for specific station costs). This cost must be factored into the analysis in order to ensure accuracy. This is important, as it provides the necessary infrastructure for future power projects to send additional electricity to the GTA region in the foreseeable future.

As another point of comparison, looking at the relative costs to produce each fuel type can provide even more insight into why Ontario's current supply mix is the way it is and what needs to change so that costs of greener energies can be controlled. Chu et al. reported data from the US Energy Information Administration (EIA), which did a study of the total cost associated with producing each fuel type (Figure 5) [12]:

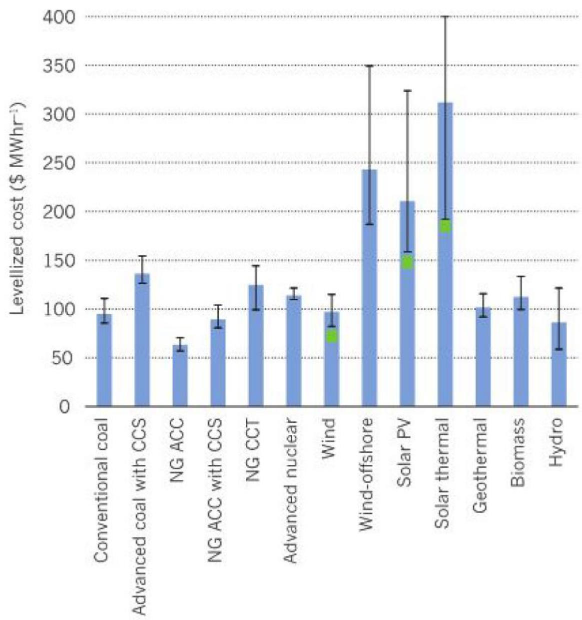


Figure 5: Projections of the 2016 cost of electricity from different energy sources made in 2010 (from Chu's Opportunities and Challenges for Sustainable Energy) [12].

As observed from Figure 5, cheapest energy source (by quite a large margin) is natural gas with the advanced combined cycle utilizing an additional steam turbine. Another thing to notice is that even if a carbon capture storage (CCS) unit is added to the natural gas combined cycle, the total cost is still lower than most (except hydro) at around $80-90 per MWh. The three most expensive alternatives are offshore wind, and both solar photovoltaic and solar thermal. Again, as stated by Jacobson, offshore wind is expensive because it requires heavy grade marine platforms/turbine materials that can withstand the harsh water environment with very little operator support/ maintenance [11]. In terms of solar, it is understandable that it might cost more since there is an upper limit to the efficiency of a single junction solar cell, called the "Shockley-Queisser Limit" based on silicon, where the upper, practical limit is considered 29% [12]. However, Chu states that this limit can be surpassed because the Carnot efficiency of a solar cell is around 94% (considering the sun is a black body of 5,800 K and the cell operates at 350 K) [12].

The US EIA chart also shows that most of the energy sources currently used in Ontario's supply mix like hydro, nuclear, wind, biomass etc. are roughly the same cost at around $100 per MWh. This means that expansion into any of these cleaner options is viable as long as there is capacity available. With natural gas at roughly $60 per MWh, it is understandable why it is so hard to adopt cleaner/renewable energies because the electricity production cost is almost twice as much, not to mention the readily abundant source of NG's from Western Canada.

Another thing to consider is how much it costs to build a new generation station. The US EIA did a 2014 study to estimate the base cost of building a typical-sized power generation station for different energy types as seen below (see Appendix, Table 11 for raw data) [24]:

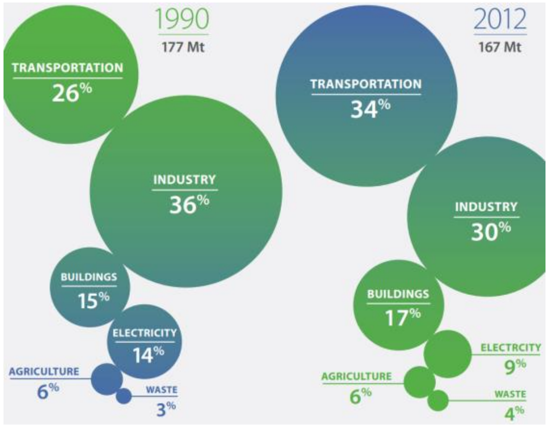
Table 5: Estimated cost of building a new electricity generating station (from the US EIA (2014 data)) [24].

Plant Technology Type	Online Year	Capacity/Size (MW)	Typical Base Cost ($/kW)	Calculated Total Cost (see Appendix, Table 12)
Conventional Gas/Oil Combined Cycle	2017	620	869	$ 538,780,000
Advanced Gas/Oil Combined Cycle	2017	400	942	$ 376,800,000
Advanced Gas Combined Cycle with CCS	2017	340	1,845	$ 627,300,000
Advanced Nuclear	2022	2,234	4,646	$ 10,379,164,000
Biomass	2018	50	3,399	$ 169,950,000
Hydro	2018	500	2,410	$ 1,205,000,000
Wind	2017	100	1,850	$ 185,000,000
Wind Offshore	2018	400	4,476	$ 1,790,400,000
Solar Thermal	2017	100	3,787	$ 378,700,000
Photovoltaic	2016	150	3,123	$ 468,450,000

One thing that is not listed on Table 5 is the potential for upgrading/repurposing an older or decommissioned plant. As an example, Ontario Power Generation estimates that repurposing a typical coal fired plant into a new biomass generation station is approximately $170 million in conversion (compared with the exact $170 million total estimated by the US EIA for a new plant) [23]. However, the estimate is for a specific plant called the Atikokan which has an operating capacity of 200 MW compared to the US EIA estimate of 50 MW (see Table 5), therefore, the cost of upgrading/repurposing a biomass plant is roughly a quarter for the same output [23]. As another example, refurbishment of the Darlington nuclear station was previously stated to be around $12.8 billion compared with the US EIA estimate of $10.4 billion [15]. Again, however, Darlington's capacity is 3,500 MW compared with the typical estimate of 2,234 MW. Therefore, Darlington is getting a capacity around 273.4 MW/billion compared to the estimate of 214.8 MW/billion. If the cost was the other way around, there would be no incentive to upgrade old plants.

4.0 Largest Sources of GHG's in the GTA

The Ontario Ministry of Environment and Climate Change released a report in 2014 listing all major sectors of GHG emissions, comparing 1990 data to 2012 (Figure 6) [25]:



Sector	Sources of Greenhouse Gas Emissions
Transportation	The combustion of fossil fuels such as diesel, gasoline and propane by passenger and commercial vehicles on and off roads, as well as rail and Ontario's share of domestic marine and air travel
Industry	Some industrial processes and stationary combustion of fossil fuels such as coke, natural gas and coal used in mining; pipelines; construction; greenhouses; production of cement, iron and steel, chemicals, paper and wood products; and other manufacturing
Buildings	The combustion of fossil fuels such as natural gas in residential, commercial and institutional buildings for space and water heating
Electricity	Generating electricity and heat by electric utilities using fossil fuels such as natural gas
Agriculture	Enteric fermentation, manure management and fertilizer application
Waste	Solid waste disposal on land, wastewater handling and waste incineration

Figure 6: Source of emissions in Ontario by sector (from the Ontario MoECC's Emissions Report) [25].

In other words, Figure 6 reveals that GHG`s produced from electricity generation actually only represents approximately 9% of the 167 Mt of gas emissions (or roughly 15 Mt). This is actually an improvement from the levels in 1990, which was around 25 Mt. A reasonable guess as to why this change is positive is the decommissioning of the coal fired plants around Ontario. Although most of the sectors show some form of stability or decrease in emissions, the transportation sector appears to be the biggest polluter, with the Ontario Ministry of Climate Change implying that the combustion of carbon-based fossil fuels leads to the greatest source of GHG`s.

With the growing GTA population and heavy road use on the 401 highway, passenger vehicles getting stuck in traffic jams and engine idling is a sizeable problem. The road infrastructure in the GTA is already dense to begin with, so future expansion is very limited. However, there are ways to decrease road use/limit vehicle pollution: improving public transportation systems like light rail trains and the potential adoption of electrical vehicles. A well to wheel analysis done by Larcher and Tarascon shows the total CO2 emissions associated with driving a petrol vs. electrical car 1 km (based on 2014 data) in Figure 7 [26]:

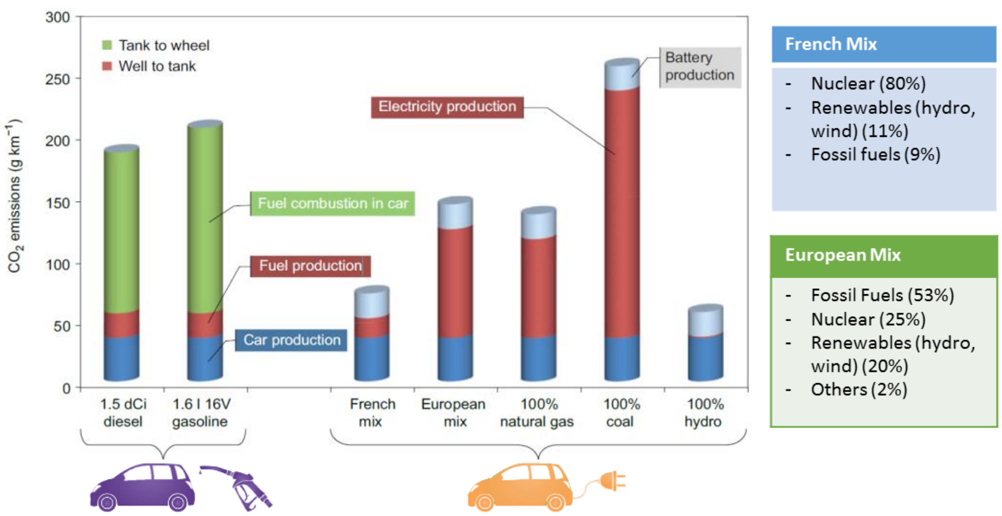


Figure 7: Well to wheel/tank analysis for total CO_2 emissions from both petrol and electric vehicles (from Larcher and Tarascon, Sustainable Batteries Review Article) [26].

Similar to how the LCA was done on different energy systems by Jacobson (which found that coal produced the most CO_2 over its entire life), Larcher and Tarascon use a basis of 1 km driven by a gasoline/diesel car vs. an electric vehicle [26]. From Figure 7, the CO_2 produced during car production is leveled across the board or negligible because they involve similar manufacturing processes. The difference begins when looking at the well to tank emissions (which accounts for CO_2 emissions during things like oil/gas processing or refining). It is observed that for gasoline/ diesel cars, minimal amounts of CO_2 are released during fuel production when compared to the electric vehicle. However, this statistic changes when factoring the tank to wheel analysis, where actual combustion of this fuel in the car engine is what produces significant quantities of CO_2. This makes sense, since using non-renewable, dirty fossil fuels to produce electricity which is than transmitted to the car for drive would lead to a lot of efficiency losses (hence, more fuel is needed to generate the same amount endpoint electricity). Therefore, it makes a lot of sense to go with something like the electric vehicle using the French mix (mostly nuclear) or hydro, since they produce, on total around 3X less CO_2 emissions. What this analysis indicates is that in order to adopt electric vehicles, the renewable/clean energy capacity in Ontario will have to be significantly increased to the point where oil and gas refining is minimal. This is in contrast to someone owning a Tesla motor vehicle in the middle of Alberta, where the energy is mostly produced from oil and gas, so the driver of the electric vehicle is unaware that they are almost producing the same amount of GHG's using a car with less mileage and range.

5.0 Analysis of Potential Energy Organization Schemes

It is now pertinent to come up with a potential energy reorganization scheme that could help Ontario deal with increased energy demands from population growth and associated pollution effects (taking the above sections into account).

5.1 Demand and Supply Projections

Currently, the IESO estimates that the peak demand for electricity (for both normal and extreme weather events over the next year) will be (Table 6) [10]:

Table 6: IESO estimates for peak electricity demands over the 2016-2017 period [10].

Season	Normal Weather Peak (MW)	Extreme Weather Peak (MW)
Summer 2016	22,587	24,598
Winter 2016-2017	22,259	23,190
Summer 2017	22,634	24,716

These values show that current usage at peak demand roughly uses only 70% of Ontario's generation capacity at most. However, the numbers in Table 6 don't tell the whole story because the projections are only for next year. In anticipation of increasing energy demand and population growth in Ontario, the Ontario Ministry of Energy has charted a plan for Ontario's power supply mix over the next couple of decades as seen below in Figure 8 [17]:

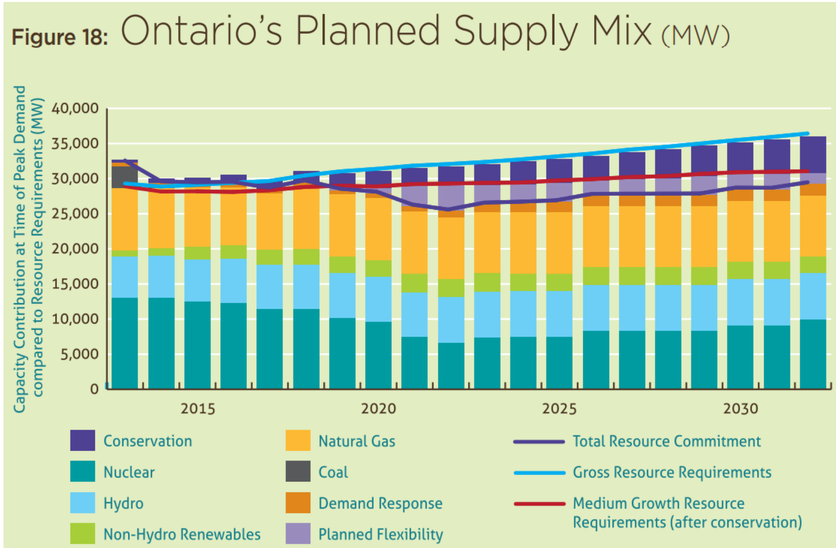


Figure 8: Ontario's planned power supply mix capacity (from the Ontario Ministry of Energy's Future Outlook Report) [17].

The chart in Figure 8 shows that the provincial government's plan involves:

- Steady reliance on both natural gas, hydro, and other renewables like biomass, solar and wind energy. There is also an implication that new projects to build more of these clean sources is not currently in the future plan (at least until after 2030) since the planned supply of natural gas is relatively constant.
- Nuclear dips down going towards 2020 because of the planned Pickering plant shutdown in 2024, however, this trends up afterwards with increased supply from the remaining Darlington and Bruce Power stations (they will be the primary baseload supply).
- The Biggest thing to take away from this chart is the idealization of the conservation bar (deep purple), which indicates that the Ontarian government believes the energy demand over the next couple of decades will level out, with the average person/industry not using as much electricity. Faruqui states that the US EIA predicted residential electricity consumption will decrease over the next several decades because most technologies will become more energy efficient (Figure 9) [27]:

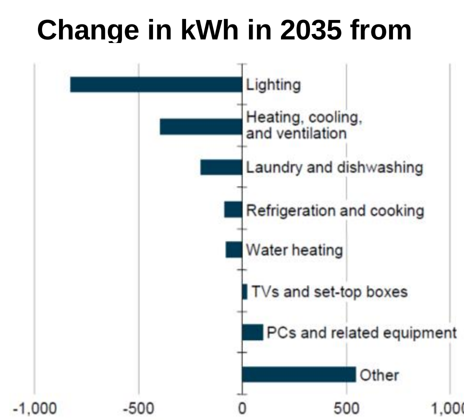


Figure 9: Change in residential consumption (kWh) per house in 2035 compared with 2010 (from Faruqui based on the US EIA, 2012 Annual Energy Outlook Conference) [27].

- Either way, it appears that demand will increase past 35,000 MW after 2030, therefore, the current capacity of Ontario`s generation mix at 35,591 MW (Table 1) might not be large enough to accommodate this growing demand.

5.2 Scenario 1: Completely Clean Generation

As the title suggests, completely clean generation implies the use of only those energy types that do not produce significant amounts of GHG's. Ontario is currently doing very well in this regard with the decommissioning of coal-fired plants and steady adoption of renewables like hydro or biofuels. However, there is still room to improve: natural gas plants are still widely used for reliable power production during peak demands, and oil and gas processing is still widely used for as an energy source for things like transportation, and building/water heating (Figure 6). Therefore, the following list of items would have to occur for Ontario to go completely green:

Table 7: Potential Action items for Ontario to go completely green (energy).

#	Action	Description	Expected Outcome
1	Replace/decommission <u>all</u> gas-fired plants	- Replace/decommission all plants involved with either baseload or peak generation - Increase capacity of greener sources - Potential repurposing into biofuel plants	- Reduction of almost all sources of GHG emissions involved with electricity generation - Increasing costs per kWh
2	<u>Refurbishment</u> of the Pickering nuclear plant	- Pickering is scheduled to close in 2024 - Refurbishment (like Darlington) to extend the overall lifetime of the power plant	- Cost of refurbishment would be similar to Darlington (since they both have similar capacities around 3000 MW) - Additional nuclear power would increase baseload generation capacity in the future
3	Replacement of <u>all</u> vehicles in GTA with electric cars	- Replacement of any diesel/gasoline vehicle with an electric vehicle operating in GTA region	- Assuming cost of car manufacturing is similar to that of conventional vehicles, cost of vehicle production would not be too burdensome. - Greater demand on electricity instead of conventional fossil fuels - Immediate decrease of the biggest source of GHG's in Ontario
4	Start construction on new green power plants	- Potential construction of new green power plants based on current technologies	- Increased capacity to Ontario's grid/offset the production lost from replacing natural gas fired plants

From the Actions in Table 7,

1.
    a. From Table 1, the total gas capacity is currently around 10,000 MW, however, only around 2,000 MW is actually produced (Table 2). From Table 6, the difference between peak and normal demand is roughly around 2,000 MW; therefore, only 2,000 MW really needs to be replaced for peak load, reliable generation with the remaining 8,000 MW capacity decommissioned. This value would expected to remain constant based on Ontario's planned mix from the Ministry of Energy (which shows that the demand response is relatively stable) (Figure 8).

    b. Repurposing NG plants with biofuels could be viable. The cost of the most previous refurbishment was $170 million for 200 MW of capacity (Atikokan plant, assuming refurbishment of coal and NG plants is similar). If 2,000 MW of capacity (for peak power demand) is necessary, then it could be assumed that 10 plants at a total cost of $1.7 billion would be necessary. However, if the total 10,000 MW were repurposed, then the cost would be $8.5 billion. Although this is a staggeringly large number, it has to be put in perspective: this will provide clean power for power demands over the projected life past 2030. In terms of electricity generation costs, current biomass plants cost around 1.5X more than a NG fired combined cycle plant (Figure 5), so this implies everyone in the GTA would pay slightly more for electricity.
    c. Reduction of greenhouse gases would roughly be 9% of 167 Mt (Figure 6) since it can be assumed that NG plants produce most of this pollution to begin with.
2. Refurbishment of the Pickering plant would be assumed to cost roughly the same amount as the Darlington plant (similar capacities), which is around $12.8 billion for 3,100 MW of baseload generation (Table 4). This would be needed to keep the total current capacity at 35,591 MW that feeds into Ontario's grid and supplies the GTA region (Table 1) since the current total already includes Pickering's generation capacity.
3.
    a. Larcher and Tarascon did a study in 2015 that estimated the average electrical vehicle using lithium-ion batteries use 20 kWh per 100 km (with the average person driving around 10,000 km per year) [26]. The total population of vehicle users in the GTA region was reported as 1.7 million people by CBC News Toronto using 2008 census data [28]. Therefore, the total power demand/capacity required for wide scale adoption of electric vehicles is roughly around 388 MW to 400 MW (conservatively).
    b. The demand of 400 MW can be met by hydroelectric capacity, which is only currently utilizing 50% of its 8,432 MW capacity based on 2015 electricity production data in Table 2.
    c. Immediate elimination of petrol vehicles will reduce GHG's considerably. Looking back on Figure 7 or the well to wheel analysis, it was observed that using a French Mix (which involves mostly nuclear and hydro, and is similar to Ontario's current supply mix) results in a reduction of CO_2 pollution from 200 g/km to 60 g/km. This implies that GHG's could be reduced by roughly 40 Mt or an immediate 25% decrease in total GHG emissions (167 Mt) (see Figure 6).
4.
    a. Another thing to consider is that if the Ontario MoECC's prediction of decreased power demand over the next couple of decades is unfounded, and demand only continues to grow past 35,000 MW (current supply capacity), then new power plants will be needed. A reliable one being a new nuclear plant, where the only restrictions are proximity to the general populace (but not too far away such that transmission losses are not big), and its location close to a water source and nuclear waste treatment facility. Many places between Oshawa and Colburg (see Figure 2) fit this description, and would require approval from the Canadian Nuclear Safety Commission which determines suitable sites for any new nuclear power plants in Canada [29].
    b. Again, using the cost estimate data from the US EIA (Table 5), a new advanced nuclear power plant would cost around $10.4 billion dollars for roughly 2,234 MW

of capacity. This would bring the total capacity of Ontario's supply mix to around 37,825 MW. Considering the Ontario Ministry of Energy projected future demand (all the way past 2030) to be around 30,000 MW considering conservation estimates [17]. This would help provide a stable supply capacity in the event that conservation estimates are a little bit off. The only tradeoff is the high cost and a turnaround time of around 8 years (that is start of project to completion as estimated by the US EIA in Table 5).

5.3 Scenario 2: Balanced Generation

Similar to the analysis done in the previous section, Scenario 2 focuses on a more reachable strategy (that closely follows the Ontario Government's current plans). However, this scenario will not drastically reduce GHG emissions from current standards since there is more a focus of a slower adoption process.

Table 8: Potential Action items for Ontario to have more balanced generation (energy).

#	Action	Description	Expected Outcome
1	Start replacement/ decommissioning of gas-fired plants involved with baseload generation	- Start the replacement/decommissioning of plants involved with baseload generation - Replacement of the lost capacity can be done through plant repurposing into biofuel or increased hydro performance	- Starting the process of reducing GHG emissions involved with electricity generation - Increasing cost per kWh
2	Refurbishment of the Pickering nuclear plant	See description and expectations in Table 7	
3	Steady adoption of electrical vehicles	- Start replacing diesel/gasoline vehicles with an electric vehicle operating in GTA region by offering rebates to consumers	- Slow adoption at first (since gasoline is still very cheap) - Slow/steady reduction of GHG's from transport.
4	Start construction on new green power plants	See description and expectations in Table 7	

From the Actions in Table 8,

1.
    a. As stated in the analysis of Scenario 1, there is roughly 10,000 MW of gas/oil capacity and only 2,000 MW is actually produced. Also, because the extreme weather peak demands are only + 2,000 MW from regular demands (Table 6), only 2,000 MW is really needed from gas generation to deal with reliable/temporary generation.
    b. Therefore, a reasonable plan to possibly pursue is the eventual decommissioning of the remaining 8,000 MW of unused gas plant capacity over the course of the next couple of decades. What this will mean is that the remaining 2,000 MW can only be used for temporary power surges, and the remaining/unused 8,000 MW of capacity will slowly be phased out by repurposed biofuel plants over the course of several decades. This would cost roughly $6.8 billion based on Scenario 1 estimates.
2. Again, similar to Scenario 1, a refurbishment of the Pickering Nuclear Plant would mean that 3,000 MW or so of extra capacity could be dependably added to the grid.

3.
   a. Currently, oil and gas prices are so low that the full scale adoption of electrical vehicles would not make economic sense. However, this does not mean that there are no incentives for buying an electric vehicle. Again, assuming that Ontario's power generation in the future will move towards something close to the French Mix shown in Figure 7, then the net CO2 emissions will begin to decrease at a steady rate in relation to the number of people transitioning and the infrastructure that needs to be built over time (like recharge stations).
   b. As an estimate, assuming that Ontario can reach full implementation of all electric vehicles by 2030 (and the adoption process begins at 2016), then over a 14 year period: 400 MW of capacity must be available solely as electric car fuel. If the supply is scaled linearly over the 14 years, then roughly 30 MW of capacity every year must be reserved for electric vehicle adoption. This does not appear to be a problem considering the total supply capacity listed in Table 2 and the fact that hydro is only operating at 50% capacity. Therefore, the 30 MW demand each year can be fulfilled by hydroelectric generation alone.
4. Similar to the analysis done in Scenario 1, a new nuclear power plant would be used for baseload generation and would add approximately 2,234 MW of capacity to the current supply mix.

5.4 Comparison of Scenarios

The following table breaks down the two proposed scenarios in terms of cost, power demand and capacity, and the reduction in GHG emissions:

Table 9: Comparison of the two energy organization scenarios posited above

<table>
<tr><th></th><th>Scenario 1: Completely Green</th><th>Scenario 2: Balanced</th></tr>
<tr><td rowspan="2">Change in Demand</td><td colspan="2">- Ontario MoE projects peak demand to decrease until past 2030 due to improved technology efficiencies.</td></tr>
<tr><td>- Immediate adoption of electric vehicles in the year 2016. This implies that 400 MW must be made available in support.</td><td>- Steady growth adoption of electric vehicles over the course of 14 years (from 2016 to 2030) means that and additional 30 MW must be made available each year.</td></tr>
<tr><td rowspan="2">Additional Energy Capacity Introduced to the Grid</td><td colspan="2">- Ontario MoE projects peak supply to steady out at around 30,000 MW until past 2030.
- Refurbishment of the Pickering nuclear plant will not produce additional energy (since it is already factored into Ontario's current supply mix) (Table 1).
- Construction of a new nuclear power plant (for both scenarios) with roughly 2,234 MW of capacity for baseload generation.</td></tr>
<tr><td>- Repurposing all gas-fired plants into biofuel plants immediately (starting 2016). No additional energy capacity would be produced. Hydroelectric would be used to replace all peak/reliable power demands.</td><td>- Repurposing of 8,000 of the 10,000 available MW of gas-fired plants into biofuel plants (starting 2016) leaving the remaining 2,000 MW as gas-fired plants to help with peak/reliable power.</td></tr>
<tr><td>Additional Costs</td><td colspan="2">- Refurbishment of Pickering will likely cost around $12.8 billion.
- Construction of a new nuclear plant will likely cost around $10.4 billion.</td></tr>
</table>

	- Immediate adoption of electric vehicles implies that electricity costs per kWh will almost double (clean energies vs. fossil fuels) (see Figure 5). - Repurposing all gas plants into biofuel will cost around $8.5 billion to replace total capacity. - Total immediate cost: $31.7 billion + large, immediate increase in electricity prices	- Slow adoption of electric vehicles implies that electricity costs per kWh will slowly increase until it is almost double (clean energies vs. fossil fuels) (see Figure 5). - Repurposing 8,000 MW of gas capacity into biofuel will cost around $6.8 billion. -Total immediate cost: $30 billion + steady increase in electricity prices
Reduction in Greenhouse Gases	- Roughly 25-34% reduction in 167 Mt of greenhouse gases immediately (from electric vehicle adoption and total repurposing of natural gas plants).	- Greenhouse gases will be reduced from 0% in 2016 to 20-29% in 2030 reduction of 167 Mt of greenhouse gases based on the slower adoption of electric vehicles and repurposing of 4/5 of all natural gas plants.

Based on Table 9, it would obviously be ideal to go with Scenario 1 or the completely green option as it will still provide enough power capacity for future demands, all the while emitting minimal pollution. However, the cost factor of going with Scenario 1 vs. Scenario 2 is a big deal. If the government is not able to pay for these massive infrastructure/construction projects, then going with the more balanced approach in Scenario 2 is reasonable as well. Also, Scenario 1 borders on the fence of feasibility, since it is completely eliminating one industry (oil and gas) from Ontario (which does not seem likely, since low oil/gas prices will always make it an attractive economic option). Therefore, Scenario 2 is the more likely scheme that can feasibly be implemented in Ontario's future over the course of several decades.

6.0 Conclusion

Ontario's current energy mix is very good. It takes its supply from many different sources ranging from nuclear, wind farms, to even biofuels. However, this does not mean that it is the best it can be. There will always be improvements that can be made to the current setup. Add onto this with the fact that Ontario's population will only become bigger and the population density situated around the GTA will continue to grow at a rapid pace which means that there could be a greater demand for energy. What this report aimed to do was provide a scenario in which the increasing population and demand for energy could be apportioned using green/clean energies because of growing concerns of climate change. Climate change from enhanced greenhouse gas emissions plays a huge factor in every new policy introduced in Canada, since the oil and gas industry drives a lot of the economy and the possible need to transition into a new industry is very frightening.

It was found in this report that a balanced approach at changing the energy supplies to greener/cleaner technologies like nuclear, hydro and biofuels can meet GTA's growing energy demands in the future. Adoption of electrical vehicles was also found to be a good idea in meeting energy demand criterion and curbing emissions. The cost would be substantial, however, GHG emissions can significantly be reduced by changing current standards in the GTA.

7.0 Recommendations

There are a couple of things that this report does not address, one of those being the loss of blue collar jobs in the oil and gas/coal industries. Although Ontario is shifting towards clean/renewable energy sources, this does not mean that everything should be treated as a positive, as there will always be job loss associated with moving away from conventional technologies/methodologies. The same thing can be said for other industries as well (like programming, where keeping up to date with the newest language is critical to getting a job). Therefore, a potential follow-up report could revolve around how the green energy shift might affect job loss and how blue collar workers might adapt/retrain to these situations.

Another thing to consider is the cost of plant decommissioning. There is no single button that will shut off everything and stop a plant's functions. Pipes or wells might need to be cemented, or perhaps equipment might be removed from the plant so that it can be repurposed in another facility. There are many different variables that can affect the total cost, therefore, it was not included in this report since it would depend on a case-by-case basis.

Because technology changes so fast, the current energy supply mix will not stay the same forever. Even energy usage projections like that done by the Ontario Ministry of Energy cannot accurately predict what will happen in the future. Maybe humans will create a new branch/sector/industry that requires massive amounts of energy and new infrastructure must be built to accommodate this demand. Or maybe technologies in the future become so efficient that energy usage and supply doesn't become a concern because the current capacity will be enough to sustain the GTA region for a long time. As another example, maybe wave and tidal energies become a feasible resource, and Ontario decides to heavily invest in these technologies. The point is, no one can predict the future, and the only thing that can be done is to take historical data and extrapolate it to get some indication about how certain trends (like energy demand) will change (where the further the projections go, the bigger the error becomes). Therefore, this report is somewhat limited by the fact that it is basing the projections of energy supply on current technologies that will probably be outdated in a short amount of time.

8.0 Notations

CCS	*Carbon Capture Storage*	*MoECC*	*Ontario Ministry of Environment and Climate Change*
CH_4	*Methane Gas*	*MoE*	*Ontario Ministry of Energy*
CO_2	*Carbon Dioxide*	*Mt*	*Metric Ton (1000 kg equiv.)*
EIA	*United States Energy Information Administration*	*MW*	*Megawatt*
g	*Gram*	*MWh*	*Megawatt-hour*
GHG	*Greenhouse Gas*	*NG*	*Natural Gas*
GIS	*Geographic Information System*	NO_x	*Nitrogen Oxides (gas category)*
GTA	*Greater Toronto Area*	O_3	*Ozone Gas*
IESO	*Independent Electricity System Operator*	*OPG*	*Ontario Power Generation*
IPCC	*International Panel on Climate Change*	$PM_{2.5}$	*Particulate Matter (2.5 microns)*
K	*Kelvin*	PM_{10}	*Particulate Matter (10 microns)*
kW	*Kilowatt*	*s*	*Second*
kWh	*Kilowatt-hour*	SO_x	*Sulphur Oxides (gas category)*
LCA	*Life Cycle Analysis*	*TW*	*Terawatt*
m	*Meter*	*TWh*	*Terawatt-hour*

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9.0 Appendix

9.1 Sample Calculations

Energy production to power capacity calculation:

- Assuming constant energy production per each hour of the year,

$$Nuclear\ Energy\ Production\ (in\ 2015) = \left(92.3\ \frac{TWh}{yr}\right)\left(\frac{1{,}000{,}000\ MWh}{1\ TWh}\right) = 92{,}300{,}000\ \frac{MWh}{yr}$$

$$Power\ Capacity\ Required = \left(92{,}300{,}000\frac{MWh}{yr}\right)\left(\frac{yr}{365\ days}\right)\left(\frac{day}{24\ hr}\right) = 10{,}536.53\ MW$$

Comparison of current power capacity to required power capacity:

$$Current\ Ontario\ Nuclear\ Power\ Capacity = 12{,}978\ MW$$

$$Nuclear\ Capacity\ Required\ (2015\ assumption) = 10{,}536.53\ MW$$

$$\%\ of\ Nuclear\ Capacity\ Used = \frac{10{,}536.53\ MW}{12{,}978\ MW} \times 100\% = 81.19\%$$

Calculating cost of new electricity generation technologies using US EIA data [24]**:**

$$Typical\ Size\ of\ a\ New\ Advanced\ Nuclear\ Plant = 2234\ MW$$

$$Base\ Overnight\ Cost\ in\ 2014\ \left(\begin{matrix} includes\ lead\ time, and\ other \\ contingencies\ like\ unforseen\ extra\ costs \end{matrix}\right) = \$\ 4{,}646\ /kW$$

$$\left(\frac{\$\ 4{,}646}{kW}\right)\left(1000\frac{kW}{MW}\right) = \$4{,}646{,}000\ /MW$$

$$\left(\frac{\$\ 4{,}646{,}000}{MW}\right)(2234\ MW\ capacity) = \$10{,}379{,}164{,}000$$

Or roughly: $10.4 billion

Average Power required for wide scale electric vehicles adoption in the GTA [26]**:**

- Assuming constant power demand per each hour of use of the year,

$$Average\ person\ driving\ amount = 10{,}000\frac{km}{yr}$$

$$Energy\ usage\ per\ electric\ vehicle = \frac{20\ kWh}{100\ km}$$

$$Power\ demand\ per\ vehicle = \left(\frac{20\ kWh}{100\ km}\right)\left(10{,}000\frac{km}{yr}\right)\left(\frac{yr}{365\ days}\right)\left(\frac{day}{24\ hrs}\right) = 0.23\ kW$$

Rough amount of vehicles in GTA [28]: $71.1\%\ of\ 2.4\ mil\ commuters = 0.711(2.4\ mil) = 1.7mil$

$$Total\ vehicular\ power\ demand = \left(\frac{0.23\ kW}{vehicle}\right)(1.7\ million\ vehicles) = 388{,}128\ kW$$

Or roughly: 388 MW

9.2 Extra Tabulated Data

Table 10: Transformer/Switching station upgrade costs in the Greater Toronto Area (Ontario MoE) [17]

Station	Estimated Cost	Expected In-Service Date
Leaside, Hearn and Manby	$148 million	2014 - 2015
Richview Transformer Station	$61.2 million	2017
Midtown Station	$115 million	2015
New Copeland Transformer Station	$195 million	2014
Clarington Transformer Station (new station)	$297 million	2017
Total Cost:	$816.2 million	

Table 11: Cost and performance for new central electrical generation stations using 2014 data (US EIA) [24]

						Contingency Factors					
Technology	Online Year[1]	Size (MW)	Lead time (years)	Base Overnight Cost in 2014 (2013 $/kW)	Project Contin-gency Factor[2]	Techno-logical Optimism Factor[3]	Total Overnight Cost in 2014[4] (2013 $/kW)	Variable O&M[5] (2013 $/mWh)	Fixed O&M (2013 $/ kW/yr.)	Heatrate [6] in 2014 (Btu/ kWh)	nth-of-a-kind Heatrate (Btu/kWh
Scrubbed Coal New	2018	1300	4	2,726	1.07	1.00	2,917	4.47	31.16	8,800	8,740
Coal-Gasification Integrated Comb Cycle (IGCC)	2018	1200	4	3,483	1.07	1.00	3,727	7.22	51.37	8,700	7,450
IGCC with Carbon sequestion	2018	520	4	5,891	1.07	1.03	6,492	8.44	72.80	10,700	8,307
Conv Gas/Oil Comb Cycle	2017	620	3	869	1.05	1.00	912	3.60	13.16	7,050	6,800
Adv Gas/Oil Comb Cycle (CC)	2017	400	3	942	1.08	1.00	1,017	3.27	15.36	6,430	6,333
Adv CC with Carbon sequestration	2017	340	3	1,845	1.08	1.04	2,072	6.78	31.77	7,525	7,493
Conv Comb Turbine[8]	2016	85	2	922	1.05	1.00	968	15.44	7.34	10,783	10,450
Adv Comb Turbine	2016	210	2	639	1.05	1.00	671	10.37	7.04	9,750	8,550
Fuel Cells	2017	10	3	6,042	1.05	1.10	6,978	42.97	0.00	9,500	6,960
Adv Nuclear	2022	2234	6	4,646	1.10	1.05	5,366	2.14	93.23	10,479	10,479
Distributed Generation-Base	2017	2	3	1,407	1.05	1.00	1,477	7.75	17.44	9,015	8,900
Distributed Generation - Peak	2016	1	2	1,689	1.05	1.00	1,774	7.75	17.44	10,015	9,880
Biomass	2018	50	4	3,399	1.07	1.01	3,659	5.26	105.58	13,500	13,500
Geothermal[7,9]	2018	50	4	2,331	1.05	1.00	2,448	0.00	112.85	9,516	9,516
Municipal Solid Waste Conventional	2017	50	3	7,730	1.07	1.00	8,271	8.74	392.60	14,878	18,000
Hydropower[9]	2018	500	4	2,410	1.10	1.00	2,651	5.76	15.15	9,516	9,516
Wind	2017	100	3	1,850	1.07	1.00	1,980	0.00	39.53	9,516	9,516
Wind Offshore	2018	400	4	4,476	1.10	1.25	6,154	0.00	73.96	9,516	9,516
Solar Thermal[7]	2017	100	3	3,787	1.07	1.00	4,052	0.00	67.23	9,516	9,516
Photovoltaic[7,10]	2016	150	2	3,123	1.05	1.00	3,279	0.00	24.68	9,516	9,516

Table 12: Intermediate cost calculation for new electrical generation stations using 2014 data (US EIA) [24]

Plant	Online Year	Size (MW)	Typical Base Cost ($/kW)	Cost ($/MW)	Total Cost ($)
Conventional Gas/Oil Combined Cycle	2017	620	869	869,000	538,780,000
Advanced Gas/Oil Combined Cycle	2017	400	942	942,000	376,800,000

Advanced Gas Combined Cycle with CCS	2017	340	1,845	1,845,000	627,300,000
Advanced Nuclear	2022	2234	4,646	4,646,000	10,379,164,000
Biomass	2018	50	3,399	3,399,000	169,950,000
Hydro	2018	500	2,410	2,410,000	1,205,000,000
Wind	2017	100	1,850	1,850,000	185,000,000
Wind Offshore	2018	400	4,476	4,476,000	1,790,400,000
Solar Thermal	2017	100	3,787	3,787,000	378,700,000
Photovoltaic	2016	150	3,123	3,123,000	468,450,000