Coal-Fired Power Plant's Air Quality Impact and Policy Implications

---What Does the Ontario's Historical Data Tell Us?

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Abstract

Coal-fired power plants, as important electricity sources, accounted for 38 percent of global electricity and 9 percent of Canada's electricity in 2017. However, the combustion of coal produces a lot of air pollutants and greenhouse gases that impose serious air quality, climate change and health risks on human beings and natural environment. Using Ontario's historical dataset from 2010 to 2014, this paper finds that the increase of 100 Megawatt's electricity from coal plants per hour would increase the hourly $PM_{2.5}$ concentration by 0.06 ug/m^3, NOx and SO_2 by 0.13 ppb and 0.057 ppb significantly. It also finds that during the hours when the wind blows from the coal plants to the air pollutant monitors, the $PM_{2.5}$ and NOx level would be higher. Compared to the further areas, the monitors within 50km from the coal plants have more serious $PM_{2.5}$ and SO_2 concentrations. This paper estimates that if Ontario would still have operated the three coal plants included in this study in 2015, it would have caused 219 heart disease deaths and 12 stroke deaths due to $PM_{2.5}$ in the populous cities within 100km from the plants, in condition that the three plants generate electricity in the average hourly output level. Facing with coal plants' air quality and health impacts, this paper suggests that for the provinces in Canada that still have coal plants, it is necessary to think about controlling the air pollutants from coal by shutting down the coal plants in the long-term, or at least relocating the plants or installing some control devices in the short-term, depending on different conditions each province has.

List of Acronyms

A.B.	Alberta
APCD	air pollutant control devices
As	arsenic
CMA	Canadian Medical Association
CO_2	Carbon Dioxide
CFPPs/coal plants/coal generation	Coal-Fired Power Plants
ERV	Emergency room visits
ECCC	Environment and Climate Change Canada
GHGs	Greenhouse gases
H	Hypothesis
HCB	hexachlorobenzene
Hg	mercury
ICAP	Illness Costs of Air Pollution
IESO	Independent Electricity System Operator
IPCC	Intergovernmental Panel on Climate Change
IEA	International Energy Agency
IDW	inverse-distance weighted
LLE	loss of life expectancy
LNBs	low NOx burners
M.B.	Manitoba
MW	Megawatt
MODIS	Moderate Resolution Imaging Spectroradiometer
NRCan	Natural Resources Canada
N.B.	New Brunswick
NDP	New Democratic Party
NO_2	Nitrogen dioxide
NO	Nitric oxide
NOx	Nitrogen oxides
NGO	non-governmental organization
NC	North Carolina

N.S.	Nova Scotia
O_3	ground-level ozone
OCCA	Ontario Clean Air Alliance
OMA	Ontario Medical Association
O&M	operation and management
PAHs	polycyclic aromatic hydrocarbons
PFT	pulmonary function tests
$PM_{2.5}$	fine particulate matter
ppb	parts per billion
QGIS	Quantum GIS
rehum	relative humidity
S.K.	Saskatchewan
SCR	selective catalytic reduction
Se	selenium
SO_2	Sulphur dioxide
SOx	Sulphur oxides
temp	temperature
VOC	volatile organic compounds
WFGD	wet flue gas desulfurization

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1. Introduction

Coal, as an organically derived material, is an important source of energy. According to International Energy Agency (IEA) and Natural Resources Canada (NRCan), the primary application of coal is electricity generation. In 2017, coal is the source of 38 percent[1] of the global electricity and 9 percent[2] of Canada's electricity (IEA, 2018 & NRCan, 2019-1). However, due to rich carbon, sulfur and nitrogen in coal, the combustion process produces a lot of hazardous chemical substances such as air pollutants (ex. fine particulate matter, Nitrogen oxides, Sulphur oxides), heavy metals and greenhouse gases (GHGs). Globally, coal plant is the source of 30.2 percent of global energy-related carbon dioxide---one of the most common GHGs---emissions in 2017 (IEA, 2018). In South and Southeast Asia, China, Central and Western sub-Saharan Africa, where the reliance on coal to generate electricity and fuel vehicles is higher than other regions in the world, the concentration of particulate matter is also much higher (GE Ecomagination, 2017). In Canada's electricity sector, although 9 percent of the electricity is supplied by coal, coal produces 77 percent of electricity-related GHGs emissions (NRCan, 2019-2), 26 percent of total Sulphur oxides (SOx) emissions and 8 percent of total Nitrogen oxides (NOx) emissions (Environment and Climate Change Canada, 2019-1). The air pollutants and heavy metals from coal combustion are sources of serious asthma and breathing difficulties, which can cause premature deaths and increase the burden of health system. The GHGs emissions contribute to global warming, which results in drought, sea level rise, flooding, extreme weather and species loss. (Union of Concerned Scientists, 2019). In order to alleviate

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[1] According to IEA, the global electricity generation supplied 25570 Terawatt-hour in 2017 and coal was the source of 9716 Terawatt-hour.

[2] According to NRCan, electricity generation consumed 33.2 tonnes (equal to 332000kg) of various energy sources in 2017. 9% of them was consumed by using coal. Statistics from IEA and NRCan are in different units.

the negative climate change effects from coal plants, the Intergovernmental Panel on Climate Change (IPCC) advocates the phase-out of coal from electricity sector worldwide by 2040 to limit the increase of global temperature within 1.5°C, as regulated in Paris Agreement (Climate Analytics, 2019). As a pioneer of clean energy, the Government of Canada announced in 2018 that Canada will shut down all the traditional coal plants by 2030. Currently, in Canada, 5 provinces still use coal as a source of electricity. They are Alberta (A.B.), Saskatchewan (S.K.), Manitoba (M.B.), New Brunswick (N.B.) and Nova Scotia (N.S.). In A.B, S.K. and N.S., more than 40 percent of the electricity relied on coal in 2017. In N.B., coal provided 15.8 percent of total electricity in 2017 (NRCan, 2019-3). Since the role of coal in electricity sector varies from province to province and it is the province who has the authority on making regulation on the electricity sector, each province has its own plan and policies on coal plants. Until now, only A.B. put on the coal phase-out on agenda and planned to shut down all the coal plants by 2030. M.B. has stopped coal in home space heating from 2017, although coal only represented 0.1 percent of M.B.'s electricity. The other three provinces have no concrete plans for coal phase-out, but they do have plans to move to cleaner energy (N.B. and N.S.) and to retrofit existing coal plants (S.K.) (Quigley, CBC, 2016).

Currently, most of the coal generation-related researches study two questions. On one side, some engineering researchers use chemical analysis and literature review to study what kind of hazardous chemical substances would be produced from coal. Based on this, some health researchers quantify the health impacts of coal, for example, the premature deaths and economic costs, through analyzing data from Canada, the United States, China, European countries and some Southeast Asian countries. On the other side, other researchers use data to estimate or predict the costs and benefits of a specific coal pollution control policy, including coal phase-out and the installation of some control devices.

This paper is interested in studying the impact of coal in electricity sector on the air pollution, including fine particulate matter ($PM_{2.5}$), NOx and Sulphur dioxide (SO_2, a derivation of SOx) within 100km of the coal plants. It is also interested in studying the health impacts of air pollution from coal on the coal plant's surrounding areas and proposing policy recommendations for the 5 provincial governments in Canada. This paper uses Ontario's historical hourly coal output, air pollutants concentration and meteorological data for analysis. In 2014, Ontario completed the coal phase-out by shutting down all the five coal plants. This initiative makes Ontario become the first North American government to eliminate the coal-fired electricity generation. Studying the impact of operating coal plants on air pollution and health in Ontario provides inspiration for analyzing coal plants' impact and thinking about relevant policy issues in other provinces.

The data from Ontario suggests that 1). The increase of 100 MW electricity per hour from coal generation will worsen the ambient air quality by increasing the $PM_{2.5}$ concentration by 0.06 ug/m^3, NOx and SO_2 by 0.13 ppb and 0.057 ppb. 2). Compared to the hours with no wind or with an upside wind (when the wind blows from the air pollutant monitor to the coal plant), the hours with a downside wind (when the wind blows from the coal plant to the monitor) tend to have more $PM_{2.5}$ and NOx concentrations. 3). Furthermore, for the monitors who have a distance of within 50km from the coal plants, the $PM_{2.5}$ and SO_2 levels are higher than the further monitors. 4). If the coal plants in this study still have operated in 2015 in the average hourly output level, the $PM_{2.5}$ would have caused 219 deaths because of heart disease and 12 people deaths due to stroke in the populous cities within 100km from the coal plants.

After analyzing the results from Ontario's data, this paper proposes three policy recommendations for provincial governments to control the air pollutants and the adverse health impacts from coal, including a long-term solution---the coal phase-out, and two short-term expediencies---the relocation of coal plants and the installation of control devices. For each option, the paper will address the conditions for the policy to be implemented effectively and some considerations for the provincial government.

The rest of the paper organizes as follows: Section 2 makes a literature review for related papers; Section 3 introduces the data source and the method to create wind direction variable; Section 4 builds two models, analyzes and compares the regression results and addresses the limitation of this paper; Section 5 proposes three policy recommendations based on the models and analyzes the considerations for each policy; Section 6 makes a conclusion.

2. Literature Review

Studies on the impact of coal-fired power plants (CFPPs/coal plants/coal generation) mainly focus on two fields. One is to study the hazardous substances emitted from coal plants and their impacts on environment. Another field, based on the 'chain of accountability', studies coal's health costs through people's exposure to the chemical substances. The latter field's studies also analyze the social and economic costs of coal generation by quantifying its health impacts.

Coal plants → Hazardous substances → People's health → Social and economic costs

Figure 1. 'Chain of Accountability' in coal generation studies

Source: Synthesized by the author

2.1 Hazardous substances from coal plants

All the research studying the coal plant's environmental impacts conclude that coal combustion is one of the big sources of air pollutants, heavy metals and fly ash, which can deteriorate air, water and land and as a result, have a bad impact on people and ecosystem.

One of the pollutants from coal plants is SOx. Sulphur occurs in coal as Sulphides, organic Sulphur, elemental Sulphur and Sulphate (Ryan & Ledda, 1997, p29). In the process of combusting coal, Sulfur is transformed into SOx, including SO_2 and Sulphate. SOx releases into atmosphere to produce sulfuric acid, which is a major constituent of acid rain and causes air, water and land pollution. The SOx emitted into the air from coal combustion was even double compared to the emission from cars, trucks and factories every year (Munawer, 2018, p88-89).

Another main pollutant during coal combustion is Nitrogen oxides (NOx). NOx is very easy to be corrosive and has a high ability of oxidizing (Levy et al., 1999). After combustion, it forms into Nitrogen dioxide (NO_2) and Nitric oxide (NO), both of which play a key role in forming ground-level ozone (O_3) and contribute to the formation of fine particulate matter ($PM_{2.5}$) (Yap et al., 2005, p3). Actually, NOx is not the only contributor of $PM_{2.5}$. SOx, coal fly ash and coal dust during combustion and post-combustion are also important sources (Chen, 2004, p744).

All the hazard air pollutants mentioned above, once inhaled by people, would cause respiratory and cardiovascular diseases, such as heart disease, stroke, pulmonary disease and lung cancer. According to Pembina Institute, a research organization which is committed to proposing the use of clean energy, Canada's coal plants account for 10 out of top 17 sources of SO_2 and 10 out of top 14 sources of NOx in 2014 (Israël et al., 2016, p9). In Alberta, a province in Canada whose electricity supply is highly dependent on coal, coal plants have been accounting for over 40% of the total emission of SO_2. In 2013, Alberta's SO_2 emission is 106,978 tonnes and NO_2 emission is 66,931 tonnes. The adverse environmental impacts of these pollutants can be visualized obviously in the maps created by John Wellner. GIS maps show that in 2013, the region with the most severe PM2.5 level in Alberta is Red Deer and the region whose ground-level ozone is the highest is North Saskatchewan in Alberta (Wellner, 2015, p9-12). Both of the two areas are close to 5 out of 6 coal plants in Alberta and share boundaries with Saskatchewan, another big consumer of coal in Canada.

Besides the pollutants, coal plants also produce GHGs, heavy metals and other hazardous substances. The GHG, especially Carbon Dioxide (CO_2), is the main source of the global climate change and causes many natural disasters. The heavy metals and other hazardous substances include lead, mercury(Hg), arsenic(As), cadmium, selenium(Se), dioxins and furans, hexachlorobenzene (HCB), polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOC). These heavy metals, after being inhaled, ingested or contacted by people, would cause a few sub-optimal health symptoms such as tiredness, sleeplessness, irritability, headaches. They could even associate with cancer and viscera diseases (Anderson et al., 2013, p26-31).

2.2 Health and economic losses from coal plants

Current studies on coal's impact on people mainly focus on its adverse health impact through exposure to air pollutants. In order to quantify air pollutants' adverse impact, the Ontario Medical Association (OMA) developed an Illness Costs of Air Pollution (ICAP) model by collecting the air quality, population and health data to assess the health and economic costs in 2000 (website, 2000) and it was improved in 2005. The model divided the health impacts into four groups: 1). Premature deaths due to both short-term and long-term exposure to air pollution; 2). Hospital admissions for respiratory and cardiovascular diseases; 3). Emergency room visits

(ERV) and 4). Minor illnesses. The ICAP model also estimates air pollution's health impact among different ages of people. The economic losses include 1). Lost productivity "due to treatment and recovery from air pollution-related illnesses"; 2). Healthcare costs due to medication; 3). The amount of money that people are willing to pay to avoid the pain and suffering from air pollution-related diseases; 4). The money that people are willing to pay to avoid the risk of losing life (OMA, 2005, p3&9). Based on this model, from 2005 to 2017, Health Canada and other federal and provincial institutions in Canada conducted several researches to estimate the adverse impact of air pollution. The estimates were very different due to data source, the time period and specific air pollutants used in different researches. However, all of them concluded that air pollutants had a huge negative effect on health and caused economic losses. OMA's estimates found that from 2005 to 2026, Ontario premature deaths due to SO_2, NO_2, CO, $PM_{2.5}$ and O_3 would increase from 6,000 to 10,000. People who are aged 65+ would be the most influenced group. The hospital admissions cases in Ontario during the same period would range from 17,000 to 24,000, among which cardiovascular diseases account for most of the cases. The ERV would increase to almost 90, 000cases and similar to hospital admissions, cardiovascular illnesses would also be the main cause. In conclusion, air pollution will influence 122 thousand people in 2026 and if taking into consideration the minor illnesses, this number will be 38.7 million cases. The total economic loss from health would be $12.9 billion in 2026 (OMA, 2005, p4-9). In 2008, the Canadian Medical Association (CMA) published a report estimating the health impact of $PM_{2.5}$ and O_3 in the federal and provincial level. Since the air pollutants were only limited to two sources and it only estimated the short-term impact, the death cases in CMA report were much less than that in OMA. According to CMA estimates, Canada's acute (short-term) premature death varies from 2,600 to 5,000 between 2008 and 2030. Central Canada takes the largest proportion followed by Western and Atlantic provinces. In 2030, the total health impact due to $PM_{2.5}$ and O_3 across Canada would be 27million cases. These health impact would cause a total economic cost of $13.7billion in 2030 (CMA, 2008, p12-21). In a report published by Health Canada in 2017, almost ten thousand's death in Canada are attributable to chronic exposure to $PM_{2.5}$ every year. Nearly five thousand people would lose their lives because of the acute and chronic exposure to NO_2 and the pollutant derived from it---O_3 (Health Canada, 2017, p7). Furthermore, Anderson and his team (Anderson et al., 2013, p59&68) estimated the proportion of $PM_{2.5}$ and O_3 from coal and used the ICAP model to study the air pollutants' impact on heath from coal plants. Their study suggested that in 2030, coal plants would trigger 2,139 health cases and 82 of them are acute or long-term premature deaths. When converting it into economic costs, these will result in $175 million losses.

Although not all of the research extract coal's impact on health, the estimates still reflect some important findings. Since coal is the main source of air pollutants, the health and economic losses resulted from coal would account for a big proportion of the total losses.

The studies of air pollutants' health impact from coal in other countries and regions, though did not apply the ICAP model, reached the same conclusion with studies in Canada. It is found that coal consumption negatively affects health by reducing life expectancy in all types of countries, no matter it is a country with low, middle or high life expectancy (Gohlke et al., 2011, p824). In Texas, a leader of power plant emissions in the U.S., the two coal power plants that produce most O_3 cause two deaths per year and the two coal plants with highest $PM_{2.5}$ result in a life loss of 260 people (Strasert, 2019, p342-343). Through two weeks' sampling during different seasons in a city in Turkey, researchers found that the concentration of air pollutants tend to increase during winter except O_3. Meanwhile, due to the proximity to coal plants and traffic density, city center has the worst air quality and people close to city center have a higher possibility to get cancer compared to people who live in rural places (Artun, 2017). In India, a big coal consumer, researchers estimated that in 2010 and 2011, the emissions from coal plants caused at least 80, 000 premature mortalities, with 10 thousands of them being children (Guttikunda, 2014).

Some studies also narrow down the coal plants adverse impact on children. Dubnov and his colleagues found that in Israel, compared to other children, the schoolchildren who live in the vicinity of a coal plant have a lower pulmonary function tests (PFT) result. Their PFT score is 6 percentage point lower than average (Dobnov, 2006). A study in New Jersey estimated that the new births are 42 percent more likely to have a low birth weight if their mothers live in the downwind side of and as far as 20 to 40 miles away from coal plants (Yang & Chou, 2015). A similar study in Southeast Asia also concluded that by 2030, over 69,000 people would lose their lives due to emission from coal in Indonesia and Vietnam. Besides influencing local people, the downwind pollution would also influence China and Thailand (Koplitz, 2017). Both of the studies suggest that the wind direction and the distance matter in evaluating the impact of air pollutants from coal plants.

Other studies also found that coal's impact on health, especially on cancer, is not as serious as people always think. For example, a study in Italy conclude that coal plants only "contributed to less than 6% of overall cancer risk." (Piersanti et al, 2018). However, just like there is no line to explain to what extent will the inhalation of air pollutants influence people's health, there is also no standard or regulation to make sure that a 6% or an even smaller percent contribution to cancer risk from coal is not significant or can be ignored.

2.3 The multiple impacts of control policies

Now that the emissions would trigger so many health problems and so much economic losses, countries with coal plants have been enacting policies to control the air pollution and thus avoid as much losses as they can. Some policies just specify the upper limitation of each air pollutant emitted from coal plants. Others, however, clearly put forward specific measures such as a coal phase-out, the relocation of coal plants or the installation of air pollutant control devices (APCD). As a result, the research related to the impact of the policies also constitute an important part of coal studies.

A. The effect of general policies

In general, researchers estimated that the impact of regulating the emissions tends to have health and economic benefits through improving air quality. According to OMA's estimates, if Canada could reduce its NOx emissions by 45% and SO_2 emissions by 75% of 1990 level in 2015, it would keep more than 50 thousand people from dying and visiting doctors, which would also save $1.7billion (Boadway et al, 1998). Li's research also found that after the introduction of the Clean Smokestacks Act which required the 14 major coal plants in North Carolina (NC) to progressively reduce NOx emission by 60% by 2009 and SO_2 emissions by 72% by 2013, the SO_2 in NC decreased by 20% every year and $PM_{2.5}$ sulfate concentrations also had an annual decrease of 8.7%. These improvements contributed to preventing 1,700 people from losing lives (Li et al, 2014).

B. The effect of the coal phase-out

A more progressive way to control the emissions from coal plants is to implement a complete coal phase-out. So far, Ontario in Canada and Pittsburgh in the U.S. have implemented this measure by shutting down the coal plants or replacing coal with other clean energy such as the natural gas, nuclear and renewable energy. However, the impact of coal phase-out is mixed.

In 2005, when Ontario started to phase out the coal gradually, a study by DSS management suggested that compared to continuing operating the coal plants, replacing coal with a combination of nuclear and natural gas would reach the best outcome by decreasing the premature death in Ontario to 5 people, the hospital admissions and the ERV to 12 and 15 cases respectively. These results would be doubled if simply replacing coal with natural gas. Meanwhile, the total cost of generation, including financial, health and environmental, would also be the least (DSS Management, 2005). Similar to DSS conclusions, Pembina Institute estimated that if the coal plants can be phase-out as early as possible (by 2030 rather than 2050), an additional 1,008 lives would be saved across Canada. The Western Canada, a region that relies heavily on coal, would be the biggest beneficiary (Israël et al., 2016). Again in 2005, Fraser Institute conducted a qualitative research to assess the costs and benefits of closing CFPPs in Ontario and concluded that coal plants only consisted a small proportion of Ontario's pollution and smog formation. The pollutants emitted from coal plants in the U.S. and from vehicles also played an important role in deteriorating Ontario's air quality. However, it did not clearly show how small it is (McKitrick et al, 2005). Then in 2017, three years after a complete coal phase-out in Ontario, a quantitative study by Fraser Institute found that based on the monthly coal generation and air quality data in Hamilton, Toronto and Ottawa, coal's contribution to $PM_{2.5}$ was significant only in Ottawa. Its NOx impact was insignificant in all of the three cities. Since coal was not a main contributor to these two pollutants, a coal phase-out had nothing to do with improving air quality. And even if coal played an important role in increasing O_3, replacing coal with natural gas still cannot work because natural gas also caused significant O_3 (McKitrick et al, 2017). While the impact of coal phase-out in Canada varies in different studies, coal's phase-out improved the air quality in Pittsburgh by decreasing $PM_{2.5}$ by 0.94ug/m^3, helping to avoid 3 respiratory deaths and 6 cardiovascular deaths in that city after 2014 (Russell et al., 2017).

C. *The effect of APCD*

In developing countries, coal is an important source of electricity generation. As a consequence, it is almost impossible to phase out coal. In order to maintain the use of coal while control the emissions to the greatest extent, coal plants in China, India and Turkey have installed different facilities to reduce SOx and NOx emissions and acquired positive heath and air quality results but the net benefit varies from country to country.

China started to apply the wet flue gas desulfurization (WFGD) to control the SOx and heavy metal from coal combustion from 1980s. A study of 30 provinces' coal plants in Chinese mainland found that from 1980 to 2007, the emissions of Hg, As and Se from coal plants decreased significantly because of the installation of WFGD (Tian et al., 2010). By analyzing how selective catalytic reduction (SCR) and low NOx burners (LNBs) would influence NOx emissions from coal plants, scholars found that the coal units with the SCR and LNBs emitted at most 6.14g/kg NOx, which is much lower than the units without these devices. Meanwhile, the only coal unit without the LNBs emits much more NO and NO_2 compared to other units that have control devices (Ma et al., 2016). Moreover, researchers concluded that if China's coal plants can combine different control devices altogether to implement multiple-pollutant control strategies rather than the simple gradual control strategy, more air pollutants would be reduced (Xiong et al., 2016). Meanwhile, the loss of life expectancy (LLE) per person would decrease from 84days to 15days (Kuo et al., 2014). 60 more lives would be saved and 16 less people would incur chronic bronchitis. What's better, although plants need to invest 5% more to install the facilities, the long-term operation and management (O&M) costs compared to the condition without control devices would be also 5% less (Zhang et al., 2015).

The APCD's overall effect in Turkey is similar to that in China. Buke found that WFGD installed in one of Turkey's biggest coal plants would prevent more than 2,300 people from losing lives and the benefit in an economic term would be $103 million per year, $23 million more than the cost (Buke et al., 2011). In India, both WFGD and SCR proved have significant impact on air quality improvement. The WFGD even decreased SO2 emissions from coal by 56%. However, after introducing the technologies, the cost of electricity increased by $9-11/MWh and the efficiency also decreased by 0.8% (Singh & Rao, 2015).

To summarize the literature, it is obvious that the coal plants emit hazardous substances and air pollutants. However, researchers from different countries still cannot reach consensus on several important questions. These include 1). Whether the coal plants have a significantly bad impact on the level of air pollution; 2). Whether the air pollution from coal significantly influence people's health in a reverse way; 3). Whether a specific measure can really improve the air quality and 4). Whether the benefits of a measure can surpass the cost. These questions need to be evaluated further.

3. Data Source and Variable Construction

This paper will study if the use of coal can increase the concentration of three air pollutants: $PM_{2.5}$, NOx and SO_2 significantly using Ontario's historical hourly data. In this process, the paper will also analyze if the concentration of the three air pollutants is higher in an area when the wind blows from the coal plant to the area than when the wind does not carry pollutants from the coal plant to the area. Moreover, this paper will also study the role of the distance between the area and the coal plant to see if the areas closer to the coal plants have a worse air quality than the further areas. Before introducing the models and conducting analysis, Section 3 will introduce the data source and the methodology to create the wind-related variable.

Coal output data. This paper uses the hourly coal output data to illustrate the use of coal. The hourly coal output data is collected from the Independent Electricity System Operator (IESO), a crown corporation which operates the electricity system in Ontario. Ontario started to work on phasing out all the five coal plants from 2003. By 2014, all coal plants had been shut down. Lakeview ceased operation in 2005, followed by Atikokan in 2012, Lambton and Nanticoke in 2013 and Thunder Bay in 2014 (Government of Ontario, 2019-1).

Currently, IESO publishes the hourly electricity output data of each power plant in the unit of Megawatt[3] (MW) from January 2010 to April 2019. Since Lakeview was shut down in 2005, it is dropped from the analysis. For the other four coal plants, the time period of hourly output data starts from 00:00:00 January 1st, 2010 to the last hour on the day the coal plants had been decommissioned. (Atikokan-24:00:00, Sep 30th, 2012; Lambton-24:00:00, Sep 30th, 2013; Nanticoke-24:00:00, Dec 31st, 2013; Thunder Bay-24:00:00, Apr 30th, 2014).

[3] Megawatt is used in electricity sector and is a unit of power. It is equal to one million watts. One watt equals to one joule per second.

Air pollutants data. The dependent variable--- hourly air pollutants data--- is available from the Ministry of the Environment, Conservation and Parks of Government of Ontario. The ministry has historical hourly data of 42 monitors in Ontario that record SO_2, NOx and $PM_{2.5}$. Both SO_2 and NOx are recorded as parts per billion (ppb) and $PM_{2.5}$ as ug/m^3.[4] In order to narrow down the analysis, only the monitors within 100km of the coal plants are considered. Calculation of the distance shows that Lambton has five relevant monitors, Nanticoke has twelve, Thunder Bay has one and Atikokan has no monitor. As a result, the final coal plants selected by this paper are Lambton, Nanticoke and Thunder Bay. Each of the eighteen monitors only has one corresponding coal plant without any overlaps. Figure2 to Figure4 show the locations of each coal plant, monitors and proximately populous cities. All the three maps are generated in Quantum GIS (QGIS).

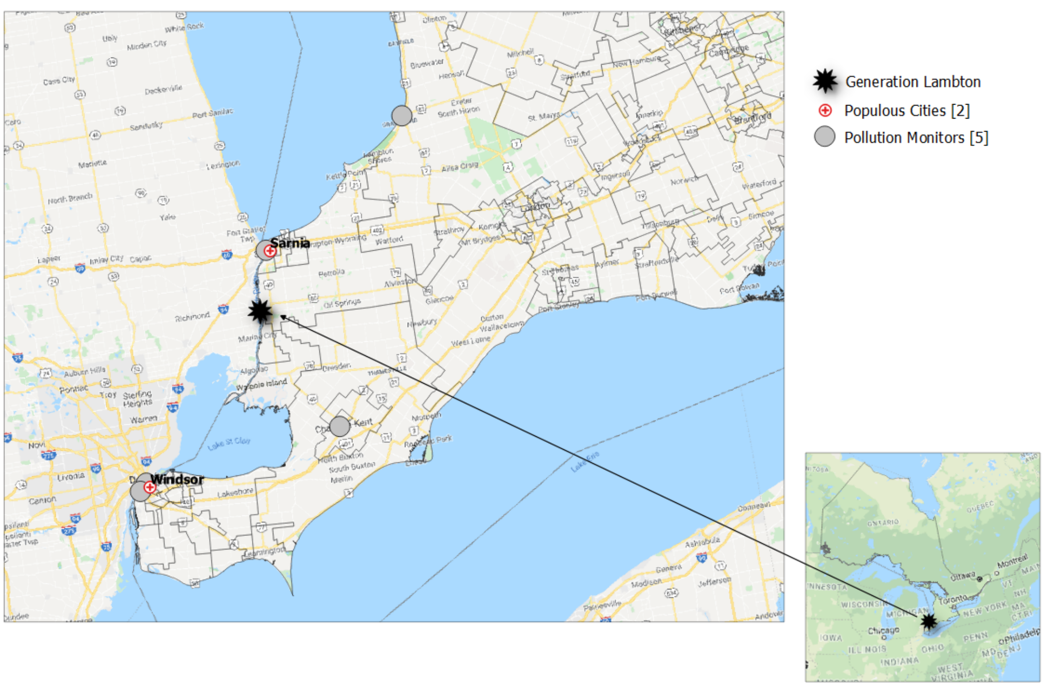

Figure2. Lambton generation and its monitors

[4] Ppb and ug/m^3 are the units to measure the concentration of chemical substances in the air or water. The bigger the number is, the more concentrated the substance is and the worse the air quality is.

Lambton was located in the southeast of Ontario. It was to the south of Sarnia on the St.Clair River and was close to the Canada-U.S.border. Among the Top 10 populous cities in Ontario, Windsor (320 thousand people) and Sarnia (144 thousand people) were close to Lambton. According to IESO's hourly capacity[5] data, as the second largest coal plant in Ontario with 4 electricity units, Lambton's capacity can be 1,924MW per hour. The operation can influence the air inhaled by at least 464 thousand people in Ontario, according to the 2011 Canada census data.

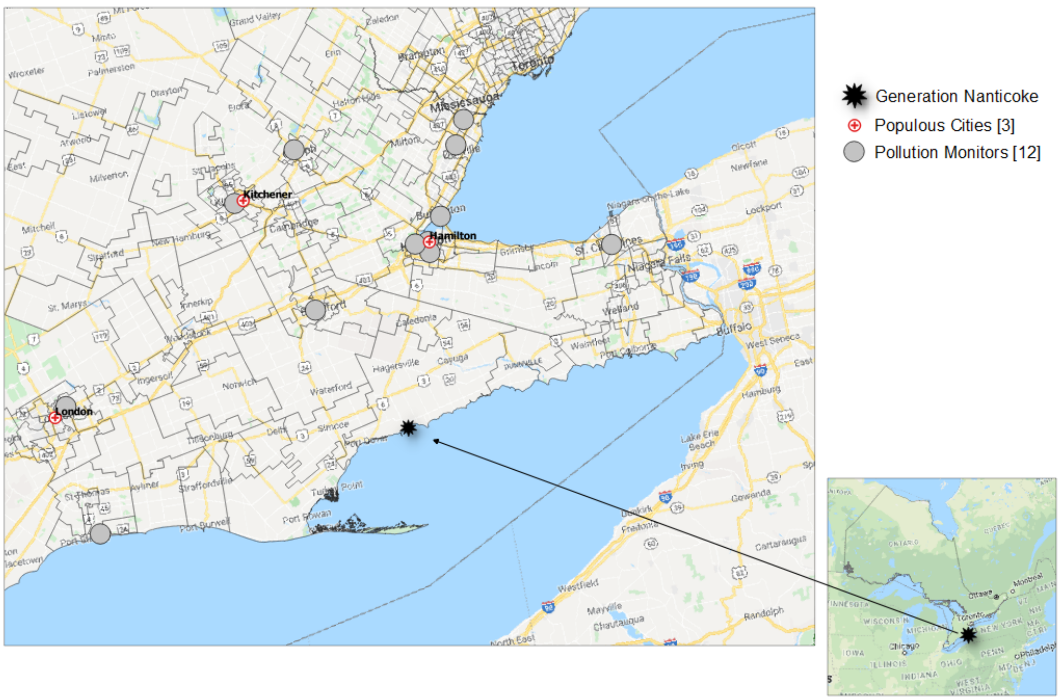

Figure3. Nanticoke generation and its monitors

Nanticoke was the largest coal plants in North America between 1972 to 2013, the year it was decommissioned. It was located in Haldimand County on the shore of Lake Erie. Consisting of 8 units, it supplied 15% of Ontario's electricity (Ministry of the Environment, 2001). The capacity of the plant can be 3,663 MW per hour. Nanticoke was close to London, Hamilton and Kitchener---three Top 10 populous cities in Ontario. With 1.48 million people living in the three

[5] Capacity is the maximum electricity output a power plant can produce.

cities, coal from Nanticoke was also likely to influence the air quality of these people. Furthermore, as the city with the largest population (5.2 million) in Canada, Toronto was 110km from Nanticoke---only 10km beyond the distance restricted in this study. As a consequence, it was reasonable to think that the 5.2 million people living in Toronto may also be influenced by coal from Nanticoke.

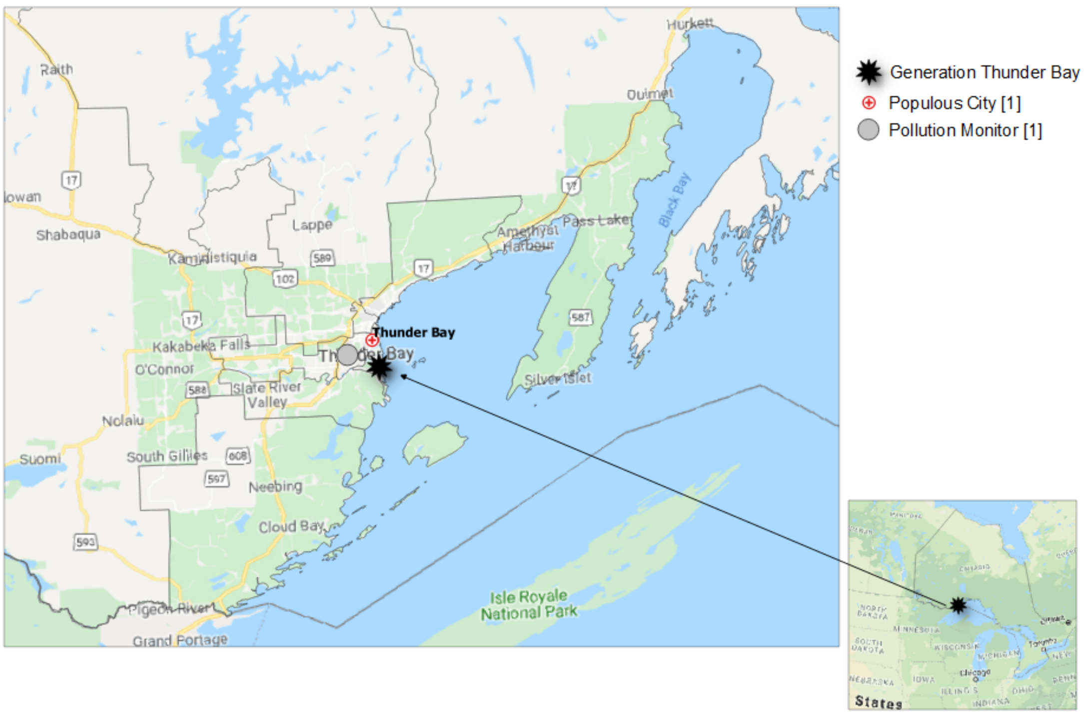

Figure4. Thunder Bay generation and its monitor

Thunder Bay coal generation was located in the Thunder Bay on the shore of Lake Superior. It had two units and the capacity was 310 MW per hour. It was the last coal plant to be shut down in Ontario. Thunder Bay mainly provided electricity to north Ontario. The populous city close to the coal generation was Thunder Bay. With approximately 100 thousand people living around, the coal plant's air pollution influence could not be ignored.

Since Lambton operated 1369 days from 2010 to 2013 and it had 5 close monitors, the sample size for Lambton's pollution monitor is 164,280 (1369 days/monitor* 24hs/day*5monitors).

Using the same method, the sample size of all the three plants is 622,992, including some missing values for the three air pollutants.

Meteorological data. Since the wind direction and other meteorological features like temperature and humidity also play key roles in conveying the air pollution from coal plants and in the formation of air pollutants, this paper also collects hourly wind direction, temperature and humidity data of coal plants from the historical weather database of Environment and Climate Change Canada (ECCC). The hourly meteorological data of each coal plant comes from the weather stations that were within 100km from the coal plants and with available hourly data. In the end, Lambton has eight weather stations. Nanticoke has twenty and Thunder Bay has 6.

Temperature is recorded in Celsius (°C) and humidity as relative humidity in percent (%), which is the ratio of the quantity of water vapour the air contains compared to the maximum amount it can hold at that particular temperature (ECCC, 2019-2). The wind direction is the direction from which the wind blows and is expressed in tens of degree. 9 means 90 degrees or an east wind, 18 means 180 degrees or a south wind. 0 means a calm wind or no wind. Figure 5 gives a detailed illustration to the wind.

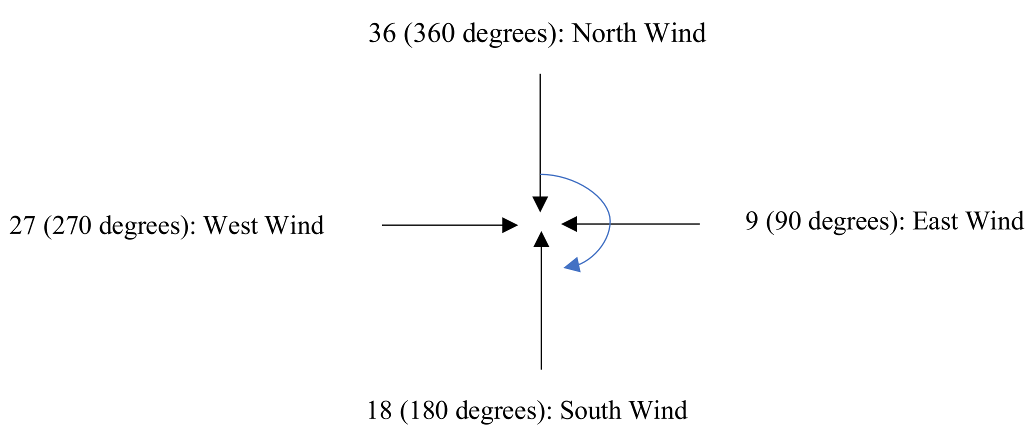

Figure5. Wind direction
Source: Synthesized by the author

This study uses the inverse-distance weighted (IDW) average to calculate the hourly temperature, relative humidity and wind direction for coal plants. The purpose is to give the closer station more influence on the final wind direction. The weight of each weather station is $1/d_i^2$, where d_i is the distance between the plant and its each corresponding weather station (Zivin et al., 2018). Under this circumstance, the closer the station is from the coal plant, the more influential its data is in calculating the finally meteorological data. Then, the paper calculates the weighted average hourly meteorological data for each plant in Stata.

The IDW temperature (temp) and relative humidity (rehum) data of the coal plants can be used directly. However, wind direction's impact on air pollutants concentration is dependent on both the hourly wind direction itself and the location of pollutant monitor. Figure 6 is an example to show how the wind direction's projection is created.

In Figure 6, the wind direction's value of the coal plant increases in a clockwise way, according to ECCC. The degree of wind direction (θ) is the IDW wind direction times 10. In radius, θ equals to wind direction times 10 times 3.14 (π) and divided by 180. In a two dimensions' world, the angel between the pollutant monitor and the coal plant (φ) increases in an anti-clockwise way, according to traditional trigonometric schematic diagram (φ is gotten by calculating the vertical and horizontal distance using latitudes and longitudes and by using trigonometric functions. Annex C shows how the φ varies according to the pollutant monitors' locations). π equals to 3.14 in radius.

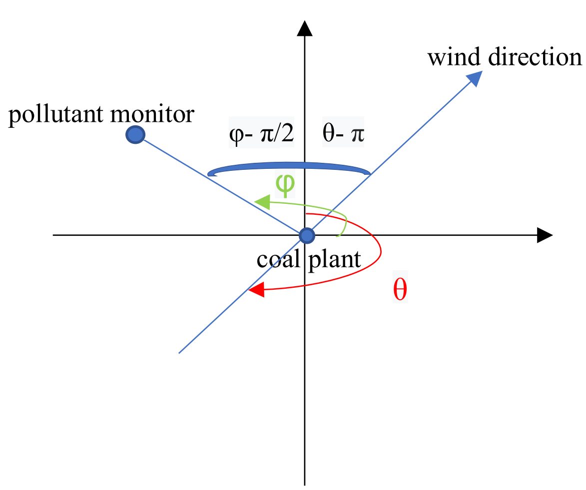

Figure6. Projection construction
Source: Synthesized by the author

This paper assumes that the smaller the angel between the wind direction and the pollutant monitor is, the more likely for the monitor to sense air pollutants. According to Figure 6, the angel is (φ- π/2+θ- π), which equals to (φ+θ-3π/2). (φ+θ-3π/2) can be adjusted to radius form by using π equals to 3.14. In order to show that a smaller angel tends to have more influence on the air pollutants, this paper uses cosine function (Yang & Chou, 2015). When the angel is zero, or when the wind blows directly from the plant to the monitor, the cosine value is 1. When the angel is between 0 degree and 90 degree, the cosine value is between 0 and 1. Both of the two situations mean that the pollutant monitor is in the downwind side of the coal plant and the bigger the cosine value is, or the smaller the angel is, the more downwind side effect the coal plant imposes on the monitor. When the angel is equal to or bigger than 90 degree, the cosine value in this paper is 0, meaning that the monitor is in the upwind side of the coal plant. The cosine value will also be 0 for the hours who have no wind. These two conditions are generally called "upwind side" in this paper, indicating that the wind does not have influence on the air quality.

4. Methodology and Findings

4.1 Descriptive statistics

Section 4 will examine the hourly coal output's impact on the air pollutants, how this impact varies when wind direction changes and varies when the distance between the coal plant and the pollutant monitors changes by building up models and running regressions. Before introducing the models, Section 4.1 shows some descriptive statistics.

Figure 7-9 plot how the average hourly pollutants' concentration changes as the hourly output increases. Generally, the correlation between the hourly output from coal and the hourly $PM_{2.5}$ concentration is positive. What's more, in the hours when the wind blows from the plant to the monitor, the $PM_{2.5}$ concentration is higher than the hours with no wind effect. For example, in all the hours that have a coal output that falls between 2000MW and 2500MW, the average $PM_{2.5}$ concentration is 9.5 ug/m^3 during the hours that encounter a wind from the coal plant and is 6.7 ug/m^3 during the hours when there is no wind or the wind does not blow from the coal plant. When the output falls between 2500MW and 3000MW, the concentration in both situations increases.

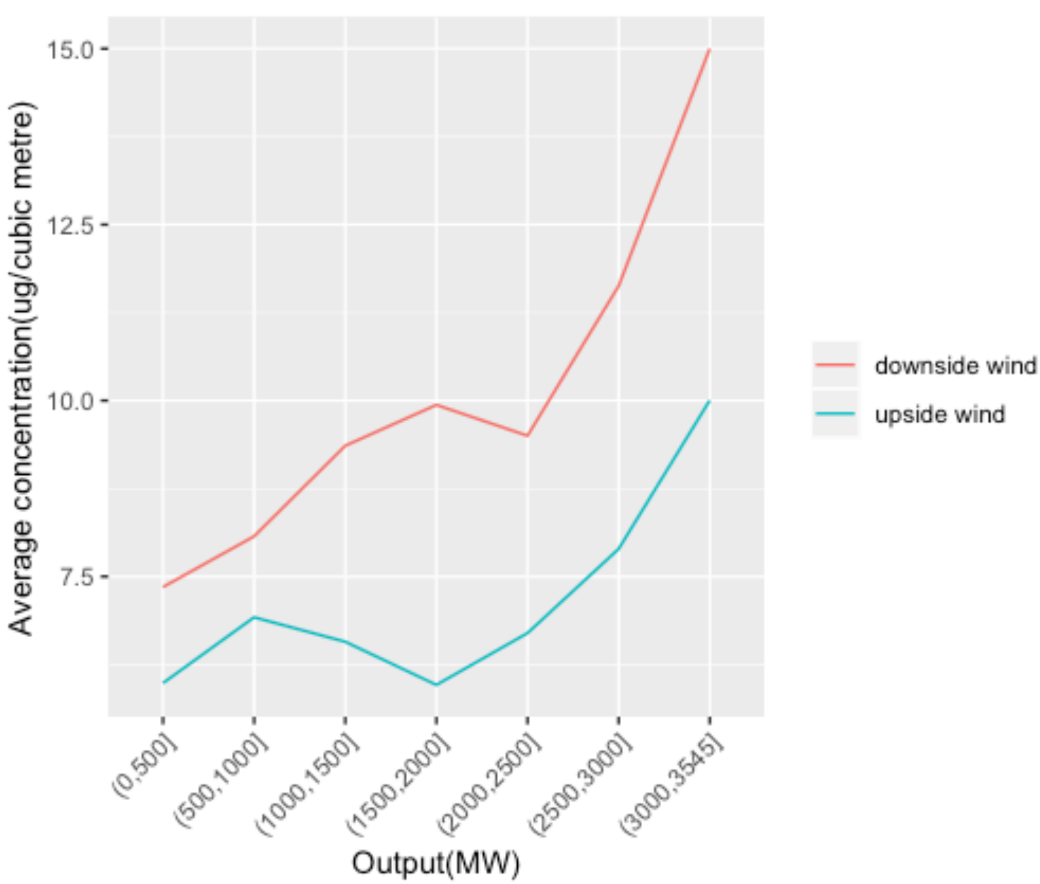

Figure7. Hourly Output Range and Corresponding Average $PM_{2.5}$ Concentration

(By Wind Situation)

Descriptive statistics show that the relationship between the average concentration of hourly NOx and the increase of coal output is hard to make a conclusion. However, in most circumstances, the NOx tends to increase when the wind blows from the coal plant to the monitor.

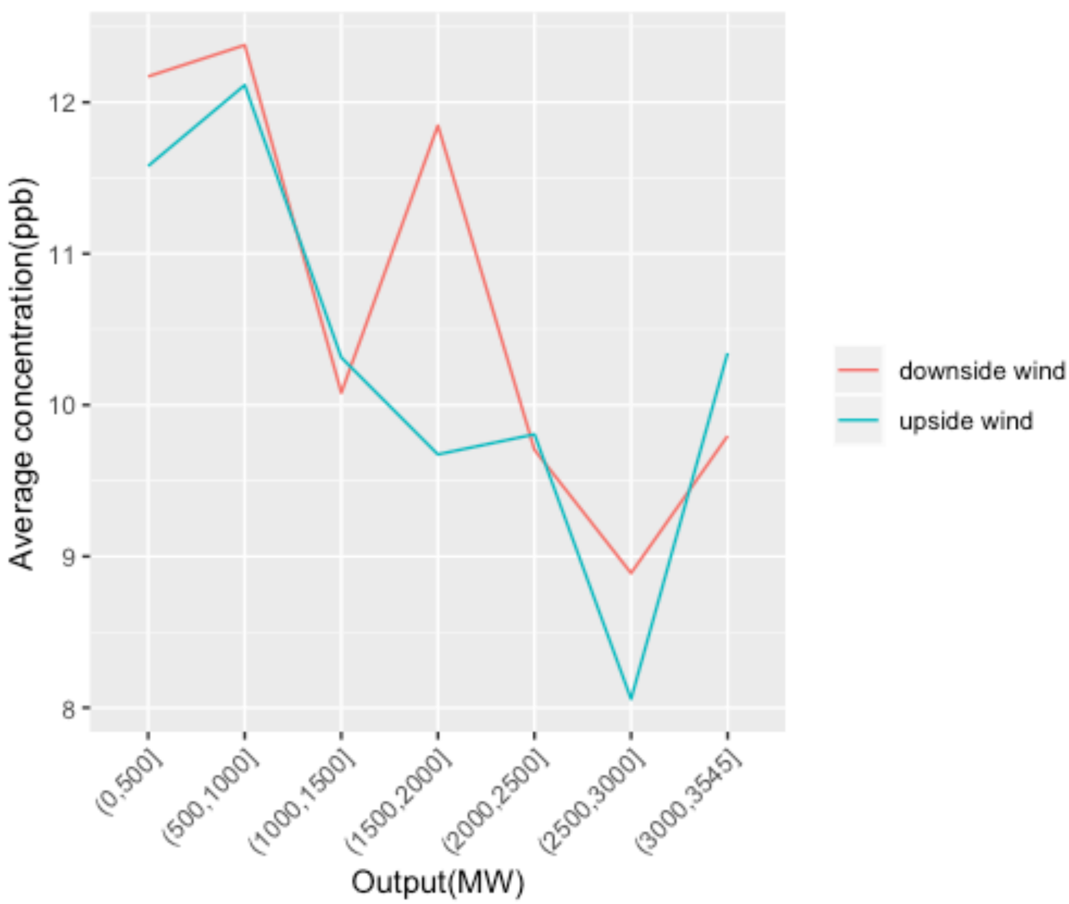

Figure8. Hourly Output Range and Corresponding Average NOx Concentration

(By Wind Situation)

Compared to the other two air pollutants, SO_2's result is a bit counterintuitive. On one side, as the coal output increases, the concentration of SO_2 falls and drops without having a pattern. On the other side, when the monitors can feel a wind from the coal plant, the concentration becomes smaller.

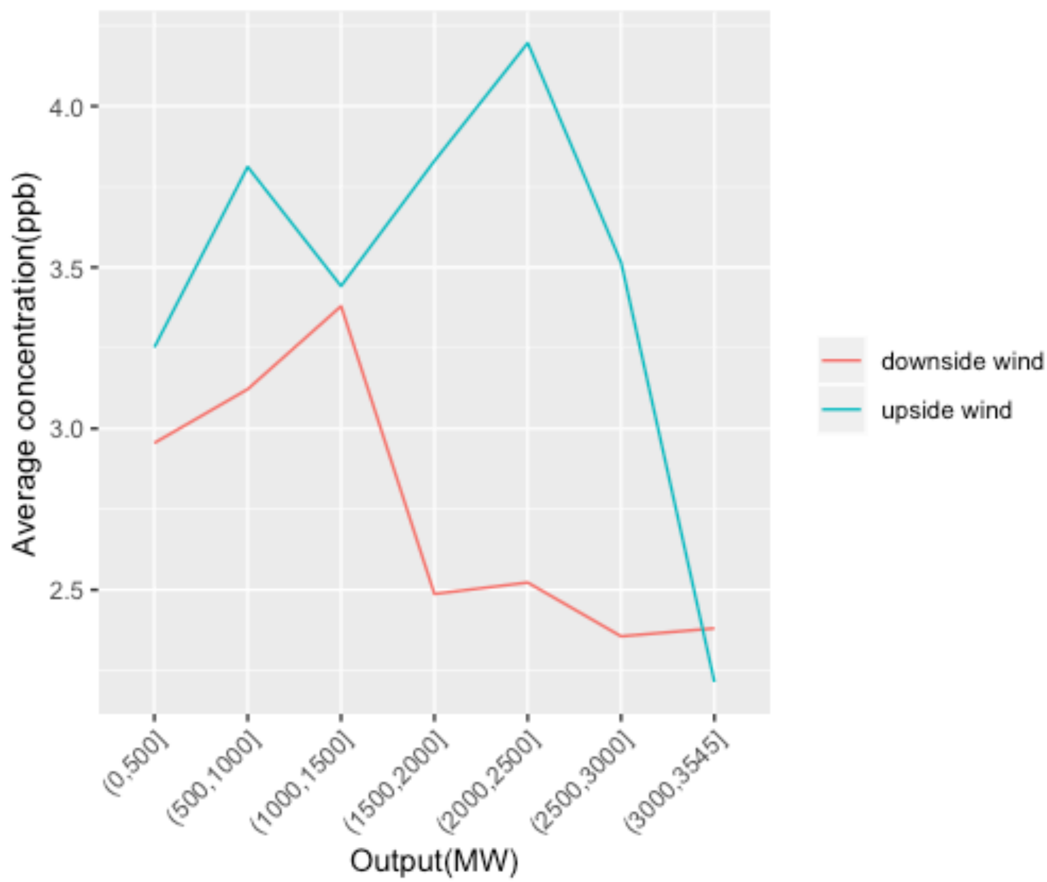

Figure9. Hourly Output Range and Corresponding Average SO_2 Concentration

(By Wind Situation)

Besides the electricity, car vehicle is also an important source of air pollutants. In order to improve the accuracy of models, this paper takes into consideration the factors from vehicles by adding a few time and place variables, including whether a day is a workday, whether the hour is during the peak hours with crowded traffic, whether the month is in winter and whether the monitor is in the urban area. Generally, the concentration in workdays, peak hours, urban areas and winter is likely to become bigger because in these time periods and places, people tend to use more vehicles. What's more, in urban areas and in winter, residence would use more electricity for home heating, which would worsen the air quality (Airlife, 2017).

Table 1 briefly show the average hourly concentration of the three air pollutants in the considered time periods and areas. Although with some holidays, workdays in this paper are from Monday to Friday. In Ontario, winter usually starts from December to February. The peak hours are from 6 am to 10 am in the morning and from 4pm to 7pm in the evening[6]. The location of each monitor, whether in rural or urban area, comes from the GIS map on the website of the Ministry of the Environment, Conservation and Parks of Government of Ontario (Government of Ontario, 2019-2). The number in parentheses is the numbers of observation.

Table 1. Average Pollutant Concentration (By Time and Area)

		$PM_{2.5}$ (ug/m^3)	NOx (ppb)	SO_2 (ppb)
Season	Winter	6.0 (150,775)	15.4 (124,931)	3.0 (40,708)
	Non-Winter	7.4 (457,907)	10.7 (384,410)	3.2 (125,116)
Day	Workday	7.1 (434,189)	12.8 (363,848)	3.1 (118,450)
	Weekend	7.1 (174,493)	9.4 (145,493)	3.3 (47,374)

[6] There are no fixed winter months or peak traffic hours durations in Ontario. The periods in this paper are decided based on the intersection of periods in various sources.

Hour	Peak	7.3 (177,753)	13.9 (148,725)	3.3 (48,413)
	Non-Peak	7.0 (430,929)	11.0 (360,616)	3.1 (117,411)
Area	Urban	7.2 (541,761)	12.3 (479,087)	3.1 (165,824)
	Rural	6.3 (66,921)	4.2 (30,254)	-

4.2 Models and results

In Section 4.2, this paper will study how did the increase of coal output affect air quality in Ontario by proposing hypothesis (H) and building up models. This paper will also use the same method to study the impact of wind direction and the impact of the distance between the coal plant and the monitor on the air quality.

H1: The hourly coal output has a positive relationship with the concentration of air pollution. The more electricity generated by coal in an hour, the higher concentrations $PM_{2.5}$, NOx and SO_2 will have.

H2: Compared with the concentration level during hours when the wind does not blow from the coal plant to the monitor or when there is no wind, the increase of coal plant's output is likely to cause higher concentrations of pollutants when the wind blows from the plant to the monitor.

In order to examine the above hypothesis, this paper builds the first model:

Model1

$$Pollutant_{it}=a+b_1*output_t+b_2*direction_{it}+b_3*output_t*direction_{it}+c_1*output_{t-1}+c_2*direction_{it-1}+c_3*output_{t-1}*direction_{it-1}+d_1*output_{t-2}+d_2*direction_{it-2}+d_3*output_{t-2}*direction_{it-2}+e_1*temp_t+e_2*rehum_t+g_1*winter_t+(g_2*year2013a_t+g_3*winter_t*year2013a_t)+k_1*dow_t+k_2*pkhrs_t+k_3*urban_i$$

In this model, $Pollutant_{it}$ is the concentration of a pollutant in monitor *i* in hour *t*. There are 18 monitors and each monitor's hours are different due to different operation periods. $output_t$ is the coal output's value in hour *t,* it varies from plant to plant and from hour to hour. It is a continuous variable and the unit is MW. The direction of its coefficient b_1 measures if the use of coal can worsen the air quality (positive b_1) or can improve the air quality (negative b_1), or it has nothing to do with the air quality (b_1 is 0). The value of the coefficient measures to what extend the use of coal can affect the air quality. The one hour's and two hours' time lags are also taken into consideration to see if the previous hours' coal output can influence the ambient air quality. $direction_{it}$ is a dummy variable which indicates the wind direction. It equals to 1 if in hour *t*, the wind blows from the coal plant to the monitor *i*. It equals to 0 if in hour *t*, the wind does not blow from the coal plant to the monitor *i* or there is no wind. Same with the $output_t$, $direction_{it}$'s time lags are also considered. $output_t*direction_{it}$ is an interactive variable. If its coefficient b_3 is positive, if means compared to an upwind or no wind, the increase of coal output will cause more air pollutants when the wind blows from the plant to the monitor. Temperature ($temp_t$) and relative humidity ($rehum_t$) of the coal plants are in the model because they play a key role in the formation of air pollutant. In detail, "aqueous-phase-chemical reactions take place in cloud and fog droplets, and in aerosol particles at relative humidities approaching 100%. These reactions can lead to production of sulfate."(Russell et.all, 2017). And "increased temperature can increase the rate of photochemical reactions, contributing significant secondary organic aerosol, especially during the summer" (Russell et.all, 2017). $winter_t$ is also a dummy variable. It equals to 1 when the date is in January, February or December. Its coefficient g_1 will tell whether the pollution is more serious in winter than in non-winter months. *year2013a* equals to 1 when the date is in Year 2013 or 2014. This variable will only be used in examining coal's impact on $PM_{2.5}$ because from Jan 1st 2013, Ontario changed the monitoring method of ambient $PM_{2.5}$ and the impact is that $PM_{2.5}$ would have a higher concentration in winter, while the real air quality remain the same. (Ministry of the Environment, Conservation and Parks). In this case, g_2 measures the influence of technology on the $PM_{2.5}$. $winter*year2013_a$ is another interactive variable. Its coefficient g_3 indicates how the season's influence on air pollution changes when there is a technology change. It is positive if from 2013, the $PM_{2.5}$ in winter is higher than previous years' winter's $PM_{2.5}$. This variable is also only for studying $PM_{2.5}$. In the end, this model includes the days of week (dow_t), peak traffic hours ($pkhrs_t$) and urban area ($urban_i$) to take the vehicles and cars factors into consideration. All the three variables are dummy variables. The variables equal to 1 when the hour is in the workday, is a peak hour, and when the monitor is in the urban area. Table 2 shows the OLS regression of Model1. All the five monitors with SO_2 data were in urban areas, therefore, $urban_i$ is not a variable in SO_2 regression.

Table 2. OLS Regression Results of Model 1

	(1)	(2)	(3)
VARIABLES	$PM_{2.5}$	NOx	SO_2
$output_t$	0.000609***	0.00127***	0.000565***
	(7.83e-05)	(0.000207)	(0.000197)
$direction_{it}$	0.353***	0.680***	-0.110*
	(0.0281)	(0.0718)	(0.0645)
$output_t*direction_{it}$	0.000252***	-9.27e-05	-0.000262**
	(4.43e-05)	(0.000117)	(0.000119)
$output_{t-1}$	-0.000309**	0.00191***	0.000693**

	(0.000123)	(0.000323)	(0.000300)
$direction_{it-1}$	0.259***	0.413***	-0.0367
	(0.0315)	(0.0803)	(0.0717)
$output_{t-1}$*$direction_{it-1}$	0.000152***	2.54e-05	-0.000185
	(5.05e-05)	(0.000133)	(0.000134)
$output_{t-2}$	0.000277***	-0.00310***	-0.00129***
	(7.79e-05)	(0.000206)	(0.000196)
$direction_{it-2}$	0.302***	0.266***	-0.0863
	(0.0281)	(0.0719)	(0.0645)
$output_{t-2}$*$direction_{it-2}$	0.000208***	-6.79e-06	-0.000241**
	(4.43e-05)	(0.000117)	(0.000119)
$temp_t$	0.242***	-0.271***	0.0978***
	(0.000956)	(0.00245)	(0.00222)
$rehum_t$	0.0768***	0.158***	-0.0525***
	(0.000505)	(0.00130)	(0.00117)
$winter_t$	1.049***	-0.450***	1.624***
	(0.0246)	(0.0590)	(0.0533)
$year2013a_t$	1.292***		
	(0.0198)		
$winter_t$*$year2013a_t$	4.147***		
	(0.0394)		
dow_t	-0.203***	3.471***	-0.154***
	(0.0161)	(0.0417)	(0.0372)
$pkhrs_t$	0.253***	2.923***	0.0713*
	(0.0164)	(0.0424)	(0.0380)
$urban_i$	0.804***	7.738***	-
	(0.0232)	(0.0794)	-
Constant	-3.147***	-8.794***	6.070***
	(0.0488)	(0.137)	(0.105)
Observations	608,423	509,092	165,787
R-squared	0.183	0.117	0.030

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Model 1 is interested in the sign and value of b_1 and b_3. The coefficient of $output_t$ (b_1) in Table 2 suggests that statistically, when holding everything else constantly, it is 99 percent sure ("***" in the right corner of the coefficient) that the increase of 1 MW's electricity from coal can averagely increase the concentration of $PM_{2.5}$ by 0.0006 ug/m^3, NOx by 0.0013 ppb and SO_2 by

0.0006 ppb. In the real context, the average hourly coal output of Generation Lambton was 263 MW and the average hourly $PM_{2.5}$ concentration of its surrounding monitors was 7.8ug/m^3, NOx was 11.7ppb and SO_2 was 3.4ppb. Therefore, when Lambton generates electricity in the full capacity level (1924 MW mentioned in Section 3) with no wind or an upside wind, the three pollutants are estimated to increase by 1ug/m^3, 2.2ppb and 1ppb, respectively. Table 3 summarizes the figures for three generations, numbers in parenthesis shows the percentage change from average level to full capacity level.

Table 3. Air Pollutants Concentration on Average and Full Generating Capacity Levels

(By Generation)

		Lambton	Nanticoke	Thunder Bay
Output (MW)	Average	263	413	14
	Full Capacity	1924	3663	310
$PM_{2.5}$ (ug/m^3)	Average	7.8	7.0	5.0
	Full Capacity	8.8 (13%)	9.0 (29%)	5.2 (4%)
NOx (ppb)	Average	11.7	11.7	13
	Full Capacity	13.9 (19%)	15.9 (36%)	13.4 (3%)
SO_2 (ppb)	Average	3.4	2.7	-
	Full Capacity	4.4 (30%)	4.7 (74%)	

In Table 3, although the variation of air pollutants concentration is not as sharp the variation of electricity output, the percentage in parenthesis indicates that when the generation operates in full capacity, the air pollution would be worse, especially for the monitors close to Generation Lambton and Nanticoke, the concentration of air pollutants would increase by at least 13%.

Besides b_1, the coefficient of $output_t*direction_{it}$ (b_3) also deserves to be explored. Results in Table 2 shows that when holding everything else constantly, it is 99 percent sure that 1 MW's increase of coal output would on average increase $PM_{2.5}$ concentration by 0.0009 ($b_1 + b_3$= 0.0006 + 0.0003) ug/m^3 when the wind blows from the plant to the monitor, while during the hours that have no wind or have an upside wind, 1 MW's increase of coal output would only increase $PM_{2.5}$ concentration by 0.0006ug/m^3. This shows that wind direction has an impact on $PM_{2.5}$ concentration. However, this conclusion cannot be applied to NOx and SO_2 concentration. In Table 2, b_3 for NOx is not significant (no "*" in the right corner of the coefficient), which means wind direction has no impact on the NOx concentration, even if b_3 is positive. b_3 for SO_2 has two "*" in the right corner of the coefficient, suggesting that it is 95% sure that the downwind direction decreases the SO_2 concentration, which is very counterintuitive. Therefore, the paper builds up Model 2 to further study the impact of wind direction on air pollutants.

Model2

$$Pollutant_{it}=a+b*realoutput_{it} +c*realoutput_{it-1} + d*realoutput_{it-2}+$$
$$e_1*temp_t+e_2*rehum_t+g_1*winter_t+(g_2*year2013a_t+g_3*winter_t*year2013a_t)+k_1*dow_t+$$
$$k_2*pkhrs_t+k_3*urban_i$$

In Model2, $realoutput_{it}$ is the real output that can be sensed by the monitor *i* from the coal plant in hour *t*. It equals to the $output_t$ times the $direction_{it}$. However, $direction_{it}$ in Model 2 is a continuous variable and it varies from 0 to 1. As discussed in Section 3, after getting the cosine value of the angel between the monitor and coal plant's wind direction for each pollutant monitor in each hour, the negative values are adjusted to 0, indicating that there is no wind or an upside wind. These two scenarios in this paper mean that the wind does not convey air pollution from the plant to the monitor. Other positive values are bigger than 0 but smaller than or equal to 1, suggesting the proportion of coal output that can be sensed by the monitor---the plant can convey 1% of its coal output pollution to the monitor or it can convey as much as 100%. Therefore, in Model 2, the real amount of coal output that can be transmitted to the monitor will not be the simple output but should be the value of the hourly output times the hourly wind direction weight. The $realoutput_{it}$ in Model2 will be equal to or smaller than the $output_t$ in Model1. The difference is that in Model1, as a dummy variable, all the downside winds' influences are the same as long as the cosine value is bigger than 0. However, in Model2, the $realoutput_{it}$ offers the larger downwind side effect more influence. In other words, the $output_t$ in Model1 is the nominal output in an hour and the $realoutput_t$ in Model2 is the real output in an hour. Model2's purpose is to study that when the larger downwind side effect makes the real output get closer to its nominal output, whether the air quality will also get worse. Time lag variables of *realoutput* have the same mechanism with $realoutput_{it.}$ All the other variables maintain the same with that in Model1.

Below is the OLS regression results for Model2. What should be noted is that in Model2, the $realoutput_{it}$ is 0 if the $output_t$ is 0, even if the cosine value is missing due to the missing of wind direction's raw data. Therefore, the numbers of observations in Model2 is more than or equal to that in Model1.

Table 4. OLS Regression Results of Model 2

VARIABLES	(1) $PM_{2.5}$	(2) NOx	(3) SO_2
$realoutput_{it}$	0.000969*** (4.83e-05)	0.00119*** (0.000128)	-8.87e-05 (0.000122)
$realoutput_{it-1}$	0.000517*** (5.99e-05)	0.000572*** (0.000159)	-4.69e-05 (0.000150)
$realoutput_{it-2}$	0.000873*** (4.82e-05)	-0.000620*** (0.000128)	-0.000509*** (0.000122)
$temp_t$	0.242*** (0.000944)	-0.273*** (0.00243)	0.0956*** (0.00222)
$rehum_t$	0.0776*** (0.000502)	0.161*** (0.00130)	-0.0525*** (0.00117)
$year2013a_t$	1.318*** (0.0196)		
$winter_t$	1.108*** (0.0242)	-0.522*** (0.0580)	1.567*** (0.0522)
$winter_t*year2013a_t$	4.097*** (0.0394)		
dow_t	-0.209*** (0.0160)	3.404*** (0.0415)	-0.176*** (0.0371)
$pkhrs_t$	0.273*** (0.0160)	3.085*** (0.0413)	0.142*** (0.0369)
$urban_i$	0.848*** (0.0231)	7.596*** (0.0793)	-
Constant	-2.734*** (0.0479)	-8.157*** (0.134)	5.906*** (0.101)
Observations	608,573	509,242	165,814
R-squared	0.185	0.115	0.028

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 4 shows that when the real hourly output gets closer to the nominal hourly output because of a larger downside wind, it is 99 percent sure that the concentrations of $PM_{2.5}$ and NOx increase on average by 0.001 ug/m^3 and 0.0012 ppb respectively. For example, when the three plants operate in the full capacity level but there is no wind or an upwind, the monitor cannot feel the output from the coal, therefore, the real output for all the monitor is 0. Based on this, when the angel in Figure 6 decreases to 60 degree or if there is a smaller downside wind, cosine value becomes bigger to ½, which means the monitor can sense half of the output from the coal plant. In this case, Lambton's monitors' real output becomes 962 MW, Nanticoke's monitors' real output is 1832 MW and Thunder Bay's is 155 MW. Therefore, $PM_{2.5}$ concentration for each of the three plants increases by 1, 1.8 and 0.2 ug/m^3. NOx concentration increases by 1.2, 2.2 and 0.2 ppb. Furthermore, when the angel is 0, cosine value is 1, which means the wind blows straightly from the coal plant to the monitor. At this time, the increase of $PM_{2.5}$ and NOx concentration for the three plants would be higher than the increase during the smaller downwind hours.

Besides the coal output and the wind direction, the role of distance between the coal plant and the monitor also deserves attention. This paper uses Model 2 to study whether the increase of the real output tends to produce more air pollutants when the coal plant is closer to the monitor.

H3: The increase of coal output has a larger effect on increasing the closer monitor's air pollution level than the further monitor's.

All the 18 monitors have a distance of less than or equal to 100km from the coal plants, however, only four monitors are within 50km from the plants. As a result, the paper divides the distances into three categories: within 50km (4 monitors), between 50km and 75km (5 monitors) and more than 75km (9 monitors). Table 5 to Table 7 shows the OLS regression results for each air pollutant under different distance levels. Figure 10 to Figure 12 plots the coefficients of $realoutput_{it}$. The length of the vertical line for each distance scenario shows the confidence interval of the coefficient, which means that the real coefficient would have 95% possibility to fall in the interval.

Table 5 and Table 6 indicate that as long as the monitor is within 100km from the coal plant, it is 99% sure that the increase of real output would worsen the air quality by increasing $PM_{2.5}$ and NOx concentrations, which is in line with the conclusions from Table 4. But the magnitude of impact varies. In Figure10, the confidence interval of $realoutput_{it}$ within 50km is not overlapped with either of the other two confidence intervals, suggesting that it is 99% sure that the areas within 50km from the coal plants endure a worse air quality than the further area by having more ambient $PM_{2.5}$ concentration. The same conclusion cannot be reached for NOx because of the overlapping of the confidence intervals.

Table 5. OLS Regression for PM $_{2.5}$ Concentration

(By Distance)

VARIABLES	(1) <=50km	(2) 50km-75km	(3) >75km
$realoutput_{it}$	0.00197***	0.000919***	0.000879***
	(0.000134)	(8.93e-05)	(6.30e-05)
$realoutput_{it-1}$	0.00101***	0.000490***	0.000482***
	(0.000162)	(0.000111)	(7.85e-05)
$realoutput_{it-2}$	0.00203***	0.000728***	0.000810***
	(0.000134)	(8.92e-05)	(6.30e-05)
$temp_t$	0.213***	0.256***	0.249***
	(0.00179)	(0.00205)	(0.00130)
$rehum_t$	0.0743***	0.0864***	0.0743***
	(0.000994)	(0.00106)	(0.000681)
$year2013a_t$	0.680***	1.681***	1.410***
	(0.0407)	(0.0408)	(0.0262)
$winter_t$	1.144***	0.742***	1.299***
	(0.0495)	(0.0506)	(0.0325)
$winter_t*year2013a_t$	3.382***	4.445***	4.196***

	(0.0804)	(0.0821)	(0.0530)
dow_t	-0.424***	-0.0111	-0.231***
	(0.0331)	(0.0332)	(0.0214)
$pkhrs_t$	0.224***	0.360***	0.245***
	(0.0330)	(0.0331)	(0.0213)
$urban_i$	-	-	0.461***
			(0.0234)
Constant	-0.935***	-2.528***	-2.585***
	(0.0854)	(0.0907)	(0.0614)
Observations	136,177	169,389	303,007
R-squared	0.177	0.183	0.199

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

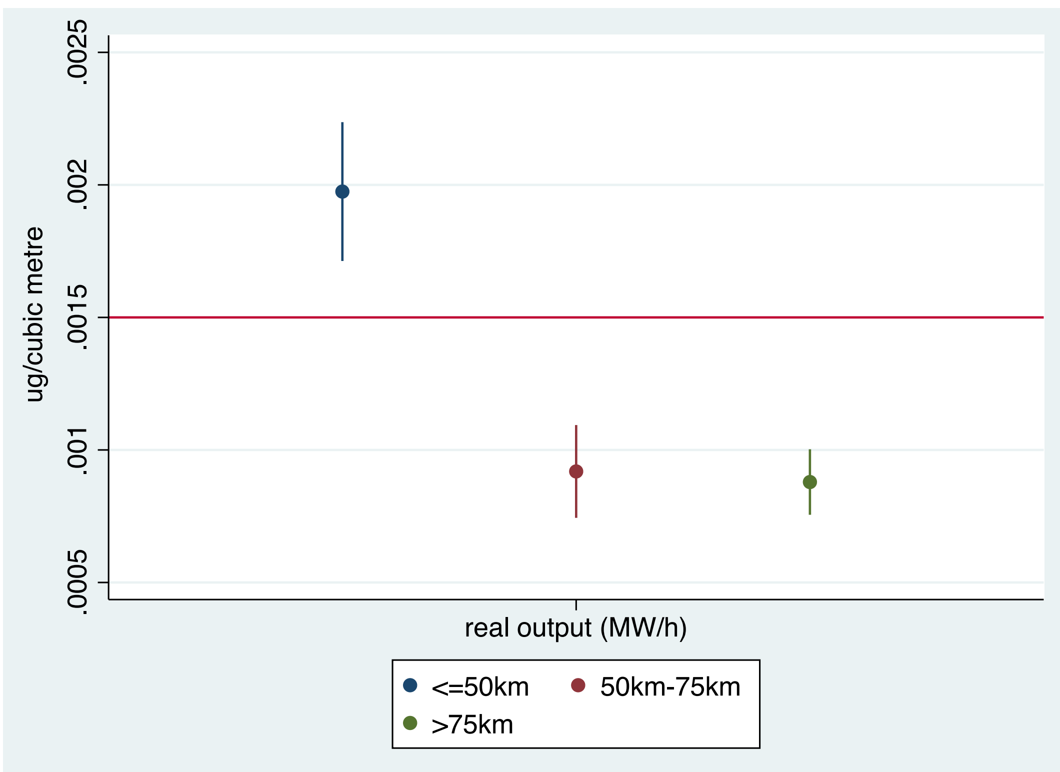

Figure 10. Impact of real output on $PM_{2.5}$ concentration (By Distance)

Table 6. OLS Regression for NOx Concentration

(By Distance)

VARIABLES	(1) <=50km	(2) 50km-75km	(3) >75km
$realoutput_{it}$	0.00152***	0.00113***	0.000824***
	(0.000239)	(0.000330)	(0.000158)
$realoutput_{it-1}$	0.000939***	0.000536	0.000407**
	(0.000289)	(0.000409)	(0.000197)
$realoutput_{it-2}$	2.17e-05	-0.00159***	-0.000668***
	(0.000238)	(0.000329)	(0.000158)
$temp_t$	-0.276***	-0.357***	-0.270***
	(0.00317)	(0.00709)	(0.00334)
$rehum_t$	0.117***	0.209***	0.162***
	(0.00177)	(0.00370)	(0.00174)
$winter_t$	-0.309***	-0.348**	-1.177***
	(0.0816)	(0.164)	(0.0773)
dow_t	2.094***	5.777***	3.229***
	(0.0590)	(0.117)	(0.0549)
$pkhrs_t$	2.195***	4.325***	3.086***
	(0.0587)	(0.116)	(0.0546)
$urban_i$			7.160***
			(0.0786)
Constant	0.884***	-0.234	-7.956***
	(0.150)	(0.317)	(0.166)
Observations	137,289	101,558	270,395
R-squared	0.141	0.116	0.123

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

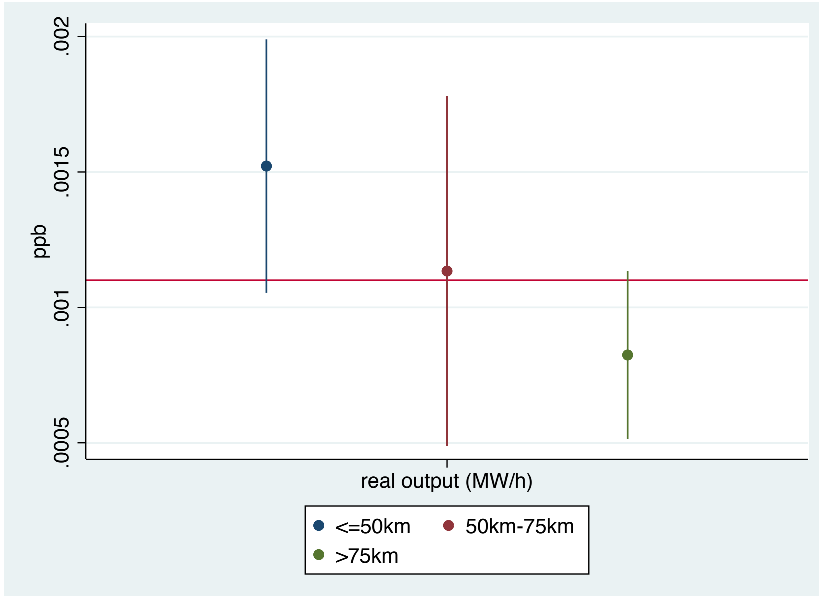

Figure 11. Impact of real output on NOx concentration (By Distance)

Results are mixed when it comes to the SO_2 concentration. For the areas within 50km from the coal plants, air quality gets worse by having more SO_2 concentration. However, when the distance falls between 50km to 75km, the increase of real output in an hour has no impact on SO_2. And when the monitor is more than 75km from the coal plant, the real output's increase even has a positive effect on the air quality, although the possibility decreases to 90%.

Table 7. OLS Regression for SO_2 Concentration

(By Distance)

VARIABLES	(1) <=50km	(2) 50km-75km	(3) >75km
$realoutput_{it}$	0.00271***	-0.000285	-0.000193*
	(0.000451)	(0.000210)	(0.000101)
$realoutput_{it-1}$	0.00200***	-0.000214	-0.000185
	(0.000535)	(0.000259)	(0.000125)
$realoutput_{it-2}$	0.00267***	-0.000886***	-0.000557***

	(0.000452)	(0.000210)	(0.000101)
$temp_t$	0.110***	0.106***	0.0580***
	(0.00665)	(0.00391)	(0.00196)
$rehum_t$	-0.0425***	-0.0590***	-0.0505***
	(0.00342)	(0.00206)	(0.00103)
$winter_t$	2.172***	0.816***	1.507***
	(0.160)	(0.0913)	(0.0459)
dow_t	-0.732***	-0.199***	0.107***
	(0.110)	(0.0652)	(0.0327)
$pkhrs_t$	0.136	0.280***	0.0178
	(0.109)	(0.0650)	(0.0325)
$urban_i$	-	-	-
Constant	5.487***	7.273***	4.756***
	(0.300)	(0.178)	(0.0888)
Observations	32,500	66,734	66,580
R-squared	0.053	0.033	0.058

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

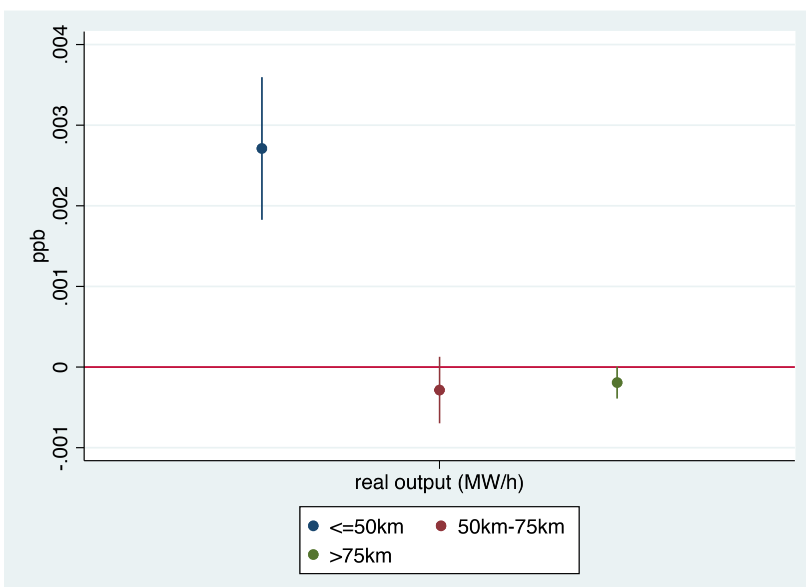

Figure 12. Impact of real output on SO_2 concentration (By Distance)

To summarize, the results from Section 4.2 indicate that the increase of electricity output from coal is very likely to worsen the air quality by increasing $PM_{2.5}$, NOx and SO_2 concentrations. Moreover, wind direction plays a key role in the concentration level of $PM_{2.5}$ and NOx. The more wind blows from the plant to the monitor, the higher concentration of $PM_{2.5}$ and NOx for the monitors to have. Areas within 50km from the coal plants tend to have worse air quality because of the increase of $PM_{2.5}$ and SO_2. These conclusions shed light on some policy inspirations.

4.3 Comparison and limitation

This section will briefly study the similarity and difference between results from the current paper and from other papers studying the air quality and health impacts of coal plants. Besides, this part would also address some limitations of models used in this paper.

On the air quality side, findings from the Ontario's historical data in this paper are aligned with most of the studies discussed in Section 2---Coal plants do have significantly positive impact on the increasing concentrations of air pollutants. However, these results are different from the results of Fraser Institute's study in Ontario (McKitrick et al., 2017). The reason behind the difference probably lie in different models and variables the two studies use. First, the institute's study focuses on coal's impact on three big populous cities including Hamilton, Toronto and Ottawa. In this case, there is no need to consider the distance's role. However, the present paper is interested in the coal's impacts on its surrounding areas within 100km. Second, the institute uses the monthly average data for analysis in order to convert the data with different frequencies into the same frequency and interpolate the emission data, while the current paper uses the hourly level's data. Third, the institute considers the influence of U.S air quality on

Ontario's air quality by collecting the U.S. $PM_{2.5}$ data. Instead, this paper gives the wind direction of local coal plants a role.

On the health cost side, previous studies have different premature deaths figures but they all suggest that the air pollution would cause loss of lives in Ontario. This paper uses the integrated exposure-response functions invented by Burnett in 2014 to estimate the premature deaths of ischemic heart disease and stroke due to $PM_{2.5}$ in the populous cities around the three coal plants in 2015. According to Burnett, the mortality of disease *j* in area *i* due to $PM_{2.5}$ is dependent on the population in area *i,* the annual mortality rate of disease *j* in region *k* and the relative risk[7] of disease *j* (dependent on the concentration of $PM_{2.5}$ in area *i*) (Apte et al., 2015). In this paper, the 100km radius of each coal plant indicates there are three areas (*i*). In Ontario (*k*) in 2015, 58, 300 people and 34, 870 people out of 13.7 million people lost lives because of ischemic heart disease and stroke (*j*) (Government of Ontario, 2019-3). Table 8 shows the estimation of premature deaths due to $PM_{2.5}$ in the populous cities that within 100km from each coal plant in 2015 if the coal plants still operate and generate electricity in the average hourly output level. The equations used in Table 8 and detailed explanations are provided in Annex D.

Table8. Estimation of Mortality due to $PM_{2.5}$ Concentration around Coal Plants (2015)

Coal Plant	Avg Coal Output/h(MW)	Average Hourly $PM_{2.5}$(ug/m^3)	Population	Ischemic Heart Disease	Stroke	Total
Lambton	262	7.8	464,000	96	12	108
Nanticoke	413	7.0	1,480,000	123	0	123
Thunder Bay	13	5.0	100,000	0	0	0

7 The relative risk varies depending on the disease and the concentration of $PM_{2.5}$. For the relative risks for stroke and heart disease at different $PM_{2.5}$ concentration level, data can be downloaded here http://ghdx.healthdata.org/record/ihme-data/gbd-2010-ambient-air-pollution-risk-model-1990-2010.

Based on Burnett's method, in 2015, if the three coal plants still operate in the average hourly output level, 108 people would have lost lives in the populous cities surrounding Generation Lambton. 123 people would have died in Nanticoke's areas around. Although these figures are different from the results in other Ontario studies, the figures only show the deaths numbers due to heart disease and stroke because of $PM_{2.5}$ in the populous cities that are close to the three coal plants. Table 8 does not include other diseases due to other air pollutants from coal in the areas that are within 100km from the coal plant but not very populous and the areas that are more than 100km from the coal plants. Therefore, the results are conservative estimations. Fortunately, Thunder Bay would have caused no premature deaths from both diseases and Nanticoke would also have caused no death from stroke because the relative risks at their $PM_{2.5}$ level for the disease is very low.

So far, the impact of Ontario's coal plants on air quality has been studied and its health impact due to $PM_{2.5}$ reduction has been estimated. However, the models in this paper still have some limitations.

First, since there is no data for Ontario's health-related data such as hospital admittances, death, asthma cases, etc, this paper cannot precisely quantify the casual effect of pollution from coal on Ontario's premature death and ERV. As a result, neither is this paper able to accurately estimate the contribution of Ontario's coal phase-out, like what have been done in other studies.

Second, this paper does not include the pollution from the U.S., an important source of Ontario's (particularly Windsor's) air pollution because of the wind. Therefore, the explanation ability of the two models in this paper is also limited.

Third, in terms of the air pollutants, this paper uses the ground station data rather than the data from Moderate Resolution Imaging Spectroradiometer (MODIS). However, MODIS data does better in observing the spatial and temporal variability of pollutant concentrations. Therefore, the ambient pollutant concentration is more precise (bigger than ground station data) and the predictive power is also higher (Liu et al, 2009).

5. Policy Implications

Findings from Ontario's historical datasets indicate that the use of coal can worsen the air quality. Besides, the downside wind and distance also play key roles in transmitting the air pollution. Moreover, the estimation suggests that the coal generation has an adverse impact on health. These conclusions offer a lot of inspirations for other provinces in Canada to counter the adverse air quality and health effect from coal generations. Currently, there are 15 coal plants in Canada and they are located in A.B., S.K., M.B., N.B., N.S.. Figure 13 shows the locations of the coal plants and the hourly coal capacity in Megawatt. The number in the parenthesis after the coal generation's name shows how many units are there in the generation (Plant Brandon in M.B. is only for emergency use).

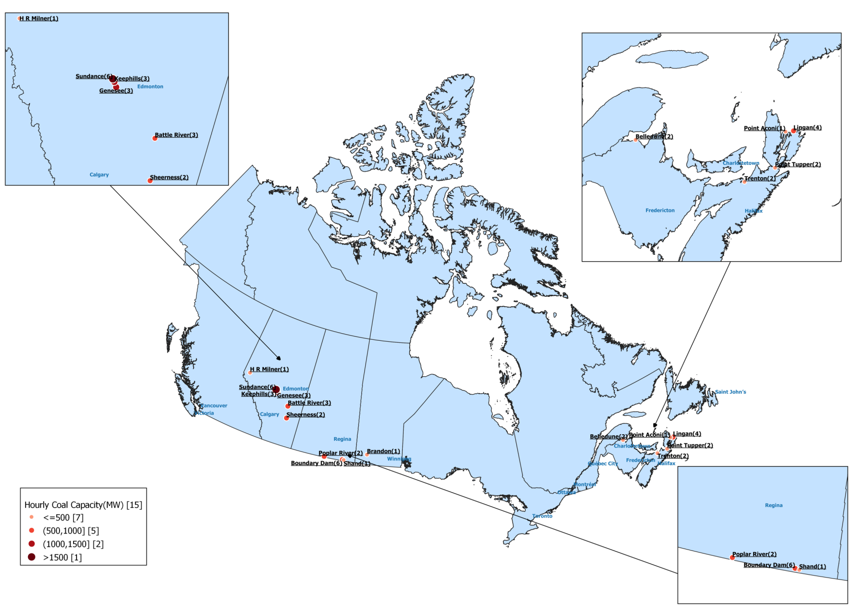

Figure13. Existing coal plants in Canada
Source: Synthesized by the author

Section 5 will propose some policy recommendations derived from the modelling for the five provincial governments that still use coal and analyze the considerations of implementing each policy recommendation effectively.

5.1 Coal phase-out

According to Model1in this paper, the use of coal increases air pollutants significantly. Therefore, a direct and permanent way to prevent the coal from worsening air quality is to stop using coal. Canada takes a leading role in the coal phase-out by "announcing the final regulations to phase-out traditional coal-fired electricity by 2030" (ECCC, 2018). In the provincial level, Alberta's "coal-generated power is to be phased-out entirely by 2030" under the current plan of New Democratic Party (NDP) (Senger & Pike, CBC, 2019). The environmental groups in NB and NS also urge for the relative provincial governments to set up a timeline for coal phase-out before 2030 to meet the deadline framed by the federal government (Doucette, CBC, 2019 & MacNeill, Conservation Council of New Brunswick, 2019).

Coal phase-out is a progressive and permanent measure to combat the bad impact of coal. To implement it requires many conditions and the provincial government needs to evaluate and consider them carefully. If the conditions are not well met, the effect and timeline of coal phase-out are likely to be influenced negatively. These conditions include:

First, the province should have sufficient endowment of alternative resources. The alternative resources include natural gas, nuclear power and renewable energy such as solar, wind, tide, biomass and so on. A sufficient endowment of either or a combination of these resources is important to ensure that the electricity price will not rise too much after eliminating coal. Otherwise, the province will rely on importing resources from other provinces or other countries, which risks at an imbalance between electricity demand and supply because of immaturity of transporting technology. All of these will cause a higher price for households to bear. Moreover, enough storage of alternative resources also guarantees the local employment. Only with the abundant natural resources can the supply chain of electricity, including exploitation, transportation, generation, transmission and distribution can be maintained so that the chain is able to guarantee or even create new job opportunities. Otherwise, if the local workers' life quality is highly influenced, the coal phase-out would trigger significant public and political resistance in municipality and individual levels (Harris et al., 2015). An example is in the town of Coronach in SK, people disagree with shutting down coal plants by saying "Closing the mine and the plant impacts everyone in the town, as businesses, services, and schools are likely to close if the majority of residents are no longer employed by the industry" because their wages and benefits are heavily relied on the coal plants and relevant industries (Fisher et al., 2018, p12).

Second, the province should have advanced technology, big spaces and enough funds for alternative resources' infrastructure. After eliminating coal, new resources will be exploited and new plants need to be built. The exploitation stage requires the province to have advanced technology. Without a proper method, the sufficient natural endowment will have no use. Moreover, the exploitation method should be high-efficient in order to lower the cost and guarantee the supply so that the cost of electricity will not rise sharply. The province should also have enough spare spaces for alternative resources' new plants. The building of new plants is inevitable for provinces that use renewable energy such as solar, wind and wave because the old coal plants cannot be converted due to natural issues. For natural gas and biomass, although they can be used in converted coal-to-gas units, the units usually "have a much shorter lifespan…… and are less efficient due to the re-engineering of the boilers and the characteristics of the different fuel types", which means the electricity suppliers will "receive a longer runway to recoup their invested capital in the conversion" (Vriens, 2018, p19). Therefore, the conversion can only be used as a short-term solution and if there is not enough and proper space for new plants, the coal phase-out timeline will be prolonged. What's more, funding is also an important factor for new plants. The building of new infrastructure will cost the provincial government a lot of money. Without a sufficient funding pool, the electricity price will rise and the household will bear higher electricity bills. In fact, from 2008 to 2016, Ontario's residential electricity costs increased by 71 per cent, a growth rate far exceeded Canada's average growth---34 per cent due to the province's building and commissioning of natural gas, wind and solar plants (Posadzki,THE GLOBE AND MAIL, 2018 & Morrow & Cardoso,THE GLOBE AND MAIL, 2018).

The first and second conditions are crucial because they help to convert reserves into usable resources and increases the competitiveness of clean energy compared to coal. In this way, the government will have an advantage over the interest groups of companies in the coal supply chain during the negotiation. According to Vriens, the coal mining industry is a big opposition force of coal phase-out in AB (2018). This is partly because coal is the source of AB's almost 50% electricity, which is very hard to be replaced.

Third, it is much easier for the province to proceed coal phase-out if the ownership of electricity sector is the public. Compared to private sectors whose main interest is to make profits, a public-owned electricity sector is able to make the government "write off their own assets and not have to renegotiate long-term supply contracts with private owners" (Harris et al., 2015, p5). Public ownership is also beneficial to lower the electricity price after coal elimination due to its positive externality. Actually, ownership plays a key role in Ontario's electricity market. On one side, since all the coal generations were public-owned and Ontario's coal was mostly imported from other provinces and the U.S, the Government of Ontario did not have to worry about the conflicting interests between coal elimination and coal generation and mining companies. On the other side, the privatization of some energy sectors in the transmission section (ex. Hydro One) stimulates the increase of electricity price after 2015. Therefore, ownership has an influence on not only the difficulty of coal phase-out but also related issues after coal phase-out. The government needs to take into consideration the energy sector's management system carefully before taking actions.

Fourth, solid research evidence from environmental and health organizations is beneficial to put the coal phase-out on agenda and accelerate the process. Even if the first three conditions of phasing out coal cannot be fully fulfilled, it does not mean that coal phase-out is impossible. The non-governmental organization (NGO) can influence the coal policy by conducting solid research to quantify the air quality, climate change and health impacts of coal. From 1970s, environmentalists in Ontario started to study coal's impact on mercury, toxics and GHG emissions. OMA also developed a professional model to estimate the health costs of coal in Ontario from 2000. Relevant NGOs played a leading role in putting the coal phase-out on agenda. They even formed a formal coalition---Ontario Clean Air Alliance (OCCA)---to influence the policy. All of the work helped to push the Government of Ontario to think about coal phase-out. On the contrary, few researches on AB's coal plants had been published by the NGO until 2013 (Adams et al., 2012). In 2013, several national and provincial NGOs published a study "*A Costly Diagnosis---Subsidizing coal power with Albertan's health*", in which the air quality and health impacts of Alberta's coal plants were estimated for different populations. Two years later, after NDP came to power, the coal phase-out plan in Alberta was declared.

To summarize, implementing coal phase-out requires the provincial government to consider if the province has natural endowment of alternative resources, good exploitation technology and enough funds and open areas, beneficial management system for electricity sector and relevant research evidence from NGOs. However, if in the short term, these requirements are hard for the province to meet so that the province still needs to rely on coal plants, according to the two models in this paper, two other solutions can be considered by the government as short-term expediencies.

5.2 Coal plant's relocation

The relocation of coal plants requires the government to consider at least two aspects:

First, the province should own a proper site and space for relocation. On the environmental side, the new site should be on the upwind side of and more than 100km away from the populous cities, according to the findings in Model2. Moreover, it is equally important that the relocation will not cause too much environmental burden on the new site. For example, the analysis on the "Coal Plants Western Movement" in China indicated that after being moved to northwestern part of China, the $PM_{2.5}$ in the northwest was increased but was at an accepted level. Therefore, if moving to another place is not at the cost of worsening the new place's air quality, the relocation can be considered (Mou et al., 2016, p741).

Second, the government would need to negotiate with various stakeholders. During the process of the site selection, the provincial government needs to have some discussions with relevant municipal governments and to learn what is the municipality's attitude towards building a new coal plant in its area. This is because, a new coal plant would cause some pollution more or less and it will take time for the government to persuade the local government that the pollution level is at an accepted level or to make some complementary policies within a proper cost. Otherwise, if the relocation cannot gain support from the municipality or the provincial government's complementary policy costs more than the benefits, this measure would be less likely to work. Meanwhile, since the relocation influences the whole supply chain of coal industry, after moving to a new site, the routes of transportation, transmission and distribution would all be influenced. Therefore, how to balance the interests between old and new actors in the supply chain also plays a key role in the success of relocation.

5.3 Installing APCD

If neither of the above policy is realistic, the last resort is to install the APCD. Due to the use of different types of coal and the meteorological variation of coal plants, the main pollutants they produce are also be different. In order to decide which APCD should be installed, it is important for the provincial government to conduct research to study which coal plant mainly produces what kind of air pollutants. The result can be used for the decisions on APCD installation.

Figure 14 describes the logic of choosing different policies. However, as discussed above, the last two policy recommendations can only be used in the short term. In the long run, the provincial governments need to facilitate coal phase-out through encouraging the development of advanced exploitation and conversion technology, negotiating with people with vested interests to make more efficient complementary policies to gain supports from them, facilitating the scientific evidence from research institutions and regulating the coal phase-out. This is because a coal phase-out contributes to not only the health of people who are affected by coal plants' air pollution impacts, but also the living environment of everyone in the context of global climate change.

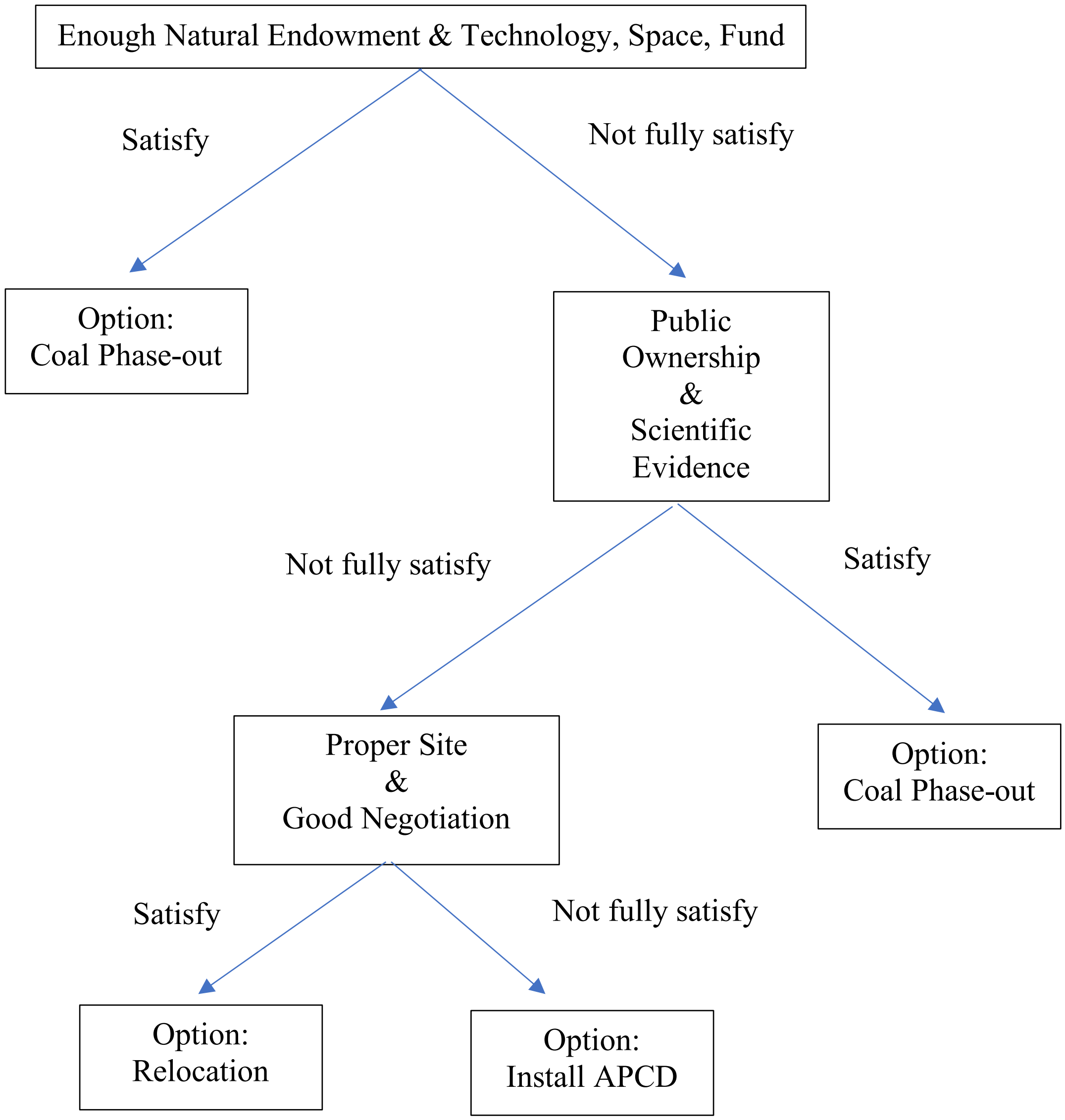

Figure14. Short-term Policy Option Stream

6. Conclusion

Results from the Ontario's historical coal and pollution data suggest that the use of coal has a negative impact on the air quality and it can increase the concentration of main air pollutants such as $PM_{2.5}$, SO_2, and NOx. Besides, the location of the coal generation also influences the ambient air pollutant concentrations of its surrounding areas. If the coal plant is in the downwind side of an area, the wind will transmit more serious $PM_{2.5}$ and NOx so that the downside area is likely to be more heavily polluted. And areas within 50km from the coal would bear more SO_2 and $PM_{2.5}$. Since the air pollutants are important sources of cancer and diseases, based on the findings from the current paper and previous literatures, this paper conservatively estimates that the operation of the three coal plants would cause 231 heart disease and stroke premature deaths due to $PM_{2.5}$ in the populous cities within 100km from the plants, not including the deaths due to other pollutants and other diseases.

Estimates from Ontario's historical data is a good reference to predict coal's impact on other provinces' air quality and health costs. To counter the negative impact of coal, the Government of Canada announced to eliminate all the coal plants by 2030. For the five provincial governments with coal plants, they need to evaluate carefully if they have the conditions to implement a permanent coal phase-out to meet the deadline proposed by the federal government. If it is not likely to make this come true in the short-time due to resource structural and economic differences, provincial governments can also relocate the coal plants or install corresponding control devices. However, in the long-term, it is crucial for provincial governments to facilitate coal phase-out through multiple rounds' negotiation with stakeholders, encouragement for more technology and for publish of scientific research evidence. This will not only save lives influenced by air pollution but also make contribution to resolving the long-term climate change issue.

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Annex

A. Coal plants' corresponding pollutant monitors

Lambton

	$PM_{2.5}$	NOx	SO_2	Area	Distance (km)
Windsor Downtown	√	√	√	Urban	71.5
Windsor West	√	√	√	Urban	75.1
Chatham	√	√	–	Urban	50.0
Sarnia	√	√	√	Urban	21.0
Grand Bend	√	√	–	Rural	83.4

Nanticoke

	$PM_{2.5}$	NOx	SO_2	Area	Distance (km)
London	√	√	–	Urban	97.2
Port Stanley	√	–	–	Rural	92.2
Brantford	√	√	–	Urban	42.5
Kitchener	√	√	–	Urban	80.5
St.Catharines	√	√	–	Urban	77.6
Guelph	√	√	–	Urban	85.3
Hamilton Downtown	√	√	√	Urban	53.1
Hamilton Mountain	√	–	–	Urban	50.1
Hamilton West	√	–	–	Urban	52.1
Burlington	√	√	–	Urban	60.7
Oakville	√	√	–	Urban	81.4
Mississauga	√	√	√	Urban	88.9

Thunder Bay

	$PM_{2.5}$	NOx	SO_2	Area	Distance (km)
Thunder Bay	√	√	–	Urban	5.6

B. Coal plants' corresponding weather stations

Lambton

Station	Distance(km)
SARNIA	26.0
SARNIA CHRIS HADFIELD A	26.0
SARNIA CLIMATE	26.4
RIDGETOWN RCS	61.8
WINDSOR A	70.2
ERIEAU (AUT)	76.7
HARROW CDA AUTO	92.3
POINT PELEE CS	94.2

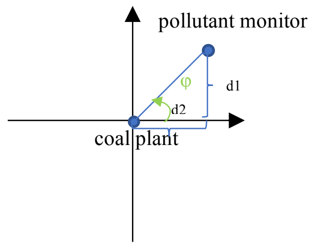
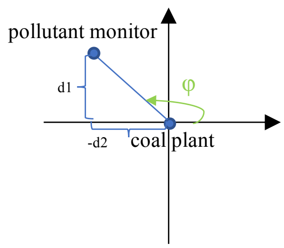
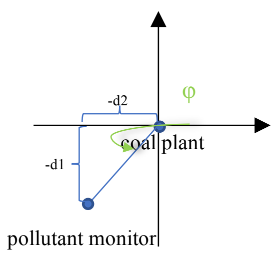
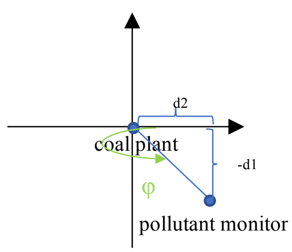
Thunder Bay

Station	Distance(km)
WELCOME ISLAND (AUT)	7.5
THUNDER BAY A1	7.5
THUNDER BAY	7.5
NORTHERN ONTARIO EER	7.8
THUNDER BAY CS	8.2
THUNDER BAY A2	8.2

Nanticoke

Station	Distance(km)
LONG POINT (AUT)	30.0
DELHI CS	41.6
HAMILTON A2	42.1
HAMILTON A1	42.3
HAMILTON RBG CS	55.6
SOUTHERN ONTARIO EMERGENCY PORTABLE WEATHER STATION	56.7
BURLINGTON PIERS (AUT)	59.2
WELLAND-PELHAM	61.8
PORT COLBORNE (AUT)	65.9
VINELAND STATION RCS	67.8
KITCHENER/WATERLOO	78.1
REGION OF WATERLOO INT'L AIRPORT	78.1
ST. CATHARINES / NIAGARA DISTRICT A	83.8
PORT WELLER (AUT)	84.1
ST CATHARINES A	84.4
GUELPH TURFGRASS	84.5
LONDON A	93.4
LONDON CS	93.4
LONDON INT'L AIRPORT	93.4
ELORA RCS	99.1

C. Four scenarios of φ

Case	Schematic diagram	tan(φ)	φ
1		d1/d2	arctan(d1/d2)
2		d1/(-d2)	arctan(d1/-d2) + π
3		-d1/(-d2)	arctan(-d1/-d2) + π
4		-d1/(d2)	arctan(-d1/d2) + 2π

D. Equations and explanations to the calculation of premature deaths.

$$M_{i,j} = P_i \times \hat{I}_{j,k} \times (RR_j(C_i) - 1), \text{ where } \hat{I}_{j,k} = \frac{I_{j,k}}{RR_{j,k}}$$

$M_{i,j}$: The numbers of premature deaths in area *i* due to disease *j*.

In this paper, i=1 for the areas within 100km from Generation Lambton.
i=2 for the areas within 100km from Generation Nanticoke.
i=3 for the areas within 100km from Generation Thunder Bay.
j=1 when the disease is heart disease.
j=2 when the disease is stroke.

P_i: The population in area *i*.

In this paper, P_1=464,000 because the population in the populous cities that are within 100km from Generation Lambton is 464,000. P_2=1,480,000. P_3=100,000.

$I_{j,k}$: The annual mortality rate due to disease *j* in region *k*.

In this paper, region k is Ontario. In 2015, Ontario has 13.7 million people, 58,340 people lost lives due to heart disease and 34,870 people dead because of stroke. Therefore, I_1=58,340/1,370,0000=0.0043, I_2=0.0025.

$RR_j(C_i)$: The relative risk of disease *j* in the concentration of $PM_{2.5}$ level C in area *i*. According to Burnett, the relative risk of heart disease and stroke in the average $PM_{2.5}$ concentration level of each coal plant is calculated in the following table:

j	Disease	$PM_{2.5}$	RR	i
1	Heart Disease	5	1	3
1	Heart Disease	7	1.02	2
1	Heart Disease	8	1.05	1
2	STROKE	5	1	3
2	STROKE	7	1	2
2	STROKE	8	1.01	1

$$\overline{RR}_{j,k} = \frac{\sum_{i=1}^{N} P_i \times RR_j(C_i)}{\sum_{i=1}^{N} P_i}$$

$\overline{RR}_{j,k}$: The average population-weighted relative risk for disease *j* in region *k*. In this paper, this indication for heart disease is 1.03, for stroke, it equals to 1.

$\hat{I}_{j,k}$: According to Burnett, "it represents…the cause-specific mortality rate that would remain for region k if $PM_{2.5}$ concentrations were reduced to the theoretical minimum risk concentration throughout that region" (Apte et al., 2015). In this paper, this indicator for heart disease is 0.0042, for stroke, it equals to 0.0025.