Transitioning Canada to 100% Wind-Water-Solar

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***Abstract*—This paper summarizes the changes in Canada's if achieving the full transition of Wind-Water-Solar energy system. It shows both cost and benefit of transitioning Canada to WWS energy. The purpose is to provide an outlook of a possible Canadian low-carbon future. All analysis is based current data, and it takes Canada regardless of different provinces and territories or other possible environment or political limitations. The energy demand and the resources demand are analysed; the reduced cost from multiple aspects after transition are being calculated to directly show reductions. The cost result shows positive trend for alleviate governmental climate cost which is encouraging Canadian government to establish and implement more environmental related policies. However, the transition would require large number of efforts of not only the governments, but also all residents in Canada. This can be challenging because it hits the bottom line of oil tycoons and other BAU energy companies. In addition, promoting people to use WWS equipment comprehensively is also difficult since the economy situation can be fluctuated over years and people are tending to what they are already getting used to.**

***Keywords*—wind, water, solar, energy system, low-carbon, Canada**

I. Introduction

In recent years, global warming has become an important issue facing society. Generally, characterized by increasing temperature, global warming increases the occurrence of natural disasters, which contribute to stagnant economic development and progress of civilization. A possible solution that reduces the economic shock is to transition from a Business-As-Usual (BAU) energy economy to a Wind-Water-Solar (WWS) energy economy (Jacobson *et al.*, 2022). Even though Canada has relatively modest greenhouse gas emissions, Canada's crude oil exploitation and exports keep increasing and gaining revenue, rising by 53.6%, up to $269.9 billion in 2022 (Statistics Canada). Such growth also increases greenhouse gas emissions which is directly contributing to further climate crisis. Thus, it is urgent to stop the government from relying heavily on non-renewable energy, mining, and the continued development of the oil sands. A full energy transition is required for Canadian's future society and economic development. And the energy transition in Canada will also contribute to reducing the United States' BAU energy consumption since Canada is the top exporter to the U.S. In addition, the per-capita carbon emission in Canada, 15.22 tons per person, is higher than in the United States (Canada Energy Regulator, 2021). Thus, an energy transition in Canada is urgently needed and will bring multiple benefits for the governments and citizens. Previous studies project the energy demand of Canada in 2050 to propose the low-cost solutions to Canadian air pollution (Jacobson, 2021), energy insecurities (Wang *et al.*, 2020) and other issues; Canada current renewable energy analysis based on province and territories. All of which are whether predicting the future or dividing the energy policies and resources to a range of large regions. This paper gives an insight into and quantifies the possibility of realizing a full (all-sector) energy transition from the perspective of Canada as a whole. The required WWS energy to replace the BAU energy in each end-use energy sector is calculated. A method of replacing BAU fuels with WWS energy in each energy category is explored. Finally, the cost of a transition in Canada's is estimated.

II. Methods

A. Overall BAU-WWS Transition Calculation

First, to estimate the benefit of a transition to WWS, the reduction in end-use energy consumption must be calculated. End-use energy is the energy people use. To know how much energy is required after the transition and how much that amount will decrease compared with BAU energy, the energy use in Canada's in six main sectors (residential, commercial, and public, agriculture/forestry, industry, transport, non-specified) was analysed. The use of seven types of energy in those sectors was also analysed. All the following calculations are based on total final consumption (end-use energy) data for Canada in 2021, from the International Energy Agency (IEA) since 2021 has the most complete data (IEA, 2021). With respect to the Table 1, some nonsignificant data from the IEA chart are omitted, because they are not end-use energy (stock changes), they have no effect on the outcome (international marine bunkers) or are included in other end-use sectors (commercial and public services).

Starting with 2021 Canadian end-use energy consumption, I project the total energy demand reduction in Canada after electrification. WWS energy powers up electric generating stations which have higher efficiency than BAU energy plants. Additionally, using WWS electricity instead of combustion reduces energy requirements significantly in transportation and heating (Erdemir and Dincer, 2019). For example, electric vehicles are much more efficient than internal-combustion engine vehicles and electric heat pumps are much more efficient than combustion heaters. Thus, the amount of current end-use BAU energy (TJ) decreases when it is converted to the energy needed for an electrified infrastructure. Table 2 provides the factors for converting BAU fuels in each sector to WWS electricity in each sector (100% Clean, Renewable Energy and Storage for Everything, Mark Z. Jacobson). The

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factors give the ratio of WWS electricity needed to BAU energy needed. Using those factors, I calculate the energy consumption required with WWS and resulting percent reduction in end-use energy needed in each sector (Table 3).

Table 1. 2021 annual-average end-use demand (TJ/year) from IEA (2023) in a business-as-usual (BAU) case.

End-use sector	Coal	Oil products	Natural gas	Biofuels and waste	Electricity	Heat	WWS heat	Total
Residential		58,294	585,383	113,333	635,652			1,392,662
Commercial and public		51,827	575,741	638	520,650	425		1,149,281
Agriculture / forestry	580	199,056	38,586	7	38,005			276,234
Non-specified						821	1,782	2,603
Industry	104,616	230,115	637,658	229,129	66,392	16,560		1,284,470
Transport		2,118,667	139,199	79,650	272,248			2,609,764
Total								6,715,014

Table 2. Factors to multiply BAU demand by to obtain WWS demand due to the efficiency of electricity over combustion.

End-use sector	Coal	Oil products	Natural gas	Biofuels and waste	Electricity	Heat	WWS heat
Residential	0.2	0.2	0.2	0.2	1	0.25	1
Commercial and public	0.2	0.2	0.2	0.2	1	0.25	1
Agriculture / forestry	0	0.19	0.19	0.19	1	0.25	1
Non-specified	0.82	0.82	0.82	0.82	1	0.25	1
Industry	0.82	0.82	0.82	0.82	1	0.25	1
Transport	0	0.19	0.19	0.19	1	0	0

Table 3. Annual-average end-use demand (TJ/year) with 100% WWS and percent difference between WWS and BAU demand.

End-use sector	Coal	Oil products	Natural gas	Biofuels and waste	Electricity	Heat	WWS heat	Total	Percent dif. WWS-BAU
Residential	0	11,659	117,077	22,667	635,652	0	0	787,054	−43.49%
Commercial and public	0	10,365	115,148	128	520,650	106	0	646,397	−43.76%
Agriculture / forestry	0	37,821	7,331	1	38,005	0	0	83,158	−69.90%
Non-specified	0	0	0	0	0	205	1,782	1,987	−23.66%
Industry	85,785	188,694	522,880	187,886	66,392	4,140	0	1,055,777	−17.80%
Transport	0	402,547	26,448	15,134	272,248	0	0	716,376	−72.55%
								3,290,750	−50.99%

B. *Current WWS Situation Calculation*

However, the total output of WWS energy needed to replace BAU fuels in the annual average does not satisfy the entire demand. This is because additional WWS energy and storage are needed to meet peaks in demand. To determine this additional demand, it would be necessary to model the time-dependent variation of supply and demand in Canada. This has been done in other studies.

Here, we estimate a set of WWS resources that will meet annual-average WWS demand. We approximate the nameplate capacities of five main WWS electrical power generation technologies (onshore wind, offshore wind, rooftop, utility PV, and hydroelectricity) in 2022, along with each of their respective capacity factors. A capacity factor is the fraction of maximum possible energy output that is realized during a year. By multiplying those two parameters and summing the result over all WWS resources, the annual average power output produced by all the current WWS equipment in 2022 can be calculated.

C. *The Supplemental Energy Calculation*

In order to estimate a mix of WWS resources to meet demand in 2021, we assume each resource meets an estimated percentage of demand, where the percentages, summed over all WWS resources, is 100%. No new hydroelectricity is assumed to be developed because the establishment of hydroelectric power stations (run-of-river power plants, reservoir power plants and storage power plants) is controversial. Hydroelectric power stations usually require large reservoir. And building those reservoirs affects the surroundings and the natural environment at a given level, large or small. It can be dangerous to residents living around the reservoir since it’s easily flooded. And dams can have huge impacts on aquatic ecosystems, since they hinder fish migration to spawn. Plus, organisms can be drawn to and killed by the system. Hydroelectricity may threaten the safety of the indigenous people and does not conform to the indigenous people’s value.

Current WWS equipment already uses land and has a specified nameplate capacity associated with it. Upon eliminating BAU energy, more WWS equipment is needed, and more nameplate capacity is needed. Based on the percentage of each type of WWS energy system (onshore wind, offshore wind, rooftop PV, Utility PV, hydroelectric) specified and the total annual average power still needed, the target power output of each type systems can be calculated.

D. Number of Devices

Then, the energy output per year of each separate systems' device is calculated based on the device's nameplate capacity and capacity factor. Next, dividing the target power output of each system by the power output of each device gives the number of devices still needed for each onshore and offshore wind, rooftop solar PV, and utility solar PV (Jacobson, 2009).

E. Land Use

The land occupation required by WWS energy depends on the installed power density. It represents the nameplate capacity of a technology that can be installed on one kilometer square. Thus, the total nameplate capacity of each different technology is needed. This is calculated in our system.

Among all 4 types of considered WWS energy systems, onshore wind turbine and utility PV need new land for because of they need suitable land for their operation. Offshore wind turbine is in the ocean and rooftop PV does not require new land. Private installment is required for rooftop PV. Specifically, much of them would be installed to power up private residence independently.

F. Cost

With the target power output of each system, the total energy production of the new WWS system can be calculated. Then, the total energy production is converted from TWh to kWh for the cost of energy production in c/kWh. The cost of energy production of each system is calculated upon its total energy production and its levelized cost of electricity.

Comparing the health cost by transferring to WWS energy and BAU energy, the condition is mainly considered due to environmental factors. According to a previous study, an estimated 3,800 people in Canada die each year due to air pollution. The value of statistic life per person is $10,000,000 (U.S. dollars). Accounting for morbidity and non-health environmental impacts increases this amount. Factor of accounting for morbidity would be influenced by the severity of the contamination in the patient's environment, the timeliness of patient visits and so on. In this regard, the renewable WWS energy can avoid this alleviate this situation and reduce the death and illness of people. Therefore, the health cost savings of Canada by transferring to WWS energy can be calculated.

Aside from those public costs savings, there are also climate cost savings. Climate cost savings in Canada mainly result from slowing down global warming. Reducing carbon emission from BAU energy reduces this cost. The entire WWS energy system can avoid 928 million tonnes of CO_2e emissions. Avoiding one tonne of CO_2e saves $500 in climate costs. Multiplying the two gives billions of dollars per year in climate cost savings.

In the end, to further compare the energy and social cost of BAU energy and WWS energy, the cost of BAU energy production is calculated. The total BAU energy consumption is converted from Terajoule to Terawatt per hour for calculation, and the average cents per kilowatt hour of coal, gas and nuclear are also being used in the calculation.

The combination of energy cost and social cost of WWS energy is directly applied to the calculation and compared with social cost of BAU energy since further demarcation between different social cost and energy cost is needed for more direct data.

III. Results

Converting the rest BAU energy to all WWS energy would lead a 50.99% reduction in total energy consumption (Table 3), with different reduction rates in each end-use sector, since each of them has varied amount of use of different types of BAU energy. Table 3 indicates energy reduction in different end-use sectors. The transport sector is resulting in the most significant reduction of 72.55%.

A. Annual Average Energy Demand in Canada after WWS-transition

The annual average energy demand in Canada after electrification based on main sector of 2021 IEA data is 104.34899 GW. These are all the energy used in the land of Canada, not including any of the exported or traded energy.

B. Current WWS Energy Supply vs. Total Energy Demand

According to current nameplate capacity and capacity factor of renewable energy equipment, the annual average power output in 2022 is 50.75064 GW, which can support 48.64% of current energy demand. And there are 53.59835 GW WWS energy in Canada still needed to supply to meet the total end-use demand.

C. Number of Devices Result

Assuming there is no prominent technology advancement, there would be more device to meet the total energy demand of Canada. There would need 825 utility PV, 2,820,966 rooftop PV, 4,735 offshore wind turbine, and 10,872 onshore wind turbines to complete the task. These are not fixed numbers, because the fraction of each type of WWS energy is interchangeable. But the total amount of energy output from all devices is fixed.

D. Land Use Result

In Canada's land, 6,685 km of new land including land and rooftop would need to realize the full transition, and 3,249 km of new land for new devices is needed. Only 0.03% land resource of Canada land is occupied by WWS. The land occupied would mostly concentrate in certain province with high demand for energy and abundant natural conditions. 98% of Canadian land mass is rural and spatial, which are suited for WWS power plant development.

E. Cost Result

Overall, the full application of WWS energy reduces both social cost and energy cost of Canada. Especially the social cost. Comparing to annual operation cost of BAU energy, which is 112 billion per year, WWS reduced 76.61% of the energy cost, resulting in 26.18 billion dollars per year. And regarding the annual BAU energy social cost, 624 billion, it can even almost eliminate all the social cost of BAU energy, resulting in an 95.81% reduction.

F. Energy Cost

The energy cost and social cost of WWS energy is $26.18 billion, which would result in both the lower energy generation costs and lower LCOE (levelized cost of energy) of daily electricity. The energy cost of onshore wind is $9.39 billion, offshore wind is $8.22 billion, rooftop PV is $6.1 billion, utility PV is $2.46 billion. This mainly includes the power plants and equipment maintenance fee, and the cost of labor. Even so, it is still much lower than BAU energy, which is on shortening and would require more hand labor.

G. Social Cost and Health Cost

$48.07 billion dollars per year health cost can be saved. In all aspects of Canadian's health cost spending, the healthcare spendings reduce the most since there would have a general decrease in the number of medical visits due to less polluted food and better-quality air by applying renewable energy. People's risk of respiratory disease is greatly reduced due to the transition. People also have little chance to be exposed to the polluted environment before. Reduces the risk of poisoning and other health hazards. This not only greatly reduces the pressure on government health care, but also enables people to live a healthier life.

The social cost mainly includes the loss on agriculture harvest, natural disaster cost, and other cost on public affairs which have to be controlled and pay-off by Canadian governments. The social cost of BAU energy is calculated based how many costs are there with every 1-ton carbon emission, which would start to make some degree of influence in the society.

H. Climate Cost

Nowadays, Canadian government is focus and spend most of the climate cost on improve homes and buildings efficiency and accelerating zero-carbon mobility to build the sustainable future society, and both initiates are targeting slowing down global warming. Other climate costs are flood damage, permafrost thaw damage, crop destruction and so on. Immediate action is needed, and the full transition to WWS energy can strongly support and accelerate the Canada's response to global warming. 464 billion per year climate cost can be saved due to full WWS energy operation, since WWS energy don't create carbon dioxide and extra pollution to manage.

IV. Discussion

Realizing the full transition from BAU energy to WWS energy requires radical and comprehensive change in energy deployment and would demand the series of cooperation and effort of Canada government, Canada citizens and corporations. The transition is demanding on future Canadian policies and policies on every province and territories. And the shift of energy application would not only rely on following global strategies like cap and trade, but also a thorough system that promote renewable energy usage from all aspects (Richardson and Harvey, 2015). This can include the shift of electricity-generating methods and a fully shift to WWS equipment. Economically developed province like Ontario have already develop plans for reducing carbon emission 80% below 1990 by 2050, and the government has committed to push those climate policies and legislation to achieve a new high-productivity economy and society with low carbon while maintaining the stability of current market. Nevertheless, on this issue, Canada government has to unify provinces and territories to implement coordination. Otherwise, differences in environmental targets between provinces and territories may not be conducive to achieving the overall goal, or it could split into different economies that relying on a range of energies.

Other than changes to power supply at the provincial level, the transition of personal equipment also requires strong policy stimulus, which involves changing people's mindset and appropriate inflation (Adebayo, 2022). The general shift of WWS equipment includes the change to electric or hydrogen fuel cell automobile, the alter from stove to induction cooktops or furnaces, and the way of heating to heat pumps or electric-heating furnaces. And people might also need to install solar Photovoltaics (PV) on rooftops instead of fully relying on centralized power supply. All of that would refit many people's current lifestyle and may lead to unwillingness and incomprehension. In addition, maintaining the current economy stability is important since this shift may requires certain stimulate from inflation to spur people to action.

Since Canadian government is already attaching much importance to climate change issue and enhancing its Paris Agreement target by developing 2030 Emission Reduction Plan, there are some other possible policies to promote the full transition to reach net-zero greenhouse gas emission in 2050. The carbon pricing is increasing by years and aiming to put the money back to the citizen's pockets. However, the separation of different types and disparate extent of application of provinces and territories (Barrington-Leigh & Ouliaris, 2017), ranging from federal application in part, federal application in full and provincial/territories system applies, the reduction would not be that enhanced. Ontario and Alberta are both apply part of the federal backstop. Ontario's end-use energy is concentred at fossil fuels and natural gas, but its electricity is mainly generated by solar and hydropower. In comparison, Alberta's end-use energy is mostly made up by natural gas and refined petroleum products, plus 89% of their electricity are produced by fossil fuels. This application demonstrates the importance of solid consideration of different situation of the provinces: Ontario's usage of fossil fuels is due to the vibrant economy while Alberta contains oil companies themselves which needed to be further regulated. It's hard to maximize the effect if they apply the same carbon pricing strategy, since the loopholes are often easily found in the non-customized policies. A few minor omissions may well result in missing the target by 2050. In addition, the current stage goal is not clear enough. Even though the governments want to guarantee the clean energy future, there are many uncontrollable influencing factors in each end-use sector. Take transportation as an example. Can the EV market diversify enough to replace the gasoline-powered car market? Whether new energy storage technologies emerge during the period? None of this can be predicted with precision. Therefore, concentrating and focusing on each sector of end-use is necessary. Otherwise, it would be too scattered and failing the big goal in the end. More smaller goals targeting each section need to be set and more detailed roadmaps need to be planned. In this way, we can better focus on improving the needs of a certain aspect. For example, setting a goal of transitioning 20% of remaining BAU vehicles to EV within 1- years would be very helpful. This will allow people to see short-term results and improve confidence, but also ensure that the big goals are completed on time with all targets meet.

The result of the paper might contain multiple sources of uncertainties. To begin with, factors to multiply BAU end-use energy by to obtain WWS Energy needed might varied under a range of specific conditions. There are too many and varied of application scenarios of BAU energy and would come to different efficiency of every single one. The factors are the overall data on the rate of conversion. However, the variations between different scenarios might lead to distinct demand of WWS electricity. Moreover, the paper is not identifying much adverse side of WWS energy since it is aiming to positive direction of energy development and hope of reducing greenhouse gas emission and methane pollution. On top of that, the source data of the paper is from 2021 since IEA's official 2023 energy data and 2022 energy data of Canada is incomplete currently. As expected, the 2023 data might be varied from 2021 data a lot which might lead different calculation results. And those data will keep varying in the future. Furthermore, the fraction of each power system that sums up the total fraction of WWS of 1 may be reapportioned according to the actual situation. The paper has also not considered any technology iteration which might increase the efficiency of energy and nameplate capacity of devices in the future. In addition, the current model doesn't take any assumption on future demand of energy. According to Canada Energy Regulator, the total energy use would decrease while the demand would increase. Especially, the electricity demand would increase 47% from 2021 to 2050, which means there might be more land and other resources needed. On top of that, the fluctuation of cost might lead to the change of the cost result in the future. There are many factors of influence: BAU energy depletion, technology advancement, policies effect, etc.

V. Conclusion

This study concludes that Canada has the ability to transfer fully to WWS energy and would benefit substantially from such a conversion. The results here can give the government and the public great confidence in promoting the transition and keeping it on the right track. Government policies are needed stimulate the transition and encourage people to take action to transition to a WWS energy-based lifestyle. If successfully implemented, not only will the transition reduce annual energy costs by 76.61% versus BAU, but it will also reduce social cost by 95.81%. As such, both citizens and the government would have less burden on the negative impact of climate change. There will be cleaner communities to live in and less illness caused by pollution across the country. Beyond that, this is also one of the best methods to cope with the energy crisis – by not capturing carbon but solving the emission problem from the root. Therefore, the transition to WWS energy will also highly improve the economy. At stake is Canada's transition to a sustainable energy future. There are certain regulation-related difficulties, but they are surely surmountable by putting the right effort. In a nutshell, the transition to WWS energy deserves more of the Canadian government's attention and a consummate plan to put into effect.

Conflict of Interest

The author declares no conflict of interest.

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