



Carbon emissions pinch analysis (CEPA) for emissions reduction and energy planning in Canada

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Abstract

Canada has made a commitment in the Paris Agreement to reduce its total greenhouse gas emissions by 40–45% from 2005 levels by year 2030 and achieving net-zero emissions by year 2050. An enhanced target has been established for the electricity sector, aiming to achieve a reduction of 88% from 2005 levels by 2030. Achieving these ambitious targets requires the implementation of new CO₂ reduction measures and policies. In this work, *carbon emissions pinch analysis* (CEPA) is used for planning energy resources in the electricity sector while aiming to achieve both country and regional targets. Different scenarios are proposed for years 2030 and 2050 based on current policies and extension of some realistic assumptions, including the use of carbon capture and storage (CCS) facilities, negative emissions technologies (NETs), and increased capacity for renewable energy sources. In year 2030, the proposed solution indicates that the reduction of CO₂ emissions of 3.1 Mt CO₂-eq. is achievable, which is lower than the country target of 14 Mt CO₂-eq. This solution can serve as the benchmark for each stakeholders at provincial level to reach their regional target. Results also show that electricity and CO₂ trading are required to meet the energy requirement and to achieve the year 2030 CO₂ emissions reduction goal at the provincial level which is the novelty of this paper. Although none of the cases has met net-zero emissions in year 2050, they do demonstrate that net zero is not far from materialisation.

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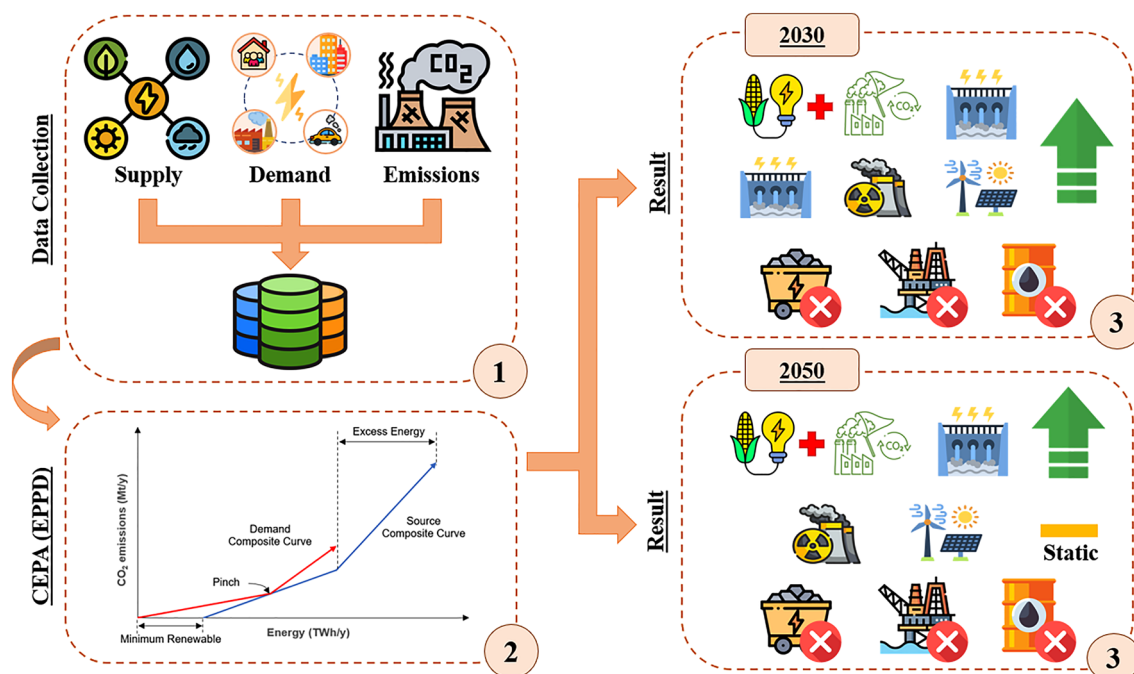
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Graphical abstract



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Introduction

Canada has a diverse energy profile due to its resource-rich nature. In years 2018–2020, most electricity in Canada was generated by renewable energy sources, mainly by hydropower (approximately 60%), despite the country having abundance of oil and natural gas resources with about 27–30 MMB/d of crude oil production and 15–17 Bcf/d of natural gas production between 2018 and 2020. (National Resources Canada 2021). Coal with the highest CO₂ emission factor only accounts for about 7% of Canada's total energy mix for electricity generation, which is mainly used in two provinces, i.e. Alberta and Saskatchewan. Meanwhile, oil and natural gas made up nearly 11% of Canada's total energy mix in electricity generation. This shows the effort of Canada for having a sustainable energy mix as means of environmental protection. While Canada has a relatively cleaner energy mix in electricity generation, the consumption of fossil fuel types in the electricity sector in Canada has to be restructured to meet the enhanced Paris agreement greenhouse gas (GHG) reduction target committed by Canada in 2021, i.e. 88% GHG emissions reduction from the 2005 level by year 2030, which corresponds to 103.3 Mt CO₂-eq. (Environment and Climate Change Canada 2023). Canada also pledges in achieving net-zero emissions by year 2050, in order to mitigate climate

change (Environment and Climate Change Canada 2023). To achieve the ambitious target of 88% emissions reductions by 2030, more careful and meticulous plannings are required in the electricity sector to bring the country closer to its 2030's and 2050's carbon reduction targets.

A well-established energy planning tool, i.e. *carbon emissions pinch analysis* (CEPA), has been adopted in this work to validate the carbon reduction targets of Canada. In the seminal work of Tan & Foo (2007), a graphical CEPA tool known as *energy planning pinch diagram* (EPPD, Fig. 1) was introduced for the optimum allocation of energy sources to the demand, by taking CO₂ emissions limit as the main constraint. To overcome the inaccuracy problem of EPPD, Foo et al. (2008) developed an algebraic technique as an alternative to supplement the graphical tool. In a later work, Lee et al. (2009) presented a mathematical programming model based on the algebraic method, which allows the incorporation of different objective functions during energy sector planning. In this current work, the EPPD is used instead of a mathematical programming model, as its graphical interface is useful for efficient visualisation by planners and effective communication with decision makers and other stakeholders.

Since its development, CEPA has become established as a conceptual tool in carbon management research. It uses carbon and energy balances simultaneously to determine

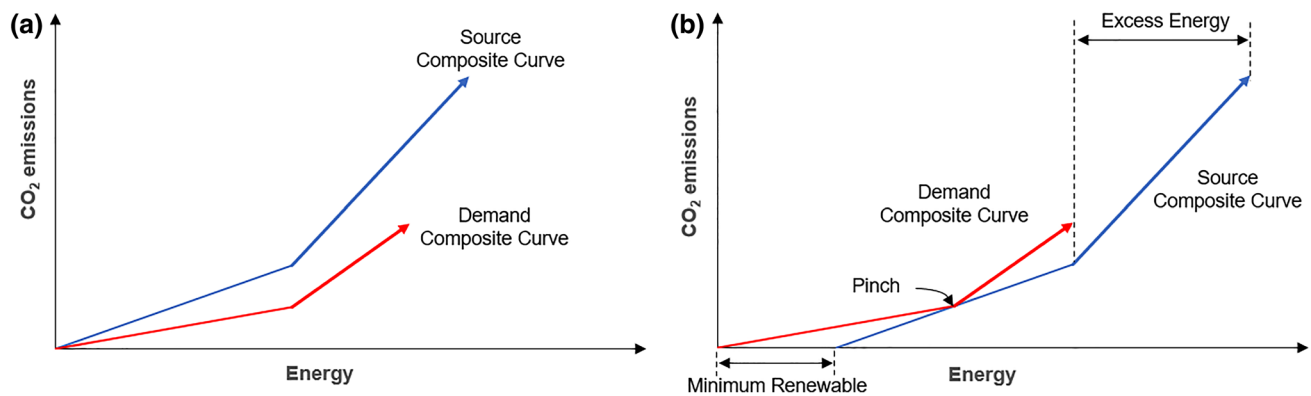


Fig. 1 Energy planning pinch diagram **a** infeasible EPPD, **b** feasible EPPD (Foo and Tan 2020)

feasible physical targets as well as the corresponding matching of sources and demands. Cost considerations are not inherently part of the CEPA methodology, but economic aspects can be used to evaluate decarbonisation options once physical optimality has been established. Some recent developments may be found in the review (Foo and Tan 2016), book chapters (Tan and Foo 2017, 2023), and textbook (Foo and Tan 2020). The technique has shown its applications in many countries, as shown in Table 1. Apart from CO₂ footprint, the methodology has been extended to incorporate various sustainability metrics, such as agricultural land footprint (Foo et al. 2008), water footprint (Tan et al. 2009), energy transformity (Bandyopadhyay et al. 2010), inoperability risk (Tan and Foo 2023), and energy return on investment (Walmsley et al. 2014). CEPA was extended to multi-dimensional analysis by considering several metrics simultaneously (Jia et al. 2016). Furthermore, recent developments seen the combined use of CEPA with other techniques to form hybrid methodologies. For instance, CEPA is combined with input–output analysis to account for economic consideration (Tan et al. 2018; Ramanath et al. 2023). Integration of CEPA with P-graph has also been reported

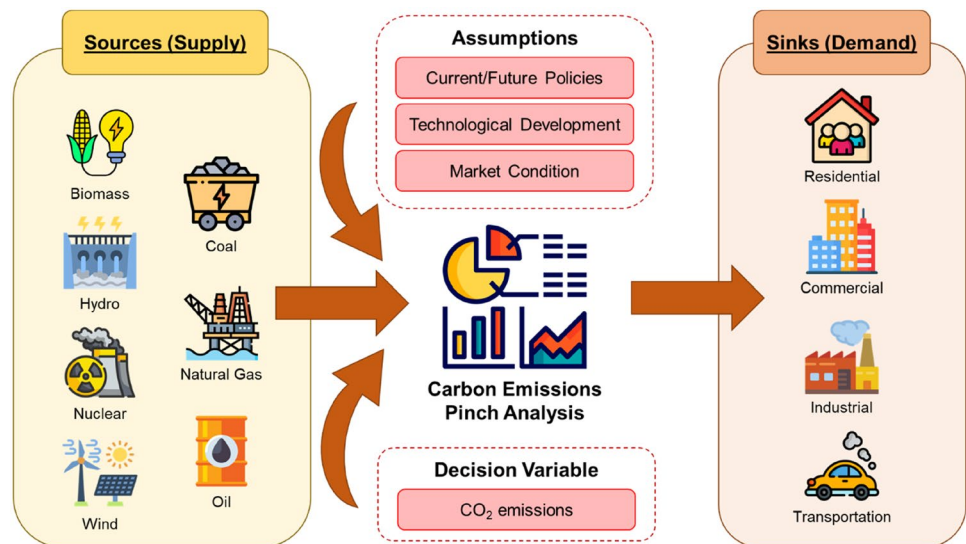
Table 1 Application of CEPA for emissions reduction and energy planning at different countries/regions

Country/Region	References
China	Li et al. (2016)
United Arab Emirates	Lim et al. (2018)
Estonia, Latvia, and Lithuania	Baležentis et al. (2019)
Nigeria	Salman et al. (2019)
European Union	Su et al. (2020)
Philippines	Tan et al. (2009)
Malaysia	Leong et al. (2019), Saleem et al. (2021)
UK	Cossutta et al. (2021)
Trinidad and Tobago	Ramsook et al. (2022)

for addressing raw material management issues (Mu et al. 2020). A recent work also showcases a thorough optimisation of waste treatment systems utilising the CEPA methodology, taking into account greenhouse gases reduction goals in accordance with national and local policies (Chew et al. 2022). In the work of Li et al. (2022), life-cycle assessment is used with CEPA to determine the optimal allocation of CO₂ while maximising the profitable external benefits. CEPA also applied in food sector to determine the optimal diet configurations in achieving the target greenhouse gas reduction without compromising on nutritional requirements (Zhang et al. 2022). These studies demonstrate the versatility and potential of CEPA in various applications, providing valuable insights for sustainable planning and decision-making.

To meet the committed reduction target, Canada issued Pan-Canadian Framework on Clean Growth in 2016 (Environment and Climate Change Canada 2016), and an additional strengthened climate plan in 2020 (Environment and Climate Change Canada 2020). In 2022, Canada further issued a report “2030 Emissions Reduction Plan: Clean Air, Strong Economy” to provide a general roadmap on how the enhanced Paris Agreement target can be achieved by 2030. The strategies for the electricity sector include phasing out coal, expanding the non-carbon emitting sources, investing in new clean technologies, connecting more regions with clean power, and introducing carbon pollution pricing (Environment and Climate Change Canada 2022). Based on this newly issued report, the electricity sector is expected to contribute to a maximum emission of 14 Mt CO₂-eq. The effectiveness of the existing actions, new measures, and future plans outlined in these reports need to be validated to ensure their successful reduction of CO₂ emissions, and more alternative pathways and scenarios should be provided to complement the plans outlined in the Canada-issued environmental reports mentioned above.

Fig. 2 General framework of energy system in Canada



Systematic decision support techniques can be used to facilitate decarbonisation plans. CEPA is a useful tool to study the performance of new measures and policies set by the Canadian government. It provides key insights on system bottlenecks that may hinder decarbonisation efforts. Moreover, CEPA can identify effective decarbonisation options for the Canadian power generation sector. However, the scope of the analysis is limited to energy and carbon balances, since these physical factors are more fundamental and immutable. Economic analysis is not included in the scope of this work, although in principle cost evaluation can be considered using other CEPA tools (e.g. see Ramanath et al. 2023).

This paper is structured as follows. In the following section, problem statement is first outlined. Next, the principle of CEPA and its graphical tool EPPD are introduced briefly. This is followed by discussion on various planning scenarios for the Canada's electricity generation sector.

Problem statement

Energy planning is the key to achieve Canada's GHG emissions reduction target in its Paris Agreement pledge. It is crucial to analyse the new measures as mentioned in the Canadian's biennial report, in order to know its emissions reduction performance (Canada Energy Regulator 2020). Therefore, the problems associated with the present study are stated as follows:

- To analyse energy planning and projected CO₂ emissions of the electricity sector in Canada for years 2030 and 2050 using CEPA. The analysis is performed based on the total energy demand in Canada, which is at the same time restricted by the maximum allowable CO₂ emissions target of the country. The ratio of the emissions target to

the total power consumption is the CO₂ emission factor of the country.

- To provide sensible scenarios for future energy planning of Canada based on its natural resources. Each of the energy resource is to be assigned to the required demand. Those sources have a certain amount of accessible energy and are characterised by a fixed CO₂ emission factor. The product of the available energy and CO₂ emission factor yields the total emissions of each energy source.

The goal of the present study is to determine the optimum mix of energy resources to meet the demand of Canadian electricity sector, while meeting its CO₂ reduction targets in years 2030 and 2050. A general framework is presented in Fig. 2 to provide an overview of the energy system studied in this work.

Methodology

One of the useful CEPA tools for the optimum planning of energy resources is the EPPD (Fig. 1). Steps for plotting the EPPD are given as follows (Foo and Tan 2020):

- Energy demands and sources are arranged ascendingly according to their CO₂ emission factor.
- *The demand composite curve* is plotted with CO₂ emissions vs energy with ascending arrangement of CO₂ emission factors. Doing this makes the latter to be represented by the gradient of each segment.
- Similarly, the *source composite curve* is plotted with CO₂ emissions vs energy with ascending arrangement of CO₂ emission factors.

- The demand and source composite curves are superimposed to form the EPPD, as shown in Fig. 1.
- The EPPD is infeasible if the source composite curve stays above and/or to the left of the demand composite curve (Fig. 1a). To restore a feasible EPPD, the source composite curve has to be shifted to the right, until it stays entirely below and to the right of the demand composite curve (Fig. 1b). CO₂-neutral, low, or negative CO₂ resources may be used as part of the energy planning to replace high CO₂ emissions resources, represented by the opening on the left of the EPPD (see Fig. 1b).

The overall CEPA methodology in this study is summarised in Fig. 3. The primary source of data for establishment of EPPD is obtained from report published by the Canada Energy Regulator (2020). The supply-side data comprise a range of electricity generation sources, including hydropower, wind, nuclear, and fossil fuels. Meanwhile, the demand-side data consist of the provincial electricity consumption in Canada. Note, however, that the emission factors of fuel are based on the work of Cossutta et al. (2021).

Following the data collection process, the EPPD is plotted. The individual segments of the demand and source composite curves depict the corresponding provincial emissions and electricity generation sources, respectively. The surplus energy produced can be determined from the EPPD. A new scenario will be produced if its CO₂ emissions exceed the

national target, while that who meets the target will progress to the next stage. The chosen scenario will then be applied to each province, in order to assess if the provincial target can be achieved. If a province fails to meet its target, electricity trading will be established so that its CO₂ emissions target can be met.

CEPA for Canada

Estimation of provincial emissions reduction target

The study is carried out at the provincial level where each provincial reduction target for electricity sector is distributed from the federal reduction target which has been committed through the Paris agreement. These regional targets will require support and engagement from all parts of society including provinces, territories, and the federal government in working towards meeting the targeted goal. One of the supports and engagements provided by the federal government to achieve the regional target is the Regional Strategic Initiatives (Environment and Climate Change Canada 2020). Under this initiative, business leaders will interact with different stakeholders from key sectors of the economy in giving experienced viewpoints for each province. Moreover, many actions or policies set by Canada federal government to reduce CO₂ emissions can serve as benchmark for those provinces. These policies will aid the provinces for initiating comprehensive action plans to reduce their contribution to CO₂ emissions. For instance, the policies include renewable energy standards and carbon pricing. By taking advantage of these policies and initiatives, provinces can work together with the federal government to achieve their regional targets and contribute to Canada's overall goal of combating climate change.

In this work, it is proposed that each provincial emissions target is set according to their historical CO₂ emissions in year 2020, calculated using Eq. (1). This approach is meant to ensure that every province will reduce their CO₂ emissions progressively. The CO₂ emissions target at the provincial level is summarised in Table 2. According to the Canadian Framework for carbon reduction, the electricity sector is targeted to contribute for a reduction of 76.6 Mt CO₂-eq. in 2030 and 90.6 Mt CO₂-eq. in 2050, both calculated based on year 2020 (Environment and Climate Change Canada 2021). Based on these reductions, the CO₂ emissions targets for electricity in 2030 and 2050 are 14 Mt CO₂-eq. and 0 Mt CO₂-eq., respectively (see data in last column of Table 2). The electricity demand for each province is obtained directly from Canada's Energy Future report, which was projected based on historical parameters such as supply, demand, economic growth,

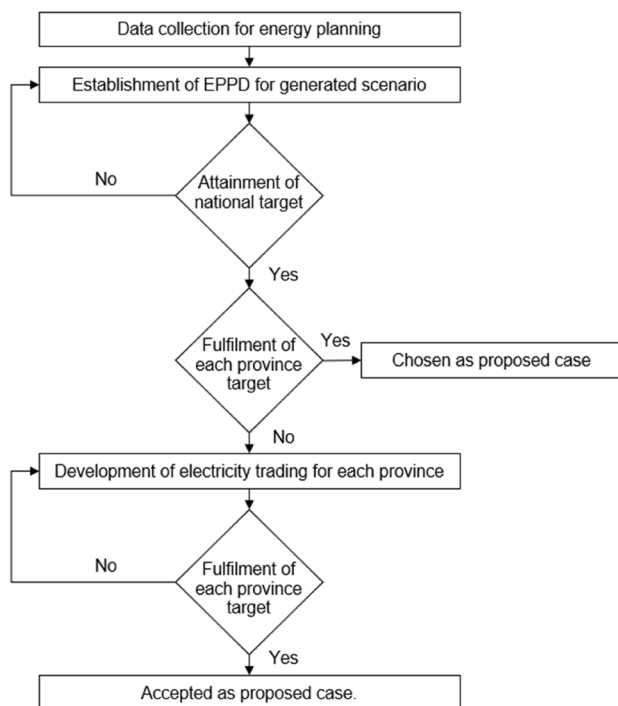


Fig. 3 Overall procedure for energy planning using CEPA

Table 2 Provincial emissions targets for the electricity sector (Canada Energy Regulator 2020)

Province		BC	AB	SK	MB	ON	QC	AC	TR	Total
Historical data in 2020	Emissions (Mt CO ₂ -eq.)	3.1	50.7	11.3	0.8	9.4	6.7	8.0	0.7	90.6
2030	Emissions target (Mt CO ₂ -eq.)	0.4	7.4	1.6	0.1	1.4	1.0	1.2	0.1	14.0
	Demand (TWh)	80.7	89.9	24.4	22.1	146.4	193.9	36.5	1.1	595.0
2050	Emissions target (Mt CO ₂ -eq.)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Demand (TWh)	108.8	103.7	29.4	27.5	191.4	230.7	40.9	1.0	733.5

BC British Columbia, AB Alberta, SK Saskatchewan, MB Manitoba, ON Ontario, QC Quebec, AC Atlantic Canada (New Brunswick, Newfoundland, Nova Scotia, and Prince Edward Island), TR Territories (Northwest Territories, Yukon, and Nunavut)

efficiency, prices, and investment (Canada Energy Regulator 2020).

$$TE_p = TE_n \times \frac{CE_p}{CE_n} \tag{1}$$

where TE_p and TE_n are targeted emissions at provincial and country levels, respectively (Mt CO₂-eq.); CE_p and CE_n are historical CO₂ emissions at provincial and country level, respectively (Mt CO₂-eq.)

Case study: CEPA of the Canada electricity sector in 2030 and 2050

Canada Energy Regulator has proposed a baseline benchmark for country’s CO₂ emissions in the electricity sector as part of Energy Future Policy 2020 (Canada Energy Regulator 2020). Energy supply and demand projections are given for two scenarios, i.e. *Evolving* and *Reference* that vary depending on how much future action is to be taken (Canada Energy Regulator 2020). Throughout the projection, the Evolving Scenario follows the historical trend of escalating action on climate change. Policies and agreements are enhanced after their timeline. Low-carbon technologies

such as solar and wind technologies, battery storage, and CCS are developed progressively. On the other hand, climate change actions are restricted to the current mechanisms and policies in the Reference Scenario. Technological advancement is confined to those with established momentum and/or market share (Canada Energy Regulator 2020). In this current work, the projection of energy supply and demand in Evolving Scenario is chosen for the planning of years 2030 (Scenario 1) and 2050 (Scenario 2). Evolving Scenario is chosen because it provides a comprehensive exploration of the current energy transition towards less carbon-intensive energy sources and technologies. Moreover, it incorporates historical data and a set of hypothetical future domestic climate actions, which is suitable for a 30 years planning scenario (towards year 2050). Therefore, it is more ambitious than the Reference Scenario. The projection for these energy sources is summarised in Table 3.

The emission factors in Table 3 are obtained from the work of Cossutta et al. (2021). It is important to note that the value includes indirect emissions such as losses during transmission and distribution, as well as well-to-tank transportation. These emission factors may differ in other’s work or any government report, but the trends should be proportionally the same.

Table 3 Summary of data for energy generation in 2020, 2030, and 2050 (Canada Energy Regulator 2020)

Source	Emission factor (Mt CO ₂ -eq./TWh) ^a	2020		2030		2050	
		Electricity	CO ₂ emissions	Electricity	CO ₂ emissions	Electricity	CO ₂ emissions
Hydropower	0.026	385.5	9.9	434.0	11.2	457.7	11.8
Wind	0.043	37.8	1.6	73.0	3.1	194.8	8.4
Nuclear	0.072	89.3	6.4	78.7	5.6	96.1	6.9
Biomass	0.168	8.8	1.5	9.7	1.6	9.7	1.6
Natural Gas	0.412	63.4	26.1	91.3	37.6	65.9	27.1
Coal	1.117	38.1	42.5	3.2	3.5	0.8	0.8
Oil	1.341	1.9	2.6	1.6	2.1	1.4	1.8
Total		624.7	90.6	691.5	64.8	826.3	58.5

Electricity generation in TWh; CO₂ emissions in Mt CO₂-eq., given as the product of emission factor with electricity generation

^aCossutta et al. (2021)

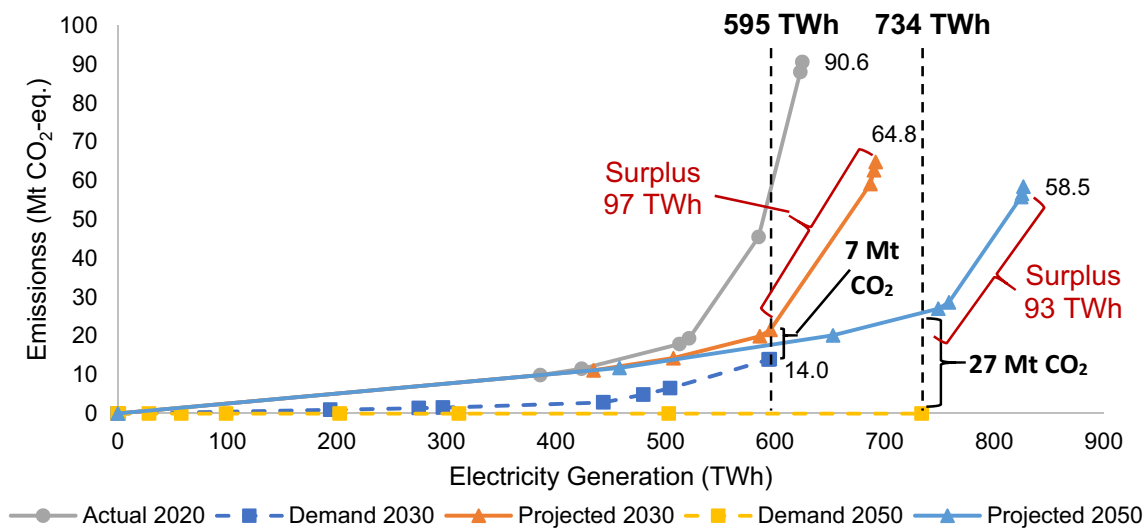


Fig. 4 Projected power generation and CO₂ emissions for Canada electricity generation in years 2020, 2030, and 2050

According to Table 3, the energy mix in year 2020 consisted of 83% renewable energy and 17% of fossil fuels. The reliance on renewable energy is expected to increase up to 86% in 2030 and 92% in 2050 (Canada Energy Regulator 2020). For year 2020, hydropower (74%) is the most abundant source among all renewable and clean energy sources in Canada (a total of 521.4 TWh) followed by nuclear (17%), wind (7%), and biomass (2%). In terms of fossil fuels, the usage of coal for electricity generation will be phased out significantly by 2030, as it has the highest emission factor. Since the utilisation of renewable energy carries the risk of lower accessibility and consistency, electricity generation will still depend on fossil fuels, particularly natural gas. Furthermore, it is deemed impractical to shut down existing fossil fuel-fired plants if they have not yet fully extended their predicted economic lifespan.

Figure 4 displays the source composite curves for years 2020, 2030 and 2050. All EPPD graphs in this paper share the same labelling convention: solid lines denote the demand side, while dotted lines represent the supply side. It should be noted that two supply graphs are featured in the study, one representing actual supply sources, and the other representing projected electricity source. It is shown that the total emissions for these years are determined as 90.6, 64.8, and 58.5 Mt CO₂-eq. Generally, each province in Canada strives to maximise the value of its generation capacity by trading the excess electricity with the USA. To improve revenue, Canada will boost its electricity generation during the daytime when electricity cost in the USA is higher than in Canada. On the other hand, Canada will reduce its electricity generation at night when electricity cost of the USA is lower than Canada. The electricity demand gap will be covered by importing a lower cost of electricity from the USA (Motalebi

et al. 2022). The exact demand for the year 2030 and 2050 is 595 TWh and 734 TWh, respectively, as shown in Fig. 4. The latter also shows the surplus electricity of 97 TWh and 93 TWh to be generated for years 2030 and 2050, respectively. These surpluses are primarily used for electricity trading with the USA to improve revenue. If we were to ignore the surplus electricity that is used for power trading with the USA (i.e. only account for power demand within Canada), the net CO₂ emissions are determined as 7 Mt CO₂-eq. and 27 Mt CO₂-eq. for years 2030 and 2050, respectively (see Fig. 4). In other words, the actual CO₂ emissions will exceed the limit set for years 2030 and 2050. Hence, more efforts are needed to reduce CO₂ emissions. In the following subsections, four cases are proposed for the respective scenarios for years 2030 and 2050.

Scenario for year 2030

Four cases proposed for year 2030 are summarised as follows:

- *CSI-S1-BM*: Coal and oil generation are removed completely, whereas natural gas generation is reduced; the generation gap is covered using maximum capacity of biomass in Canada.
- *CSI-S2-RE*: Each renewable energy except biomass is increased by 10%; the remaining generation gap is covered with natural gas.
- *CSI-S3-HCCS*: No fossil fuel generation; it is assumed that 50% of biomass plants are installed with CCS (BECCS), making them as negative emissions technologies (NETs); generation gap is covered using a mix of

nuclear (25%) and renewable energy (10% wind and 11% hydropower).

- *CS1-S4-RE-FCCS*: Same generation mix as CS1-S3-HCCS, with the exception of 100% biomass plants equipped with CCS.

For case CS1-S1-BM, biomass residues such as corn grain, wheat, and straw that are readily available in Canada are used for power generation. Note that the CO₂ emissions from biomass power plants are negligible since they are absorbed during the growth of biomass. Furthermore, it is assumed that all biomass residues come from agricultural waste, so only GHG emissions are produced during transportation. Table 3 presents data on the present capacity of biomass for electricity generation, which is currently 8.8 TWh. Notably, this quantity is below the maximum capacity of biomass for electricity generation that is reported in the study by Liu et al. (2014). This observation highlights the untapped potential for utilising biomass as a viable source of electricity, which should be explored and employed to promote sustainable energy production. Therefore, this scenario is designed to investigate the impact of increased biomass quantity on CO₂ emissions. Based on Fig. 5, there are no visible changes in CO₂ emissions for the projected demand of 595 TWh. Nevertheless, for the total supply of 692 TWh, case CS1-S1-BM shows a reduced emissions of 9.3 Mt CO₂-eq. (= 64.8–55.5 Mt CO₂-eq.). This is due to GHG emissions for biomass being relatively lower than natural gas. In this case, there is a surplus of 7.5 Mt CO₂-eq. emissions between energy demand and supply. This implies that reducing fossil fuel generation and the maximum use of biomass is not sufficient in meeting the emissions target in 2030.

Case CS1-S2-RE has the aim to evaluate whether renewable energy and nuclear power can achieve the 2030 target, without increasing the usage of biomass. The latter has been reported to remain constant for several decades to come, as stated in Table 3. As such, this scenario is devised to assess the influence of increased renewable energy share on CO₂ emissions. In this case, renewable energy of hydropower and wind as well as nuclear power is increased by 10%. This amount is forecasted based on the available ongoing projects in Canada, along with predictions from other reports. For instance, Site C project in British Columbia (1100 MW), Muskrat Falls project in Newfoundland and Labrador (824 MW), as well as Keeyask project in Manitoba (695 MW) are the three recent large-scale hydropower projects that are anticipated to be operational by year 2024 (IHA 2020; IEA 2022a). The values assigned to each project are their installed capacity which represent the maximum power output that a hydropower plant can generate under optimal conditions. Under the net-zero emissions by 2050 Scenario, hydropower sustains an average yearly generation growth rate of approximately 3% during 2022–2030, enabling the provision of around 5700 TWh of electricity per annum (IEA 2022b). Besides, the Canadian federal government collaborates with the Federation of Canadian Municipalities in funding Hydro Ottawa project, to establish a net-zero community (Natural Resources Canada 2021). This initiative aims to reduce greenhouse gas emissions by utilising hydroelectricity from the Ottawa River. In addition, Canada Energy Regulator predicts that by year 2042, the wind capacity will be tripled due to favourable market conditions and a large supply of high-quality wind resources (IEA 2022a). In terms of nuclear energy, there have been plans to construct numerous nuclear reactors; nevertheless,

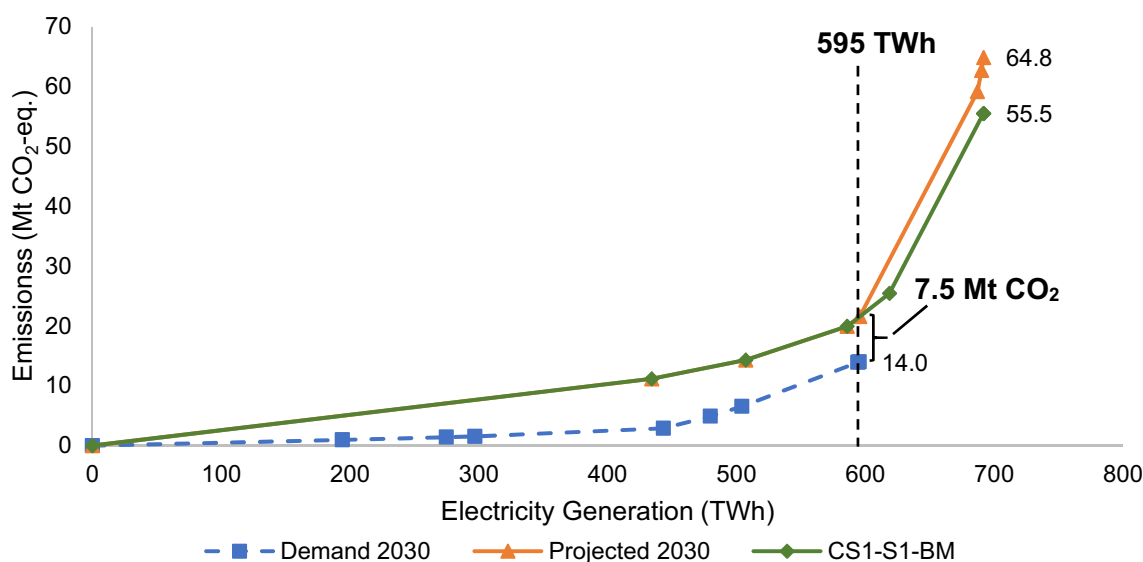


Fig. 5 EPPD of CS1-S1-BM for the year 2030

they have been delayed, lapsed, or abandoned in favour of massive renovation of existing capacity (IEA 2022a). This renovation will extend their operational lifetime and increase existing capacity for electricity generation. All these evidences suggested that there are still opportunity to expand the use of renewable energy by year 2030. Figure 6 shows that there are 3.1 Mt CO₂-eq. emissions difference between the projected scenario and CS1-S2-RE for the same demand of 595 TWh. Overall, there is a total reduction of 25.8 Mt CO₂-eq. between them. Despite this, a surplus of 4.4 Mt CO₂-eq. is identified. Hence, this case cannot accomplish the target even it does have a lower amount of CO₂ emissions as compared to earlier case, i.e. CS1-S1-BM (with total emissions of 55.5 Mt CO₂-eq.)

The configuration for cases CS1-S3-HCCS and CS1-S4-FCCS is similar, i.e. no usage of fossil fuels in electricity generation, with the generation gap filled by 25% of nuclear energy and a mix of renewable energies. The latter will consist of 10% for wind, while 11% for hydropower. The increment of nuclear energy in these two scenarios is higher than that in CS1-S2-RE case; this is due to massive refurbishment of nuclear power plants in Canada. For example, Darlington reactors are undergoing refurbishment for its units 1 and 3, while unit 2 has completed its refurbishment in year 2020 (CBC News 2016). Bruce Power will also refurbish its 8 reactor units following a similar plan (CBC News 2016). As of year 2022, Ontario Power Generation planned to shut down two Pickering A units by year 2024 but decided to keep four Pickering B units operating through to year 2026 (World Nuclear News 2022). Nevertheless, Ontario Power Generation reassess the feasibility of refurbishing the Pickering B units and adds another 30 years of operation

(World Nuclear News 2022). These refurbishment plans will improve their existing capacity as they will increase the efficiency of the reactors.

The capacity of biomass power plants with CCS is the main difference between CS1-S3-HCCS and CS1-S4-FCCS. As it is challenging to have all biomass power plants to be installed with CCS before year 2030, it has been assumed that only 50% of them will have CCS facilities installed in case CS1-S3-HCCS. On the other hand, case CS1-S4-FCCS served as a theoretical case where all biomass power plants are installed with CCS. Since power produced by burning biomass is thought to be carbon neutral, adding CCS to these biomass power plants would make them negative emissions technology (NET). Hence, it is presumed that their emission factors are -0.6 Mt CO₂-eq./TWh (Ooi et al. 2013). According to Fig. 7, both CS1-S3-HCCS and CS1-S4-FCCS have negative CO₂ emissions when compared with the projected demand at 595 TWh. The former has CO₂ emissions of -6.75 Mt CO₂-eq., while the latter removes -17.76 Mt CO₂-eq. from the atmosphere. In terms of exact demand requirements, CS1-S3-HCCS can satisfy the threshold of 14 Mt CO₂-eq.; the latter is indicated by the demand curve in Fig. 7. However, based on the projected supply in 2030, this case is estimated to produce around 15.7 Mt CO₂-eq. which is slightly above the emissions target. On the other hand, CS1-S4-FCCS can fulfil the CO₂ emissions target for the electricity sector.

Table 4 presents the overall energy mix for all cases in year 2030. As shown, the key aspect for all these cases is to increase the usage of clean energy sources and to reduce the dependence on fossil fuel sources. In fact, increasing the

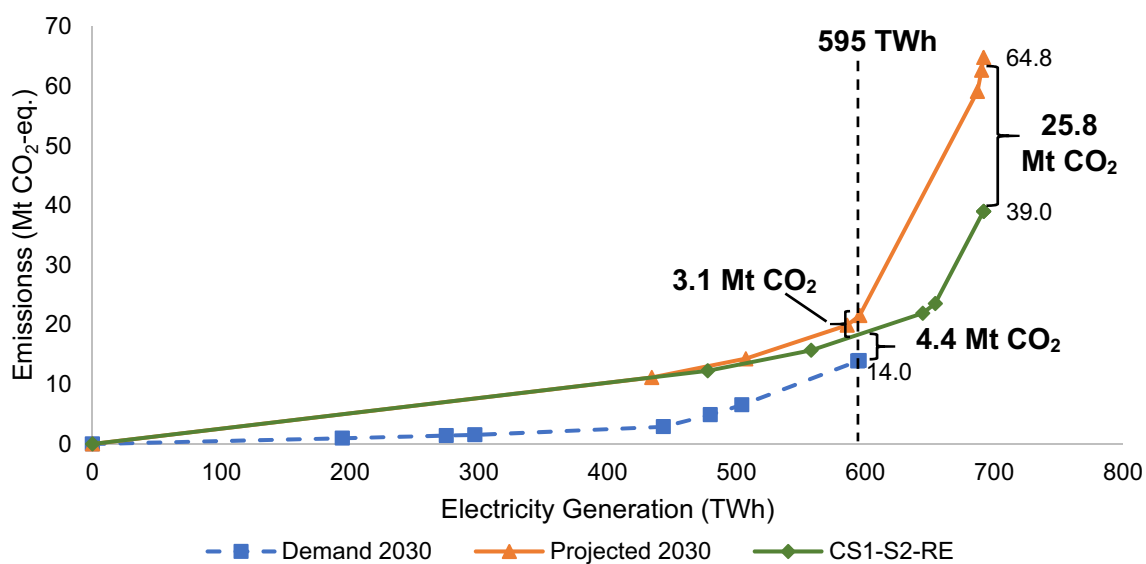


Fig. 6 EPPD of CS1-S2-RE for the year 2030

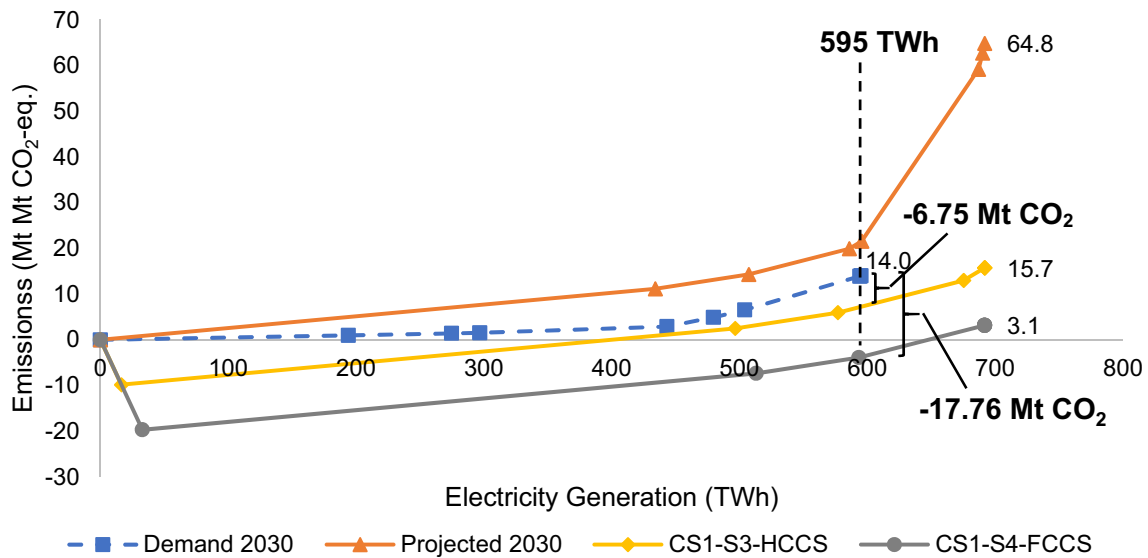


Fig. 7 EPPD of CS1-S3-HCCS and CS1-S4-FCCS for the year 2030

Table 4 Summary of all cases for the year 2030

Source	CS1-S1-BM		CS1-S2-RE		CS1-S3-HCCS		CS1-S4-FCCS	
	Electricity	CO ₂ emissions	Electricity	CO ₂ emissions	Electricity	CO ₂ emissions	Electricity	CO ₂ emissions
Hydropower	434.0	11.2	477.4	12.3	480.0	12.3	480.0	12.3
Wind	73.0	3.1	80.3	3.5	80.3	3.5	80.3	3.5
Nuclear	78.7	5.6	86.6	6.2	98.4	7.0	98.4	7.0
Biomass	32.8	5.5	9.7	1.6	16.4	2.8	0.0	0.0
Biomass + CCS	–	–	–	–	16.4	–9.8	32.8	–19.7
Natural Gas	73.0	30.1	37.5	15.4	0.0	0.0	0.0	0.0
Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oil	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	691.5	55.5	691.5	39.0	691.5	15.7	691.5	3.1

capacity of renewable energy will reduce CO₂ emissions. Nevertheless, this is insufficient to reduce CO₂ emissions to the target set for year 2030, as shown in the cases of CS1-S1-BM and CS1-S2-RE. At the exact projected demand for the year 2030, only CS1-S3-HCCS and CS1-S4-FCCS can fulfil the CO₂ emissions target. This indicates that increasing renewable energy without the implementation of CCS technology will not achieve the CO₂ emissions target. Therefore, the use of CCS technology should be further utilised for scenario planning of year 2050 which is consistent with the reported finding (SaskPower 2022).

Although CS1-S4-FCCS is a theoretical case, it is the only case that can fulfil the regional target emissions in year 2030. Hence, CS1-S4-FCCS is applied to each province to determine if they can meet their respective targets. In each province, capacity for renewable energy, i.e. hydropower and wind, is increased by 11 and 10%, respectively. Meanwhile, generation using nuclear energy is improved by 25%. All

biomass plant is assumed to be equipped with CCS, making them NETs. The selection of provinces to build these plants is determined by their CO₂ emissions and existing biomass power plant capacity. The priority is given to the province which require larger CO₂ emissions reduction targets, and those having greater biomass power plant capacity. From Table 2, it can be observed that AB, SK, ON, QC and AC need to undergo larger CO₂ emissions reduction among the provinces. As of year 2017, these provinces have biomass power plant capacity as follows: ON (694.6 MW), AB (356.8 MW), QC (347.3 MW), AC (257.4 MW), SK (1.6 MW) (Natural Resources Canada 2017). Therefore, AB, ON, and QC have been chosen to increase their biomass capacity power plants that are equipped with CCS technology, whereas the other provinces will retain their existing capacity. Figure 8 illustrates the CO₂ emissions before and after the proposed case CS1-S4-FCCS is adopted in each province. CO₂ surplus (with red colour font) represents

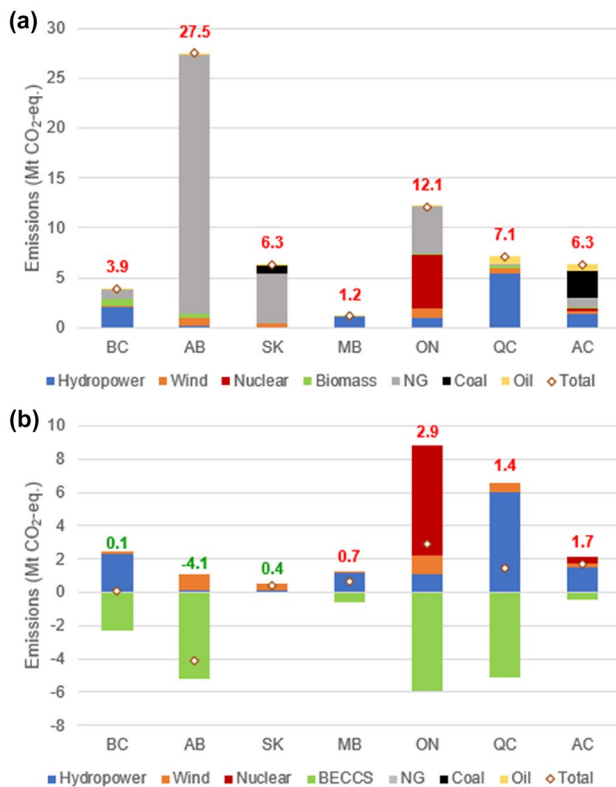


Fig. 8 Summary of CO₂ emissions for all provinces in year 2030 **a** projected scenario; **b** CS1-S4-FCCS (red colour font indicates exceeded province's target, and green font indicates provincial targets are met)

provinces that are emitting CO₂ more than their allowable target, whereas CO₂ deficit (with green colour font) represents those that are meeting their permitted emissions target. Note that Territories (Northwest Territories, Yukon, and Nunavut) are omitted in this analysis because the electricity demand and CO₂ emissions are relatively low. It can be seen that all provinces do not meet their respective target emissions in Fig. 8a. On the other hand, provinces MB, ON, QC, and AC are shown to be CO₂ surplus after CS1-S4-FCCS is adopted, as shown in Fig. 8b. It is important to note that the use of NET (BECCS) allows many provinces to stay below their allowable CO₂ target. For instance, the BC province has a negative emissions of 2.31 Mt CO₂-eq. (due to the use of BECCS), which almost completely remove its emissions of 2.42 Mt CO₂-eq. (originated from hydropower and wind), making it almost achieving net-zero emissions.

In order to meet the overall emissions target, electricity trading is to be carried out among provinces; this is discussed in the following section.

Electricity trading between provinces for year 2030

Table 5 presents the electricity demand and generation after applying CS1-S4-FCCS in each province. Electricity

trading can take place between CO₂ surplus provinces with CO₂ deficit provinces, to ensure that the demand of provinces is met while CO₂ emission limits are observed. An important assumption made here is that CO₂ emissions due to the building of new transmission lines are negligible in long run. For this case, MB, ON, QC, and AC are provinces with CO₂ surplus, whereas BC, AB, and SK experience CO₂ deficit. The pairing in electricity trading is done with nearby provinces to avoid electricity loss due to long transmission lines. In line with the provincial targets, this strategy aims to reduce CO₂ emissions in MB and ON while satisfying the electricity demand of AB and SK. Given the absence of a neighbouring province that requires additional electricity demand, QC and AC will be exporting their electricity directly to the USA. On the other hand, BC which is CO₂ deficit province will trade its electricity with AB.

The amount of electricity traded between these selected provinces is depending on their respective demand. For instance, AB requires an additional of 54.4 TWh electricity, while SK is lacked of 11.3 TWh electricity after applying CS1-S4-FCCS (see last row of Table 5). In other words, a total of 65.7 TWh (= 54.4 + 11.3 TWh) of electricity will need to be traded from BC, MB, and/or ON. The primary reason for AB and SK to be a CO₂ deficit and energy deficit province is that they are heavily relied on fossil fuels for power generation before transitioning to renewable sources. The overdependence on non-renewable energy sources resulted in the substantial release of CO₂ emissions. In contrast, other provinces have made significant strides in adopting renewable energy sources, which has helped reducing their carbon footprint. Therefore, the changes for other provinces are not that obvious as compared to AB and SK after adopting CS1-S4-FCCS case.

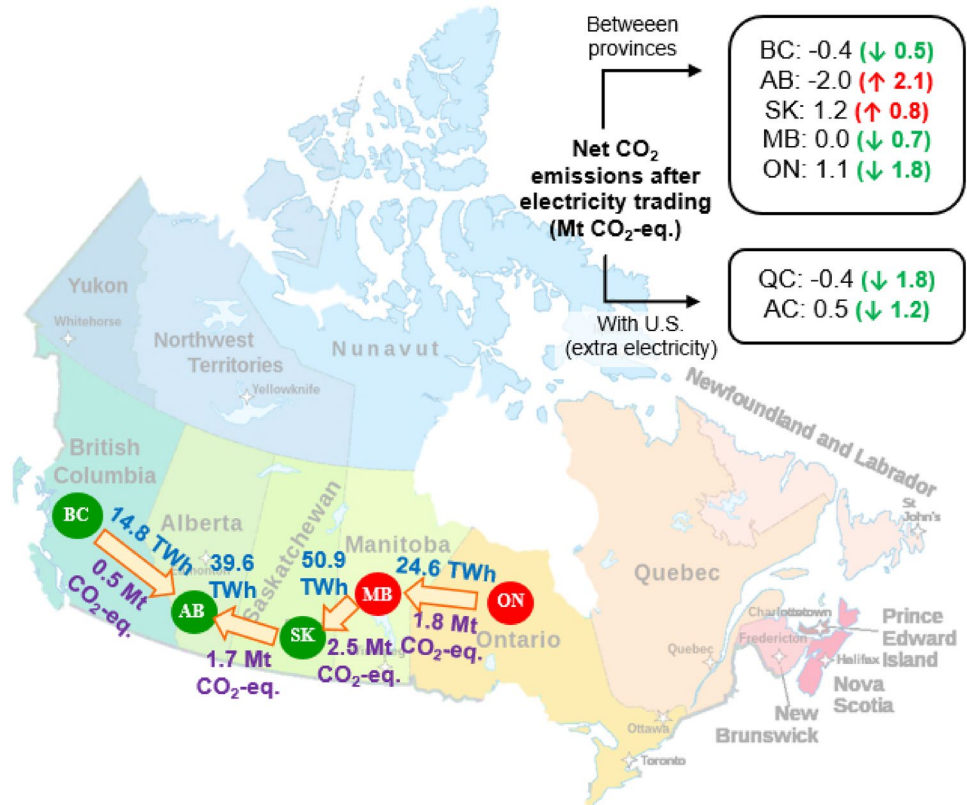
Figure 9 shows the transfer of electricity demand between provinces with CO₂ surplus and those that experience CO₂ deficit. It also displays the increase/decrease in CO₂ emissions for each province. As shown, a total of 65.7 TWh of electricity will be sold from BC to AB (14.8 TWh) and MB to SK (50.9 TWh) in order to satisfy their electricity demand. For SK, it is expected to consume 11.3 TWh of electricity and supply the remaining amount of 39.6 TWh to AB. This results with the increase in CO₂ emissions for AB and SK by 2.1 and 0.8 Mt CO₂-eq., respectively. At the same time, 24.6 TWh of MB's electricity will need to be brought from ON to meet its provincial demand and emissions target of 0.1 Mt CO₂-eq. In the case of QC and AC, it is not feasible to supply electricity directly to AB and SK due to the considerable distance between these provinces. Instead, the electricity generated from ON will be supplied to MB, while a big portion of MB's electricity will be delivered to SK. This reduces the distance for transmission lines and minimises power loss during electricity trading. The

Table 5 Electricity demand and generation for each province in Canada in the year 2030

Province	BC	AB	SK	MB	ON	QC	AC	TR	Total
Demand in 2030 (TWh)	80.7	89.9	24.4	22.1	146.4	193.9	36.5	1.0	595.0
CS1-S4-FCCS (TWh)	95.6	35.6	13.2	48.8	171.0	255.6	70.8	1.0	691.5
Difference (TWh)	<i>14.9</i>	<i>-54.4</i>	<i>-11.3</i>	26.7	24.7	61.7	34.4	0.0	96.5

The bold and italic is referred as CO₂ surplus provinces and CO₂ deficit provinces

Fig. 9 Electricity trading between provinces and their net CO₂ emissions (CS1-S4-FCCS). Adapted from Wikipedia.com



electricity traded from QC and AC to the USA will reduce their emissions by 1.8 and 1.2 Mt CO₂-eq., respectively, and help them to achieve their respective emissions targets of 1.0 and 1.2 Mt CO₂-eq. With electricity trading, all provinces will have their targeted CO₂ emissions met and demand fulfilled.

Scenario for net zero in year 2050

Based on Canada Energy Regulator, both Evolving and Reference Scenarios present a variety of possible outcomes for Canada’s energy sector up to year 2050 (Canada Energy Regulator 2020). These scenarios served as a benchmark to investigate how a hypothetical energy future would unfold for Canadians over the long run. However, neither scenario shows the significant reductions in fossil fuel usage required to reach net-zero emissions by year 2050. Policy and technological factors would need to act more quickly than they

have in the past. In order to narrow the generation gap and to achieve emissions net zero in year 2050, the following four cases are suggested:

- *CS2-S5-NGCCS*: same generation mix as the projected scenario for year 2050 (refer Table 3) but with all natural gas power plants equipped with CCS facilities; CCS is expected to lower CO₂ emissions by 85% (Babae and Loughlin 2017); coal generation is completely replaced with natural gas.
- *CS2-S6-GBCCS*: similar setting as with CS2-S5-NGCCS, however, with 34% of natural gas generation is replaced by biomass power plants with CCS.
- *CS2-S7-NU*: same as CS2-S6-GBCCS; with 10% of natural gas; the rest is covered by nuclear energy.
- *CS2-S8-HYDRO*: identical to CS2-S6-GBCCS; but power generation with natural gas is replaced completely by hydropower.

As stated in the proposed framework in the Clean Electricity Regulations, all new or existing natural gas power plants should be installed with CCS by year 2035 (Jeyakumar 2022). Although these Clean Electricity Regulations are expected to be enforced in 2023, it is anticipated that the regulations will soon prohibit the combustion of fossil fuels in power plants without CCS. Moreover, traditional coal-fired units must be phased out by year 2030 to achieve a net-zero grid. These initiatives are taken into account in CS2-S5-NGCCS. In another case with the same generation mix, CS2-S6-GBCCS is created to reduce the reliance on power generation with natural gas. Furthermore, it is assumed that BECCS will replace 34% of natural gas generation in CS2-S6-GBCCS. According to the EPPDs in Fig. 10, both cases of CS2-S5-NGCCS and CS2-S6-GBCCS have a positive surplus of CO₂ emissions, i.e. 34.2 and 11.0 Mt CO₂-eq., respectively. As shown, a similar trend is expected for projected case of year 2050 and CS2-S5-NGCCS because they have the same generation mix. The usage of CCS in all natural gas power plants shows a reduction of 41.5% (i.e. a reduction of 24.3 Mt from 58.5 Mt CO₂-eq) in CO₂ emissions, demonstrating the effectiveness of this technology. The combination of NGCCS and BECCS shows a reduction of 81.2% (i.e. reduction from 58.5 to 11 Mt CO₂-eq.) in CO₂ emissions as displayed in Fig. 10. However, both cases outlined here do not fulfil the net-zero CO₂ emissions goal.

Canada has some policies such as the 2018 Small Modular Reactor (SMR) Roadmap and the 2020 SMR Action Map to initiate the deployment of SMR (IEA 2022a). SMR is advanced nuclear power plants with generation capacities of up to 300 MWe per unit, which is approximately one-third of conventional nuclear power plants (IEA 2022a).

The advantages of SMR include improved safety features, lowered initial capital expenditure (due to smaller size), and better location flexibility. The present SMR development plan in Canada involves three main streams. The first stream entails constructing a grid-scale SMR with a capacity of 300 MW at the Darlington nuclear site in Ontario by 2028 (Ministry of Energy 2023). Following this, additional units would be built in Saskatchewan, with the first SMR projected to be operational by year 2034 (Ministry of Energy 2023). The second stream includes the development of two fourth-generation, advanced SMRs at the Point Lepreau nuclear site in New Brunswick (Ministry of Energy 2023). ARC Clean Energy aims to be fully operational by 2029, while Moltex Energy plans to have its spent fuel recovery system and reactor in operation at the same site by the early 2030s (Ministry of Energy 2023). The third stream seeks to replace diesel in remote communities and mines using micro-SMRs (Ministry of Energy 2023). Moreover, there are approximately ten vendors that propose various SMR design concepts to Canadian Nuclear Safety Commission which has recently started official licence evaluation (IEA 2022a). These SMRs are foreseen as futuristic technology since they are effective, productive, and emissions-free. Hence, CS2-S7-NU is developed by replacing natural gas generation with nuclear power plant. The 10% of natural gas generation is used as reservation for backup purposes to balance the grid and to ensure a steady supply of electricity. This case has the aim to investigate the efficacy of SMR deployment towards net-zero emissions. Nevertheless, Fig. 11 shows that the CO₂ emissions of this case have similar emissions pattern as that in CS2-S6-GBCCS (Fig. 10).

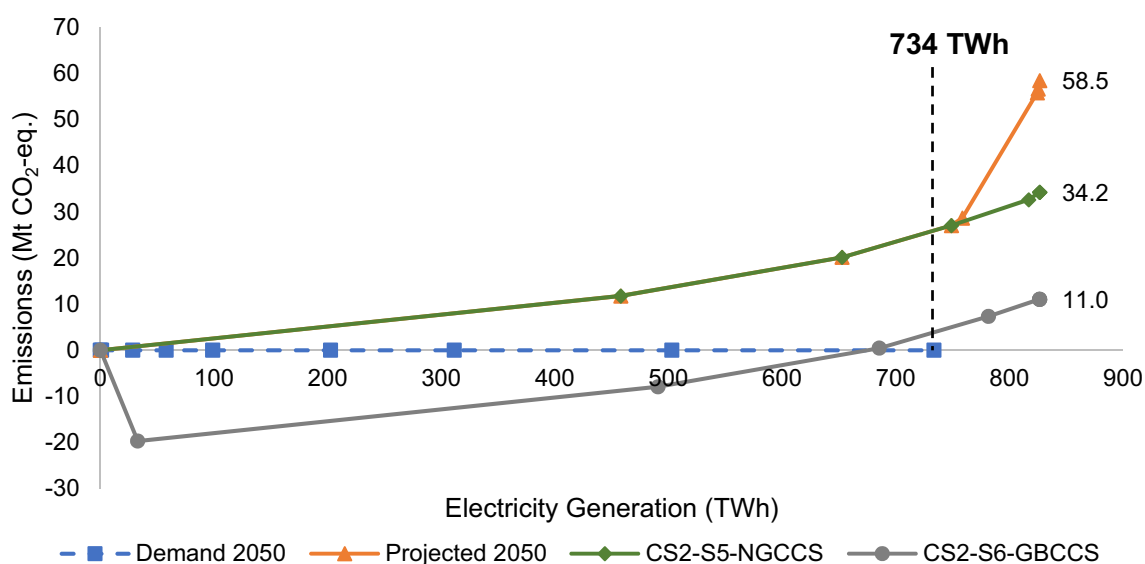


Fig. 10 EPPD of CS2-S5-NGCCS and CS2-S6-GBCCS for year 2030

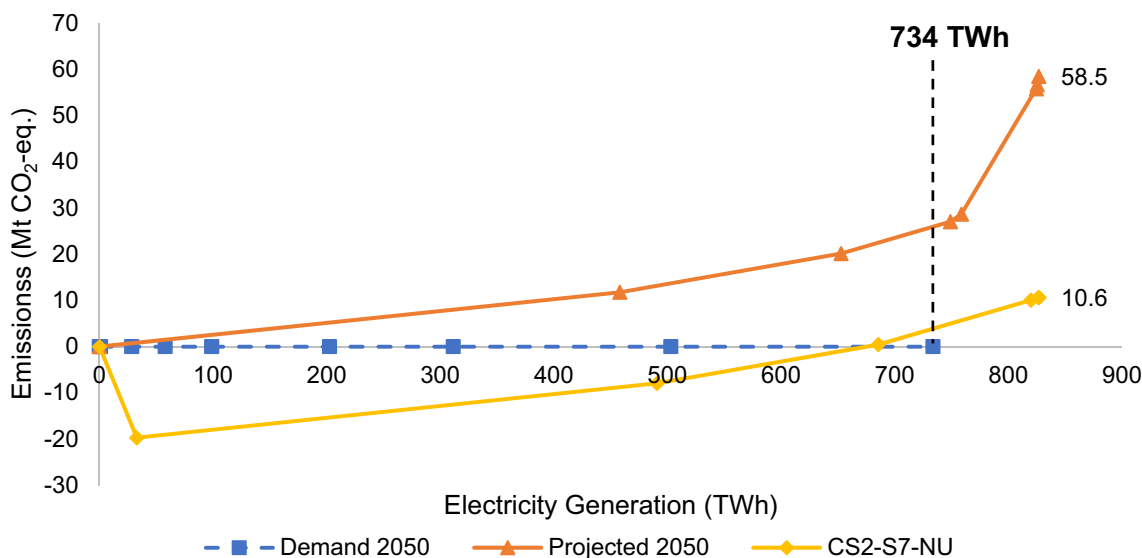


Fig. 11 EPPD of CS2-S7-NU for the year 2030

CS2-S8-HYDRO serves as a theoretical case where all natural gas is replaced by hydropower. Hydropower is chosen as the replacement for the generation gap because it has the lowest emission factor. Besides, WaterPower Canada has initiated four research projects to investigate ways to increase the installed capacity of hydropower in Canada from almost 85,000 to 100,000 MW by 2035 and beyond (Carriann Stocks 2022). These projects involve the issuing of white papers on electricity generation costs by source, grid services associated with hydropower generation, storage, and transmission in Canada, and assessments of the

technical and economic potential of pumped storage hydropower, as well as refurbishments and redevelopments for old hydropower plants (Carriann Stocks 2022). Hence, this theoretical case is important to check whether net-zero CO₂ emissions can be reached by year 2050. Although all energy is now generated from renewable sources, the net-zero target is still not achievable. As illustrated in Fig. 12, net zero is only attainable if no extra electricity is generated for electricity trading with the USA.

Detailed generation mix for all cases for year 2050 is summarised in Table 6. Even though it is shown that none

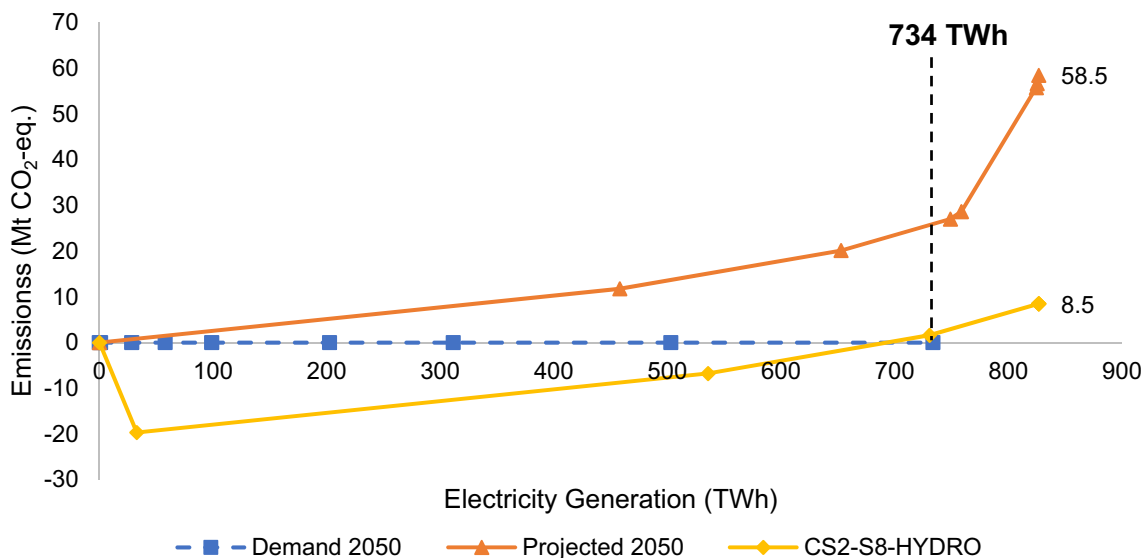


Fig. 12 EPPD of CS2-S8-HYDRO for the year 2030

Table 6 Summary of all cases for the year 2050

Source	CS2-S5-NGCCS		CS2-S6-GBCCS		CS2-S7-NU		CS2-S8-HYDRO	
	Electricity	CO ₂ emissions	Electricity	CO ₂ emissions	Electricity	CO ₂ emissions	Electricity	CO ₂ emissions
Hydropower	457.7	11.8	457.7	11.8	457.7	11.8	502.7	12.9
Wind	194.8	8.4	194.8	8.4	194.8	8.4	194.8	8.4
Nuclear	96.1	6.9	96.1	6.9	134.2	9.6	96.1	6.9
Biomass	9.7	1.6	–	–	–	–	–	–
Biomass + CCS	–	–	32.8	–19.7	32.8	–19.7	32.8	–19.7
Natural Gas + CCS	68.1	5.6	44.9	3.7	6.8	0.6	–	–
Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oil	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	826.3	34.2	826.3	11.0	826.3	10.6	826.3	8.5

of the cases for year 2050 has met net-zero emissions, Figs. 10, 11 and 12 show that net zero is not far from materialisation, especially if the extra power generation (for trading with the USA) is not considered. Alternatively, CO₂ emissions of the extra generated power are accounted for by the USA, where the power is traded.

Figure 13 presents the CO₂ emissions before and after CS2-S8-HYDRO (case with lowest CO₂ emissions) is adopted to the projected scenario in each province. Note

that the CO₂ emissions do include the CO₂ emissions from the extra electricity that were to be traded with the USA. As shown in Fig. 13, only province AB has fulfilled the net-zero emissions. Hence, to assess if each province can accomplish their provincial target, the extra power generation (for trading) is ignored, while electricity trading is carried out among provinces (similar to that in Scenario 2030).

Electricity trading between provinces for year 2050

Table 7 shows the electricity demand and generation after case CS2-S8-HYDRO is adopted for each province. As observed, provinces with extra electricity generated and CO₂ emissions less than 2.5 Mt CO₂-eq. will undergo electricity trading with the USA. These provinces include QC and AC. BC is not included in this context as the amount of extra electricity is relatively less compared to QC and AC. For this case, BC, AB, SK, MB, and ON will be selected for electricity trading to meet their electricity demand. BC, SK, MB, and ON are provinces with CO₂ surplus, whereas AB encountered CO₂ deficit. Although SK has CO₂ surplus, it does not meet the electricity demand for its province. Table 7 shows that AB needs an additional of 31.4 TWh electricity, whereas SK requires another 4.5 TWh of electricity. Therefore, a total of 35.9 TWh (= 31.4 + 4.5 TWh) of electricity will need to be traded from BC, MB and ON.

Figure 14 illustrates the trading of electricity among provinces. It also indicates the increase/reduction of CO₂ emissions for each province. In order to meet the electricity demand for AB and SK, a total of 35.9 TWh of electricity are to be exported from BC and MB. As a result, CO₂ emissions for AB and SK increase by 1.0 and 0.1 Mt CO₂-eq., respectively. On top of that, 3.0 TWh of electricity will need to be bought from ON to MB in order to meet its provincial demand. Doing this leads to reduced CO₂ emissions of MB to 0.1 Mt CO₂-eq. Despite the reduction in CO₂ emissions to 4.0 Mt CO₂-eq., ON still has an additional of 10 TWh of electricity that can be exported to the USA. It is

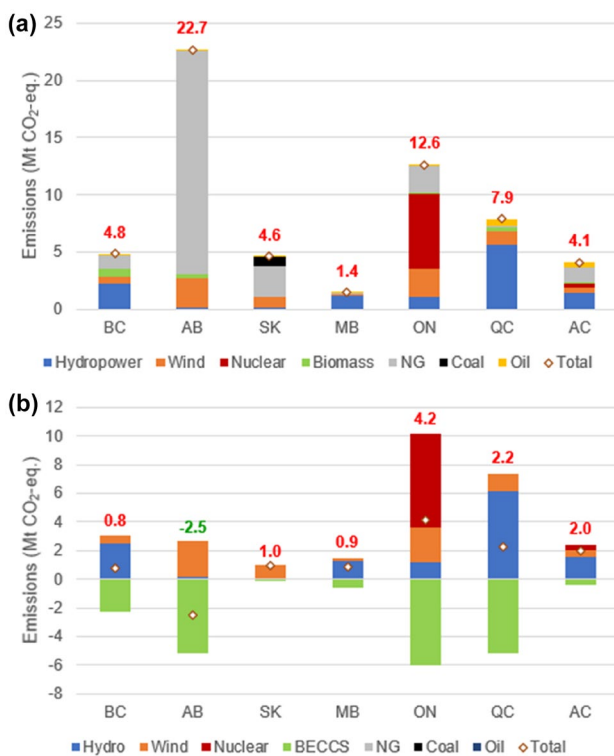


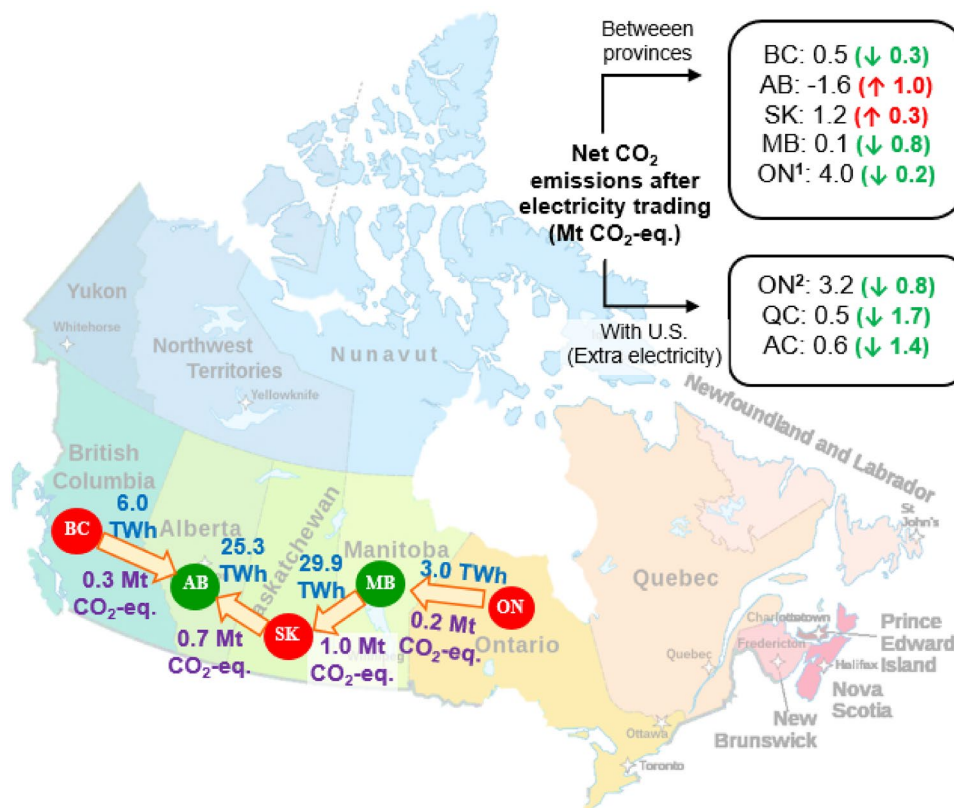
Fig. 13 Summary of CO₂ emissions for all provinces in year 2050 **a** projected scenario; **b** CS2-S8-HYDRO (red colour font indicates exceeded province's target, and green font indicates provincial targets are met)

Table 7 Electricity demand and generation for each province in Canada in the year 2050

Province	BC	AB	SK	MB	ON	QC	AC	TR	Total
Demand in 2030 (TWh)	108.8	103.7	29.4	27.5	191.4	230.7	40.9	1.0	733.5
CS2-S8-HYDRO (TWh)	115.2	72.3	25.0	54.6	204.4	277.1	76.9	1.0	826.3
Difference (TWh)	6.3	<i>-31.4</i>	<i>-4.5</i>	27.2	13.0	46.41	36.0	0.0	92.8

The bold and italic is referred as CO₂ surplus provinces and CO₂ deficit provinces

Fig. 14 Electricity trading between provinces and their net CO₂ emissions (CS2-S8-HYDRO). Adapted from Wikipedia.com. Note: ON¹ refers to CO₂ emissions after electricity trading between provinces, whereas ON² refers to CO₂ emissions after exporting electricity to the USA



worth noting that the CO₂ emissions in ON are the highest (3.2 Mt CO₂-eq.) after exporting electricity to USA. This is due to the fact that nuclear power plants, which account for around half of the sources, are the major contributors to electricity generation in ON. Since these power plants are constructed before year 2000, it is anticipated that they would have lower CO₂ emissions and efficiency levels. Hence, there will be a decrease in emissions with the newly proposed SMR. Aside from ON, all provinces in Canada have CO₂ emissions that are nearly zero. These emissions are expected to decrease further in the future as CCS and NET technology advances.

From the above analysis, it may be observed that CCS is a crucial technology for Canada to achieve net-zero emissions in year 2050. The use of CCS on biomass power plants (i.e. BECCS) helps to offset CO₂ emissions from other sources of generation. BECCS may be crucial for ensuring the security of energy supply due to its non-fluctuating characteristics. Therefore, the potential availability of CCS hubs and

facilities should be further developed as suggested in the key new actions of 2030 Emissions Reduction Plan (Environment and Climate Change Canada 2020). It is important to note that in the coming decades, technological advancements such as progressive decreases in emission factors, development of hydrogen and metal fuels (Bergthorson 2018), and new cleaner sources and commercialisation of various NETs (Santos et al. 2019) will help to reduce the total CO₂ emissions. Finally, note that constant emissions factors have been utilised in this study. It is very likely that the emissions factors of all technologies will improve for the decades to come, which will lead to reduced emissions for coming years.

Conclusion

In this paper, CEPA was used for the decarbonisation planning of Canada's electricity sector. Country and provincial CO₂ emissions for the electricity sector were analysed to

provide insights into Canada's energy policy for the sector. Scenario-based recommendations that are aligned with country policy were generated for Canada to achieve its Paris agreement on its CO₂ emissions target. A total of eight cases using different decarbonisation strategies were explored, i.e. four cases for the years 2030 and 2050, respectively. The strategies include the increased usage of renewable energy and CCS implementation. Both renewable energy sources and CCS are essential in lowering CO₂ emissions. The analysis also found that government projections under Evolving Scenario do not seem to accelerate quickly enough to meet the CO₂ emissions target. In year 2030, the electricity sector is found to be emitting 10.9 Mt CO₂-eq. lower than the country emissions target of 14 Mt CO₂-eq. (case CS1-S4-FCCS). Provinces of ON and QC that do not meet their provincial target need to undergo electricity trading with CO₂ deficit provinces as the emissions reduction strategy. On the other hand, for year 2050, none of the cases meet the national target of achieving net-zero emissions. The only province that can achieve their regional target in case CS2-S8-HYDRO (lowest CO₂ emissions) is AB. Apart from ON, all provinces can reach their regional target after electricity trading is carried out among the provinces, and by neglecting additional electricity that is traded with the USA.

A limitation of this study is its reliance on current electricity generation technology to generate recommendations, which may become outdated in the next 20 years. Furthermore, this study only focuses on reducing CO₂ emissions without taking into account cost or other environmental impact indicators such as water and land footprints that are relevant to energy system planning. This study also acknowledges that transmission constraints, such as transmission capacity, transmission line losses, and transmission costs, have not been accounted for in the analysis. To address these limitations, future work can extend the current methodology to include cost as well as other environmental impact indicators. The increased penetration of renewables, large-scale deployment of NETs, and electrification of transport may be incorporated to provide more diverse decarbonisation strategies for the country. Moreover, importing electricity from neighbouring countries such as the USA can be a potential solution to address transmission constraints. This approach will facilitate the fulfilment of transmission constraints and support the development of a sustainable electricity trading system.

Author contributions Chew did calculation and wrote the main manuscript. Gan initiated initial calculation works. Heng provided data and feedback. Nair reviewed and provided feedback. Foo reviewed and revised the paper. Tan reviewed and revised the work.

Declarations

Conflict of interest The authors declare no conflict of interest in this work.

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