THE UNIVERSITY OF BRITISH COLUMBIA

Clean Energy Research Centre (CERC)

Part I

Clean Energy Pathways to Meet British Columbia's Decarbonization Targets

Haoqi Wang, Roland Clift, and Xiaotao Bi

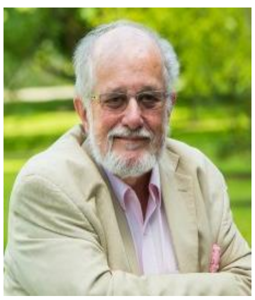
University of British Columbia

January 2022

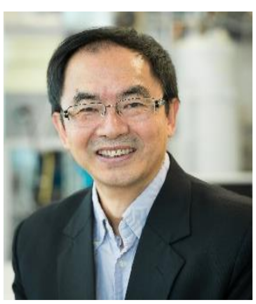
Photos by unsplash.com

Biographies

Haoqi Wang worked on life cycle environmental analysis and techno-economic analysis of bioenergy systems in British Columbia during his PhD study as a PICS fellow and postdoctoral research at the Department of Chemical and Biological Engineering, University of British Columbia, under the supervision of Xiaotao Bi and Roland Clift. He is now an assistant professor in the College of Materials and Environmental Engineering, Hangzhou Dianzi University, China.



Roland Clift is emeritus professor (founding director) in the Centre for Environment and Sustainability, University of Surrey, UK, and an adjunct professor at the Department of Chemical and Biological Engineering, University of British Columbia. His research interests are in life cycle assessment, industrial ecology and sustainable energy systems. He is a fellow of the Royal Academy of Engineering, UK, and a past member of the UN Intergovernmental Panel on Climate Change (IPCC).



Xiaotao Bi is a professor in the Department of Chemical and Biological Engineering and the director of UBC's Clean Energy Research Centre. His current research focuses on particle technology and fluidized bed reactors for biomass thermo-catalytic conversion, green and sustainable engineering, and integrated assessments of clean energy systems. He is a fellow of the Canadian Academy of Engineering and Engineers Canada.

UBC Clean Energy Research Centre
2360 East Mall
Vancouver, BC Canada V6T 1Z3
Phone: 604-827-4342
Email: cerc@cerc.ubc.ca
Website: www.cerc.ubc.ca

Executive Summary

The two phases of CleanBC set out strong policy support for further developing renewable energy in the province as a contribution in achieving BC's 2030 Greenhouse Gas (GHG) mitigation target. However, the CleanBC framework lacks strong demand-side measures, to reverse the growth of energy demand in BC. Attempts have been made to reduce energy use in land transportation but action plans for other sectors, especially industry, are lacking. As a result, even with moderate energy demand reduction (10%), the CleanBC framework will not reach the 2030 target. Even if demand is reduced more sharply (25%), the current supply of renewable electricity and bioenergy is still insufficient to meet demand: the additional supply of renewable energy will be immense.

Future demand reduction cannot be predicted with precision, but any reduction reduces emissions. Growth in demand is predicted mainly for heating, mobility, and industrial production. The pursuit of lower cost and higher profit will lead to continuous but slow improvement in energy efficiency. However, decoupling demand from economic and population growth requires transformative change in business models and personal behaviors, and therefore more stringent policy measures.

Electrification is seen as a core strategy for GHG mitigation in BC. However, electricity supply is insufficient to meet the growth in demand inherent in the electrification-centered strategy. Even with Site C and radical demand reduction, about 60 PJ of additional supply will be needed to meet the 2030 target, and 160 PJ for carbon neutrality in 2050. New electricity generation will be needed by 2030 and beyond, comparable in magnitude to the projected output of the current Site C project. This implies installing hundreds of wind turbines and millions of solar panels.

The bioenergy-centered strategy is an alternative to a strategy dominated by electrification; it would dramatically increase demand for bioenergy. As the first step, it must fully exploit existing waste biomass, predominantly woody waste. Even then, roughly 250 and 450 PJ of additional primary bioenergy supply will be needed for 2030 and 2050, respectively. This is well beyond any foreseeable waste supply within BC.

Hence, strategies that rely solely on either electricity or bioenergy will raise demand beyond sustainable and manageable supplies. There is no single 'silver bullet' renewable energy source to meet BC's GHG mitigation targets: it is essential to utilize all the available bioenergy and renewable electricity resources and promote a balanced renewable energy portfolio. The limited time frame to 2030 emphasizes the difficulty of securing the renewable energy needed and the urgency of action to reduce demand. For the long-term target of carbon neutrality, the supply problems emphasize the need for a balanced renewable energy strategy.

Table of contents

1. Background

In 2007, British Columbia introduced the Climate Change Accountability Act to mitigate provincial emissions of greenhouse gases (GHGs). Amendments introduced in 2018 established reduction targets: 40% below 2007 levels by 2030, 60% by 2040, and 80% by 2050. However, policy measures under the act, including the carbon tax and low-carbon fuel mandate, have not stemmed the rise in emissions: in 2019, BC's GHG emissions were 68.6 million tonnes (Mt), 5% above the 65.7 Mt emitted in 2007 [1]. The increase is mainly attributable to fossil fuel consumption - in 2019, 891 PJ of natural gas (NG) and refined petroleum products (RPP) provided 70% of energy supply in BC [2].

The CleanBC Phase 1 plan [3], published in 2018, gave more detail on the 2030 target and announced action plans to mitigate GHG emissions across BC's economy. It was supplemented in 2021 by a Roadmap to 2030 (CleanBC Phase 2 [4]), with quantified reduction targets for heating, mobility, industrial production, and waste management (see Table 3-1 below). CleanBC focuses on electrification, bioenergy, methane emission reduction, and efficiency improvement. Additionally, low-carbon hydrogen is to be promoted for heavy-duty vehicles and heating in buildings and industrial processes [3]. The plan depends on decoupling emissions from economic growth but does not address reducing economy-wide energy demand or matching renewable energy supply to demand. Only three policy actions to reduce demand are included: increasing the carbon tax, reducing distance travelled by light-duty vehicles by 25%, and reducing energy use by heavy-duty vehicles by 10% [4].

Electrification, relying on a low-carbon electricity supply mainly from hydroelectric sources, is a key component of the plan, to be promoted across all sectors. Some electrification technologies, such as heat pumps, electric motors, and electric vehicles, do have efficiency advantages over their fossil fuel counterparts. However, electrification increases the overall demand for electricity, raising the question of whether the supply of renewable electricity in BC will be sufficient.

Furthermore, the potential contribution of bioenergy needs to be examined. CleanBC sees renewable natural gas and liquid biofuels as low-carbon alternatives to natural gas distributed via the grid and fossil transport fuels, with the low-carbon fuel standard expected to be increasingly stringent. However, the plan ignores possible uses for biomass with higher efficiencies than refined biofuels, including low-grade heat for district heating and gasification-combustion to provide high-grade energy for industrial processes.

Against this background, this paper sets out an analysis to investigate pathways to achieve BC's GHG mitigation targets. Future clean energy scenarios to meet BC's GHG mitigation targets are presented in Section 2. Key findings on strategies for promoting and prioritizing clean energy development are presented in Section 3, and the details are included in Part II of this paper series.

2. Future Energy Profile in BC and the Potential Role of Bioenergy and Renewable Electricity

2.1 Baseline future energy demand

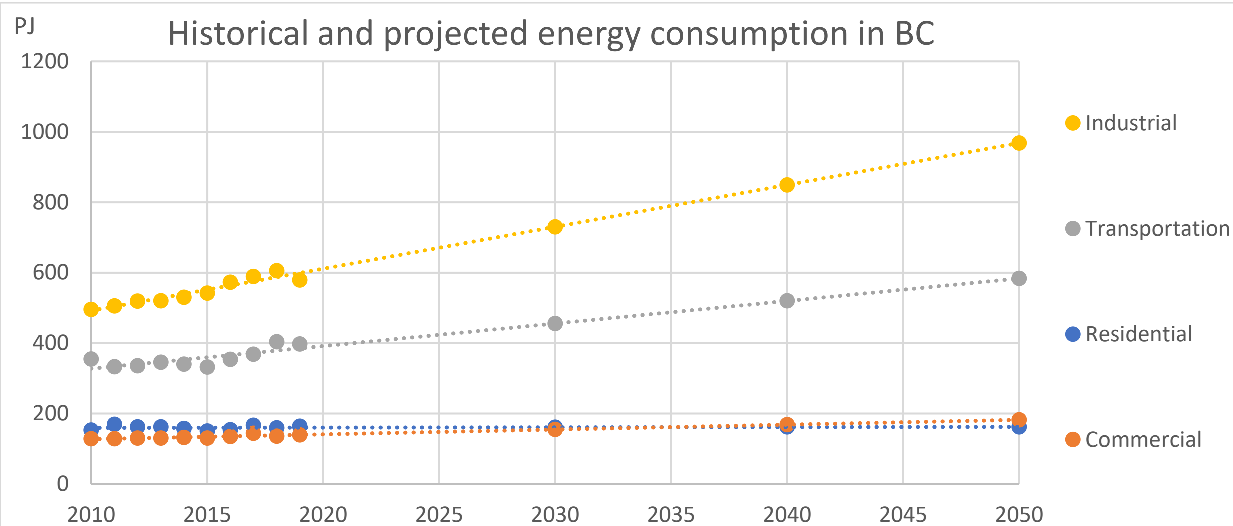


Figure 2-1 Historical and projected energy consumption in BC's different sectors

Baseline future energy demand refers to the anticipated energy demand for "business as usual", reflecting current projections of economic activity, population growth, and moderate efficiency improvement but excluding climate policies. Based on BC's historical energy consumption from 2010 to 2019 [5], baseline energy demand is expected to grow, particularly in the industrial and transportation sectors (see Figure 2-1). This will generate 68.6 Mt of GHGs from fossil fuels in 2030 and 87.4 Mt in 2050 (see Figure 2-2), a severe challenge for GHG mitigation.

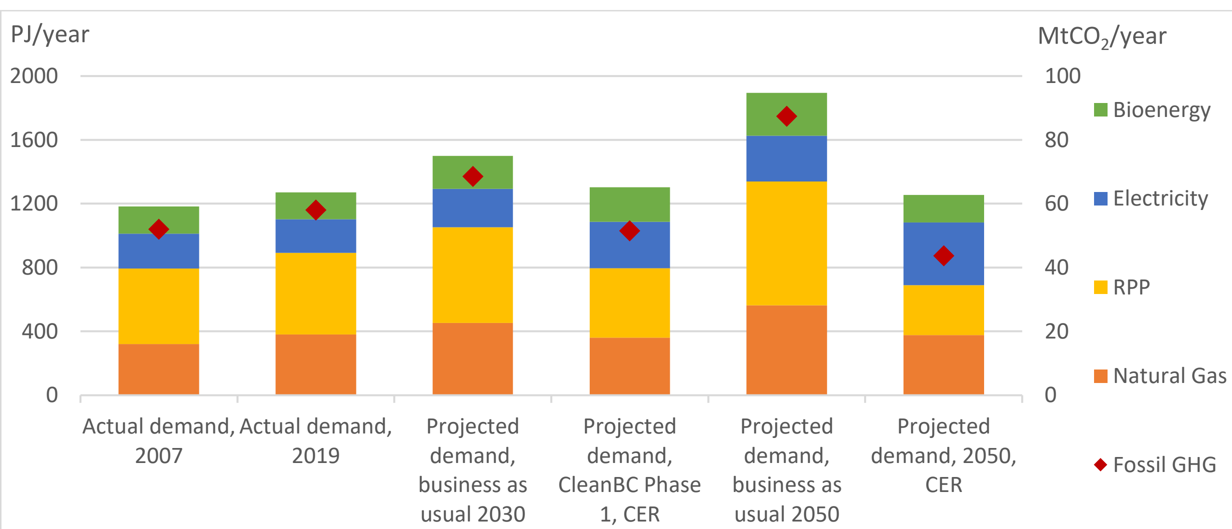


Figure 2-2 Projection for BC's energy demand and GHG emissions from fossil fuels in 2030

The growth in baseline energy demand is associated with industrial production, mobility, and heating in commercial and residential buildings. Canada Energy Regulator (CER) [2] has produced "optimistic" projections for BC, assuming CleanBC Phase 1 is fully implemented, augmented by further policy effort and continuous technological improvement. Even with the optimistic projections, fossil fuel consumption in 2030 will exceed 800 PJ (see Figure 2-2), directly emitting 51.5 Mt of GHGs, far above BC's 2030 target of 38.0 Mt. For 2050, ideally a time frame to approach carbon neutrality, CER's optimistic projection foresees 770 PJ of fossil fuel consumption, directly emitting 43.7 Mt of GHGs. This projection does not include the recently announced CleanBC Roadmap to 2030, but it still shows that meeting BC's GHG mitigation targets depends critically on decoupling energy use from economic growth.

Therefore, possible scenarios for BC to meet its GHG reductions for 2030 and 2050 are explored in the following sections. As a basis for constructing these energy scenarios, the potential in BC for increasing use of biomass, generation and use of renewable electricity, and using hydrogen as an energy carrier has been assessed. The salient conclusions are summarized in Section 3; details are given in the accompanying document "Part II: Clean Energy Strategies for Mitigating Greenhouse Gas Emissions in British Columbia". An important finding is that future energy scenarios must deploy the optimal uses of clean energy, giving the greatest GHG mitigation at the lowest cost, as both bioenergy and renewable electricity will be in short supply.

2.2 Energy scenarios for 2030 target

Energy flows in the different scenarios are represented in terms of Sankey diagrams: the left-hand axis in each case shows the different primary energy sources, the central line shows the forms in which the energy is distributed, and the right-hand axis shows end-use.

2.2.1 Scenario 1: CleanBC with moderate energy demand reduction

As shown in Figure 2-3, economy-wide electrification will substantially increase electricity demand. In addition to BC's current renewable electricity generation capacity and the capacity to be provided by the Site C project, Scenario 1 will require a further 54.1 PJ, which is 9 times the totality of BC's wind and solar capacity, or 2.9 times the capacity of the Site C project. As estimated in Part II of this paper series, the output of one Site C project equals that of 30 km^2 of solar panels or nearly 700 average sized (2.5 MW) wind turbines in BC. The challenges presented by the enormous new demand, limited time frame towards 2030, and intermittency of solar and wind electricity generation are obvious.

Scenario 1 also foresees substantial increase in demand for all forms of bioenergy. The current bioenergy supply refers to wood residues and liquid biofuels currently consumed in BC, as well as wood pellet exports (see Part II). As global bioenergy demands are expected to increase continuously, importing bioenergy will become increasingly difficult and expensive. Therefore, for the reason of energy security, pellets currently exported should be diverted for domestic uses.

Clean Energy Research Centre

Waste streams, mainly unused wood residues and methane from landfill gases and anaerobic digestion of waste, must be prioritized for bioenergy production. However, after fully exploiting the energy potential of these waste streams, an additional supply of 118.8 PJ of liquid biofuels will still be needed, which is equivalent to about 200 PJ of primary bioenergy before conversion and even higher than the current bioenergy supply. If this new bioenergy supply is to be provided within BC, fundamental changes in forest management and residue collection systems will be needed, to ensure thorough recovery and utilization of wood residues, dead trees, and forest thinning, which is also in the interest of wildfire prevention [6]. Planting energy crops on marginal land may also be considered.

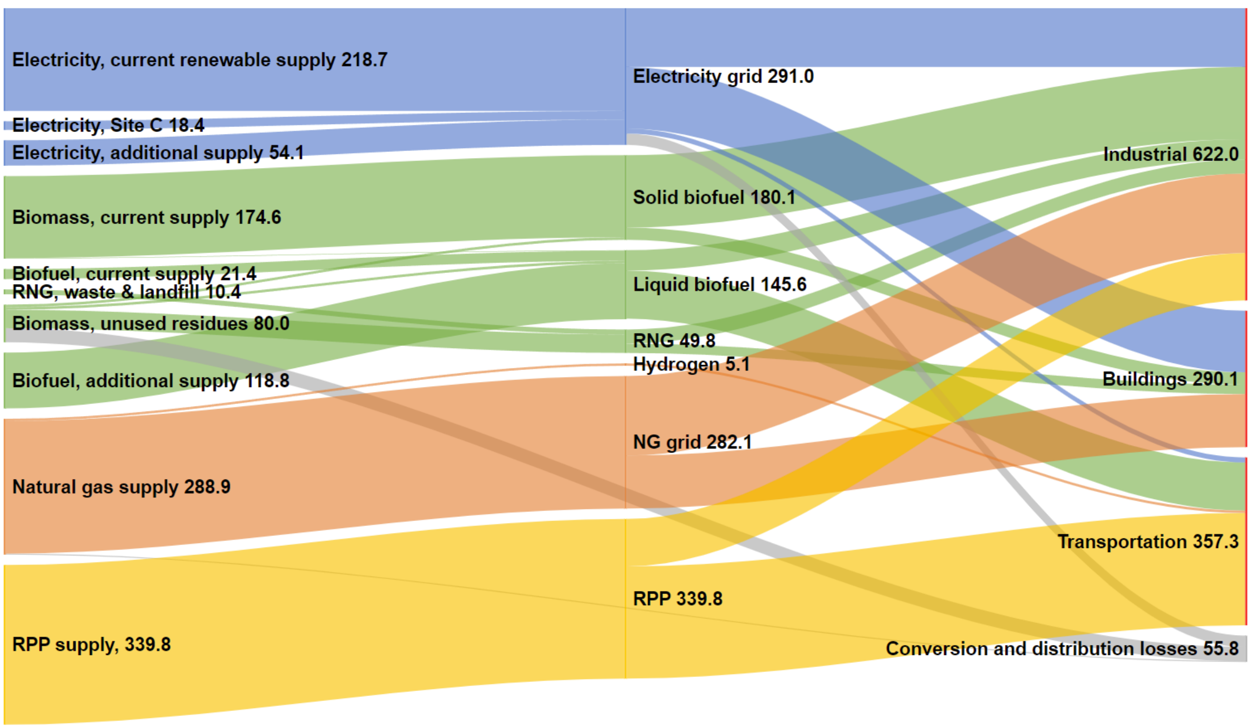


Figure 2-3 Scenario 1 (CleanBC with moderate energy demand reduction)

However, Scenario 1 can only achieve 12.6 Mt of GHG mitigation from energy transformation. As shown in Table 2-1, GHG mitigations across all sectors are far below the sectoral targets. Including the non-energy action plans in CleanBC, such as CCS and methane emission mitigation, the total GHG reduction is estimated to be 15.8 Mt, which is slightly more than half the 2030 target. As the additional renewable energy supply required for Scenario 1 is already enormous, securing even more will be technically and economically unrealistic. Therefore, much deeper reduction of energy demand is necessary across the economy.

Table 2-1 Sectoral GHG mitigations in 2030

	Buildings	Transportation	Industry
Sectoral targets	59-64%	27-32%	38-43%
Scenario 1	31%	29%	20%
Scenario 2	38%	37%	35%
Scenario 3	64%	37%	41%
Scenario 4	64%	37%	41%

2.2.2 Scenario 2: CleanBC with accelerated energy demand reduction

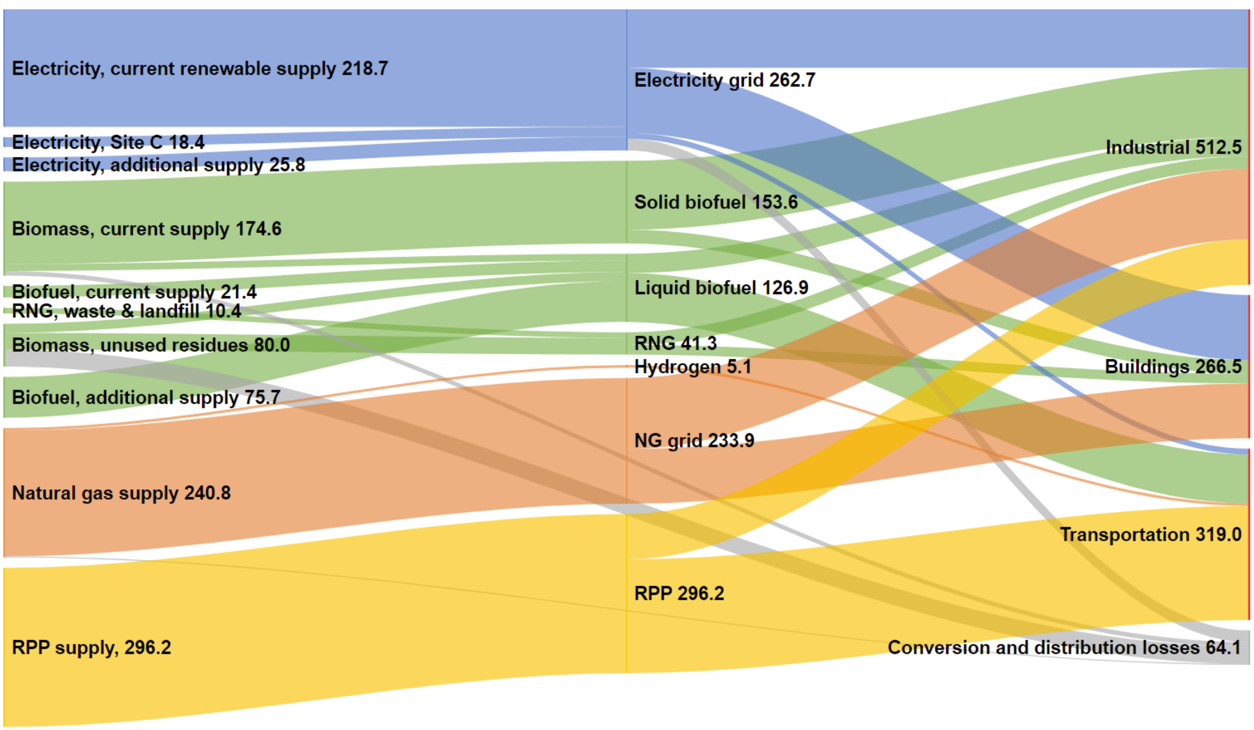


Figure 2-4 Scenario 2 (CleanBC with accelerated energy demand reduction)

Scenario 2 differs from Scenario 1 in assuming deeper reductions in economy-wide energy demand: 25% reduction by 2030 (2.5% annually from 2021). Given the historical rise in energy demand, this assumption is obviously ambitious and optimistic. In addition to reducing energy use in transportation, as laid out in CleanBC Roadmap, use in buildings and industries must be reduced substantially by efficiency improvement plus measures such as modifying buildings to reduce heating and cooling loads and integrating industrial operations to use waste heat.

Comparison between Scenarios 1 and 2 confirms that energy demand reduction is essential to contain renewable energy demand at manageable levels and achieve further mitigation: the additional demands for renewable electricity and biofuels in Scenario 2 are 25.8 and 75.7 PJ, respectively, much smaller than in Scenario 1. The additional renewable electricity could be supplied if the output of wind generation in BC grows by 14% annually, a global average predicted by IEA [7] (See Part II).

Together with non-energy GHG mitigation actions in CleanBC, GHG emissions are reduced by 22.2 Mt, a much greater reduction than in Scenario 1 but still 4.1 Mt short of the 2030 target. In terms of sectoral mitigations, Scenario 2 represents 37% reduction in the transportation sector, fulfilling BC's sectoral target. However, GHG mitigations in buildings and industries are 38% and 35%, slightly lower than the respective sectoral targets. Further actions to achieve the 2030 target are explored in Scenarios 3 and 4.

2.2.3 Scenario 3: Enhanced electrification and Scenario 4: increased use of bioenergy

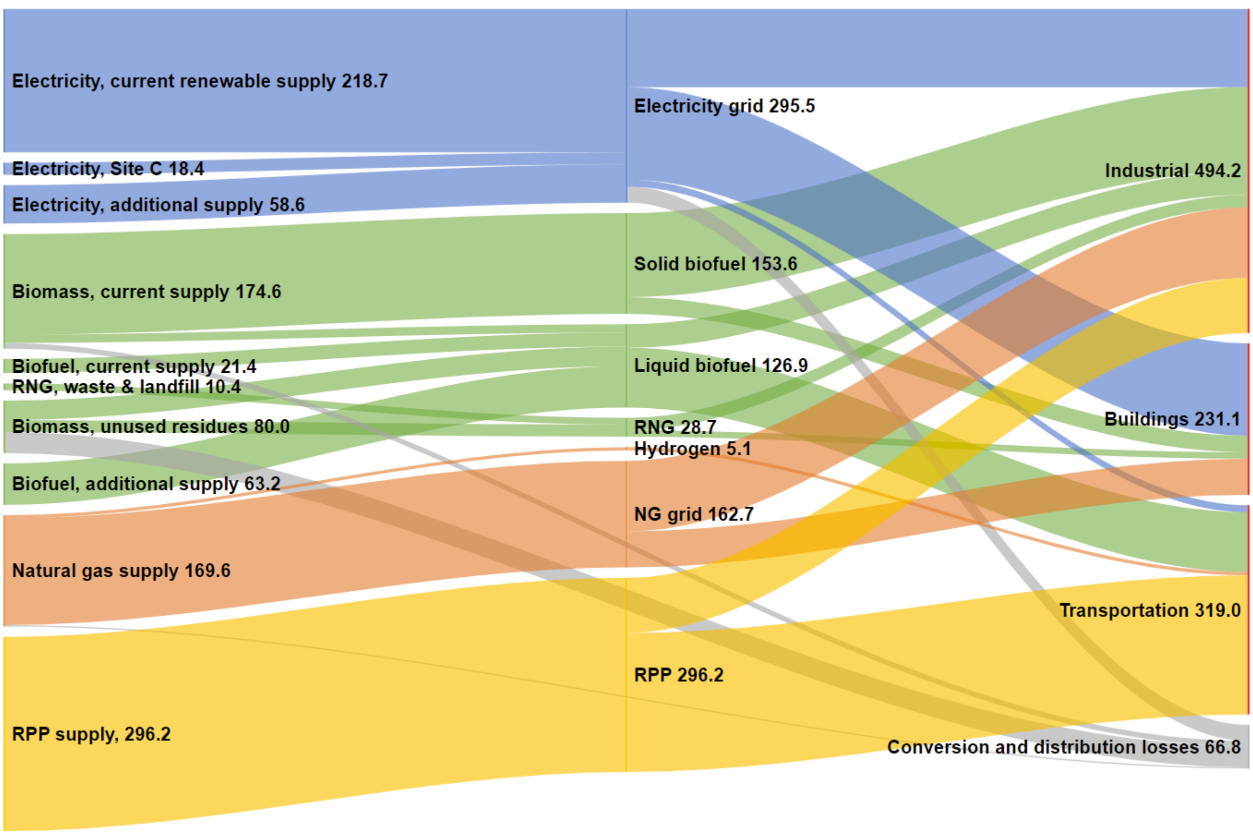


Figure 2-5 Scenario 3: CleanBC with enhanced electrification

Scenarios 3 and 4 build on the assumptions in Scenario 2, i.e., fully enacted CleanBC policies and accelerated energy demand reduction, but explore how the further reductions needed to achieve the GHG mitigation targets for 2030 might be achieved. In line with BC's sectoral mitigation targets, emissions are to be reduced by a further 2.7 Mt (64%) from buildings and 1.4 Mt (41%) from industries.

In Scenario 3, shown in Figure 2-5, the additional reductions are achieved by electrification to further reduce natural gas use, mainly through increased use of heat pumps in buildings and electric motors in industries. This increases demand for low-carbon electricity by an additional 58.6 PJ. Electrification will reduce the overall demand for RPP and natural gas and therefore reduce demand for biofuels to blend into these fossil fuels, so that Scenario 3 requires a slightly smaller additional supply (63.2 PJ) of liquid biofuels than Scenario 2.

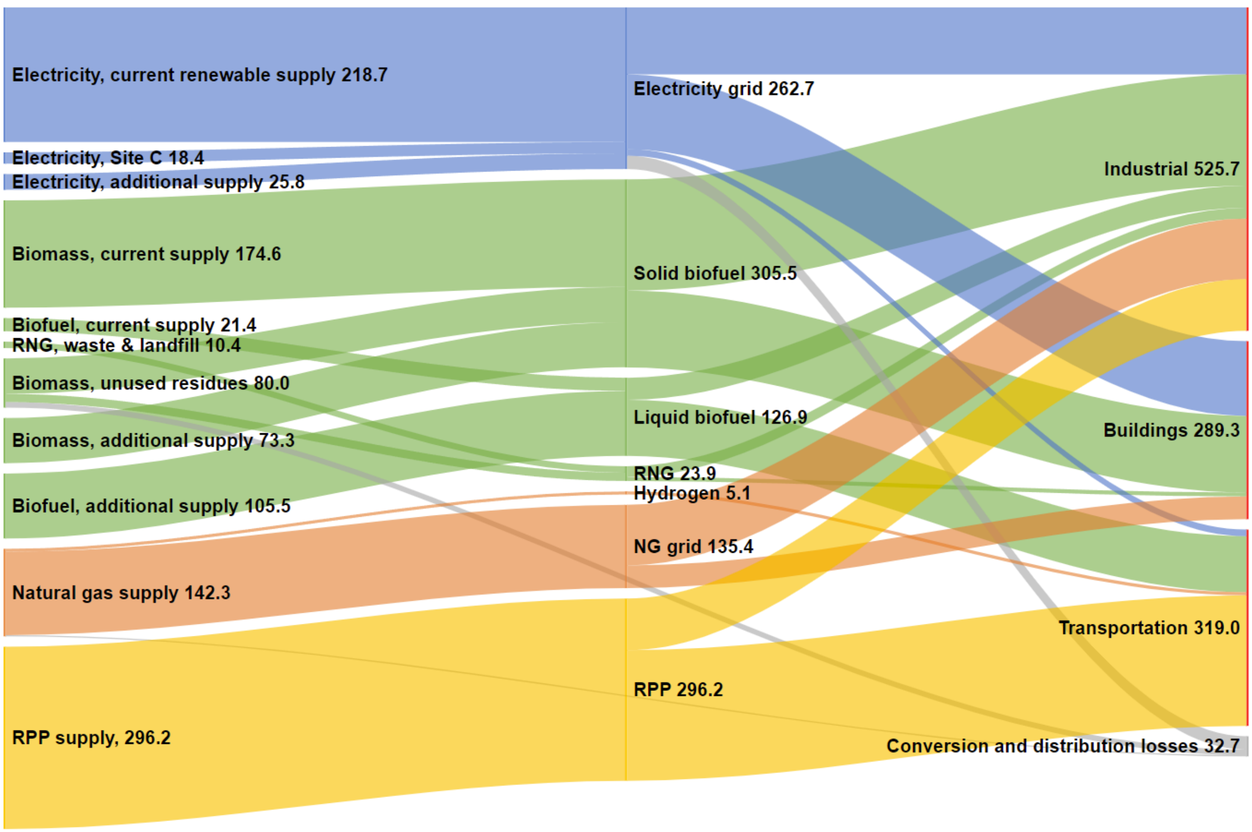


Figure 2-6 Scenario 4: CleanBC with increased use of bioenergy

Scenario 4, shown in Figure 2-6, relies on bioenergy for further GHG mitigation, including biomass-fired district heating systems for buildings and biomass gasification-combustion systems for industries. After fully exploiting the bioenergy potentially available in wood residues, other organic waste and landfill, Scenario 4 requires additionally 73.3 PJ (3.7 million ODT) of solid biomass and 105.5 PJ of liquid biofuels (176 PJ of primary bioenergy before conversion). Securing this additional bioenergy will be an enormous challenge (see Part II).

2.3 Energy scenarios for carbon neutrality in 2050

The time horizon is now extended to 2050 by exploring scenarios to achieve carbon neutrality, building on the CleanBC framework. Accelerated reduction of energy demand is no less indispensable. Therefore, all the scenarios assume that energy demand will decrease by 25% in buildings and 50% in other sectors by 2050. Light-duty vehicles will be 100% electric [4]. Following the BC Hydrogen Strategy, GHG reduction of 7.2 Mt [3] will be achieved through using hydrogen, by replacing diesel fuel in 88% of the heavy-duty vehicle fleet. This will require 50.7 PJ of blue hydrogen. Methane emissions from industries and waste management are assumed to be reduced by 95%. To illustrate the problems, two extreme scenarios are considered – maximum electrification and maximum use of bioenergy – but the most realistic scenarios are likely to lie between the two.

2.3.1 Scenario 5: Carbon neutrality via enhanced electrification

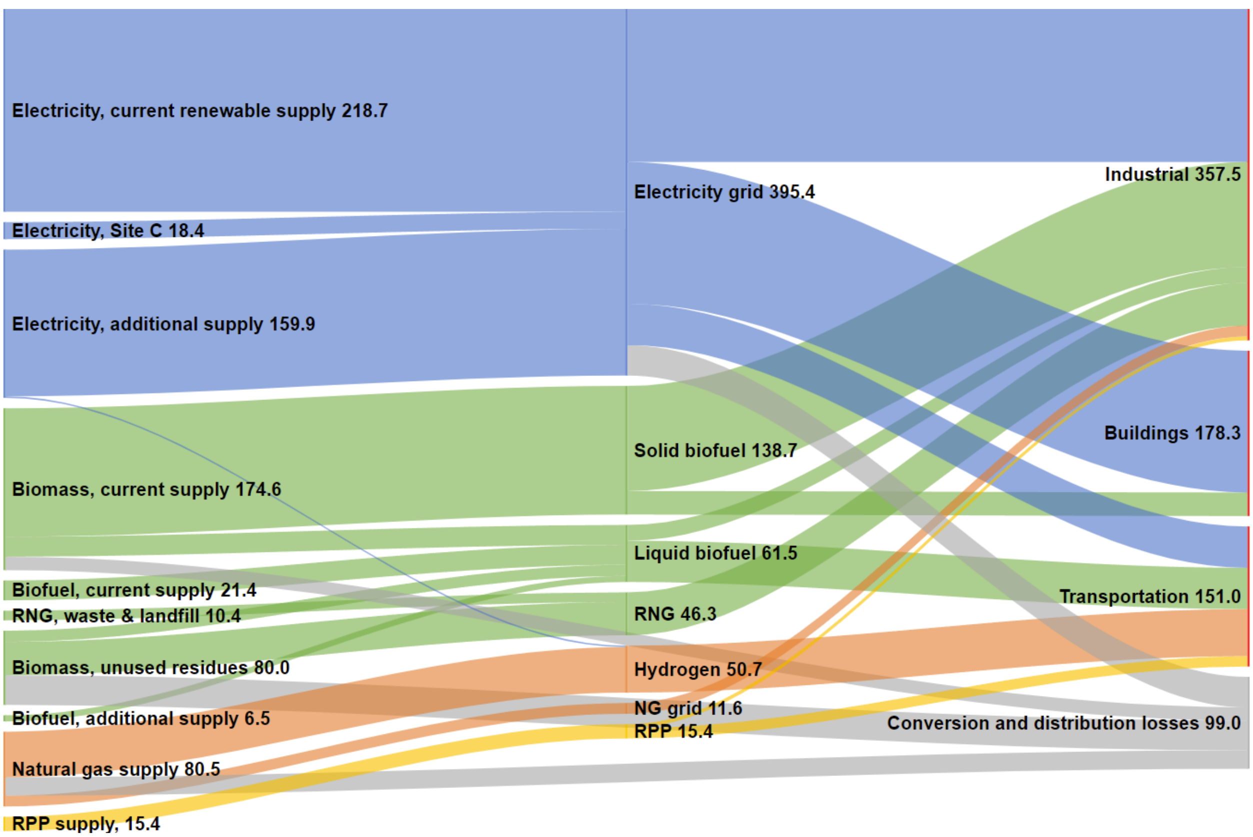


Figure 2-7 Scenario 5 (Carbon neutrality with electrification strategy)

In Scenario 5, shown in Figure 2-7, GHG mitigations beyond CleanBC are assumed to be achieved mainly by electrification, with the most efficient options prioritized in each sector. Heat pumps and EVs eliminate fossil fuel consumption in buildings and transportation, respectively. Electric motors eliminate industrial fossil fuel consumptions for motive power, including RPP for industrial machinery and hauling and natural gas for fluid compression in the oil and gas industry. However, natural gas use in manufacturing is mostly for thermal energy: high-temperature heating and kilns. In the absence of data on use in different applications, it is assumed here that the use of electric motors will displace 70% of natural gas and 80% of RPPs used throughout industry. For the remaining fossil fuel usage, it is assumed that low-carbon fuel standards for liquid fuels and natural gas will be increased to 80%. Taken together, these measures can mitigate GHG emissions from energy by more than 90%. Potential emissions from the remaining fossil fuel uses and non-energy sources are estimated to be 8 Mt, but are assumed to be eliminated by CCS.

As shown in Figure 2-7, 160 PJ of additional renewable electricity supply will be needed for the electrification strategy in Scenario 5, equivalent to the output of nine projects on the scale of Site C. While such dramatic expansion of renewable electricity may be technically possible, the investment needed is huge and action needs to start immediately. If the entirety of the additional supply is provided by intermittent wind and solar generation, the share of intermittent electricity in BC's grid will reach 40% by 2050, leading to difficult but accomplishable challenges to grid management (see Part II). However, in spite of the increase in low carbon fuel standards for liquid and gaseous fuels, the demand for bioenergy will be only slightly above current levels, mostly due to increased electrification and reduced overall energy demand, and should be easily manageable. Most natural gas will be used for hydrogen production; together with CCS at stationary sources, this should be technologically straightforward. Only 27.0 PJ of fossil fuels will be used in conventional industrial applications, with the GHG emissions mitigated by technologies involving direct air capture.

2.3.2 Scenario 6: Carbon neutrality through increased use of bioenergy

In Scenario 6, shown in Figure 3-8, carbon neutrality is achieved through enhanced production and use of bioenergy. Biomass-fired district heating systems, especially sufficiently large to incorporate pre-gasification for lower air emissions [8], and industrial gasification-combustion systems are further promoted to replace 60% of natural gas consumption in buildings and industries, due to their high conversion efficiencies. Low carbon fuel standards are increased to 100% to eliminate fossil fuels. The remaining 6.6 Mt of GHG emissions will be mitigated by CCS. This strategy will require an additional supply of 155 PJ of liquid biofuels (258 PJ of primary bioenergy before conversion) plus 202 PJ of solid biomass. As stated in Section 3.2.1, production of biomass is subject to restrictions of land availability and GHG emissions from land-use change. Therefore, securing such a large additional bioenergy supply sustainably within BC, through utilization of waste biomass and plantation of energy crops, is speculative.

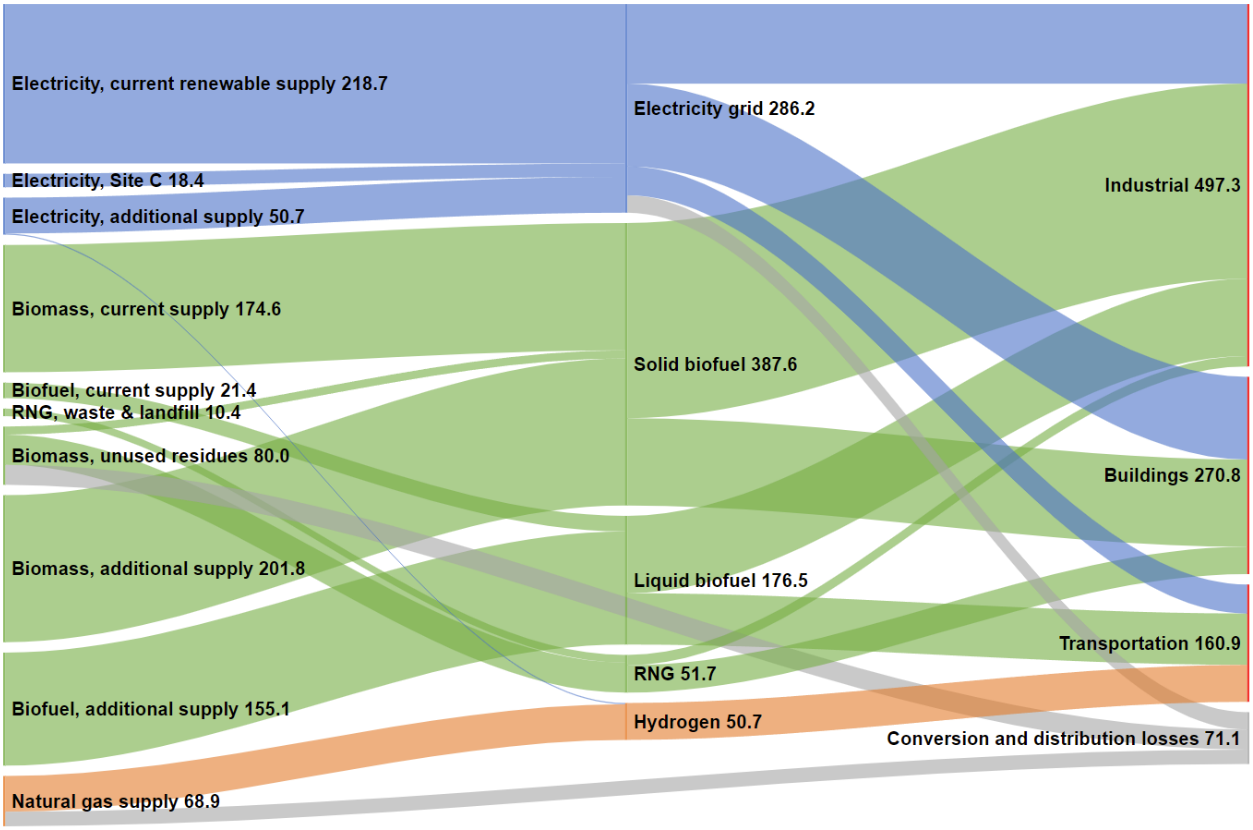


Figure 2-8 Scenario 6 (Carbon neutrality with promotion of bioenergy)

2.4 Discussion

Scenarios 3 and 5 represent maximal use of low-carbon electricity while scenarios 4 and 6 include maximum use of bioenergy. They show that any strategy relying primarily on either electrification or bioenergy faces enormous supply problems. The most realistic ways to decarbonize the energy system beyond the CleanBC action plans will no doubt lie between these extremes. However, the main conclusion remains: all available bioenergy and electricity resources need to be exploited to meet the province's targets.

The various electrification, bioenergy, and hydrogen options differ significantly in the efficiency of energy use. The scenarios all assume that, to minimize primary energy demand, the most efficient technologies are preferred: electric heat pumps and motors, biomass-fired heating system, and hydrogen fuel cells. Actual energy demand will be even higher if less efficient options are deployed: electric resistance heating, refined biofuels, and hydrogen combustion. Similarly, hydrogen is assumed to be produced by the most efficient route: steam-methane reforming (SMR) of natural gas combined with Carbon Capture and Sequestration (CCS). Using electrolysis or biomass gasification would raise future demands for renewable energy even further and diminish the role natural gas can play in a carbon-neutral economy.

Table 2-2 Impact of energy demand reduction on renewable energy needed in addition to supply in 2019, electricity from Site C project and bioenergy from existing waste streams

Demand reduction by 2030		15%	20%	25% (base)	35%	35%
Additional supply (PJ) in Scenario 3:	Electricity	79	69	59	49	38
	Liquid biofuel	96	80	63	47	30
	Solid biomass	0	0	0	0	0
Additional supply (PJ) in Scenario 4:	Electricity	46	36	26	16	5
	Liquid biofuel	122	114	106	97	89
	Solid biomass	100	87	73	60	46
Demand reduction by 2050		**40%**	**45%**	**50% (base)**	**55%**	**60%**
Additional supply (PJ) in Scenario 5:	Electricity	221	190	160	129	99
	Liquid biofuel	42	24	7	-11	-21
	Solid biomass	0	0	0	0	-13
Additional supply (PJ) in Scenario 6:	Electricity	83	67	51	35	19
	Liquid biofuel	211	183	155	127	99
	Solid biomass	274	244	202	155	108

Furthermore, all the Scenarios include accelerated energy demand reduction. A sensitivity analysis has been carried out to investigate the significance of reducing overall energy demand. As shown in Table 3-2, for every 5% of further reduction in overall energy demand, the additional renewable electricity supply required to achieve BC's 2030 target can be reduced by 10 PJ, with similar reductions in demand for biomass and biofuels. Demand reductions for the 2050 scenarios are even larger. Therefore, progressive reduction of overall energy demand is essential to meet BC's GHG targets for 2030 and beyond. This challenging task requires substantial efficiency improvement and also behavioral changes induced by more stringent policy measures.

3. Clean Energy Sources for BC

A full assessment of potential sources of low-carbon energy in BC is set out in the accompanying document: "Part II: Clean Energy Strategies for Mitigating Greenhouse Gas Emissions in British Columbia". A summary is provided here.

BC has enormous potential for bioenergy production. Waste biomass available in BC could provide about 20% of the energy currently provided by fossil fuels [9]. The main source is unused wood residues generated during logging and sawmilling; this material is currently destroyed by slash burning, to ensure that it does not provide a potential fuel for wildfires. Trees killed by mountain pine beetle infestation are another source, although long-term availability is uncertain. Waste biomass is available in animal manure, crop residues, and the organic fraction of municipal solid waste (MSW). Energy crops, such as short-rotation coppice, could also be produced [10].

Most of the available biomass is lignocellulosic ("woody"). It can be used directly as fuel for generation of electricity or heat, gasified to produce Renewable Natural Gas (RNG) or liquid fuels including methanol and ethanol, or pyrolyzed to produce a range of liquid biofuels including aviation fuel. Following a general principle, the greatest GHG mitigation with the lowest cost is achieved by the simplest processes: direct use as fuel, including for district and industrial heating [9]. Syngas combustion generates lower health impacts [8]. Converting biomass to refined biofuels has lower efficiency and much higher costs [11].

Animal manure and food waste can be processed into biogas by anaerobic digestion. The gas can be used directly to generate heat and/or electricity or can be upgraded to RNG, and the digestate residue can be used to displace synthetic fertilizers. The greatest GHG mitigation at the lowest cost results from using the biogas in integrated operations combining animal husbandry, glasshouse cultivation and, preferably, mushroom production, following the industrial symbiosis principle [12], [13]. Upgrading the biogas to RNG brings lower GHG benefits at higher cost [13].

It has been demonstrated in Section 2 that even with the Site C project completed and radical energy demand reduction, BC will not have surplus renewable electricity, as future electricity demands will dramatically increase. Other primary energy sources must therefore be explored. Wind energy could make a significant contribution in BC [7]. Solar Photovoltaic production is less favourable in BC [2] but can be deployed in niche applications, such as local uses for charging electric vehicles, as well as in large solar farms linked to the grid. Increasing wind and solar will increase the proportion of intermittent generation in the provincial grid way beyond the present level of 2.5% but, based on experience elsewhere, at least 20% should be readily manageable. Combined heat and power generation, providing dispatchable renewable electricity and low-carbon steam/heat to industrial operations, should be retained and possibly increased.

Given that the demand for renewable electricity is expected to rise in the future, the most effective uses should be prioritised. For land transport, this means powering electric vehicles, which is more energy-efficient than using electricity to produce liquid fuels (“electrofuels”). For industrial applications, replacing natural gas and diesel engines by electric motors is the preferred use. In buildings, the preferred use is in heat pumps to replace resistive and gas-fired heaters.

Hydrogen is an energy carrier that can be produced from different primary energy sources: electricity, by electrolysis of water; biomass, by gasification; or natural gas, by steam methane reforming [3]. Given the scarcity of renewable electricity and biomass in BC and the need to mitigate GHG emissions, “blue” hydrogen, which is produced from natural gas with the CO_2 sequestered, is recommended; this represents the only sizeable use for natural gas consistent with a low-carbon economy. The hydrogen is recommended for powering fuel cell vehicles, preferably heavy-duty ones, to replace internal combustion engines. Direct combustion of hydrogen is not a preferred use because it loses the advantage of fuel cells and is less efficient than direct use of the primary energy from which the hydrogen is produced.

4. Conclusions and Recommendations

The two phases of CleanBC include a full suite of policy measures for promoting renewable energy and reducing methane emissions and thus represent firm steps towards achieving BC's 2030 GHG mitigation target. However, a problem in the CleanBC framework is the lack of comprehensive action to address the growth of energy demand in BC associated with growth in economic activity and population. Even though the CleanBC Roadmap attempts to reduce energy use in the transportation sector, similar action plans in buildings and industries are lacking. Scenario 1 shows clearly that the CleanBC framework, together with moderate demand reduction of 5% by 2030, is unable to reach the 2030 target. In all the other scenarios, rapid demand reduction of 25% by 2030 and 50% by 2050 is assumed, but the current supply of renewable electricity and bioenergy is still far from enough to meet the growing needs. The additional supply of renewable energy needed for BC's GHG mitigation targets will be immense.

The extent of demand reduction achievable in 2030 and 2050 cannot be predicted reliably, but any further demand reduction moves closer to meeting GHG mitigation targets. Naturally driven by desire for lower cost, energy efficiency can be expected to improve continuously but slowly. Decoupling energy demand from economic and population growth needs stringent policy measures to achieve transformational rather than incremental change. Growth in demand in BC is predicted to arise mainly for heating, mobility, and industrial production. Energy consumption for home heating and personal mobility is largely a matter of behavioral change, which may be induced by both voluntary desire for a sustainable future and involuntary policy measures.

Electrification is seen as a core strategy for GHG mitigation in BC. With radical demand reduction and electrification-centered strategy, an additional electricity supply of about 60 PJ will be needed for BC's 2030 target, and 160 PJ for carbon neutrality in 2050. These numbers are obtained from hypothetical scenarios, but show that the current electricity supply is clearly insufficient. The new projects needed will be comparable in magnitude to the output of the Site C project, i.e., hundreds of wind turbines and millions of solar panels, representing both challenges and opportunities for utilizing all the available wind, solar, and hydroelectric generation resources in BC. On the other hand, as electrification progresses, the demand for conventional fuel and consequently biofuels for blending will be expected to peak and decline. By 2050, currently available biomass residues will meet demand for bioenergy if the electrification-centered strategy is implemented.

The bioenergy-centered strategy is an alternative to a strategy dominated by electrification. It would dramatically increase demand for bioenergy. As the first step, it must fully exploit existing waste biomass, including wood residues, agricultural waste, food waste, and landfill gases. In addition to securing sustainable bioenergy supply, this would reduce atmospheric emissions of non-GHG pollutants. Even so, roughly 250 and 450 PJ of additional primary bioenergy supply will be needed for BC's 2030 target and carbon neutrality in 2050, respectively. Provision of such a large quantity of biomass is well beyond foreseeable waste collection from BC's current forestry and agricultural sectors. To further expand bioenergy supply, the sustainability of forest and farmland management and emissions from land-use changes must be carefully investigated.

Hence, strategies that rely solely on either renewable electricity or bioenergy will raise demand for the respective renewable energy beyond sustainable and manageable levels. Therefore, there is no single 'silver bullet' renewable energy source to meet BC's GHG mitigation targets: it is essential to utilize all the available bioenergy and renewable electricity resources and promote a balanced renewable energy portfolio. The limited time frame to 2030 emphasizes the difficulty of securing the renewable energy needed. For the long-term target of carbon neutrality, the supply problems emphasize the need for a balanced renewable energy strategy.

References

[1] British Columbia, "Provincial greenhouse gas emissions inventory," 2021. https://www2.gov.bc.ca/gov/content/environment/climate-change/data/provincial-inventory (accessed Nov. 24, 2021).

[2] Canada Energy Regulator, "Canada's Energy Future 2020," 2020. [Online]. Available: https://www.cer-rec.gc.ca/en/data-analysis/canada-energy-future/2020/index.html.

[3] British Columbia, "B.C. Hydrogen Strategy," 2019.

[4] British Columbia, "CleanBC Roadmap to 2030," 2021.

[5] Canada Energy Regulator, "Canada's Energy Future 2019," 2019.

[6] R. Clift, H. Wang, X. Bi, J. Bulkan, D. Roeser, T. Sowlati, K. Kunzler, "How a missing group of agents inhibits development of the bioenergy sector in British Columbia," in *7th Social LCA Conference*, 2020.

[7] IEA, "Renewables 2021 - Analysis and forecast to 2026," 2021.

[8] O. Petrov, X. Bi, and A. Lau, "Impact assessment of biomass-based district heating systems in densely populated communities. Part I: Dynamic intake fraction methodology," *Atmos. Environ.*, vol. 115, pp. 70–78, 2015, doi: 10.1016/j.atmosenv.2015.05.036.

[9] H. Wang, S. Zhang, X. Bi, and R. Clift, "Greenhouse gas emission reduction potential and cost of bioenergy in British Columbia, Canada," *Energy Policy*, vol. 138, 2020, doi: 10.1016/j.enpol.2020.111285.

[10] M. Labrecque and T. I. Teodorescu, "High biomass yield achieved by Salix clones in SRIC following two 3-year coppice rotations on abandoned farmland in southern Quebec, Canada," *Biomass and Bioenergy*, vol. 25, no. 2, pp. 135–146, 2003, doi: 10.1016/S0961-9534(02)00192-7.

[11] H. Wang, X. Bi, and R. Clift, "Utilization of forestry waste materials in British Columbia: Options and strategies," *Renew. Sustain. Energy Rev.*, vol. 150, 2021, doi: 10.1016/j.rser.2021.111480.

[12] S. Zhang, H. Wang, X. Bi, and R. Clift, "Synthesis and Assessment of a Biogas-Centred Agricultural Eco-Industrial Park in British Columbia," *J. Clean. Prod.*, vol. 321, 2021.

[13] H. Wang, X. Bi, and R. Clift, "A case study on integrating anaerobic digestion into agricultural activities in British Columbia: Environmental, economic and policy analysis," *Environ. Pollut.*, vol. 271, 2021, doi: 10.1016/j.envpol.2020.116279.