SUPPLEMENTAL MATERIALS

FOR

THE FUTURE OF FREIGHT

PART C: IMPLICATIONS FOR ALBERTA OF ALTERNATIVES TO DIESEL

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A project associated with

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1. Introduction

This document provides additional details and references behind the results and conclusions contained in the following **CESAR Scenario** report:

> Layzell DB, Lof J, McElheran K, Narendran M, Belanger N, Straatman B, Sit S. 2020. **The Future of Freight Part C:** Implications for Alberta of Alternatives to Diesel. CESAR Scenarios Vol 5, Issue 1: 1-58 https://www.cesarnet.ca/sites/default/files/pdf/cesar-scenarios/CESAR-Scenarios-Future_of_Freight_C.pdf [1]

Section 2 of this document provides details on some of the calculations behind the incumbent fossil diesel to Internal combustion Engine (FD-ICE) energy system that is used to set the bar for the deployment of a future energy system.

Subsequent sections in this document summarize the calculations for the bio-based diesel, to internal combustion engine (BD-=ICE) energy system (Section 3), the Grid to battery electric (G-BE) energy system (Section 4), the natural gas to hydrogen fuel cell electric (NG-HFCE) energy system (Section 5) and the Wind and Solar to hydrogen fuel cell electric (WS-HFCE) energy system (Section 6).

2. Setting the Bar: Alberta and the Supply of North American Diesel.

Table S1 shows the origin of some of the key numbers behind Figure 2.2A in Layzell et al. 2019 [1]

Table S1: Alberta Crude Production and Refining

Item	Parameter	Unit	Value	Note
1	Alberta Crude Production in 2016	PJ/y	7,871	{1}
2	*Light/Med*		*780*	
3	*Heavy*		*299*	
4	*SCO*	*PJ/y*	*2,036*	{2}
5	*Synbit*		*473*	
6	*Dilbit*		*4,283*	
7	Refinery Input	PJ/y	8,173	{3}
8	*AB Crude*	*PJ/y*	*7,871*	{4}
9	*Other Feed stock and Fuels*		*302*	{5}
10	Refinery Output from AB Crude	PJ/y	6,972	{6}
11	*Diesel*		*2,286*	
12	*Gasoline*	*PJ/y*	*2,799*	{7}
13	*Aviation Fuel*		*262*	
14	*Other RPP*		*1,624*	

Notes:

{1} *Item 1 = Sum (Items 2 to 6).*

{2} Based on AER's ST3: Alberta Energy Resource Industries Monthly Statistics [2].

{3} *Item 7 = Sum (Items 8 to 10).*

{4} *Item 8 = Item 1.*

{5} Adapted from refinery model built using data from the EIA [3]–[7], data from GHGenius [8], and Statistics Canada energy input/output tables [9]–[11]; includes all other sources of input energy (hydrogen, oxygenates, NG, still gas, coal, electricity, steam, etc.).

{6} *Item 10 = Sum (Items 11 to 14).*

{7} Based on North American crude oil and RPP flows attributable to Alberta crude production; calculated using the following sources: oil imports and exports reported by NEB [12] and Statistics Canada [13], oil and RPP disposition by refinery/region from Statistics Canada [10], and RPP proportions in refinery output by region adapted from GHGenius [8].

Table S2 and S3 provide details associated with Figure 2.2C and 2.3, respectively in Layzell et al., (2019)[1].

Table S2: Alberta Diesel Consumption

Item	Parameter	Unit	Value	Note
1	Diesel Production from AB Crude	PJ/y	2,286	{1}
2	Diesel Demand in AB	PJ/y	258	{2}
3	*HDV*		*97*	
4	*Other Road Freight*		*43*	
5	*Other Freight Transp.*	*PJ/y*	*27*	{3}
6	*Passenger*		*10*	
7	*Other Uses*		*81*	
8	Ratio of Production to AB Demand		8.9	{4}

Notes:

{1} *Item 1 = Table S1 Item 11.*

{2} *Item 1 = Sum (Items 3 to 7).*

{3} 2016 values reported by StatsCan [14].

{4} *Item 8 = Item 1/Item 2*, for simplicity, this study uses "9x AB" to denote energy from all diesel produced from AB crude.

Table S3: Kinetic Energy Targets

Item	Parameter	Unit	Value	Note
1	Kinetic Energy from Diesel Consumed in AB (1x AB)			
2	*HDV Demand Only*	*PJ/y*	*34*	{1}
3	*All Diesel Demand*		*90*	{2}
4	Kinetic Energy from All Diesel Produced from AB crude (9x AB)			
5	*HDV Demand Only*	*PJ/y*	*300*	{3}
6	*All Diesel Demand*		*800*	{4}

Notes:

{1} *Item 2 = Table S2 Item 3 x 0.35*, where 35% = the efficiency of an FD-ICE powertrain [15].

{2} *Item 3 = Table S2 Item 2 x 0.35*, just as in {1}.

{3} *Item 3 = Table S2 Item 3 x Table S2 Item 8 x 0.35*, just as in {1}.

{4} *Item 3 = Table S2 Item 2 x Table S2 Item 8 x 0.35*, just as in {1}.

The calculations and data sources behind Figure 2.4 in Layzell et al, (2019) [1] are summarized in Table S4.

Table S4: Emissions from FD-ICE

Item	Parameter	Unit	Value	Note
1	Total Emissions	kt CO_2e/PJ diesel	96	{1}
2	*Crude extraction, upgrading, refining & transport*	*kt CO_2e/PJ diesel*	*21*	{2}
3	*Upstream*		*4*	
4	*Combustion*		*71*	{3}
5	Emissions from AB diesel consumption (1x AB)			
6	*HDV only*	*Mt CO_2e/yr*	*9*	{4}
7	*All Diesel*		*25*	{5}
8	Emissions from diesel produced from AB crude (9x AB)			
9	*HDV only*	*Mt CO_2e/yr*	*83*	{6}
10	*All Diesel*		*220*	{7}

Note:

{1} *Item 1 = Sum(Items 2 to 4)*

{2} Adapted from IHS Energy report on GHG intensity of oil production [16].

{3} Combustion emissions for heavy-duty diesel vehicles from Canada's National Inventory Report (NIR) 2018, Annex 6 Table A-16 [17].

{4} *Item 6 = Item 1 x Table X2 Item 3*

{5} *Item 7 = Item 1 x Table X2 Item 2*

{6} *Item 9 = Item 1 x Table X2 Item 3 x Table X2 Item 8*

{7} *Item 10 = Item 1 x Table X2 Item 2 x Table X2 Item 8*

3. Bio-Based Diesel to Internal Combustion Engine (BD-ICE) Energy System

The calculations and data sources behind Figure 4.2 in Layzell et al (2019) [1] are summarized in Table S5.

Table S5: Potential for Biodiesel from Canola in AB

Item	Parameter	Units	Value					Note
1	Crop Yield for Canola Seed	t seed/ha	1.4					{1}
2	Oil Content of Canola	t oil /t seed	0.4					
3	Canola Oil to Biodiesel Conversion	t biodiesel/t oil	1.0					{2}
4	Biodiesel Yield from Canola Oil/ha	t biodiesel/ha	0.6					{3}
5	Energy Content of Biodiesel	GJ_{HHV}/t biodiesel	39.8					{1}
6	Biodiesel Energy Yield/ha	GJ_{HHV} biodiesel/ha	22.7					{4}
			Current	1X Alberta		9X Alberta		
				HDV	All Diesel	HDV	All Diesel	
7	Canola Oil Production for Food	PJ/yr	50	50	50	50	50	{5}
8	Canola Oil Production for Biodiesel	PJ/yr	4.4	97	258	859	2287	{6}
9	**Total**		**55**	**146**	**307**	**908**	**2337**	
10	Total Agricultural Land in Alberta	Mha/yr	20.3					{7}
11	Total Cropland in Alberta	Mha/yr	10.2					{8}
12	Cropland in Canola Production	Mha/yr	2.4					{7}
13	Cropland in Canola Production for Food	Mha/yr	2.2	2.2	2.2	2.2	2.2	{9}
14	Cropland in Canola Production for Biodiesel	Mha/yr	0.2	4.3	11.4	37.9	100.8	{10}
15	**Total**		**2.4**	**6.4**	**13.5**	**40.0**	**103.0**	
16	Proportion of AB Cropland in Canola	%	24%	63%	133%	393%	1010%	{11}

Notes:

{1} Taken from E.G. Smith et al. [18].

{2} Assuming 1 t oil + 0.1 t methanol yields 1 t biodiesel + 0.1 t glycerol, referring to E.G. Smith et al. [18].

{3} *Item 1 × Item 2 × Item 3.*

{4} *Item 4 × Item 5.*

{5} *Item 13 × Item 6.*

{6} Calculated as Current Production (ML/yr) [19] × Biodiesel Energy Density (MJHHV/L) [20] ÷ 1000 = 126 x 35 ÷ 1000 = 5.3.

{7} From Statistics Canada [14].

{8} Data from Statistics Canada, Land Use Table [21].

{9} *Item 12 - Item 14.*

{10} Current amount is converted into Mha/yr by *Item 8 ÷ Item 6*. The projected amounts refer to *Item 8 ÷ Item 6* across the row.

{11} *Item 15 ÷ Item 11.*

The calculations and data sources behind Figure 4.3 in Layzell et al. (2019) [1] are summarized in Table S6.

Table S6: Annual Biomass Residue Availability

Item	Feedstock	Feedstock Energy Content {1}	Canada		Alberta		Note
			Resource Potential	Energy Potential	Resource Potential	Energy Potential	
		GJ_{HHV}/dry t	Mt dry/yr	PJ/yr	Mt dry/yr	PJ/yr	
From Forestry			*56*	*1132*	*8*	*159*	
1	Forest Residues	20.1	19	377	3	58	{2}
2	Forests Killed by Fire	20.1	2	43	0	5	{3}
3	Pest/Disease Killed Forests	20.1	2	42	0	9	{4}
4	Unused AAC + Residues	20.1	33	670	4	86	{5}
From Agriculture			*71*	*1258*	*13*	*236*	
6	Crop Residues	18.0	62	1125	12	214	{6}
7	Livestock Manure	16.6	8	133	1	22	{7}
From Municipal Wastes and Biosolids			*6*	*131*	*1*	*21*	
9	Ind'l/Municipal Waste	20.1	6	131	1	21	{8}
11	TOTAL (ALL)		133	2521	22	415	

Notes:

{1} HHV values for forestry and municipal waste sections from elemental composition equation of C. Sheng et al. [22]; crop residue from Klass [23], and manure from [24] and [25].

{2} Calculated from Statistics Canada average forest production volume (2010 to 2014; m^3/yr) assuming residues = 40% of production volume, but only 63% of residues are available. To convert residue volume to dry biomass, assumes 0.5 t (dry) / m^3. (J Stephens, Torchlight, pers. Comm.).

{3} Data on forest area killed from National Forestry Database, Table 3.1 [26], assuming 100 m^3 biomass/ha, density of 0.325 t (wet) biomass/m^3 and 50% water content to give t (dry) biomass/yr. Then assumes 50% of biomass is available as residues from burned trees and 50% of the residue portion can be removed.

{4} Data on area of moderate to severe defoliation and beetle-killed trees by major insects from National Forestry Database, Table 3.1 [26], assuming 100 m^3 biomass/ha, density of 0.325 t (wet) biomass/m^3 and 50% water content to give t (dry) biomass/yr. Then assumes 25% of infected trees are killed and 50% of those trees are available for removal.

{5} Data on average forest production volume (m^3/yr) in Alberta and Canada from (J Stephens, Torchlight, pers. Comm.) The annual allowable cut (AAC) data is from National Forestry Database [26]. Assumes that the extra trees from the AAC areas are harvested, including the residues.

{6} Data on crop yield (t (wet)/yr) and land areas from Statistics Canada, Table: 32-10-0359-01 [27], converted to t (dry) yield/yr assuming initial moisture content from literature [28]–[32]. Then residues (t (dry)/yr) calculated from straw : yield ratios [33], [34] before finally subtracting a proportion (ca 1-1.5 t (dry)/ha) of residues not accessible as they were needed to maintain soil carbon [35].

{7} Selected livestock and poultry animal numbers from Statistics Canada. Table 32-10-0155-01 [36] was used to calculate manure production based on data from [25] and [24] to give t (wet) manure/yr. Assuming moisture content from [37], [38], estimates of recoverable manure, and manure energy content in GJHHV/t (dry) from [18], estimates were made of GJHHV manure available per year.

{8} Disposal of waste (t (wet)/yr), by source from Statistics Canada, Table: 38-10-0032-01 [39] were adjusted to account for materials diverted, by type, Table: 38-10-0034-01 [40] to give total waste that goes to landfill. Assumes 33% of landfill waste is wood or paper with a 22.5% water content to calculate t (dry) waste wood or paper /yr.

The calculations and data sources behind Figure 4.4 in Layzell et al. (2019) [1] are summarized in Table S7.

Table S7: Annual Bio-Based Diesel Production Potential and Demand

Item	Parameter	Units	Value	Note
1	Annual Lignocellulosic Biomass Availability in AB	PJ/yr	415	{1}
2	Output from Fischer-Tropsch Synthesis of Biomass Residue			
3	*Maximum Bio-Based Diesel Production*	*PJ/yr*	*161*	{2}
4	*Other Energy Products*	*PJ/yr*	*49*	{3}
5	Bio-Based Diesel Required to Replace Fossil Diesel Demand in AB (1x AB)			
6	*HDV Only*	*PJ/yr*	*97*	{4}
7	*All Diesel*	*PJ/yr*	*258*	{5}
8	Bio-Based Diesel Required to Replace all Fossil Diesel Produced from AB Crude (9x AB)			
9	*HDV Only*	*PJ/yr*	*858*	{6}
10	*All Diesel*	*PJ/yr*	*2286*	{7}

Notes:

{1} From Table S6 Item 11 (Total AB Energy Potential).

{2} *Item 3 = Item 1 x 0.388*, where 38.8% = the conversion efficiency of biomass residue to bio-based diesel via FT-synthesis [41].

{3} *Item 4 = (Item 1 x 0.51) - Item 3*, where 51% = the conversion efficiency of biomass residue to all output energy products via FT-synthesis [41].

{4} *Item 6 = Table S2 Item 3.*

{5} *Item 7 = Table S2 Item 4.*

{6} *Item 9 = Item 6 x Table S2 Item 8.*

{7} *Item 10 = Item 7 x Table S2 Item 8.*

The calculations and data sources behind Figure 4.5 in Layzell et al. (2019) [1] are summarized in Table S8.

Table S8: Annual Emissions of BD-ICE Energy System

Item	Parameter	Units	Value				Note
1	Emissions per Unit Energy	kt CO_2bio/PJ	184				{1}
2	*Upstream and FT Process*	*kt CO_2bio/PJ*	*113*				{2}
3	*Bio-Based Diesel Transport*		*0.3*				
4	*Combustion*		*71*				
5	Annual Emissions						
6	*1x AB, HDV Only*	*Mt CO_2bio/yr*	*17.8*				{3}
7	*1x AB, All Diesel*		*47.5*				{4}
8	Global Warming Potential (GWP)	Mt CO_2e/ Mt CO_2bio	0	0.2	0.4	1	{5}
9	Annual Emissions						
10	*1x AB, HDV Only*	*Mt CO_2e/yr*	*0.0*	*3.6*	*7.1*	*17.8*	{6}
11	*1x AB, All Diesel*		*0.0*	*9.5*	*19.0*	*47.5*	{7}

Notes:

{1} *Item 1 = Sum (Items 2 to 4).*

{2} From analysis done for The Future of Freight B [42].

{3} *Item 6 = Item 1 x Table S7 Item 6.*

{4} *Item 6 = Item 1 x Table S7 Item 7.*

{5} Range of Global Warming Potential multipliers deemed reasonable based on literature [43]–[47].

{6} *Item 10 = Item 6 x Item 8.*

{7} *Item 11 = Item 7 x Item 8.*

4. Grid to Battery Electric (G-BE) Energy System

The calculations and data sources behind Figure 5.1 in Layzell et al. (2019) [1] are summarized in Table S9.

Table S9: Annual Grid Generation Required to Replace Fossil Diesel

Item	Parameter	Units	Value	Note
1	2016 Public Grid Generation	TWh/yr	62.5	{1}
2	Grid Generation Required to Replace Fossil Diesel Demand in AB (1x AB)			
3	*HDV Only*	*TWh/yr*	15.4	{2}
4	*All Diesel*	*TWh/yr*	40.9	{3}
5	Grid Generation Required to Replace all Fossil Diesel Produced from AB Crude (9x AB)			
6	*HDV Only*	*TWh/yr*	138	{4}
7	*All Diesel*	*TWh/yr*	368	{5}

Notes:

{1} From AESO 2017 Annual Market Statistics [48].

{2} *Item 3 = Table S3 Item 2 / (0.68 x 0.90 x 3.6 PJ/TWh),* where 68% = the powertrain efficiency of a battery electric vehicle and 90% = grid transmission efficiency [42].

{3} Item 4 = Table S3 Item 3 / (0.68 x 3.6 PJ/TWh), just as in {2}.

{4} *Item 6 = Item 3 x Table S2 Item 8*.

{5} *Item 7 = Item 4 x Table S2 Item 8*.

The calculations and data sources behind Figure 5.2 in Layzell et al. (2019) [1] are summarized in Table S10.

The calculations and data sources behind Figure 5.4 in Layzell et al. (2019) [1] are summarized in Table S11.

Table S10: Grid Intensity and Total Emissions - 2016 and 2030 (Projection)

Source	2016		2030	
	Gen. % {1}	**Carbon Intensity**	**Gen. %** {2}	**Carbon Intensity**
	%	$kgCO_2e/MWh$	%	$kgCO_2e/MWh$
Coal	61%	1008	0%	1008
Cogen	17%	350	20%	350
CC	9%	390	46%	390
SC	1%	525	4%	525
Hydro	3%	0	3%	0
Wind	7%	0	24%	0
PV	0%	0	1%	0
Biomass/Other	1%	0	2%	0
Imports	0.7%	0	0%	0
Total	**100%**	**719**	**100%**	**270**

Notes:

{1} Based on AESO Annual Market Statistics 2017 [48].

{2} CESAR projection; 70% NG and 30% renewables.

Table S11: Annual Emissions from Grid Generation Required to Replace Fossil Diesel

Item	Parameter	Units	Value	Note
1	Emissions from Grid Generation Required to Replace Fossil Diesel Demand in AB (1x AB)			
2	*HDV Only*	*Mt CO_2e/yr*	4.52	{1}
3	*All Diesel*	*Mt CO_2e/yr*	12.0	{2}
4	Emissions from Grid Generation Required to Replace All Fossil Diesel Produced from AB Crude (9x AB)			
5	*HDV Only*	*Mt CO_2e/yr*	40.7	{3}
6	*All Diesel*	*Mt CO_2e/yr*	108	{4}

Notes:

{1} Item 2 = Table S9 Item 3 x (270 + 23.8) kg CO2e/TWh x 10-9 Mt/kg, where 270 kg CO2e/TWh = GHG intensity of a future AB grid comprised of 70% NG based generation and 30% renewable generation (see Table S10), and 23.8 kg CO2e/TWh = upstream GHG intensity of grid generation (mainly from NG production and processing) [49].

{2} Item 3 = Table S9 Item 4 x (270 + 23.8) kg CO2e/TWh x 10-9 Mt/kg, just as in {1}.

{3} Item 5 = Item 3 x 9.

{4} Item 6 = Item 4 x 9.

5. Natural Gas to Hydrogen Fuel Cell Electric (NG-HFCE) Energy System

The calculations and data sources behind Figure 6.1 and 6.2 in Layzell et al. (2019) [1] are summarized in Table S12.

Table S12: NG to H_2 required to replace fossil diesel

Item	Parameter	Unit	Value	Note
1	Alberta NG production (2016)	PJ/yr	4,378	{1}
2	Alberta NG demand (2016)	PJ/yr	2,195	{2}
3	*Residential, Commercial & Transport*		*407*	
4	*Oil Sands*		*664*	
5	*Industrial*	*PJ/yr*	*491*	{3}
6	*Electrical Gen.*		*360*	
7	*Reprocessing Shrinkage (NGL extraction)*		*273*	
8	H_2 required to replace AB fossil diesel demand (1x AB)			
9	*HDV Only*	*PJ/yr*	*76*	{4}
10	*All diesel*		*202*	{5}
11	H_2 required to replace all fossil diesel produced from AB crude (9x AB)			
12	*HDV Only*	*PJ/yr*	*683*	{6}
13	*All diesel*		*1,817*	{7}
14	NG required to produce H2 (1x AB)			
15	*HDV Only*	*PJ/yr*	*98*	{8}
16	*All diesel*		*260*	{9}
17	NG required to produce H2 (9x AB)			
18	*HDV Only*	*PJ/yr*	*881*	{10}
19	*All diesel*		*2,342*	{11}

Note:

{1} *Item 1 = 299 m^3/d x 365 d/yr x 40.14 MJ_{HHV}/m^3*, where 299 m^3/d = Alberta NG production as reported by the Alberta Energy Regulator [1], and 40.14 MJ_{HHV}/m^3 = energy density of natural gas [2].

{2} *Item 2 = Sum (Items 3 to 7)*

{3} 2016 Alberta NG demand as reported by Alberta Energy Regulator [2], Fig S5.6

{4} *Item 9 = Table S3 Item 2 / 0.47/0.95*, where 0.47 = efficiency of an HFCE powertrain [42] and 0.95 reflects leakage of hydrogen in distribution and retail.

{5} *Item 10 = Table S3 Item 3 / 0.47 / 0.95*, as in {4}

{6} *Item 12 = Item 9 x Table S2 Item 8.*

{7} *Item 13 = Item 10 x Table S2 Item 8.*

{8} *Item 15 = Item 9 x 1.29 $GJ_{HHV}NG$ / $GJ_{HHV}H_2$*, where 1.29 = ratio of natural gas to produced H_2 via Steam Methane Reforming [42]

{9} *Item 16 = Item 10 x 1.29 $GJ_{HHV}NG$ / $GJ_{HHV}H_2$*, as in {8}

{10} *Item 18 = Item 15 x Table S2 Item 8.*

{11} *Item 19 = Item 16 x Table S2 Item 8.*

The calculations and data sources behind Figure 6.3 in Layzell et al. (2019) [1] are summarized in Table S13.

Table S13: Emissions associated with the Production of H_2 using the Alberta Grid

Item	Process	Units	**2016 Grid** 719 kg CO_2 eq./MWh		**2030 Grid** 270 kg CO_2 eq./MWh		Note
			No CCS	**90% CCS**	**No CCS**	**90% CCS**	
1	NG Production and Processing	$kgCO_2eq /GJ_{HHV}\ H_2$	12	12	12	12	{1}
2	Steam Methane Reforming Process	$kgCO_2eq /GJ_{HHV}\ H_2$	66	7	66	7	{2}
3	Electricity Generation	$kgCO_2eq /GJ_{HHV}\ H_2$	18	23	7	9	{3}
4	*Generation for SMR e-*	*$kgCO_2eq /GJ_{HHV}\ H_2$*	*3*	*7*	*1*	*3*	{4}
5	*Generation for Distribution e-*	*$kgCO_2eq /GJ_{HHV}\ H_2$*	*15*	*15*	*6*	*6*	{5}
6	**TOTAL**	**$kgCO_2eq /GJ_{HHV}\ H_2$**	**96**	**42**	**85**	**27**	{6}

Notes:

{1} *Item 1 = 1.29 $GJ_{HHV}NG/GJ_{HHV}H_2$ x 9.4 kg CO_2e/GJ_{HHV}*, where 1.29 $GJ_{HHV}NG/GJ_{HHV}H_2$ = NG to H_2 ratio for steam methane reforming [42], and 9.4 kg CO2e/GJ_{HHV} = upstream emissions associated with the production of NG in Alberta (adapted from [49]).

{2} *Item 2 = 65.5 kg $CO_2e/GJ_{HHV}H_2$ x (1 - % Carbon Capture)*, where 65.5 kg CO2e/$GJ_{HHV}H_2$ = carbon intensity of SMR per NREL model [50], and % Carbon Capture = 0% and 90% for the No CCS and 90% CCS scenarios, respectively.

{3} *Item 3 = Item 4 + Item 5.*

{4} *Item 4 = Electricity Used in SMR x 0.277 MWh/GJ x Grid Emission Intensity*, where Electricity used in SMR = 0.015 $GJ/GJ_{HHV}H_2$ and 0.017 $GJ/GJ_{HHV}H_2$ in the No CCS and 90% CCS cases, respectively, and Grid Emission Intensity = 719 kg/CO_2e and 270 kg/CO_2e for the 2016 and 2030 grids, respectively (See Table S10 for more detail on each grid scenario).

{5} *Item 5 = 0.082 GJ/GJ H_2 x 0.277 MWh/GJ x Grid Emission Intensity*, where 0.082 GJ/GJ H_2 = the amount of electrical generation required for compression and distribution of H_2, and Grid Emission Intensity = 719 kg/CO_2e and 270 kg/CO_2e for the 2016 and 2030 grids, respectively (See Table S10 for more detail on each grid scenario).

{6} *Item 6 = Item 1 + Item 2 + Item 3.*

The calculations and data sources behind Figure 6.4 in Layzell et al. (2019) [1] are summarized in Table S14.

Table S14: Annual Emissions from NG-HFCE Energy System

Item	Process	Units	Value				Note
			HDV Only		All Diesel		
			No CCS	90% CCS	No CCS	90% CCS	
1	Emissions from H_2 Required to Replace AB Fossil Diesel Demand (1x AB)	Mt CO_2e/yr	6.4	2.1	17.1	5.5	{1}
2	*NG Production and Processing*	*Mt CO_2e/yr*	*0.9*	*0.9*	*2.5*	*2.5*	{2}
3	*Steam Methane Reforming*	*Mt CO_2e/yr*	*5.0*	*0.5*	*13.2*	*1.3*	{2}
4	*Electricity Generation*	*Mt CO_2e/yr*	*0.5*	*0.7*	*1.4*	*1.7*	{2}
5	Sequestered Carbon (1x AB)	Mt CO_2e/yr	0.0	4.4	0.0	11.6	{3}
6	Emissions from H_2 Required to Replace All Fossil Diesel Produced from AB Crude (9x AB)	Mt CO_2e/yr	57.8	18.6	153.8	49.6	{4}
7	*NG Production and Processing*	*Mt CO_2e/yr*	*8.3*	*8.3*	*22.1*	*22.1*	{5}
8	*Steam Methane Reforming*	*Mt CO_2e/yr*	*44.8*	*4.5*	*119.1*	*11.9*	{5}
9	*Electricity Generation*	*Mt CO_2e/yr*	*4.7*	*5.9*	*12.5*	*15.6*	{5}
10	Sequestered Carbon (9x AB)	Mt CO_2e/yr	0.0	39.2	0.0	104.2	{6}

Notes:

{1} *Item 1 = Sum (Items 2 to 4).*

{2} *Item 2 = Table S13 Items 1 to 3 x H_2 requirement*, where H_2 requirement = Table S12 Items 9 and 10 for the HDV and All Diesel scenarios respectively.

{3} 90% of only the Steam Methane Reforming emissions are assumed to be sequestered in the 90% CCS scenario.

{4} *Item 4 = Sum (Items 7 to 9).*

{5} *Item 5 = Table S13 Items 1 to 3 x H_2 requirement*, where H_2 requirement = Table S12 Items 12 and 13 for the HDV and All Diesel scenarios respectively.

{6} 90% of only the Steam Methane Reforming emissions are assumed to be sequestered in the 90% CCS scenario.

6. Wind & Solar to Hydrogen Fuel Cell Electric (WS-HFCE) Energy System

The calculations and data sources behind Figure 7.4 in Layzell et al. (2019) [1] are summarized in Table S15.

Table S15: Electricity generation required for H_2 production and public grid demand

Item	Parameter	Unit	Value: 1x AB HDV Only	Value: 1x AB All diesel	Value: 9x AB HDV Only	Value: 9x AB All diesel	Note
1	H_2 required to replace fossil diesel demand	PJ/yr	76	202	683	1,817	{1}
2	Electricity required to produce H_2 via electrolysis	TWh/yr	29	78	264	703	{2}
3	*Wind*	*TWh/yr*	*22*	*59*	*198*	*527*	{3}
4	*Solar*	*TWh/yr*	*7*	*20*	*66*	*176*	{4}
5	Electricity required to meet AB public grid demand (2016)	TWh/yr	62.5				{5}
6	Total Demand for Power generation	TWh/yr	92	141	327	765	{6}
7	*Wind*		56	96	235	564	{7}
8	*Solar*		19	32	78	188	{7}
9	*Other*		17	13	13	13	{7}

Note:

{1} *Item 1 = Table S12 Items 9,10,12,13*

{2} *Item 2 = Item 1 x 1.392 x 0.2778 TWh/PJ,* where 1.392 = the ratio of electricity input to H2 output in PEM electrolysis [41]

{3} *Item 3 = Item 2 x 0.75*, where 0.75 = assumed share of wind generation in electrolysis energy demand

{4} *Item 4 = Item 2 x 0.25*, where 0.25 = assumed share of solar generation in electrolysis energy demand

{5} 2016 public grid demand as reported by the AESO in their 2017 Annual Market Statistics [2]

{6} *Sum of Item 2 + Item 5*

{7} Extracted from **Figure 7.3A** assuming that 100% of the public grid is equal to 62.5 TWh/yr of generation, plus the Electricity Requirements for H2 production from Item 2

The calculations and data sources behind Figure 7.5 in Layzell et al. (2019) [1] are summarized in Table S16.

Table S16: Wind turbines, solar panels, & total land area required in WS-HFCE system

Item	Parameter	Unit	Value				Note
			1x AB		9x AB		
			HDV Only	All diesel	HDV Only	All diesel	
1	Wind turbines (4.8 MW)	#	3,723	6,340	15,581	37,374	{1}
2	*H_2 production*	#	*1,460*	*3,881*	*13,117*	*34,910*	{2}
3	*Public grid*		*2,262*	*2,459*	*2,464*	*2,464*	
4	Wind total land area	km^2	4,182	7,123	17,503	41,985	{3}
5	*H_2 production*	*km^2*	*1,640*	*4,360*	*14,735*	*39,217*	{4}
6	*Public grid*		*2,542*	*2,763*	*2,768*	*2,768*	
7	Wind direct land area	km^2	54	91	224	538	{5}
8	*H_2 production*	*km^2*	*21*	*56*	*189*	*503*	{6}
9	*Public grid*		*33*	*35*	*35*	*35*	
10	Solar land area	km^2	506	861	2,117	5,078	{7}
11	*H_2 production*	*km^2*	*198*	*527*	*1,782*	*4,743*	{8}
12	*Public grid*		*307*	*334*	*335*	*335*	

Footnotes

{1} *Item 1 = Item 2 + Item 3*

{2} *Item (2, 3) = (Table S15 Item (3, 7) / (0.359 x 4.8 MW/turbine X 8760 h/yr))*1e6 MW/TW;* 35.9% = capacity factor of wind in AB [1]

{3} *Item 4 = Item 5 + Item 6*

{4} *Item (5, 6) = Item (2,3) x (4.8 MW x 1.12 km^2/turbine);* 1.12 km^2/4.8 MW wind turbine = wind turbine density calculated from [3] and [4].

{5} *Item 7 = Item 8 + Item 9*

{6} *Item (8, 9) = Item (2,3) x (4.8 MW x 0.003 km^2/MW);* 0.003 km^2/MW = wind turbine direct land use from [5]

{7} *Item 10 = Item 11 + Item 12*

{8} *Item (11, 12) = (Table S15 Item (4, 8) / (0.17 MW X8760 h/yr)*1e6 MW/TW)/ 24.87 MW/km2;* 17% = capacity factor for wind; 24.87 = solar panel density from *[4]*

The calculations and data sources behind Figure 7.6 in Layzell et al. (2019) [1] are summarized in Table S17.

Table S17: Annual O_2 production and consumption in WS-HFCE system

Item	Parameter	Unit	Value				Note
			1x AB		9x AB		
			HDV Only	All diesel	HDV Only	All diesel	
1	Total H_2 required (energy)	PJ / yr	76	202	683	1817	{1}
2	Total H_2 required (mols)	Tmol H_2 / yr	0.27	0.71	2.40	6.38	{2}
3	Total O_2 produced (mols)	Tmol O_2 / yr	0.13	0.35	1.20	3.19	{3}
4	Total O_2 produced (mass)	Mt O_2 / yr	4.3	11.4	38.4	102.1	{4}
5	Oxy-fired CC share of public grid	%	13.5%	13.1%	13.1%	13.1%	{5}
6	Oxy-fired NG-CC generation to grid	TWh / yr	8.4	8.2	8.2	8.2	{6}
7	O_2 consumed for oxy-fired NG-CC grid generation	Mt O_2 / yr	4.3	4.2	4.2	4.2	{7}
8	Excess O_2	Mt O_2 / yr	0	7.2	34	98	{8}

Notes:

{1} *Item 1 = Table S15 Item 1*

{2} *Item 2 = Item 1 / (141.24 PJ_{HHV}/Mt H_2 x 2.016 Mt H_2 /Tmol H_2)* , where 141.24 = the energy density of H_2 [1] and 2.016 = the molecular weight of H_2

{3} *Item 3 = Item 2 x (0.5 Tmol O_2 / Tmol H_2)*, where 0.5 = the ratio of produced oxygen to hydrogen molecules in electrolysis

{4} *Item 4 = Item 3 x 31.998 Mt O_2/Tmol O_2*, where 31.998 = the molecular weight of O_2

{5} Calculated from Figure 7.3 in Layzell et al. for each level of hydrogen demand

{6} *Item 6 = Item 5 x 62.5 TWh/yr*, where 62.5 TWh = the size of the 2016 public grid in Alberta as reported by the AESO [2]

{7} *Item 7 = (Item 6 / 0.51) x 3.6 PJ/TWh x (1/890.4 PJ CH_4 / Tmol CH_4) x 2 Tmol O_2 / Tmol CH_4 x 31.998 Mt O_2 / Tmol O_2,* where 51% = efficiency of NG-CC power generation [3], 890.4 = molar energy density of CH_4 [1], 2 = molecular ratio of O_2 to CH_4 in combustion, and 31.998 = the molecular weight of O_2

{8} *Item 8 = Item 4 -Item 7*

The calculations and data sources behind Figure 7.7 in Layzell et al. (2019) [1] are summarized in Table S18.

Table S18: Annual greenhouse gas (GHG) emissions associated with a 62.5 TWhr public grid in the WS-HFCE energy system.

Item	Parameter	Unit	Value				Note
			1x AB		9x AB		
			HDV Only	All diesel	HDV Only	All diesel	
1	Oxy-fired NG-CC generation to grid	TWh / yr	8.4	8.2	8.2	8.2	{1}
2	Fossil fuel generation without CCS	TWh/yr	4.2	0.0	0.0	0.0	{2}
3	CO_2 from oxy-fired NGCC	Mt CO_2/yr	2.9	2.9	2.9	2.9	{3}
4	*Sequestered*	Mt CO_2/yr	*2.6*	*2.6*	*2.6*	*2.6*	{4}
5	*Emitted as GHG*	Mt CO_2e/yr	*0.29*	*0.29*	*0.29*	*0.29*	
6	CO_2 from fossil fuel gen without CCS	Mt CO_2e/yr	1.56	0.00	0.00	0.00	{5}
7	Total GHG emissions	Mt CO_2e/yr	1.85	0.29	0.29	0.29	{6}
8	GHG Intensity of electrical grid	kg CO_2e/MWh	29.7	4.6	4.6	4.6	{7}

Note:

{1} *From Table S17, Item 6*

{2} *From Figure 7.3*

{3} *Calculated as [(Item 1 x 3.6 PJe/TWh)/(0.51 PJe/PJCH4 x 890.4 PJ CH_4 / Tmol CH_4)] x 1 Tmol CO_2 / Tmol CH_4 x 44.009 Mt CO_2 / Tmol CO_2,* where 51% = efficiency of NG-CC power generation [1], 890.4 = molar energy density of CH_4 [2], 1 = molecular ratio of CO_2 to CH_4 in combustion, and 44.009 = the molecular weight of CO_2

[4} Assumes 90% of oxyfired CO_2 production (Item 3) is sequestered and 10% is emitted to the atmosphere

[5} Calculated as Item 2 x 0.370 Mt CO_2/TWhr, where 370 is the GHG intensity of NG combined cycle generation

[6} *Item 7 = Item 5 + Item 6*

{7} Item 8 = Item 7 / 62.5 TWhr/yr x 1000 kg/tonne, where 62.5 is the assumed size of the public grid

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