

# SUPPLEMENTAL MATERIALS

FOR

## THE FUTURE OF FREIGHT

### PART B: ASSESSING ZERO EMISSION DIESEL FUEL ALTERNATIVES FOR FREIGHT TRANSPORTATION IN ALBERTA

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A project associated with



## 1. Introduction

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

Lof J, McElheran K, Narendran M, Belanger N, Straatman B, Sit S, Layzell DB. 2019. **The Future of Freight Part B: Assessing Zero Emission Diesel Fuel Alternatives for Freight Transport in Alberta.** **CESAR Scenarios** Vol 4, Issue 2: 1-63 (<https://www.cesarnet.ca/publications/cesar-scenarios>)

## 2. Methodology

Details on the Typical HDV trip in Canada are provided in **Table S1**, while **Table S2** provides the energy conversion values (as higher heat values) used for energy feedstocks and fuels.

**Table S3** provides details on our calculation of the greenhouse gas intensities (kg CO<sub>2</sub>e/MWh) for the public electrical grid of Alberta in 2016, and in 2030 assuming that the 2030 grid will have no coal-fired generation and 30% renewables. Note that these calculations only consider the public grid that would be used for electrical vehicle charging, H<sub>2</sub> compression, etc. We do not include the large ‘behind the fence’ industrial generation that is dominated by natural gas cogeneration.

**Table S1. Calculations for a Typical HDV Trip in Canada**

Item	Parameter	Units	Value	Note
1	Distance	km	750	{1}
2	Truck weight (loaded)	tonnes	27	{2}
3	Fuel efficiency of loaded heavy duty FD-ICE freight trucks	L/tonne·100km	1.4	{3}
4	Diesel required per trip	L	283	{4}
5	Kinetic energy required for a trip	GJ	3.8	{5}

Notes:

- {1} Average long distance shipment by freight in Canada [1].
- {2}  $Item\ 2 = 17t\ payload + 10t\ tractor$ , where 17t = average payload for Canadian Class 8B (heavy) trucks in 2013 [2], and 10t = assumed weight of tractor unit.
- {3}  $Item\ 3 = 2.22\ L/t_{load} \cdot 100km \times 17\ t_{load} / Item\ 2$ , where 2.22 L/t<sub>load</sub>·100km is the average fuel efficiency of for-hire truck carriers in Canada [3].
- {4}  $Item\ 4 = Item\ 1 \times Item\ 2 \times Item\ 3 / 100km$ .
- {5}  $Item\ 5 = Item\ 4 \times 0.35 \times 38.4\ GJ/m^3 \times 1\ m^3 / 1000\ L$ , where 35% = the efficiency of a FD-ICE power train (Table S4) and 38.4 GJ/m<sup>3</sup> = the energy content of fossil diesel (Table S2).

**Table S2. Energy Content of Feedstock and Fuels**

Item	Parameter	Units	Value	Note
1	AB Crude Oil	GJ <sub>HHV</sub> /bbl	6.2	{1}
2	Diesel	GJ <sub>HHV</sub> /m <sup>3</sup>	38.4	{2}
3	Biomass Residue			
	<i>Straw Bales</i>		17.8	{3}
	<i>Wood Chips</i>	MJ <sub>HHV</sub> /kg <sub>(dry)</sub>	20.1	
4	FT Bio-Based Diesel	GJ <sub>HHV</sub> /m <sup>3</sup>	38.4	{4}
5	Hydrogen	MJ <sub>HHV</sub> /kg	141.2	{5}

**Notes:**

- {1} Weighted average of the energy content of crude oil produced in Alberta - adapted from energy content and crude oil production numbers reported by the NEB [4].
- {2} From Environment and Climate Change Canada's National GHG Inventory [5].
- {3} Adapted from a literature review of the energy content of biomass from various sources on a dry basis [6], [7].
- {4} Same as fossil diesel (Item 3).
- {5} Adapted from GHGenius [8], a life cycle assessment tool developed by (S&T) Squared Consultants Inc. ("Fuel Char" worksheet).

**Table S3: Alberta Electrical Grid GHG Intensity in 2016 and 2030 (Projection)**

Item	Source	2016 Grid <sup>{1}</sup>			2030 Grid (Projection) <sup>{2}</sup>		
		Gen. Share %	Conversion Eff. %	Carbon Intensity kgCO <sub>2</sub> e/MWh	Gen. Share %	Conversion Eff. %	Carbon Intensity kgCO <sub>2</sub> e/MWh
1	Coal	61%	33%	1008	0%	33%	1008
2	<b>NG Subtotal</b>	<b>27%</b>	<b>55%<sup>{3}</sup></b>	<b>372<sup>{4}</sup></b>	<b>70%</b>	<b>52%<sup>{3}</sup></b>	<b>387<sup>{4}</sup></b>
3	<i>NG Cogeneration</i>	17%	60%	350	20%	60%	350
4	<i>NG Combined Cycle</i>	9%	51%	390	46%	51%	390
5	<i>NG Single Cycle</i>	1%	35%	525	4%	35%	525
6	<b>Renewable Subtotal</b>	<b>11%</b>	<b>100%<sup>{3}</sup></b>	<b>0<sup>{4}</sup></b>	<b>30%</b>	<b>100%<sup>{3}</sup></b>	<b>0<sup>{4}</sup></b>
7	<i>Hydro</i>	3%	100%	0	3%	100%	0
8	<i>Wind</i>	7%	100%	0	24%	100%	0
9	<i>PV</i>	0%	100%	0	1%	100%	0
10	<i>Biomass / Other</i>	1%	100%	0	2%	100%	0
11	Imports	0.7%	100%	0	0%	100%	0
12	<b>Grid Total / Wtd. Avg</b>	<b>100%</b>	<b>41%<sup>{3}</sup></b>	<b>719<sup>{4}</sup></b>	<b>100%</b>	<b>61%<sup>{3}</sup></b>	<b>270<sup>{4}</sup></b>

Notes:

- {1} Based on AESO Annual Market Statistics 2017 [9].
- {2} Future grid comprised of 70% natural gas and 30% renewable generation.
- {3} *Wtd. Avg Conversion Eff. = Sum (Gen. Share) ÷ Sum (Gen. Share ÷ Conversion Eff.),* harmonic weighted average of conversion efficiency with respect to generation share.
- {4} *Wtd. Avg Carbon Intensity = Sum (Conversion Eff. x Carbon Intensity),* arithmetic weighted average of carbon intensity with respect to generation share.

### 3. Fossil Diesel-Internal Combustion Engine (FD-ICE) Energy System

**Table S4** provides details and references on the values we used for feedstock retention percentages and energy conversion efficiency for each stage in the FD-ICE energy system. The embedded feedstock price and the fuel cost estimates for the energy system are provided in **Table S5**, and the calculated GHG emissions associated with the trip are provided in **Table S6**.

**Table S4. FD-ICE Efficiency and Feedstock Retention**

Item	Parameter	Units	Value	Note
1	Crude oil recovery Feedstock Retention (FR)	%	98%	{1}
2	Crude oil recovery efficiency	%	87%	{2}
3	Diesel refining FR	%	92%	{3}
4	Diesel refining efficiency	%	89%	{4}
5	Diesel dist. and dispensing efficiency	%	96%	{5}
6	Diesel power train efficiency	%	35%	{6}

**Notes:**

- {1} Adapted from GHGenius [8], a life cycle assessment tool developed by (S&T) Squared Consultants Inc. Loss of 2% of feedstock attributable to crude products consumed during recovery.
- {2} Based on data from [8]; includes all energy feedstock consumed in crude recovery as well as losses incurred during recovery, upgrading, and transportation of crude.
- {3} From analysis of refinery input/output model built using data from EIA [10]–[14] and Statistics Canada [15]–[17]; the ratio of crude oil to refined diesel was estimated to be 1.08 : 1 for a FR of 92.4%.
- {4} Based on the same refinery model as in {3}; ratio of all input feedstock (NG, electricity, RPPs, etc.) to output diesel was estimated to be 1.12 GJ<sub>in</sub>/GJ<sub>out</sub> in energy terms.
- {5} Assumes 4% losses via spills, evaporation, etc. during transportation and distribution.
- {6} As found on pg. 54 of McKinsey & Co's analysis of transportation power-trains in Europe [18].

**Table S5. Energy Costs and Prices for FD-ICE System**

Item	Parameter	Units	Range			Note
			Low	Mid	High	
1	Cost of recovered crude oil	2016 U\$/bbl	32	47	64	{1}
		2016 C\$/GJ	6.23	9.18	12.52	
Embedded feedstock cost at:						
2	Diesel production	2016 C\$/L	0.26	0.38	0.52	{2}
		2016 C\$/GJ	6.74	9.93	13.55	
3	Diesel distribution and dispensing	2016 C\$/L	0.27	0.40	0.54	{3}
		2016 C\$/GJ	7.02	10.34	14.11	
4	Kinetic energy	2016 C\$/GJ	20	30	40	{4}
Estimated price of energy:						
5	Wholesale price of diesel	2016 C\$/L	0.58	0.75	0.92	{5}
		2016 C\$/GJ	15.07	19.62	23.96	
6	Retail price of diesel	2016 C\$/L	0.69	0.86	1.04	{6}
		2016 C\$/GJ	17.86	22.36	27.22	
7	Kinetic energy	2016 C\$/GJ	51	64	78	{7}

**Notes:**

- {1} Calculated weighted average prices of Canadian Light Sweet and Western Canadian Select for 2013-2017 as reported by the AER [19], [20].
- {2} Calculated as Item 1 ÷ implied feed stock retention in diesel refining (0.92). See Table S4 for detail.
- {3} Calculated as Item 2 ÷ implied feed stock retention in diesel dist. and dispensing (0.96). See Table S4 for detail.
- {4} Calculated as Item 3 ÷ efficiency of a diesel internal combustion engine (0.35). See Table S4 for detail.
- {5} Wholesale diesel prices from 2013-2017 as reported by Kent Group Ltd [21].
- {6} Retail diesel prices without taxes from 2013-2017 as reported by Kent Group Ltd [21].
- {7} Calculated as Item 6 ÷ efficiency of a diesel internal combustion engine (0.35). See Table S4 for detail.

**Table S6. FD-ICE Emissions per Trip (kg CO<sub>2</sub>e/trip)**

Item	Source	Primary	Upstream	Total	Note
1	Crude Production, Upgrading, and Transport	137	21	158	{1}
2	Refining	92	29	120	
3	RPP Transport	4	0	4	{2}
4	Combustion	803	0	803	
5	Total	1036	49	1085	

Notes:

{1} Adapted from IHS Markit report on Well-to-Wheel emissions of oil sands and conventional crude production, transport and refining [22].

{2} Based on Environment Canada's National Inventory Report (NIR) 2018 [23].

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

**Table S7** provides details and references on the values we used for feedstock retention percentages and energy conversion efficiency for each stage in the BD-ICE energy system. The embedded feedstock price and the fuel cost estimates for the energy system are provided in **Table S8**, and the calculated GHG emissions associated with the trip are provided in **Table S9**.

**Table S7. BD-ICE Efficiency and Feedstock Retention**

Item	Parameter	Units	Value	Note
1	Biomass drying and processing efficiency	%	96%	{1}
2	Biomass drying and processing FR	%	98%	{2}
3	Fischer-Tropsch biorefining efficiency	%	51%	{3}
4	Biodiesel dist. and dispensing efficiency	%	96%	{4}
5	FT BD-ICE power train efficiency	%	35%	{5}

Notes:

{1} Includes diesel consumed in harvesting and transporting biomass residue.

{2} Assumed 2% losses in drying and pre-processing.

{3} Adapted from van Vleit et al [24]; 51% was the feed to fuel (biomass to diesel) conversion efficiency of a FT refinery that used biomass as its primary feedstock.

{4} Assumed same FR as fossil diesel since the same distribution and dispensing infrastructure should be used for bio-based FT diesel.

{5} Assumed same efficiency as FD-ICE powertrain.

**Table S8. Energy Costs and Prices for BD-ICE System**

Item	Parameter	Units	Range			Note
			Low	Mid	High	
1	Cost of delivered biomass	2016 C\$/GJ	4.42	5.94	7.31	{1}
Embedded feedstock cost at:						
2	Bio-based (Fischer-Tropsch) diesel production	2016 C\$/L	0.34	0.46	0.56	{2}
		2016 C\$/GJ	8.85	11.89	14.63	
3	Diesel distribution and dispensing	2016 C\$/L	0.35	0.48	0.58	{3}
		2016 C\$/GJ	9.22	12.39	15.24	
4	Kinetic energy	2016 C\$/GJ	26.34	35.40	43.55	{4}
Estimated price of energy:						
5	Wholesale cost of bio-based diesel	2016 C\$/L	0.99	1.14	1.26	{5}
		2016 C\$/GJ	25.94	29.71	32.94	
6	Retail cost of bio-based diesel	2016 C\$/L	1.13	1.29	1.43	{6}
		2016 C\$/GJ	29.38	33.65	37.31	
7	Kinetic energy	2016 C\$/GJ	84	96	107	{7}

## Notes:

- {1} Range based on literature review of cost of delivered biomass from sources such as straw, switchgrass and forest residue [6], [7], [25].
- {2} Calculated as Item 1 ÷ (feedstock efficiency of processing biomass x feed to fuel efficiency of Fischer-Tropsch diesel plants) = Item 1 ÷ (0.98 x 0.51) [24]. See Table S7 for more detail.
- {3} Calculated as Item 2 ÷ implied feed stock retention in diesel dist. and dispensing (0.96). See Table S7 for more detail.
- {6} Calculated as Item 3 ÷ efficiency of a diesel internal combustion engine (0.35). See Table S7 for more detail.
- {5} Range based on literature review of the economics of Fischer-Tropsch diesel production [24], [26].
- {6} Calculated as Item 5 x 1.13, the average wholesale to retail markup on fossil diesel in Alberta for 2013-2017 (13%, derived from prices reported by Kent Group [21]). Assumed same wholesale to retail markup as fossil diesel since the same distribution and dispensing infrastructure should be used for bio-based FT diesel.
- {7} Calculated as Item 6 ÷ efficiency of a diesel internal combustion engine (0.35). See Table S7 for more detail.



**Table S9. BD-ICE Emissions per Trip**

Item	Parameter	Unit	Value			Note
1	Biomass Required	GJ/trip	22.7			{1}
2	Biomass Required	kg(dry)/trip	1127.6			{2}
3	Bio-Based Diesel Used in Harvest	GJ diesel/trip	0.47			{3}
4	Bio-Based Diesel Used in Harvest	kg Diesel/trip	10.2			{4}
5	Carbon in Biomass	kg C /trip	558.2			{5}
6	Carbon in Bio-Based Diesel	kg C/trip	8.9			{6}
7	Total Carbon Emissions	kg CO <sub>2</sub> bio/trip	2078			{7}
8	Reference FD-ICE Emissions	kg CO <sub>2</sub> bio/trip	1085			{8}
10	GWP	CO <sub>2</sub> eq/CO <sub>2</sub> bio	0.1	0.2	0.4	{9}
11	CO <sub>2</sub> e/trip	kg CO <sub>2</sub> eq/trip	207.8	415.6	831.2	{10}

## Notes:

- {1} Based on van Vliet et al.'s analysis of biomass based Fischer-Tropsch synthesis plants [24].
- {2}  $Item\ 2 = (Item\ 1 \times 1000\text{kg} / t) / (20.1\ GJ_{HHV} / t_{dry})$ , where  $20.1\ GJ_{HHV} / t_{dry}$  = the assumed energy content of woody biomass residue based on literature review [6], [7].
- {3} Adapted from [27], includes diesel used in gathering, processing and transportation of woody biomass residue.
- {4}  $Item\ 4 = Item\ 3 \times 45.6\ GJ_{HHV} / t \times 0.001\ t / kg$ , where  $45.6\ GJ_{HHV} / t$  is the energy density of diesel [28].
- {5}  $Item\ 5 = Item\ 2 \times 50\%$ , where 50% = the carbon content by weight of woody biomass [29].
- {6}  $Item\ 6 = Item\ 3 \times 87\%$ , where 50% = the carbon content by weight of diesel [30].
- {7}  $Item\ 7 = (Item\ 5 + Item\ 6) \times 3.66$  where 3.66 = molar mass ratio of carbon to carbon dioxide.
- {8} Calculated for FD-ICE system, see Table S5 Item 5.
- {9} Range of Global Warming Potential multipliers deemed reasonable based on literature [31]–[35].
- {10}  $Item\ 11 = Item\ 7 \times Item\ 10$ .

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

**Table S10** provides details and references on the values we used for feedstock retention percentages and energy conversion efficiency for each stage in the G-BE energy system. The embedded feedstock price and the fuel cost estimates for the energy system are provided in **Table S11**, and the calculated GHG emissions associated with the trip are provided in **Table S12**.

**Table S10. G-BE Efficiency and Feedstock Retention**

Item	Parameter	Units	Value	Note
1	Natural gas production efficiency and FR	%	90%	{1}
2	Power generation (2030 AB grid) efficiency	%	61%	{2}
3	Electricity transmission and distribution efficiency	%	90%	{3}
4	Charging and on-board electronics efficiency	%	76%	{4}
5	<i>Charging and Power Electronics Unit (PEU) efficiency</i>	%	80%	{5}
6	<i>On-board electronics efficiency</i>	%	95%	{6}
7	Electric motor efficiency	%	90%	{7}

Notes:

- {1} Adapted from GHGenius [8], 10% loss attributable to recovery, transmission and processing of NG.
- {2} See Table S3.
- {3} Historically, line losses during electrical transmission have been in the range of 4-6% in Alberta [36], while losses attributable to electricity distribution are around 5% [37]. So, total losses due to transmission and generation can be estimated as  $95\% \times 95\% = 90\%$ .
- {4} *Item 3 = Item 4 x Item 5*. The energy available to the motor is the energy at the outlet, minus charging losses, minus energy consumed by the vehicle's on-board electronics.
- {5} The net efficiency of charging the vehicle - while this number is heavily dependant on factors such as the state of charge of the battery, method of power delivery (single phase vs. 3-phase, 110V vs 240V) and ambient temperature [38], 80% is a reasonable estimate accounting for Alberta's harsh winter conditions (modern BEVs advertise charging efficiencies of around 90% under optimal conditions).
- {6} Estimated energy consumed by on-board electronic systems (includes HVAC) is around 5%. In harsh conditions where there is a significant difference between ambient and desired cabin temperature, this number can be as high as 35% [39].
- {7} Efficiency of a 3-phase induction motor [40].

**Table S11. Energy Costs and Prices for G-BE System**

Item	Parameter	Units	Range			Note
			Low	Mid	High	
1	Cost of delivered natural gas	2016 C\$/GJ	2.02	2.83	4.35	{1}
2	Cost of electricity generation	2016 C\$/MWh	18	42	84	{2}
		2016 C\$/GJ	5.08	11.58	23.28	
Embedded feedstock cost at:						
3	Distributed (i.e. delivered) electricity	2016 C\$/MWh	20	46	93	{3}
		2016 C\$/GJ	5.64	12.87	25.87	
4	Electricity on board	2016 C\$/GJ	7.42	16.93	34.04	{4}
5	Kinetic energy	2016 C\$/GJ	8.25	18.81	37.82	{5}
Estimated price of energy:						
6	Transmission cost	2016 C\$/MWh		43		{6}
		2016 C\$/GJ		12		
7	New infrastructure markup	multiplier	1.20	1.40	1.60	{7}
8	Distributed electricity	2016 C\$/MWh	96	147	216	{8}
		2016 C\$/GJ	27	41	60	
9	Electricity on board	2016 C\$/GJ	35	54	79	{9}
		2016 C\$/MWh	126	193	284	
10	Kinetic energy	2016 C\$/GJ	39	60	88	{10}

**Notes:**

- {1} From AESO daily prices averaged per year for 2012-2017 as reported by the AESO in their Annual Market Statistics 2017 [9].
- {2} Annual average of the hourly pool price for 2012-2017 as reported by the AESO in their Annual Market Statistics 2017 [9].
- {3} Calculated as Item 2 ÷ efficiency of transmission and distribution in Alberta as in Table S10, Item 3 (0.90).
- {4} Calculated as Item 3 ÷ efficiency of charging the battery electric vehicle from delivered grid power as in Table S10, Item 4 (0.76); includes losses in power electronics. See Table S10 for more detail.
- {5} Calculated as Item 4 ÷ energy conversion efficiency for motor as in Table S10, Item 10 (0.90).
- {6} From AESO's Transmission Rate Projection [41] which projects transmission prices to increase from \$33/MWh in 2018 to \$43/MWh by 2022.
- {7} This system would require significant additions to the grid infrastructure, be it electrification of roads, or adding transmission and distribution capacity, and substations to support a network of charging stations. To account for this, we have assumed a range of multipliers which mark-up the cost of delivered electricity.
- {8} Calculated as (Electricity rate + Item 6) x Item 7, where the electricity rate is the average annual electricity rates paid by commercial consumers in 2013-2017 as reported by the AUC [42].
- {9} Calculated as Item 8 ÷ efficiency of charging the battery electric vehicle from delivered grid power as in Table S10, Item 3 (0.76); includes losses in power electronics. See Table S10 for more detail.
- {10} Calculated as Item 9 ÷ energy conversion efficiency for an electric motor as in Table S10, Item 10 (0.90). See Table S10 for more detail.

**Table S12. G-BE Emissions per Trip**

Item	Parameter	Units	Grid Scenario		Note
			2016 Grid 719 kg CO <sub>2</sub> eq./MWh	2030 Grid 270 kg CO <sub>2</sub> eq./MWh	
1	Electricity Generation	kgCO <sub>2</sub> eq /trip	1239	449	{1}
2	Upstream Total	kgCO <sub>2</sub> eq /trip	45	79	{2}
3	<i>Upstream NG</i>	kgCO <sub>2</sub> eq /trip	29	79	{3}
4	<i>Upstream Coal</i>	kgCO <sub>2</sub> eq /trip	16	0	{4}
5	Total	kgCO <sub>2</sub> eq /trip	1284	528	{5}

Notes:

- {1} *Item 1 = 6.2 GJ/trip x 0.277 MWh/GJ x Grid Emission Intensity*, where 6.2 GJ = the amount of electrical generation required per trip, and Grid Emission Intensity = 719 kg/CO<sub>2</sub>e and 270 kg/CO<sub>2</sub>e for the 2016 and 2030 grids.
- {2} *Item 2 = Item 3+ Item 4.*
- {3} *Item 3 = NG used in power gen. x 9.4 kg CO<sub>2</sub>e/GJ<sub>HHV</sub>*, where NG used in power gen = 3.1 GJ and 8.4 GJ for the 2016 and 2030 grids respectively, and 9.4 kg CO<sub>2</sub>e/GJ<sub>HHV</sub>NG = upstream emissions associated with the production of NG in Alberta (adapted from [43]).
- {4} *Item 4 = Coal used in power gen. x 1.7 kg CO<sub>2</sub>e/GJ<sub>HHV</sub>*, where Coal used in power gen = 9.5 GJ and 0 GJ for the 2016 and 2030 grids respectively, and 1.7 kg CO<sub>2</sub>e/GJ<sub>HHV</sub>NG = upstream emissions associated with the production of coal in Alberta [23].
- {5} *Item 5 = Item 1 + Item 2.*

## 6. Natural Gas to H<sub>2</sub> Fuel Cell Electric (NG-HFCE) Energy System

**Table S13** provides details and references on the values we used for feedstock retention percentages and energy conversion efficiency for each stage in the NG-HFCE energy system. The embedded feedstock price and the fuel cost estimates for the energy system are provided in **Table S14**, and the calculated GHG emissions associated with the trip are provided in **Table S15**.

**Table S13. NG-HFCE Efficiency and Feedstock Retention**

Item	Parameter	Units	Value	Note
1	Natural gas production efficiency and FR	%	90%	{1}
2	Hydrogen production via Steam Methane Reforming (SMR) FR	%	78%	{2}
3	Hydrogen production via Steam Methane Reforming (SMR) efficiency	%	77%	{3}
4	Hydrogen distribution and dispensing FR	%	95%	{4}
5	Hydrogen distribution and dispensing efficiency	%	88%	{5}
6	PEMFC efficiency	%	55%	{6}
7	Inverter and power electronics efficiency	%	95%	{7}
8	Electric motor efficiency	%	90%	{8}

Notes:

- {1} Adapted from GHGenius [8], 10% loss attributable to recovery, transmission and processing of NG.
- {2} Based on ratio of 1.29 GJ<sub>HHV</sub> NG / GJ<sub>HHV</sub> H<sub>2</sub> from a NREL model for centralized hydrogen production from Steam-Methane Reforming with CO<sub>2</sub> Capture [44].
- {3} From the same model used for Item 2, with the addition of electricity used throughout the SMR process.
- {4} Losses of 5% attributed to energy used and leaks during hydrogen transportation and dispensing [45] – assumes a 500km round trip distance from H<sub>2</sub> production facility to distribution and dispensing site.
- {5} Includes losses in Item 4 as well as energy consumed to compress the produced hydrogen both for transportation and for dispensing [45].
- {6} Based on consultation with PEMFC manufacturer, Ballard.
- {7} Based on consultation with hydrogen systems manufacturer, Hydrogenics.
- {8} Efficiency of a 3-phase induction motor [40].

**Table S14. Energy Costs and Prices for the NG-HFCE System**

Item	Parameter	Units	Range			Note
			Low	Mid	High	
1	Cost of delivered natural gas feedstock	2016 C\$/GJ	2.02	2.83	4.35	{1}
Embedded feedstock cost at:						
2	H <sub>2</sub> production via SMR with 90% CCS	2016 C\$/GJ	2.60	3.65	5.60	{2}
3	Compressed and delivered (retail) H <sub>2</sub>	2016 C\$/GJ	2.74	3.85	5.91	{3}
4	Electricity on board	2017 C\$/GJ	5.25	7.37	11.31	{4}
5	Kinetic energy	2016 C\$/GJ	5.83	8.19	12.57	{5}
Estimated price of energy:						
6	Wholesale price of H <sub>2</sub> at SMR plant with 90% CCS	2016 C\$/kg	1.34	1.53	1.85	{6}
		2016 C\$/GJ	9.47	10.80	13.10	
7	Cost of distributing H <sub>2</sub> via tube trucks	2016 C\$/kg	1.50	2.42	3.71	{7}
		2016 C\$/GJ	10.63	17.11	26.29	
8	Cost of compressing and dispensing H <sub>2</sub>	2016 C\$/kg	0.98	1.20	1.59	{8}
		2016 C\$/GJ	6.90	8.50	11.23	
9	Retail price of H <sub>2</sub>	2016 C\$/kg	4.19	5.66	7.86	{9}
		2016 C\$/GJ	30	40	56	
10	Electricity on board	2016 C\$/GJ	57	77	107	{10}
		2016 C\$/MWh	205	276	384	
11	Kinetic energy	2016 C\$/GJ	63	85	118	{11}

**Notes:**

- {1} From AESO daily prices averaged per year for 2012-2017 as reported by the AESO in their Annual Market Statistics 2017 [9].
- {2} Calculated as Item 1 ÷ feedstock retention for SMR with 90% CCS as in Table S13, Item 2 (0.78) [44].
- {3} Calculated as Item 2 ÷ feedstock retention for distribution / dispensing as in Table S13, Item 4 (0.95).
- {4} Calculated as Item 3 ÷ energy conversion efficiency for PEM fuel cell as in Table S13, Item 6 x Item 7 (0.55 x 0.95 = 0.52).
- {5} Calculated as Item 4 ÷ energy conversion efficiency for motor as in Table S13, Item 8 (0.90).
- {6} Calculated using NREL's model of a SMR plant with 90% CCS [44] as in Figure 3.10 [46] [ $\$/\text{kg H}_2 = \text{Item 1} * 0.22 + 0.90$ ], assuming the delivered natural gas feedstock price (Item 1). To convert  $\$/\text{kg}$  to  $\$/\text{GJ}_{\text{HHV}}$ , multiply by 7.08 kg H<sub>2</sub>/GJ<sub>HHV</sub> H<sub>2</sub>.
- {7} Assumes transportation of hydrogen via tube trucks; based on literature [47]–[49] and consultation with freight carriers.
- {8} Includes capital and operating expenditures for compression, storage, and dispensing infrastructure calculated from an NREL study [50].
- {9} Calculated as (Item 6 + Item 7 + Item 8) \* 1.1 to include an additional retail markup.
- {10} Calculated as Item 9 ÷ energy conversion efficiency for PEM fuel cell as in Table S13, Item 6 x Item 7 (0.55 x 0.95 = 0.52). A conversion factor of 3.6 GJ/MWh was used to calculate price per MWh.
- {11} Calculated as Item 10 ÷ energy conversion efficiency for motor as in Table S13, Item 8 (0.90).

**Table S15. NG-HFCE Emissions per Trip**

Item	Process	Units	2016 Grid		2030 Grid		Notes
			270 kg CO <sub>2</sub> eq./MWh		719 kg CO <sub>2</sub> eq./MWh		
			No CCS	CCS	No CCS	CCS	
1	NG Production and Processing	kgCO <sub>2</sub> eq /trip	100	100	100	100	{1}
2	Steam Methane Reforming Process	kgCO <sub>2</sub> eq /trip	540	54	540	54	{2}
3	Electricity Generation	kgCO <sub>2</sub> eq /trip	156	158	59	59	{3}
4	<i>Generation for SMR e-</i>	kgCO <sub>2</sub> eq /trip	25	27	9	10	{4}
5	<i>Generation for Distribution e-</i>	kgCO <sub>2</sub> eq /trip	131	131	49	49	{5}
6	<b>TOTAL</b>	<b>kgCO<sub>2</sub>eq /trip</b>	<b>796</b>	<b>313</b>	<b>699</b>	<b>214</b>	{6}

## Notes:

- {1} *Item 1 = 10.6 GJ<sub>HHV</sub>/trip x 9.4 kg CO<sub>2</sub>e/GJ<sub>HHV</sub>, where 10.6 GJ<sub>HHV</sub>/trip = NG required for SMR, and 9.4 kg CO<sub>2</sub>e/GJ<sub>HHV</sub> = upstream emissions associated with the production of NG in Alberta (adapted from [43]).*
- {2} *Item 2 = 65.5 kg CO<sub>2</sub>e / GJ<sub>HHV</sub>H<sub>2</sub> x 8.3 GJ<sub>HHV</sub>H<sub>2</sub> x (1 - % Carbon Capture), where 65.5 kg CO<sub>2</sub>e / GJ<sub>HHV</sub>H<sub>2</sub> = carbon intensity of SMR per NREL model [44], 8.3 GJ<sub>HHV</sub>H<sub>2</sub> = H<sub>2</sub> production required per trip, and % Carbon Capture = 0% and 90% for the No CCS and 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 = 0.13 GJ/trip and 0.14 GJ/trip in the No CCS and 90% CCS cases, respectively, and Grid Emission Intensity = 719 kg/CO<sub>2</sub>e and 270 kg/CO<sub>2</sub>e for the 2016 and 2030 grids, respectively (See Table S3 for more detail on each grid scenario).*
- {5} *Item 5 = 0.66 GJ/trip x 0.277 MWh/GJ x Grid Emission Intensity, where 0.66 GJ/trip = the amount of electrical generation required for compression and distribution of H<sub>2</sub>, and Grid Emission Intensity = 719 kg/CO<sub>2</sub>e and 270 kg/CO<sub>2</sub>e for the 2016 and 2030 grids, respectively (See Table S3 for more detail on each grid scenario).*
- {6} *Item 6 = Item 1 + Item 2 + Item 3.*

## 7. Wind and Solar to H<sub>2</sub> Fuel Cell Electric (WS-HFCE) Energy System

**Table S16** provides details and references on the values we used for feedstock retention percentages and energy conversion efficiency for each stage in the WS-HFCE energy system. The embedded feedstock price and the fuel cost estimates for the energy system are provided in **Table S17**, and the GHG emissions were effectively zero.

**Table S16. WS-HFCE Efficiency and Feedstock Retention**

Item	Parameter	Units	Value	Note
1	PEM electrolysis efficiency	%	72%	{1}
2	Hydrogen distribution and dispensing FR	%	95%	{2}
3	Hydrogen distribution and dispensing efficiency	%	88%	{3}
4	PEM-FC efficiency	%	55%	{4}
5	Inverter and power electronics efficiency	%	95%	{5}
6	Electric motor efficiency	%	90%	{6}

Notes:

- {1} Assumes a conversion ratio of around 1.4 GJ of electricity per 1 GJ of hydrogen [51].
- {2} Losses of 2% attributed to energy used and leaks during hydrogen transportation and dispensing [45].
- {3} Includes losses in Item 4 as well as energy consumed to compress the produced hydrogen both for transportation and for dispensing [45].
- {4} Based on consultation with PEMFC manufacturer, Ballard.
- {5} Based on consultation with hydrogen systems manufacturer, Hydrogenics.
- {6} Efficiency of a 3-phase induction motor [52].



**Table S17. Energy Costs and Prices for WS-HFCE System**

Item	Parameter	Units	Range			Note
			Low	Mid	High	
1	Levelized cost of wind and solar generation	2016 C\$/MWh	30	40	67	{1}
		2016 C\$/GJ	8.45	11.00	18.53	
Embedded feedstock cost at:						
2	H <sub>2</sub> production via PEM electrolysis	2016 C\$/kg	1.66	2.16	3.64	{2}
		2016 C\$/GJ	12	15	26	
3	Compressed and delivered H <sub>2</sub>	2016 C\$/kg	1.75	2.28	3.84	{3}
		2016 C\$/GJ	12.40	16.14	27.19	
4	Electricity on board	2016 C\$/GJ	23.72	30.89	52.05	{4}
5	Kinetic energy	2016 C\$/GJ	26.36	34.32	57.83	{5}
Estimated price of energy:						
6	Wholesale price of H <sub>2</sub> at PEM electrolysis plant	2016 C\$/kg	3.10	3.87	5.01	{6}
		2016 C\$/GJ	21.9	27.4	35.5	
7	Cost of distributing H <sub>2</sub> via tube trucks	2016 C\$/kg	1.50	2.42	3.71	{7}
		2016 C\$/GJ	10.63	17.11	26.29	
8	Cost of compressing and dispensing H <sub>2</sub>	2016 C\$/kg	0.98	1.20	1.59	{8}
		2016 C\$/GJ	6.90	8.50	11.23	
9	Retail price of H <sub>2</sub> (retail)	2016 C\$/kg	6.13	8.23	11.34	{9}
		2016 C\$/GJ	43.40	58.29	80.28	
10	Electricity on board	2016 C\$/GJ	83	112	154	{10}
		2016 C\$/MWh	299	402	553	
11	Kinetic energy	2016 C\$/GJ	92	124	171	{11}

**Notes:**

- {1} From results of the AESO's Renewable Electricity Program (REP) [1], Lazard's LCOE Analysis [2], and CERI's Guide to Electricity Generation Options in Canada [3].
- {2} Calculated as Item 1 ÷ conversion efficiency of PEM electrolysis (electricity to H<sub>2</sub>) as in Table S16, Item 1 (0.72).
- {3} Calculated as Item 2 ÷ feedstock retention rate of hydrogen compression and distribution as in Table S16, Item 2 (0.95).
- {4} Calculated as Item 3 ÷ energy conversion efficiency for PEM fuel cell as in Table S16, Item 4 x Item 5 (0.55 x 0.95 = 0.52).
- {5} Calculated as Item 4 ÷ energy conversion efficiency for motor as in Table S16, Item 6 (0.90).
- {6} Adapted from DOE analysis of hydrogen production costs via PEM electrolysis [4].
- {7} Assumes same range of transport costs as NG-HFCE system (Table S14, Item 7).
- {8} Assumes same range of compression, storage, and dispensing costs as NG-HFCE system (Table S14, Item 7).
- {9} Calculated as (Item 6 + Item 7 + Item 8) \* 1.1 to include an additional 10% retail markup.
- {10} Calculated as Item 9 ÷ energy conversion efficiency for PEM fuel cell in as in Table S16, Item 4 x Item 5 (0.55 x 0.95 = 0.52). A conversion factor of 3.6 GJ/MWh was used to calculate price per MWh.
- {11} Calculated as Item 10 ÷ energy conversion efficiency for motor as in Table S16, Item 6 (0.90).

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