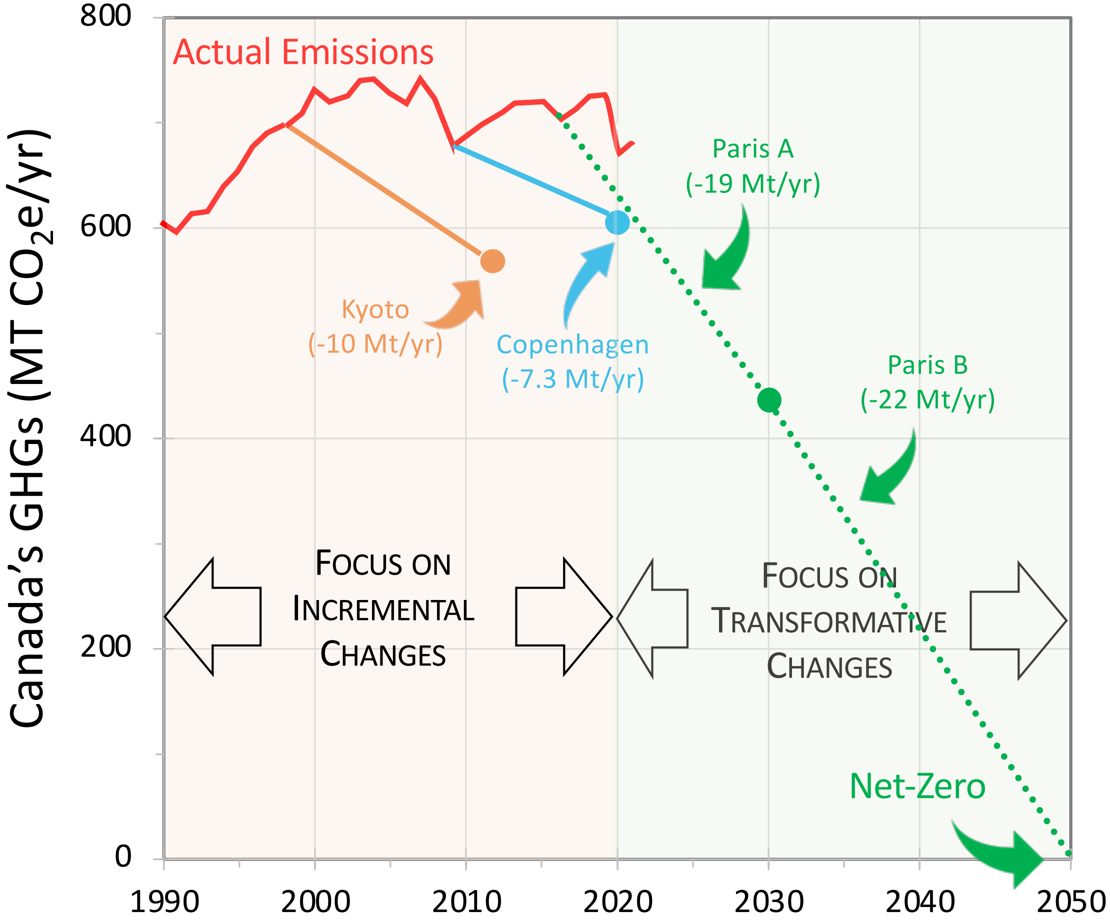
Hydrogen & the Transition to Net-Zero Greenhouse Gas Emissions: Ontario as a Case Study

David B Layzell PhD, FRSC.
Energy Systems Architect, The Transition Accelerator
Faculty Emeritus Professor, CESAR, University of Calgary

Email: dlayzell@transitionaccelerator.ca
Web: www.transitionaccelerator.ca

January 5, 2024

Canada's Greenhouse Gas (GHG) Emissions



To date, Canada's 'incremental' strategies have only been successful in stabilizing GHGs.

But to address climate change, the developed world must achieve net-zero GHG emissions by 2050.

This will require ***Transformative Changes****, esp. in energy systems that account for 82% of Cdn GHGs.*

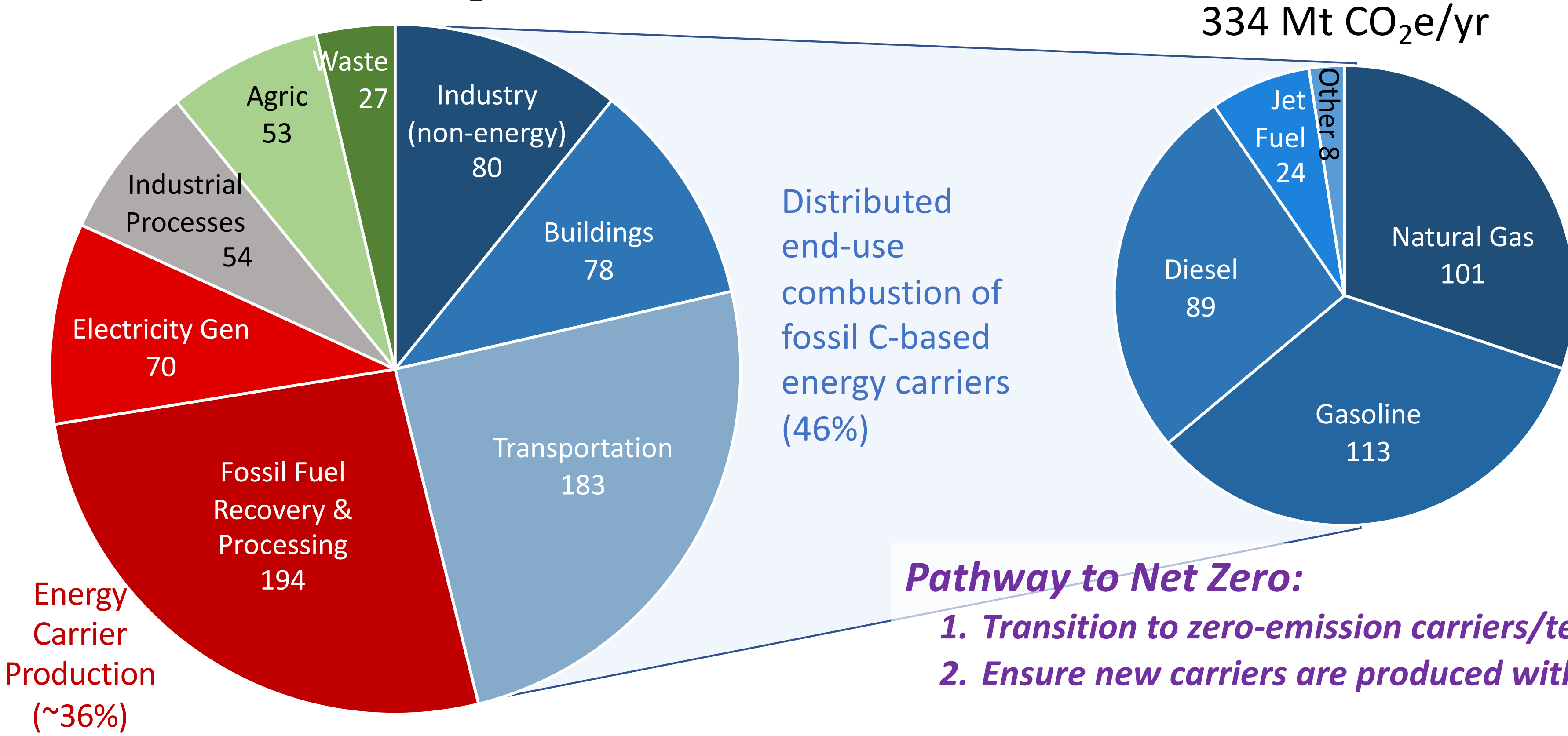
The Problem:

46%: End-use combustion of energy carriers

36%: Production of the energy carriers

Canada's GHG Emissions (2019)
738 Mt CO_2e/yr

End-use combustion of fossil
C-based Energy Carriers
334 Mt CO_2e/yr



Pathway to Net Zero:

1. ***Transition to zero-emission carriers/technologies***
2. ***Ensure new carriers are produced without GHGs***

From NIR, 2022

Zero GHG Emission Energy Carriers

Must be produced & used with minimal or no GHG Emissions

Electricity — The default choice, but not good fit for all markets *(e.g. Long distance and heavy-duty transport, high temperature heat, large temporal shifts in demand).*

Biofuels — Uses existing technologies (drop-in fuels) but limited feedstock without threatening food supply / ecosystems.

Hydrogen (H_2) — Energy-rich gas that produces only water (H_2O) when used.

N_2 → Haber-Bosch ↓

Ammonia (NH_3) — AKA Fertilizer. Energy-rich gas/liquid made from H_2 & N_2 (air)

FF with CCS — Some role for end use sectors *(e.g. Steel, cement).* Larger potential role in energy carrier production

* CCS= Carbon Capture and Geological Storage

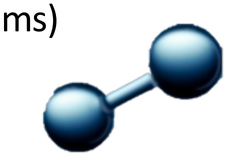
How Can Canada Transition to Net Zero & What is the Role for H_2 and NH_3?

Outline

1. Hydrogen (H_2) 101
2. Towards a new H_2 value chain
3. A Scenario for the Transition of Ontario's 2019 Energy System to Net-Zero
4. Conclusion

The Periodic Table of the Elements

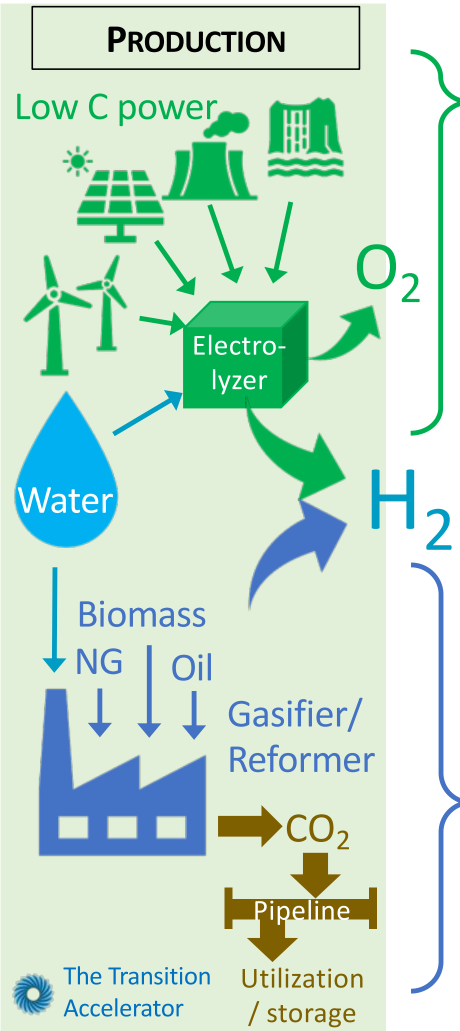
- ❑ The smallest, lightest and most common element in the Universe (~74% all atoms)
- ❑ Hydrogen atoms can form bonds with many other atoms:
  - ➢ H_2O (water), $C_6H_{12}O_6$ (carbohydrates), CH_4 (hydrocarbons); H_2 (Hydrogen)
- ❑ H_2 energy per mass: 2.5 X NG, 2.8 X gasoline
- ❑ H_2 energy per volume:
  … as GAS 1/3rd of NG; …. as LQD (-253°C): ¼ of diesel
- ❑ H_2 is most efficiently moved in pipelines as a gas



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H Hydrogen Nonmetal																	2 He Helium Noble Gas
2	3 Li Lithium Alkali Metal	4 Be Beryllium Alkaline Earth Me											5 B Boron Metalloid	6 C Carbon Nonmetal	7 N Nitrogen Nonmetal	8 O Oxygen Nonmetal	9 F Fluorine Halogen	10 Ne Neon Noble Gas
3	11 Na Sodium Alkali Metal	12 Mg Magnesium Alkaline Earth Me											13 Al Aluminum Post-transition M	14 Si Silicon Metalloid	15 P Phosphorus Nonmetal	16 S Sulfur Nonmetal	17 Cl Chlorine Halogen	18 Ar Argon Noble Gas
4	19 K Potassium Alkali Metal	20 Ca Calcium Alkaline Earth Me	21 Sc Scandium Transition Metal	22 Ti Titanium Transition Metal	23 V Vanadium Transition Metal	24 Cr Chromium Transition Metal	25 Mn Manganese Transition Metal	26 Fe Iron Transition Metal	27 Co Cobalt Transition Metal	28 Ni Nickel Transition Metal	29 Cu Copper Transition Metal	30 Zn Zinc Transition Metal	31 Ga Gallium Post-transition M	32 Ge Germanium Metalloid	33 As Arsenic Metalloid	34 Se Selenium Nonmetal	35 Br Bromine Halogen	36 Kr Krypton Noble Gas
5	37 Rb Rubidium Alkali Metal	38 Sr Strontium Alkaline Earth Me	39 Y Yttrium Transition Metal	40 Zr Zirconium Transition Metal	41 Nb Niobium Transition Metal	42 Mo Molybdenum Transition Metal	43 Tc Technetium Transition Metal	44 Ru Ruthenium Transition Metal	45 Rh Rhodium Transition Metal	46 Pd Palladium Transition Metal	47 Ag Silver Transition Metal	48 Cd Cadmium Transition Metal	49 In Indium Post-transition M	50 Sn Tin Post-transition M	51 Sb Antimony Metalloid	52 Te Tellurium Metalloid	53 I Iodine Halogen	54 Xe Xenon Noble Gas
6	55 Cs Cesium Alkali Metal	56 Ba Barium Alkaline Earth Me	*	72 Hf Hafnium Transition Metal	73 Ta Tantalum Transition Metal	74 W Tungsten Transition Metal	75 Re Rhenium Transition Metal	76 Os Osmium Transition Metal	77 Ir Iridium Transition Metal	78 Pt Platinum Transition Metal	79 Au Gold Transition Metal	80 Hg Mercury Transition Metal	81 Tl Thallium Post-transition M	82 Pb Lead Post-transition M	83 Bi Bismuth Post-transition M	84 Po Polonium Metalloid	85 At Astatine Halogen	86 Rn Radon Noble Gas
7	87 Fr Francium Alkali Metal	88 Ra Radium Alkaline Earth Me	**	104 Rf Rutherfordium Transition Metal	105 Db Dubnium Transition Metal	106 Sg Seaborgium Transition Metal	107 Bh Bohrium Transition Metal	108 Hs Hassium Transition Metal	109 Mt Meitnerium Transition Metal	110 Ds Darmstadtium Transition Metal	111 Rg Roentgenium Transition Metal	112 Cn Copernicium Transition Metal	113 Nh Nihonium Post-transition M	114 Fl Flerovium Post-transition M	115 Mc Moscovium Post-transition M	116 Lv Livermorium Post-transition M	117 Ts Tennessine Halogen	118 Og Oganesson Noble Gas
			*	57 La Lanthanum Lanthanide	58 Ce Cerium Lanthanide	59 Pr Praseodymium Lanthanide	60 Nd Neodymium Lanthanide	61 Pm Promethium Lanthanide	62 Sm Samarium Lanthanide	63 Eu Europium Lanthanide	64 Gd Gadolinium Lanthanide	65 Tb Terbium Lanthanide	66 Dy Dysprosium Lanthanide	67 Ho Holmium Lanthanide	68 Er Erbium Lanthanide	69 Tm Thulium Lanthanide	70 Yb Ytterbium Lanthanide	71 Lu Lutetium Lanthanide
			**	89 Ac Actinium Actinide	90 Th Thorium Actinide	91 Pa Protactinium Actinide	92 U Uranium Actinide	93 Np Neptunium Actinide	94 Pu Plutonium Actinide	95 Am Americium Actinide	96 Cm Curium Actinide	97 Bk Berkelium Actinide	98 Cf Californium Actinide	99 Es Einsteinium Actinide	100 Fm Fermium Actinide	101 Md Mendelevium Actinide	102 No Nobelium Actinide	103 Lr Lawrencium Actinide

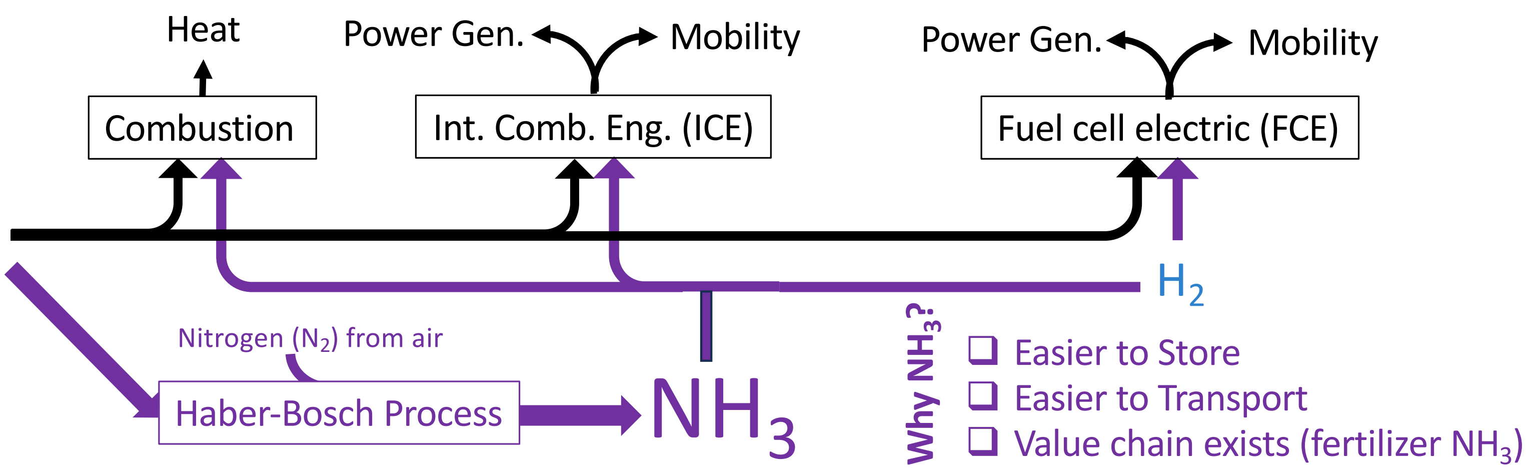
From:
https://pubchem.ncbi.nlm.nih.gov/periodic-table/

Making and Using Hydrogen (H_2) and Ammonia (NH_3)



"Green" Hydrogen:

- ❑ Cost depends on price of electricity (every \$10/MWh adds \$0.50/kg H_2 to cost). So at \$80/MWhr, H_2 cost is \$4/kg + ~\$1/kg H_2 for capital and operation costs = \$5/kg H_2
- ❑ Capital cost of electrolyzers is declining



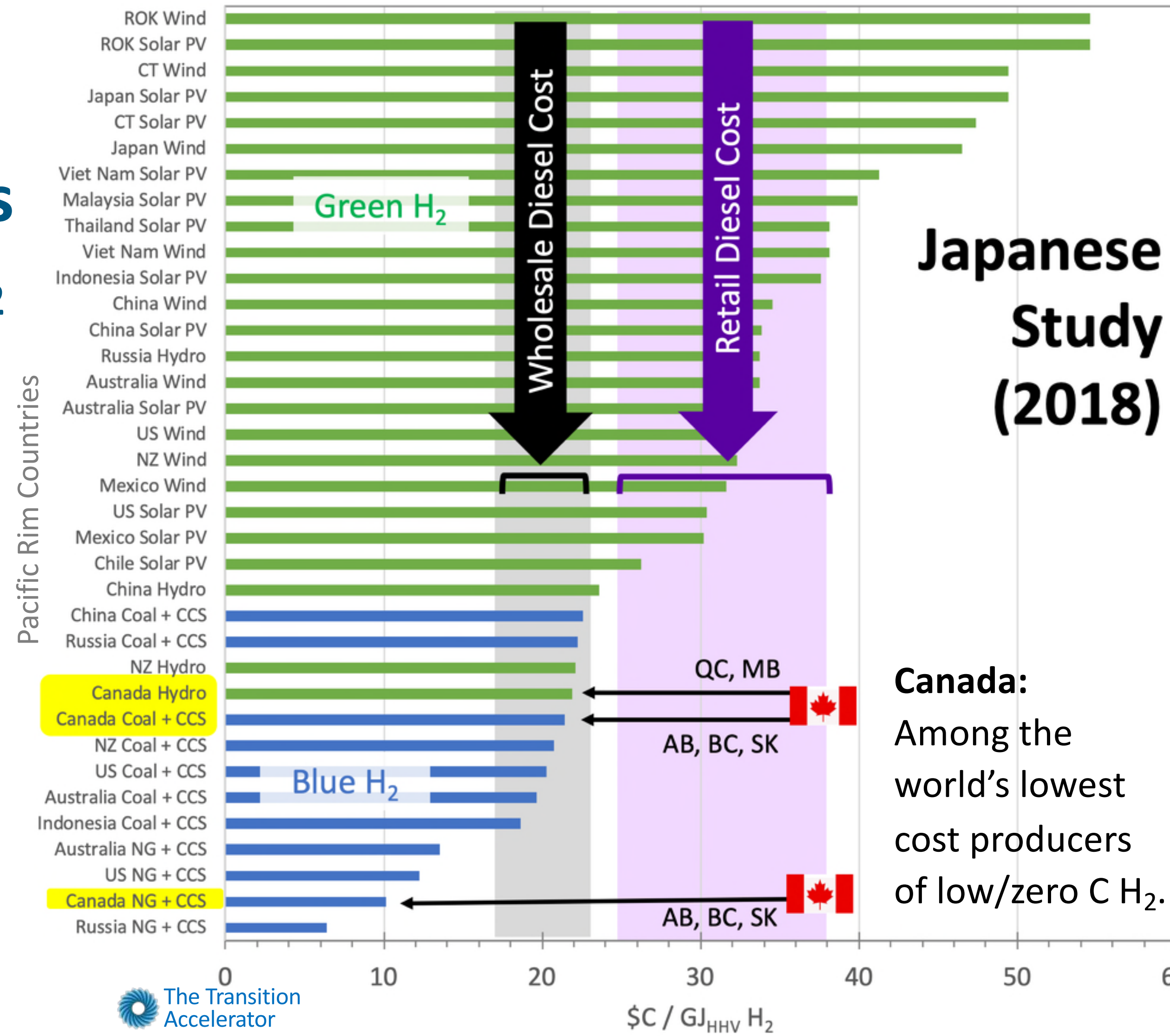
"Blue" Hydrogen:

- ❑ Cost depends on scale of production (ideally <200 t H_2/d), availability of CO_2 storage and the price of natural gas (every \$1/GJ NG adds \$0.20/kg H_2 to cost). So at \$5/GJ NG, H_2 cost is \$1/kg + ~\$0.80/kg for capital and operation costs = \$1.80/kg H_2

Canada: Among the world's lowest cost producers of 'Blue' & 'Green' H_2

From fossil fuels (NG) coupled to carbon capture and storage (CCS)

From water electrolysis using very low C electricity (wind, PV, hydro, nuclear)



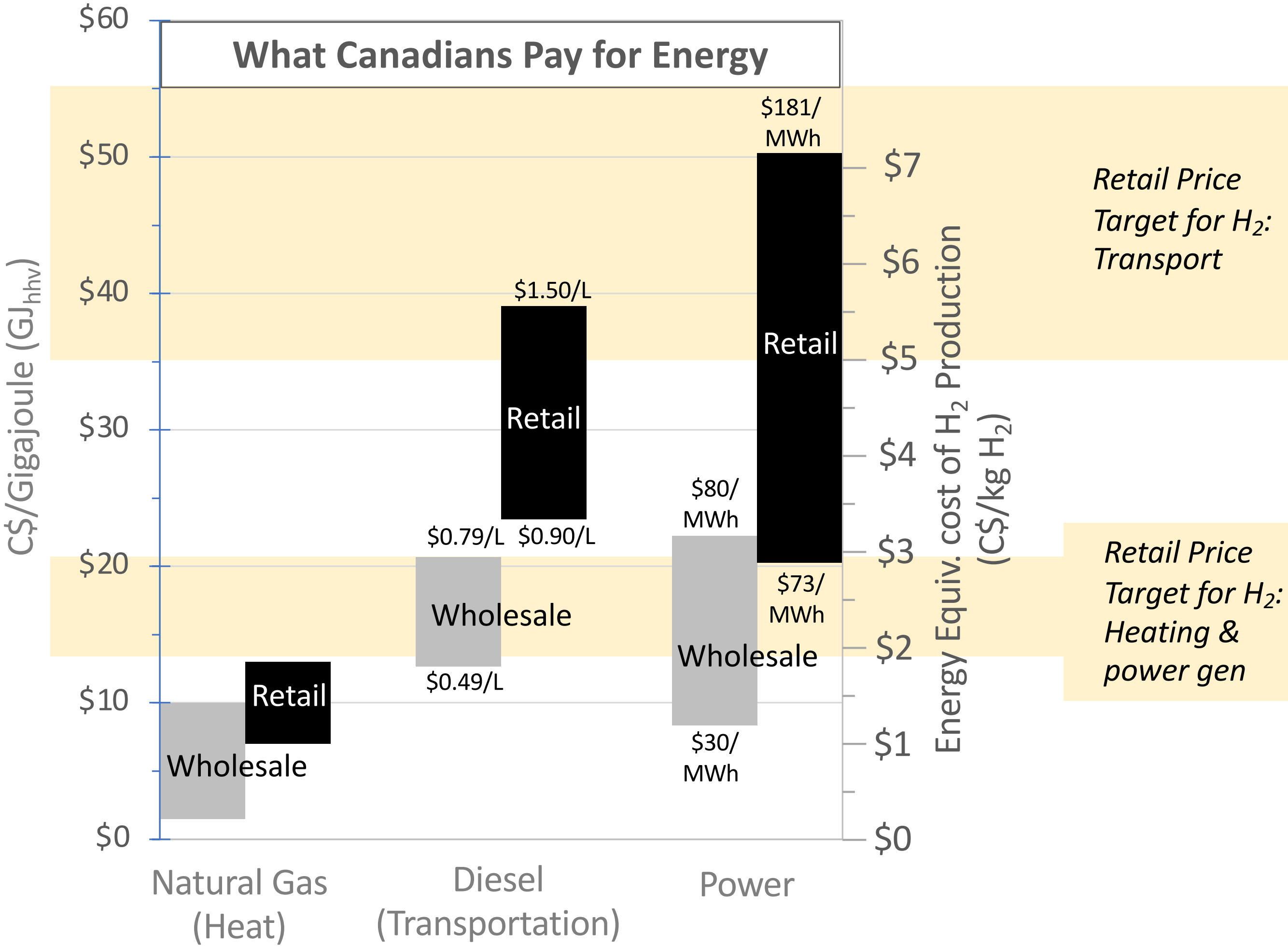
Japanese Study (2018)

Canada: Among the world's lowest cost producers of low/zero C H_2.

Adapted from Asia Pacific Energy Research Centre. 2018. Perspectives on H_2 in the APEC Region. (Figure 3.4)
https://aperc.ieej.or.jp/file/2018/9/12/Perspectives+on+Hydrogen+in+the+APEC+Region.pdf

The Transition Accelerator

What markets offer the most potential in the short term?



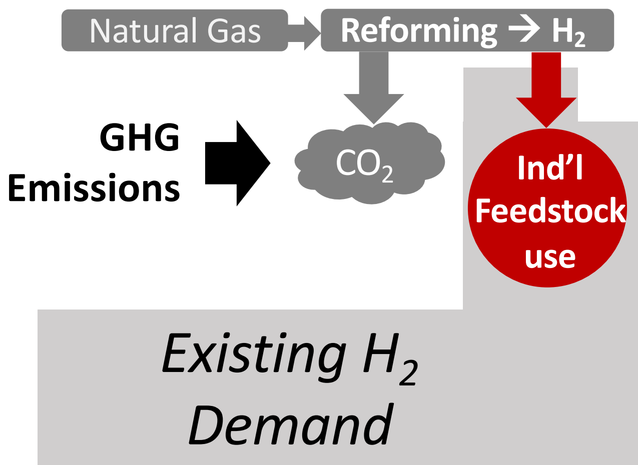
Per unit of energy, Canadians pay more for transportation fuels than for heating fuels.

… so today, the economics for H_2 is more promising for the transportation than the heating sector.

Outline

1. Hydrogen (H_2) 101
2. Towards a new H_2 value chain
3. A Scenario for the Transition of Ontario's 2019 Energy System to Net-Zero
4. Conclusion

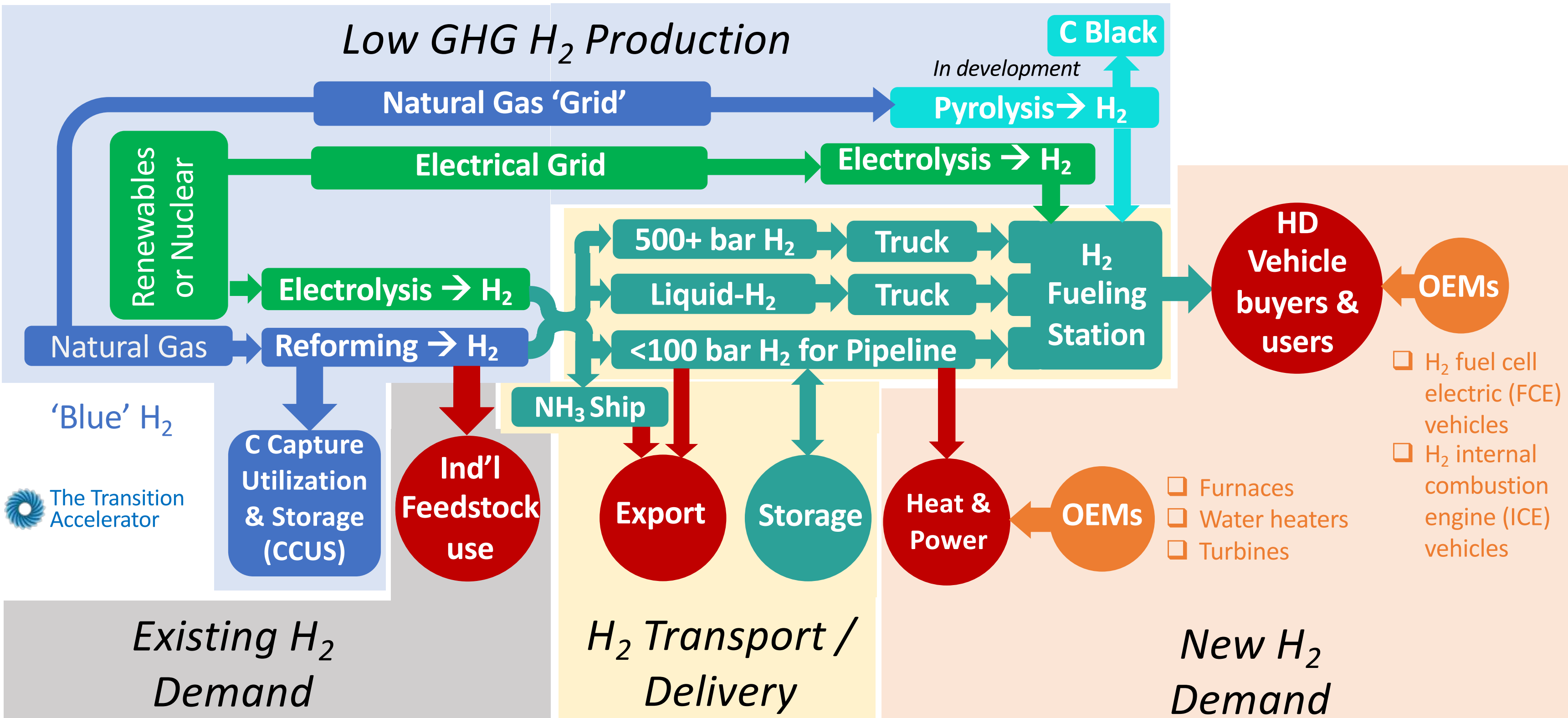
Today's Hydrogen Value Chain

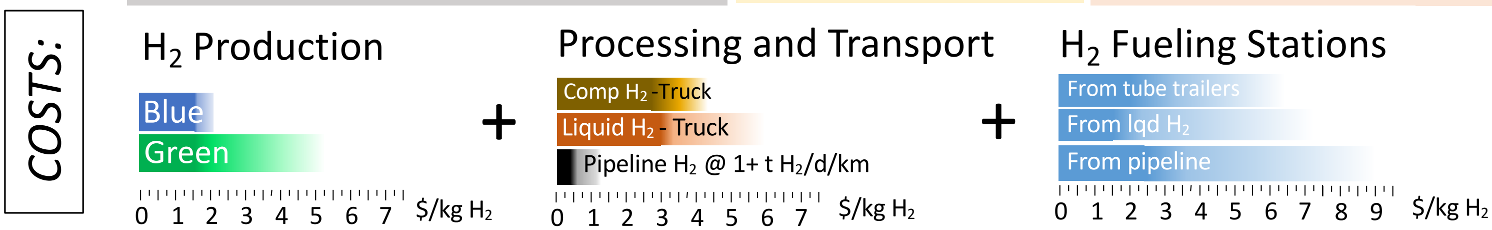


About 8-9 kt H_2/day in Canada for

- ❑ Bitumen upgrading to SCO
- ❑ Crude Oil to Refined Petrol. Prod. (RPP)
- ❑ Fertilizer (Ammonia) production
- ❑ Chemical & material production

New Value Chain For a Net-Zero Hydrogen Economy





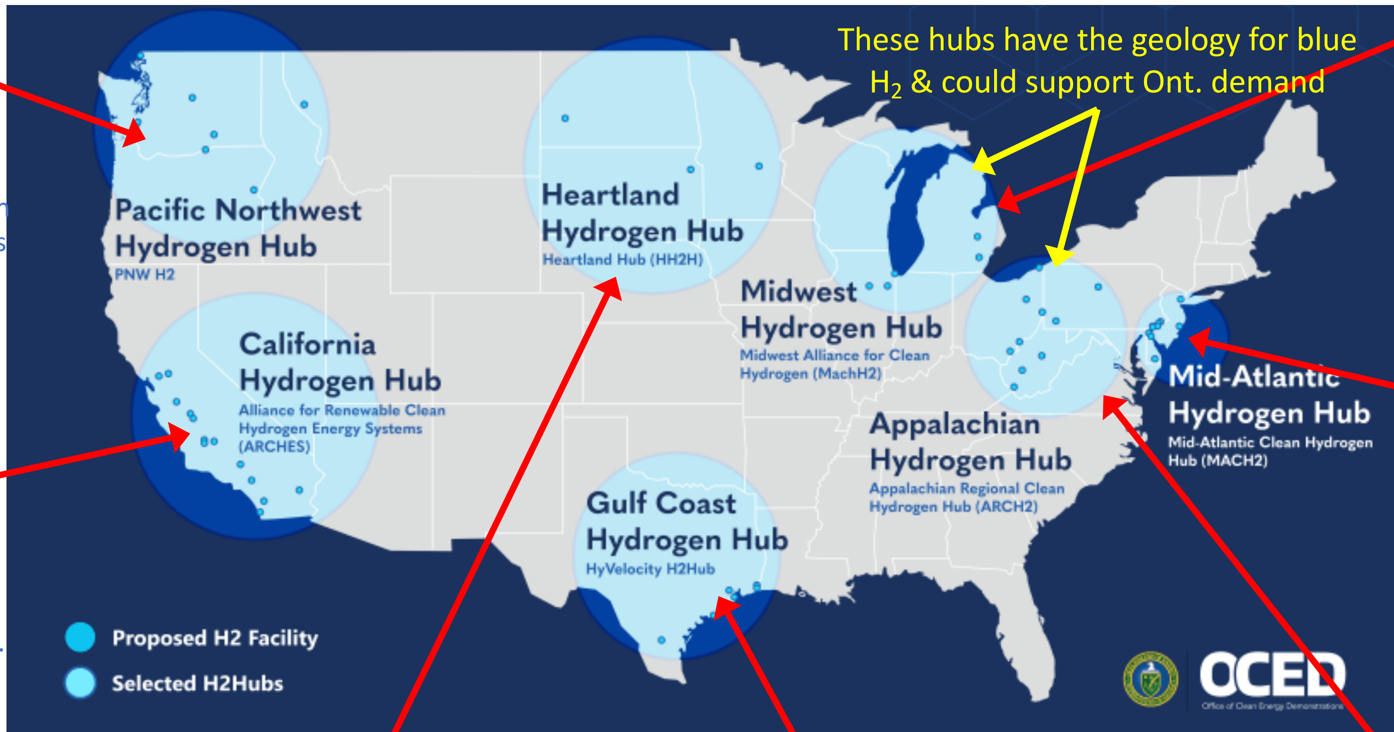
Price Targets:

- ❑ Heat & Power: \$2-3/kg H_2 (energy equiv.: 5-8 cents/kWh$_e$)
- ❑ Transportation: \$5-9/kg

US Invests US$7 Billion in Hydrogen Hubs (Oct 2023)

Pacific NW
- US1B
- Renew. $e^- > H_2$
- HD transport
- Fertilizer prod'n
- Port operations
- Air pollution

California
- US$1.2B
- Renew. $e^- > H_2$
- Biomass > H2
- Buses, HD Trucks. Port Operations
- Air pollution



Midwest
- US$1B
- Nucl. $e^- > H_2$
- Renew. $e^- > H_2$
- NG+CCS > H_2
- Steel & Glass prodn
- Power gen
- HD transport,
- Aviation fuels

Mid-Atlantic
- US$750M
- Nucl. $e^- > H_2$
- Renew. $e^- > H_2$
- O&G Sector
- HD Trucks, buses, street sweepers)
- Combined heat & power

Heartland
- US$925M
- NG+CCS > H_2
- Fertilizer prod'n,
- Power Gen & Space heating

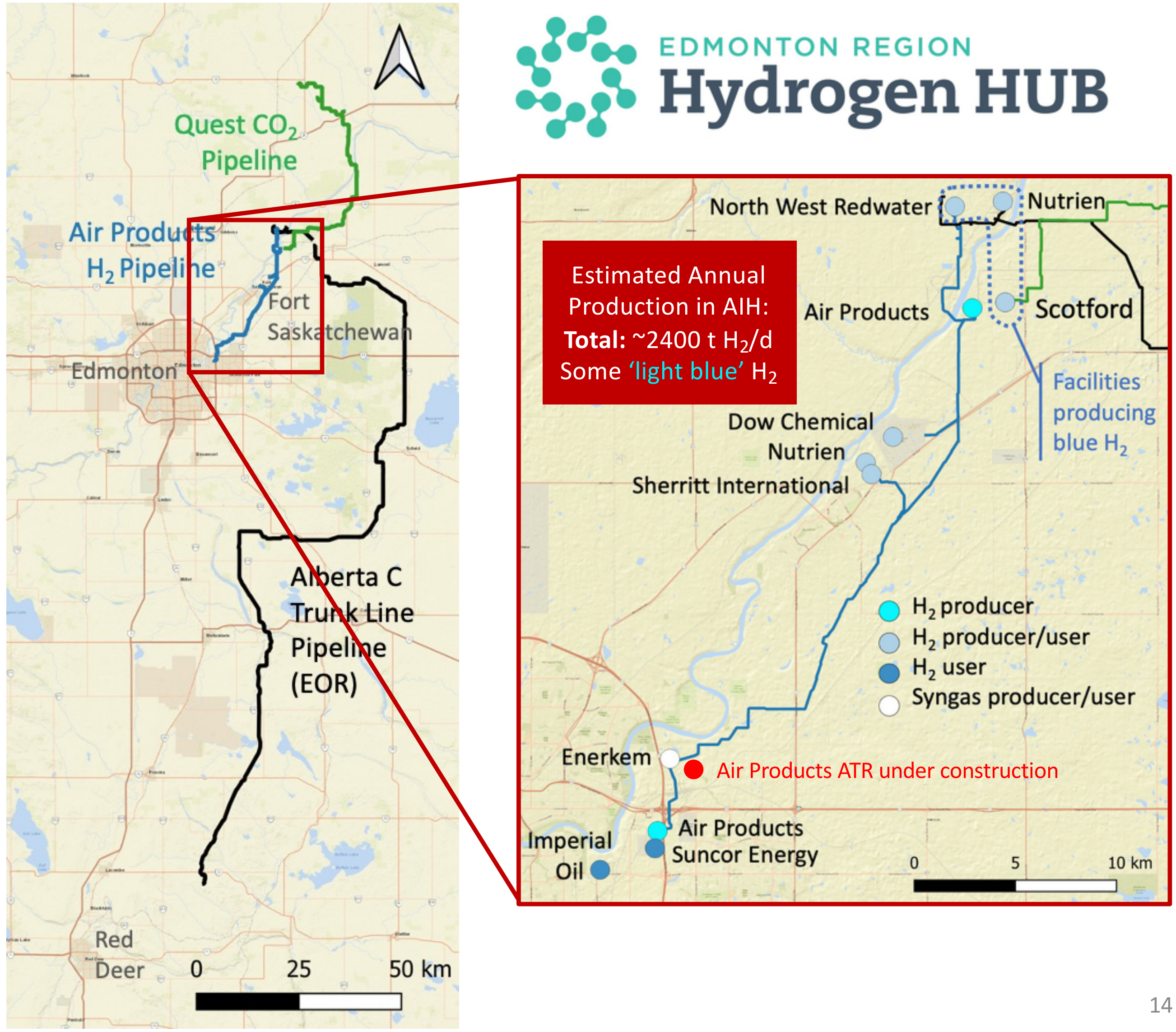
Gulf Coast
- US$1.2B
- NG+CCS > H_2; Renew. $e^- > H_2$; Storage
- O&G sector, Fertilizer Prod'n
- Power Gen & Space heating
- Trucks, marine fuel (methanol0

Appalachian
- US$925M
- NG+CCS > H_2
- H_2 pipelines
- HD vehicles

https://www.energy.gov/oced/regional-clean-hydrogen-hubs-selections-award-negotiations

Some Low GHG H_2 initiatives in Canada

Electrolytic Hydrogen Production in Canada (to support cars, trucks, buses, trains or space heating)



Progress to Date

H_2 Refueling Station for HD Vehicles

EDMONTON: OPENED IN OCT 2023
CALGARY: OPENING IN LATE 2024

AMTA Alberta Motor Transport Association

TRAVELLING ROAD SHOW WITH H_2 VEHICLES

Hyzon (HFCE)

(HFCE)

NIKOLA TWO™

Up to 40 t GVW

hydra

H_2-Diesel Dual Fuel (HD2F) Vehicles

PrairiesCan

AZETEC

ALBERTA ZERO-EMISSION TRUCK ELECTRIFICATION COLLABORATION

- ❑ Design, Build and Trial World's first two 63.5 t GVW HD Vehicle

- ❑ Currently being built in Montreal
- ❑ Will arrive in Edmonton Q1 2024
- ❑ Will move freight on Hwy 2 in 2024-25

AMTA Alberta Motor Transport Association

EMISSIONS REDUCTION ALBERTA

Progress to Date (Continued)

AZEHT
ALBERTA ZERO-EMISSION HYDROGEN TRANSIT

EMISSIONS REDUCTION ALBERTA

- Two H_2 fuel cell electric buses on road in Edmonton & Strathcona in 2023-24;

Strathcona Transit

Edmonton Transit

CP

HYDROGEN-POWERED LINE-HAUL FREIGHT LOCOMOTIVE

- First HFCE locomotive retrofit in 2022
- Two other locomotives being converted now.

YEG EDMONTON INTERNATIONAL AIRPORT

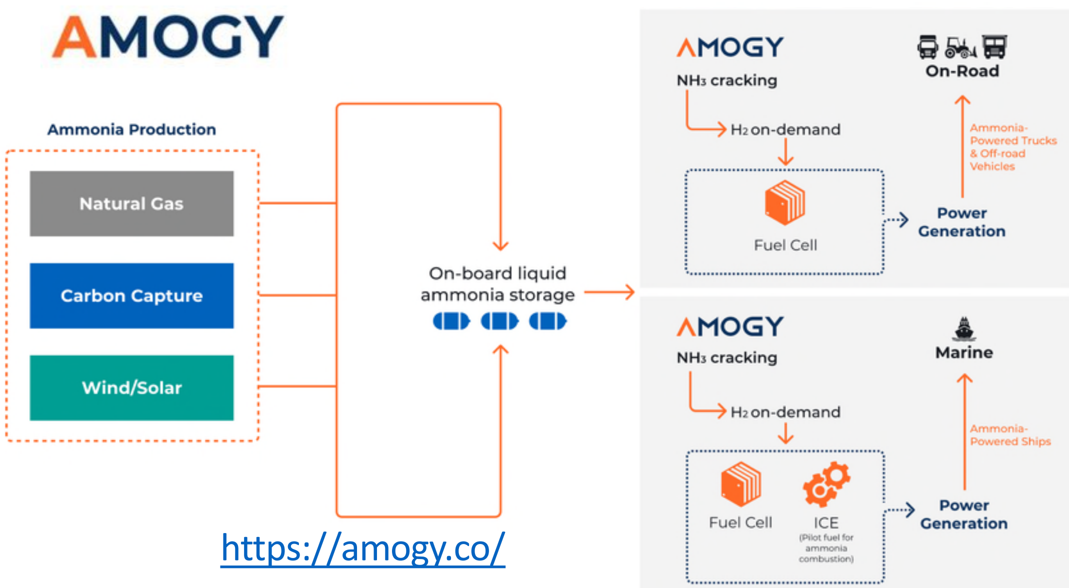
YEG PURCHASES 100 H_2 FUEL CELL ELECTRIC CARS

ATCO

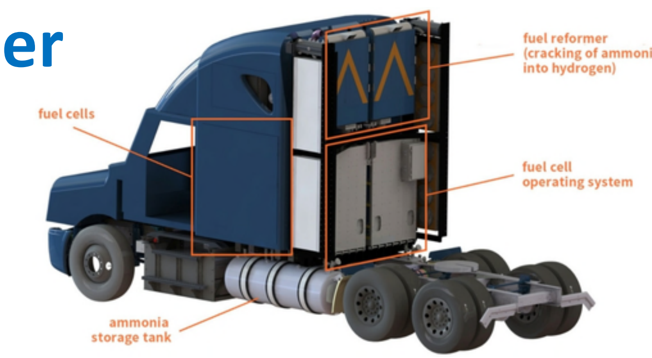
Fort Saskatchewan Hydrogen Blending Project

- *To decarbonize space heating*

Other Initiatives: NH_3 as an Energy Carrier



https://amogy.co/

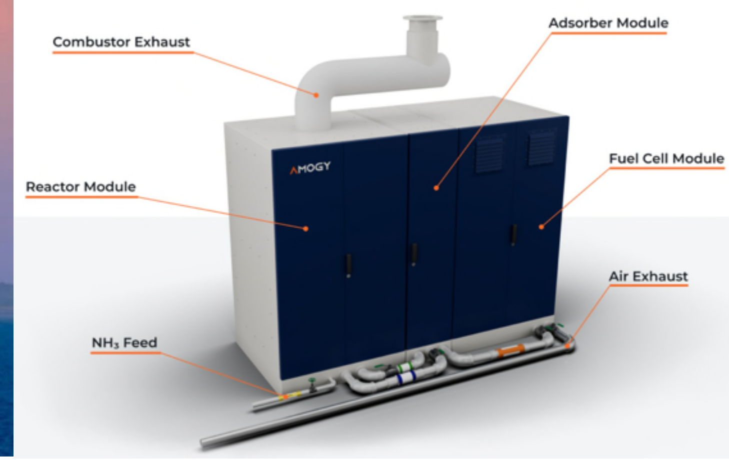


https://www.kedglobal.com/future-mobility/newsView/ked202301180010

Marine Applications

https://amogy.co/industries/

Off-grid, zero emission power generation



https://robbreport.com/motors/aviation/h2fly-aircraft-liquid-hydrogen-fuel-1234740571/

https://www.euractiv.com/section/aviation/news/airbus-to-test-hydrogen-jet-engine-in-step-towards-zero-emission-aviation/

https://www.canarymedia.com/articles/air-travel/zeroavias-hydrogen-powered-test-plane-is-nearly-ready-for-takeoff

What's coming?

Hydrogen for Aviation

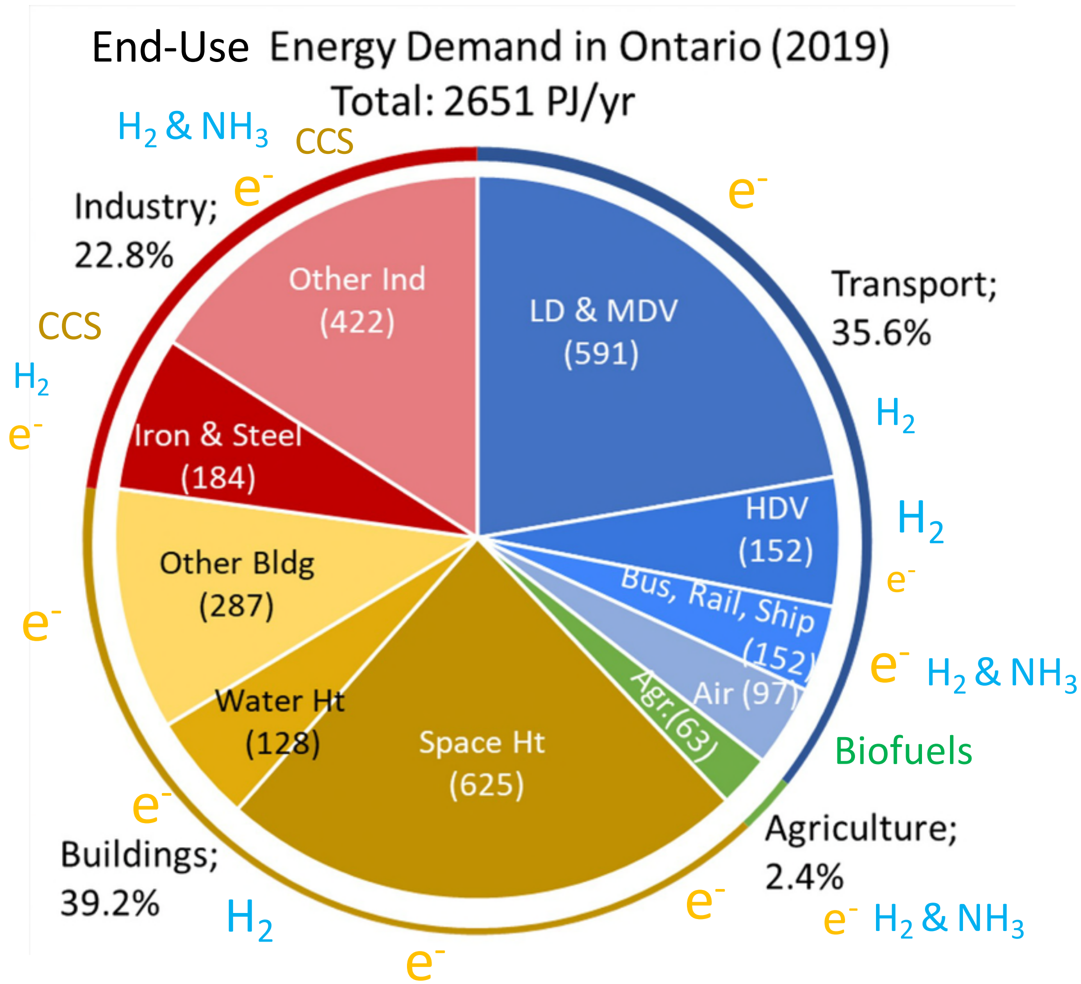
Outline

1. Hydrogen (H_2) 101
2. Towards a new H_2 value chain
3. A Scenario for the Transition of Ontario's 2019 Energy System to Net-Zero
4. Conclusion

Transitioning Ontario's 2019 Energy System to Net-Zero

End-Use Energy Demand in ON

(not including electricity or O&G production)



What are the most credible and compelling net-zero solutions for these sectors?

e^-

Biofuels

H_2

NH_3

CCS

Features of a 2019 Net-Zero Energy Transition in Ontario

END USE DEMAND

	Low GHG Electricity		Bio-fuels		Hydrogen	
Existing:		**138 TWhr**		**117 PJ**		**0 t H_2/d**
Additional	Transport	34	Transport	56	Transport	3,647
Additional	Agriculture	4	Agriculture	1	Agriculture	353
Additional	Buildings	61	Buildings	1	Buildings	3,221
Additional	Industry	50	Industry	47	Industry	2,063
	TOTAL	**287 TWhr**	**TOTAL**	**222 PJ**	**TOTAL**	**9,284 t H_2/d**
		2.1 X		**1.9 X**		**+ 2716 (power prod'n) = 12,000 t H_2/d**

SOURCES?

Low GHG Electricity:

- ❑ Nuclear
- ❑ Wind & Solar
- ❑ Imported Hydro (QC)
- ❑ H_2 for peaking

Bio-fuels:

- ❑ Forestry residues
- ❑ Municipal solid waste
- ❑ Agricultural residues
- ❑ Some Agric'l crops

Hydrogen:

- ❑ From wind, solar, nuclear when e^- supply>demand
- ❑ From Natural Gas Pyrolysis
- ❑ Import blue H_2 from USA

Conclusions

- To address climate change, it is imperative that we transition away from traditional FF-based energy carriers, and towards zero-emission energy carriers like electricity, biofuels, hydrogen and ammonia.
- In our end-use sector analysis for the 2019 Ontario energy system: the net-zero transition required a doubling in grid power and biofuels, and ~12,000+ t H_2/day.
- Some green and blue H_2 could be produced in Ontario, but most will need to be imported, probably from Michigan or Ohio. H_2 pipelines will be essential to achieve price targets.

David B Layzell PhD, FRSC.
Email: dlayzell@transitionaccelerator.ca
Web: www.transitionaccelerator.ca