HYDROGEN AS A SUSTAINABLE FUEL: ITS ROLE GLOBALLY AND IN ONTARIO

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Motivation

- address concerns related to conversion of energy practices
- investigate systems that alleviate environmental concerns
- create clean solutions for local and global energy needs

Trivia

- What is th
- How abou

	2007	2012	2017[p]	2007 to 2017
	number			% change
Canada	**32,887,928**	**34,750,545**	**36,708,083**	**11.6**
Newfoundland and Labrador	509,039	526,450	528,817	3.9
Prince Edward Island	137,721	145,080	152,021	10.4
Nova Scotia	935,071	944,943	953,869	2.0
New Brunswick	745,407	756,777	759,655	1.9
Quebec	7,692,736	8,085,906	8,394,034	9.1
Ontario	12,764,195	13,413,702	14,193,384	11.2
Manitoba	1,189,366	1,250,265	1,338,109	12.5
Saskatchewan	1,002,048	1,086,018	1,163,925	16.2
Alberta	3,514,031	3,880,755	4,286,134	22.0
British Columbia	4,290,988	4,546,290	4,817,160	12.3
Yukon	32,557	36,058	38,459	18.1
Northwest Territories	43,374	43,594	44,520	2.6
Nunavut	31,395	34,707	37,996	21.0

[p] preliminary
Note: Population estimates as of July 1.
Source: Statistics Canada, CANSIM table 051-0005.

Trivia

- How many vehicles are registered in Canada?

	Canada (map)				
Type of vehicle	**2013**	**2014**	**2015**	**2016**	**2017**
	Number				
Total, vehicle registrations	31,718,809	32,565,521	33,168,805	33,771,855	34,320,737
Total, road motor vehicle registrations	23,006,222	23,538,817	23,923,806	24,269,868	24,566,696
Vehicles weighing less than 4,500 kilograms	21,261,660	21,729,596	22,067,778	22,410,030	22,678,328
Vehicles weighing 4,500 kilograms to 14,999 kilograms	550,572	575,363	591,897	590,023	605,353
Vehicles weighing 15,000 kilograms or more	432,684	455,004	464,322	462,908	471,541
Buses	88,878	90,650	90,551	90,643	90,925
Motorcyles and mopeds	672,428	688,204	709,258	716,264	720,549
Trailers	6,686,145	6,904,643	7,094,079	7,269,669	7,514,793
Off-road, construction, farm vehicles	2,026,442	2,122,061	2,150,920	2,232,318	2,239,248

Trivia

- How many vehicles are registered in Ontario?

	Ontario (map)				
Type of vehicle	**2013**	**2014**	**2015**	**2016**	**2017**
	Number				
Total, vehicle registrations	11,263,085	11,438,574	11,685,875	11,948,296	12,273,788
Total, road motor vehicle registrations	8,103,065	8,192,530	8,358,366	8,538,070	8,707,286
Vehicles weighing less than 4,500 kilograms	7,625,689	7,710,424	7,866,332	8,037,343	8,199,865
Vehicles weighing 4,500 kilograms to 14,999 kilograms	118,726	120,176	122,686	125,157	128,564
Vehicles weighing 15,000 kilograms or more	117,840	118,941	122,462	125,594	129,084
Buses	29,516	29,706	29,837	30,043	30,318
Motorcyles and mopeds	211,294	213,283	217,049	219,933	219,455
Trailers	2,486,733	2,550,705	2,612,930	2,680,796	2,811,917
Off-road, construction, farm vehicles	673,287	695,339	714,579	729,430	754,585

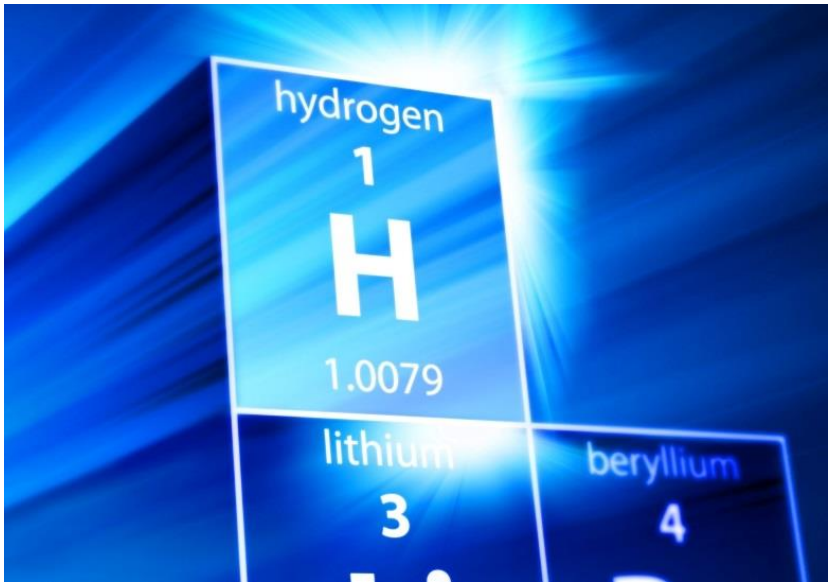
Why Hydrogen?

- Gasoline $C_8H_{16} + 12O_2 \Rightarrow 8CO_2 + 8H_2O$

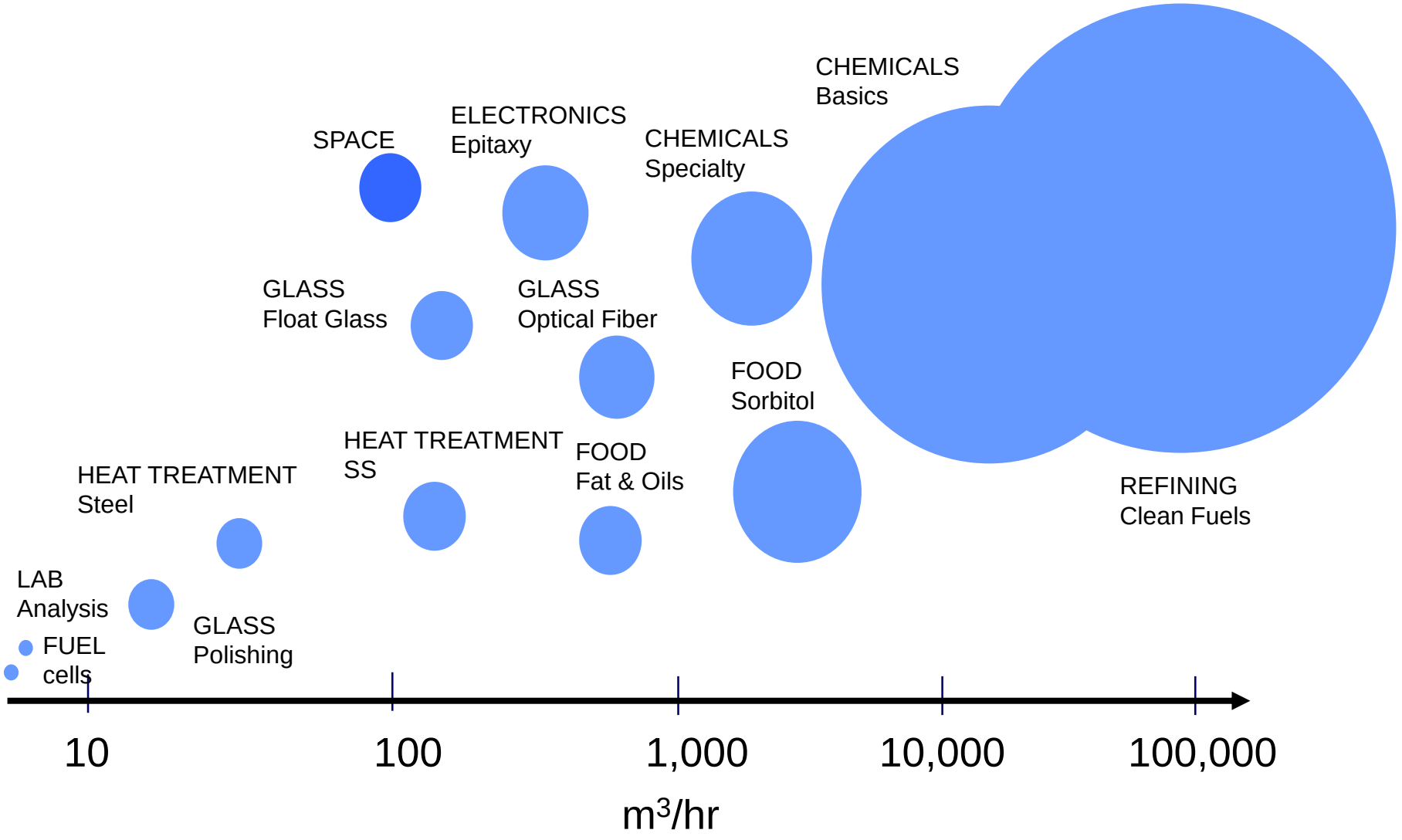
- 99% of carbon in gasoline is emitted in the form of CO_2
- The average vehicle outputs about 4.6 metric tons of CO_2 per year
  - Canada: 158 metric megatons
  - Ontario: 56.5 metric mega tons
  - The World: 5.5 metric giga tons (5,500 mega tons)
- Hydrogen as fuel: $2H_2+O_2 \Rightarrow 2H_2O$

Hydrogen

- lightest element on the periodic table
- exists in molecular forms as water or other organic compounds
- highly flammable in air at a wide range of concentrations
- high enthalpy of combustion compared to its size

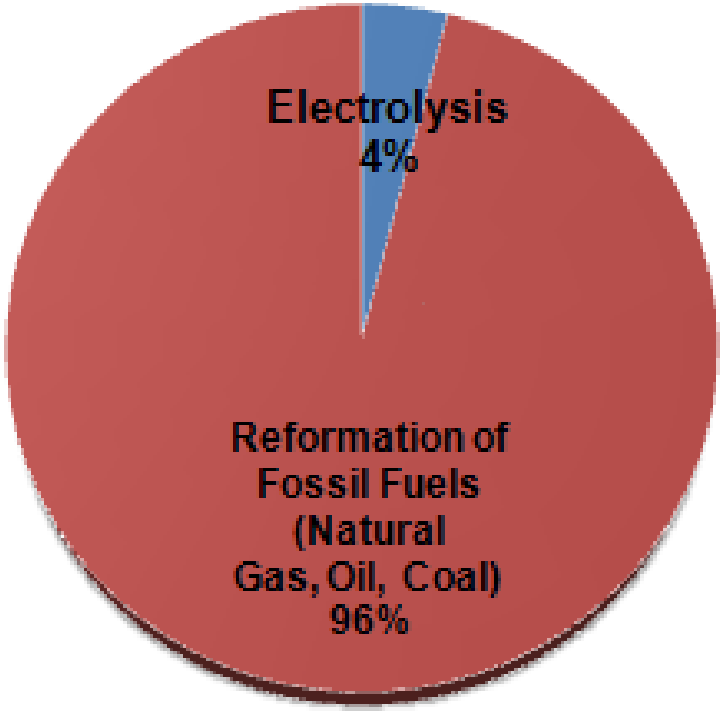


Hydrogen Use



Present Hydrogen Production

Source: Hydrogenics



Hydrogen Production Processes

Fossil fuel

- Steam reforming of natural gas
- Catalytic decomposition of natural gas
- Partial oxidation of heavy oil
- Coal gasification

Non-fossil fuel

- Water electrolysis
- Thermochemical water decomposition
- Photochemical
- Photoelectrochemical
- Photobiological

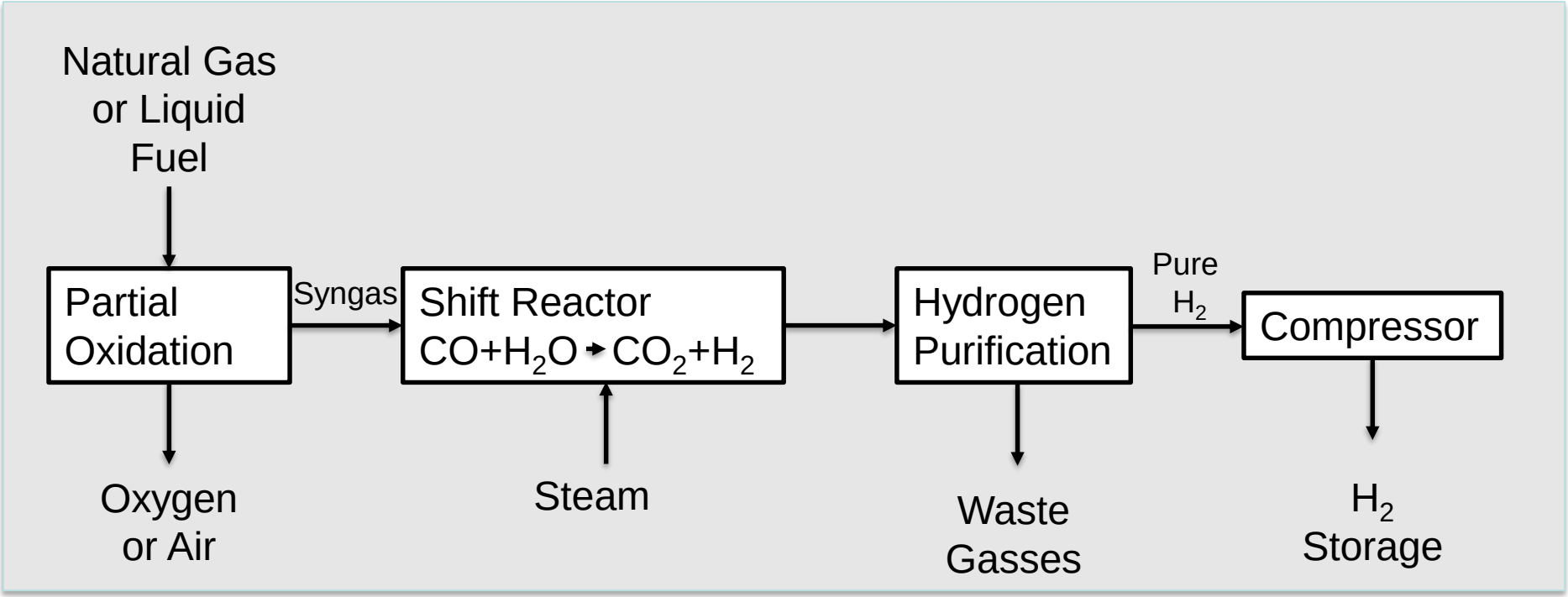



Steam Methane Reforming

$$CH_4 + H_2O_{(g)} \rightarrow CO + 3H_2 \quad \Delta\bar{h}_r = +251\,\text{MJ/kmol } CH_4$$
$$CO + H_2O_{(g)} \rightarrow CO_2 + H_2 \quad \Delta\bar{h}_r = -41.2\,\text{MJ/kmol } CO$$
$$CH_4 + 2H_2O_{(g)} \leftrightarrow CO_2 + 4H_2 \quad \Delta\bar{h}_r = +209.8\,\text{MJ/kmol } CH_4$$

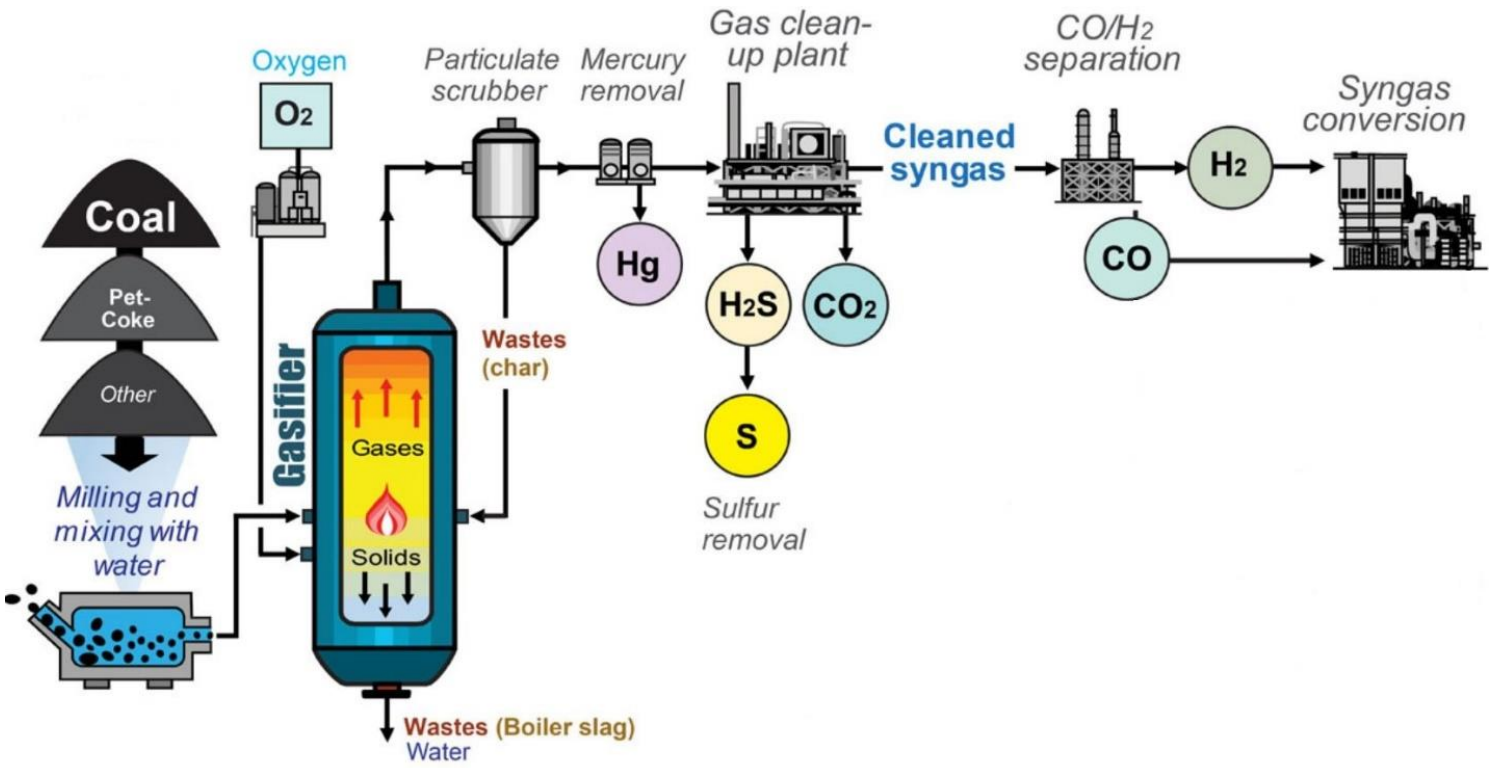
- Output is syngas, hence impure hydrogen gas
- Cannot be used in most situations in industry
- 3 common methods to filter the syngas:
  - pressure-swing adsorption (PSA) to isolate H_2
  - PSA to isolate CO_2 and then condense the remaining H_2O
  - and a membrane used to filter the hydrogen.

Partial Oxidation of Oil



- Ratio of CO_2 emissions to H_2 generation - 3:1
- Purity of hydrogen: 99.99%
- Generally perceived as being able to produce hydrogen quicker than SMR and requires less space for production

Coal Gasification



- More than double the emissions level for SMR
- A relatively inefficient process compared to SMR, having a 59% thermal efficiency
- Hydrogen extracted from unrefined product

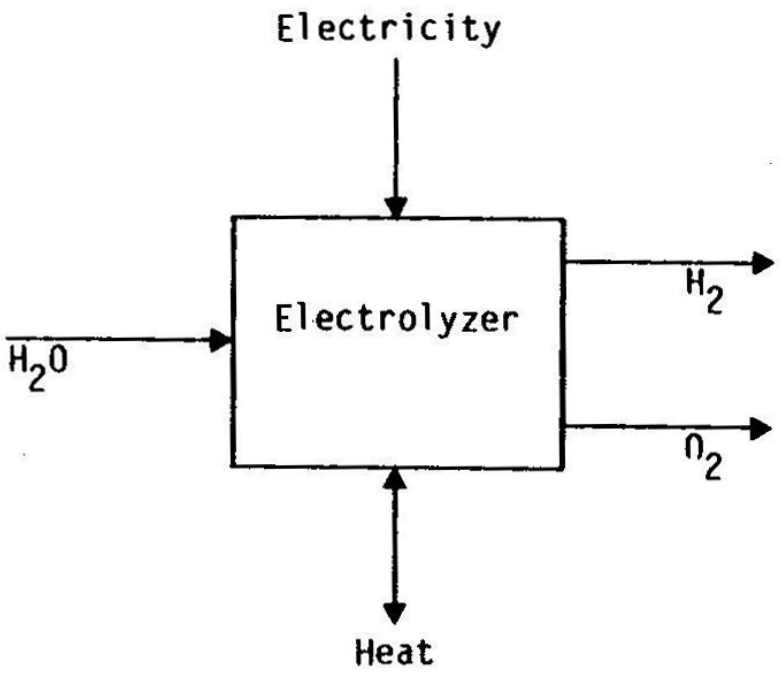
Petroleum Coke Reforming

$$C_{(gr)} + H_2O \rightarrow CO + H_2$$
$$2CO = C_{(gr)} + CO_2$$
$$C_{(gr)} + 2H_2 \rightarrow CH_4$$

- Petcoke is formed through refinement processes
- A major by-product of the oil sands hence, specifically interesting in a Canadian context
- High CO_2 emissions during utilization
- High temperature requirements (above 1300 K)

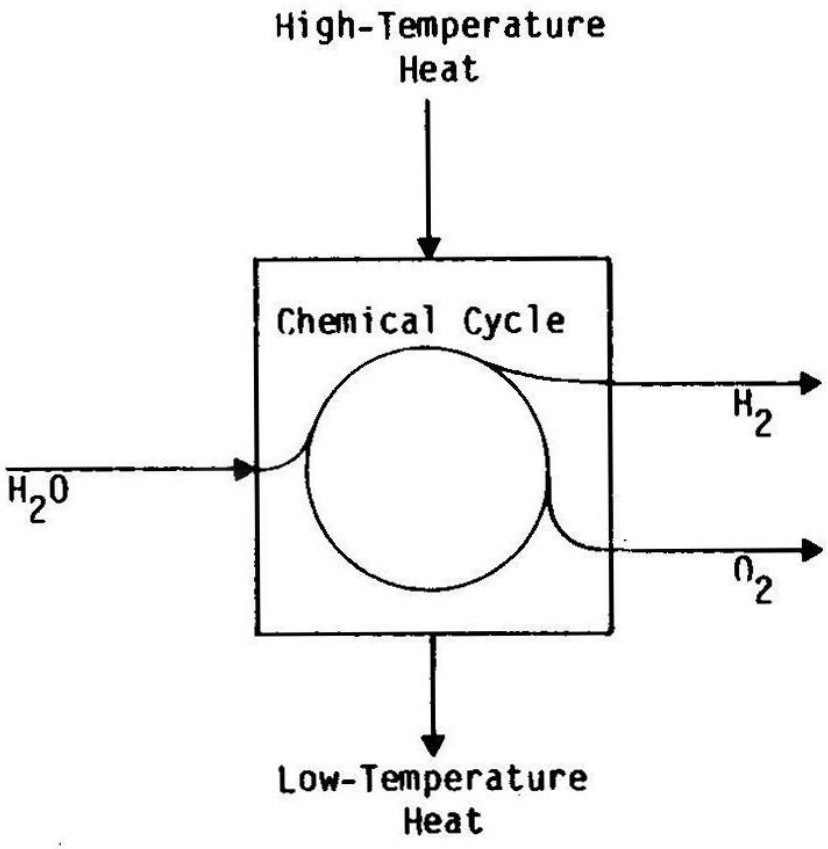
Non-fossil Energy Sources for H_2

Water Electrolysis



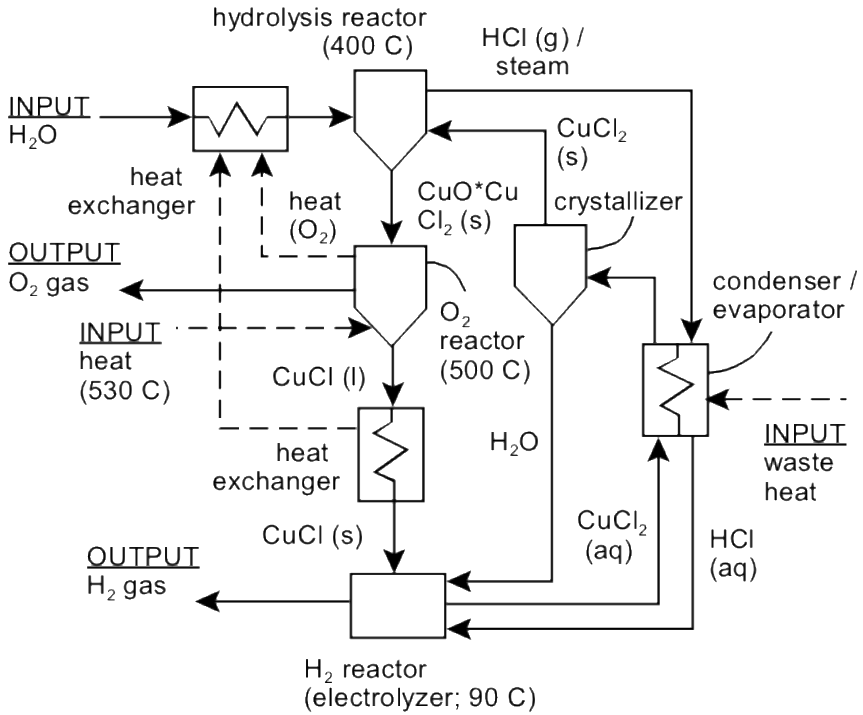
- 99.99% purity
- Electricity-to-hydrogen performance is related to mass transfer
- Higher cost than that of fossil fuel based methods

Thermochemical Water Decomposition



- Advantages:
  - Oxygen and hydrogen are produced in different reactors => safe
  - Hydrogen purity is 99.999% => suitable for fuel cells
  - Chemicals are recycled internally => no emissions
- Disadvantages:
  - Expensive
  - Low efficiency
  - High temperature requirements

Cu-Cl Cycle Conceptual Layout



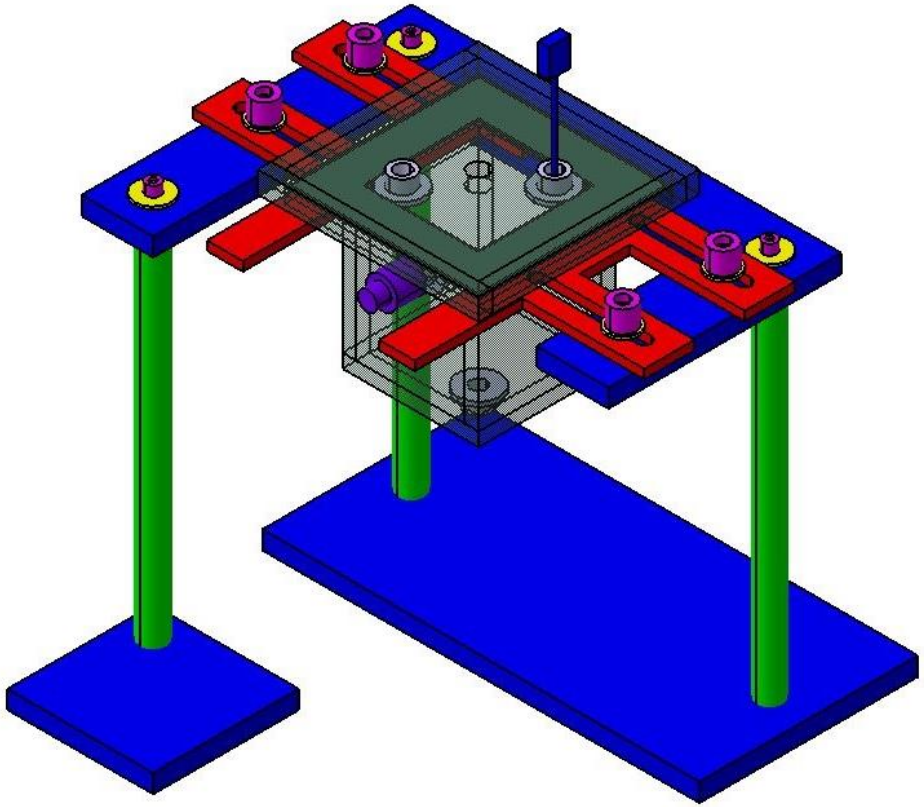
Reaction	Process and heat flow	Major reaction
A	Electrolysis for hydrogen production	$2CuCl(aq) + 2HCl(aq) + V_E = H_2(g) + 2CuCl_2(aq)$ in aqueous solution, at 30-90°C
B	Hydrolysis of cupric chloride, endothermic	$2CuCl_2(s) + H_2O(g) + Q = Cu_2OCl_2(s) + 2HCl(g)$, at 350-400°C
C	Oxygen production, endothermic	$Cu_2OCl_2(s) + Q = 2CuCl(molten) + 0.5O_2(g)$, at 500-530°C
Summation of all reactions		$H_2O(l) = H_2(g) + ½O_2(g)$ (net reaction)
(a) Symbols: *aq* – aqueous, *g* – gas, *l* – liquid, *Q* – heat, *s* – solid, V_E – electricity		

Thermochemical Water Decomposition

Copper-Chlorine Cycle

Quenching of CuCl in water:

- Studies performed using the lumped sum analysis
- Studies were performed in presence of air -> CuCl complexes formed
- Simulations are currently underway using COMSOL Multiphisics
- The experimental set-up is being constructed and experiments will commence July 5th

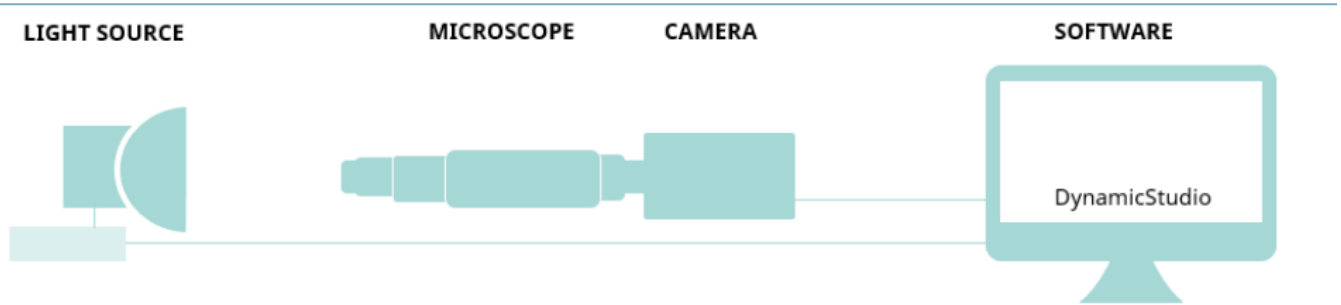


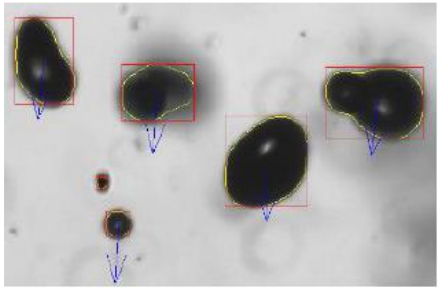
Thermochemical Water Decomposition

Copper-Chlorine Cycle

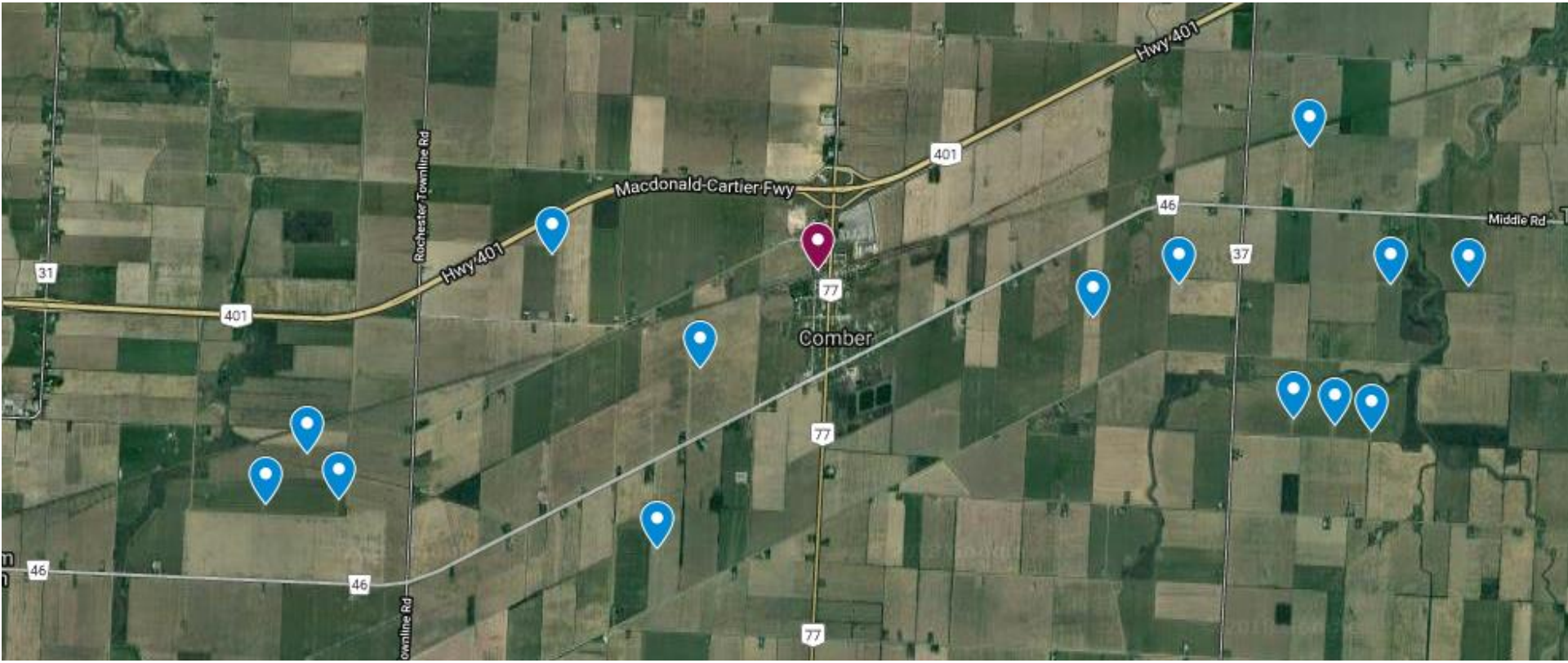
Quenching of CuCl in water:

- Flow of CuCl observed with Shadow Imager (CFI)
  - FlowSense EO CCD camera (low noise)
  - Magnification to $5x10^{-6}$ m via long distance microscope and macro lens
  - ShadowStrobe used with dual power laser which includes a motion attenuator
- Temperature variations observed with thermal camera

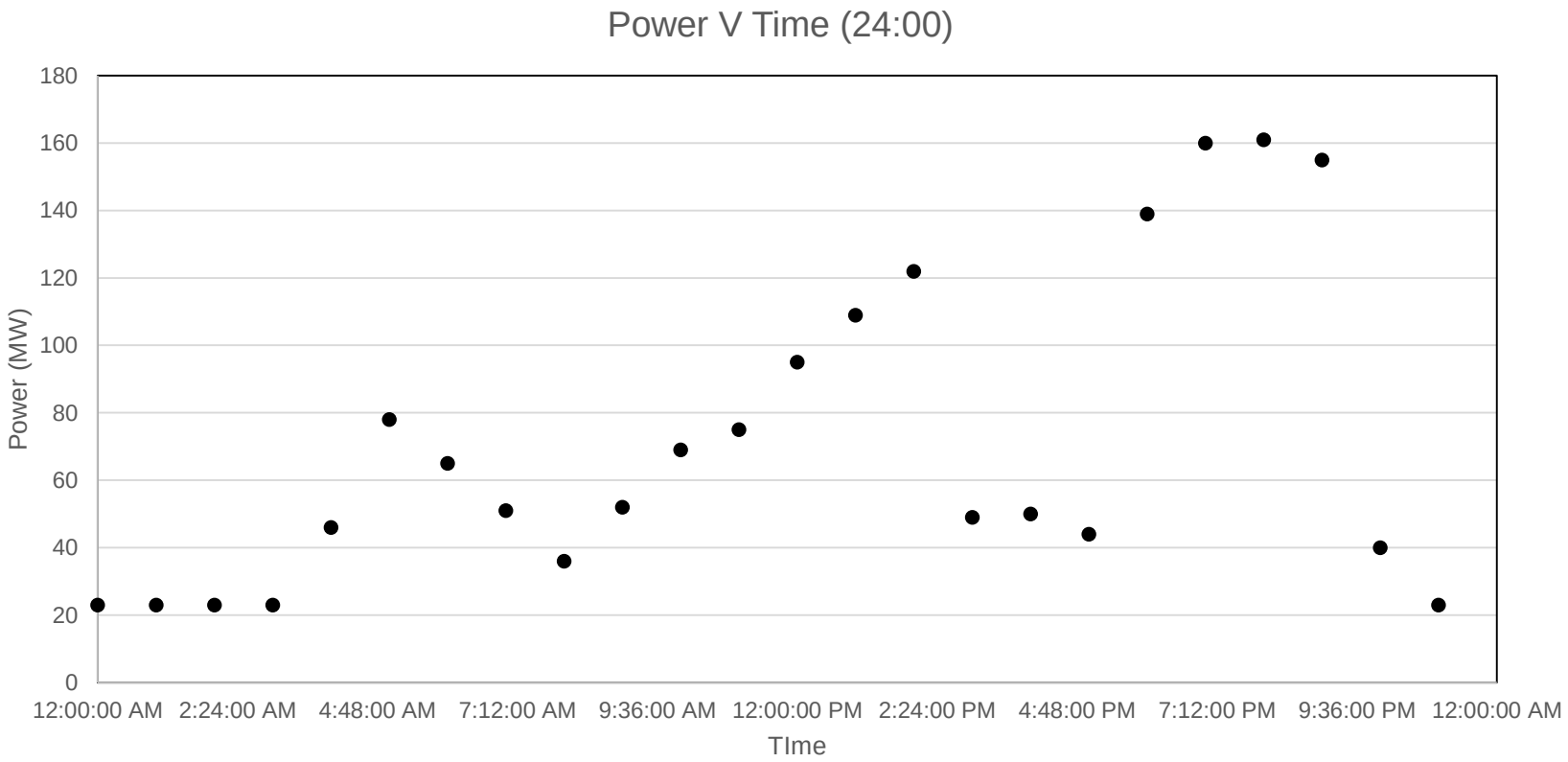




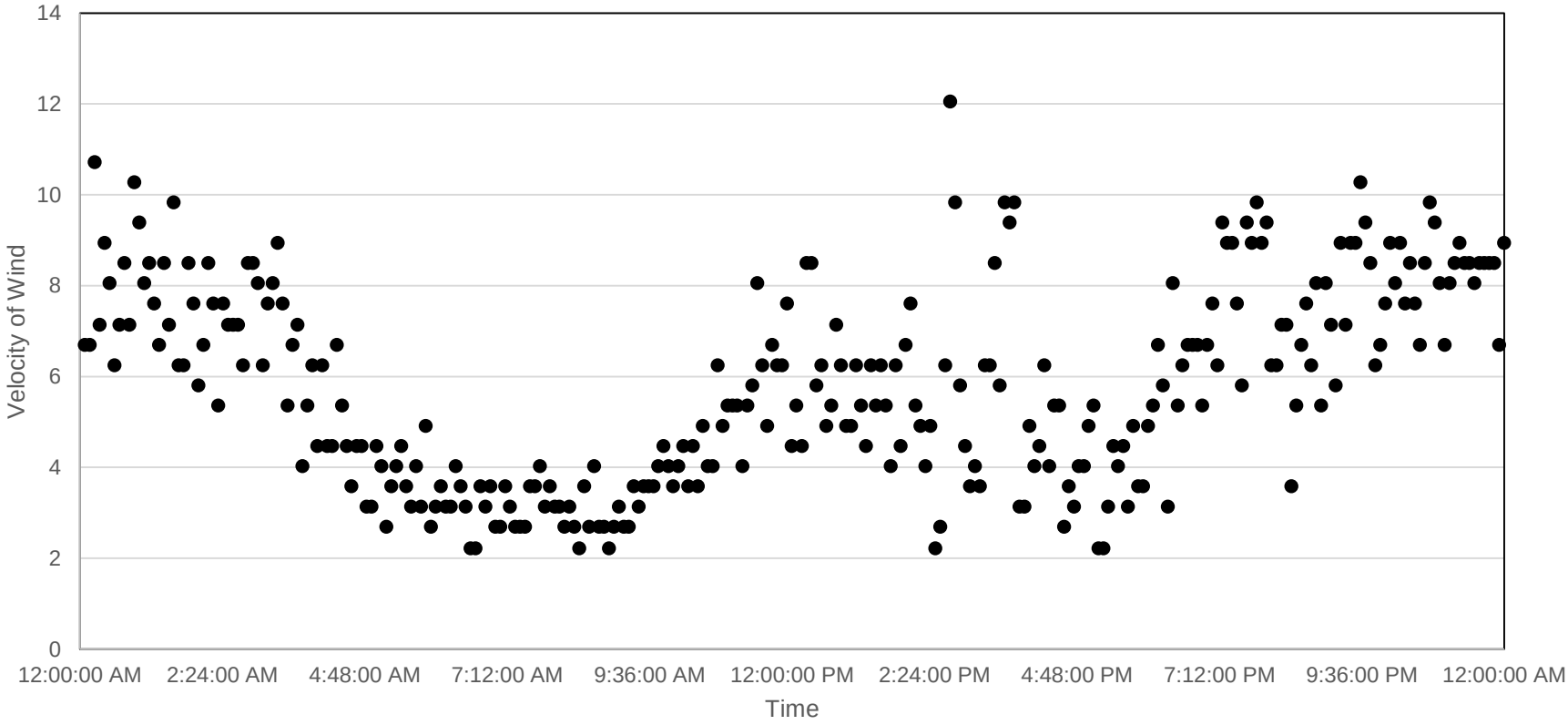
Comber Wind farm



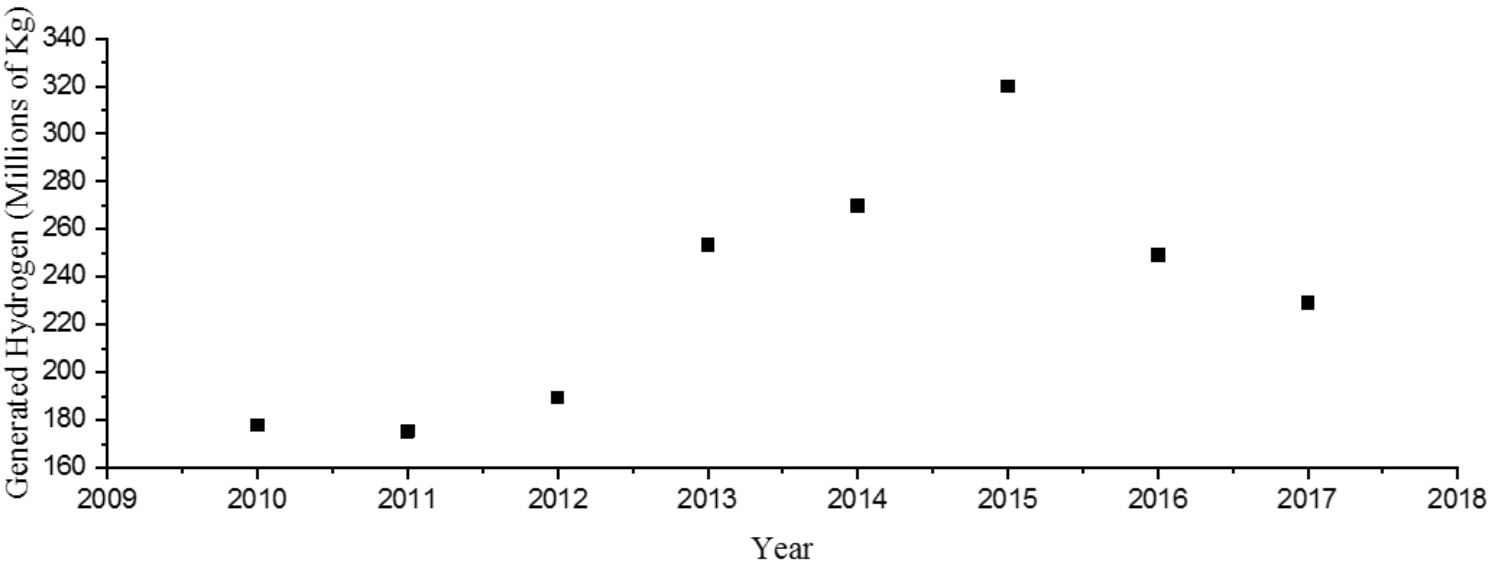
Output V Time



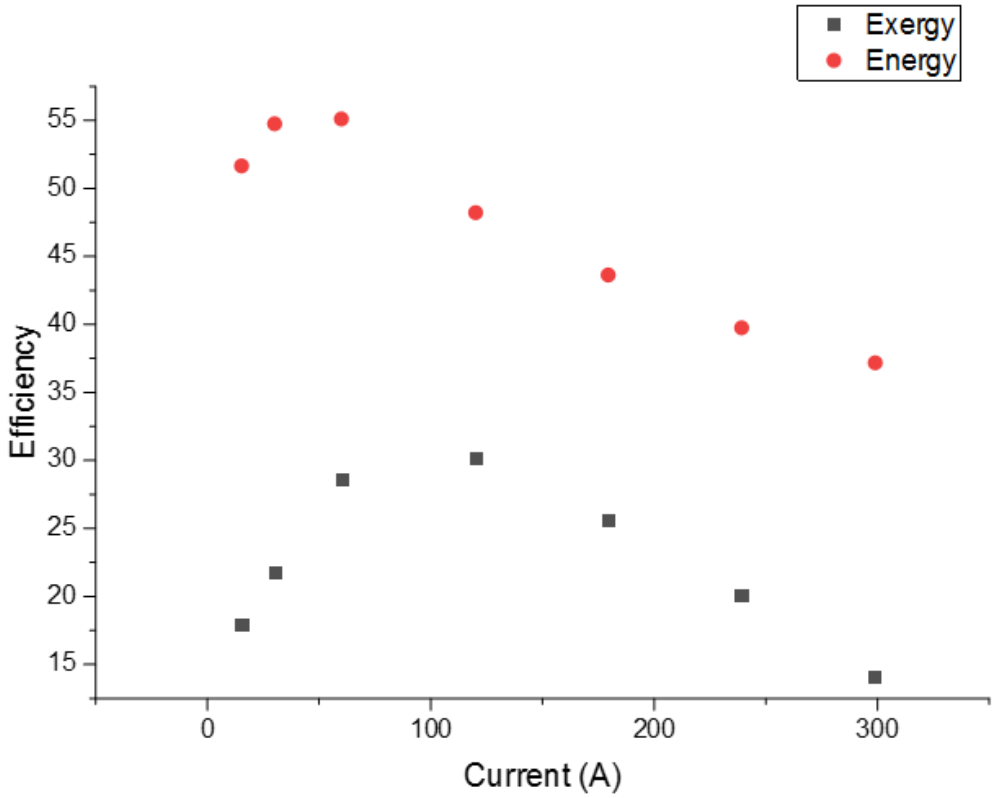
Speed V Time


14
12
10
8
6
4
2
0
Velocity of Wind
12:00:00 AM
2:24:00 AM
4:48:00 AM
7:12:00 AM
9:36:00 AM
12:00:00 PM
2:24:00 PM
4:48:00 PM
7:12:00 PM
9:36:00 PM
12:00:00 AM
Time

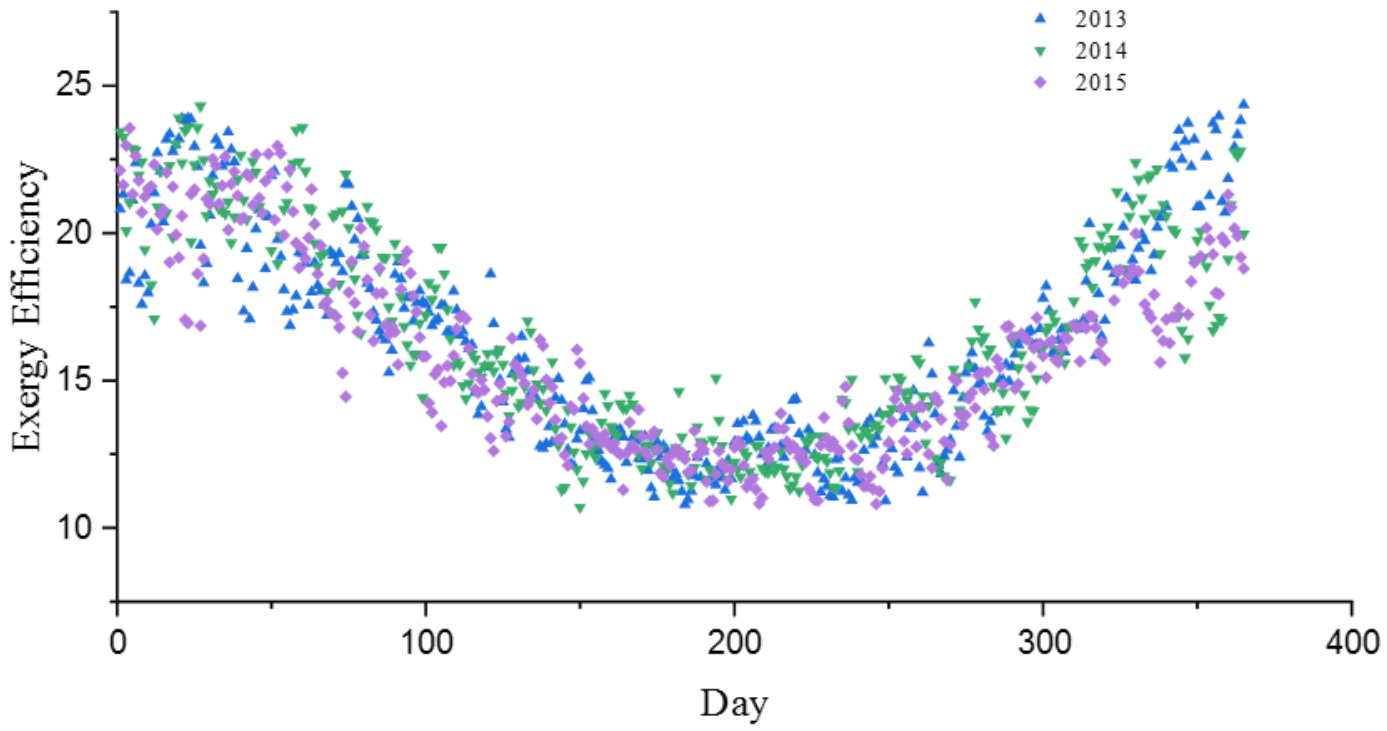
Hydrogen Generation Based on Excess Grid



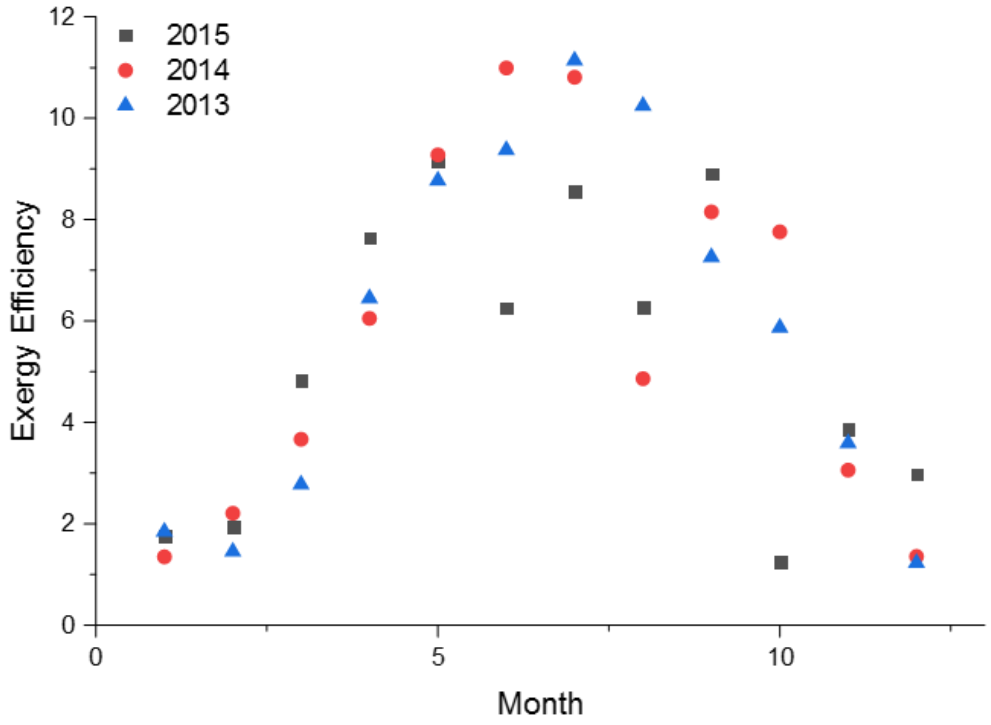
Hydrogen Fuel Cell Exergy



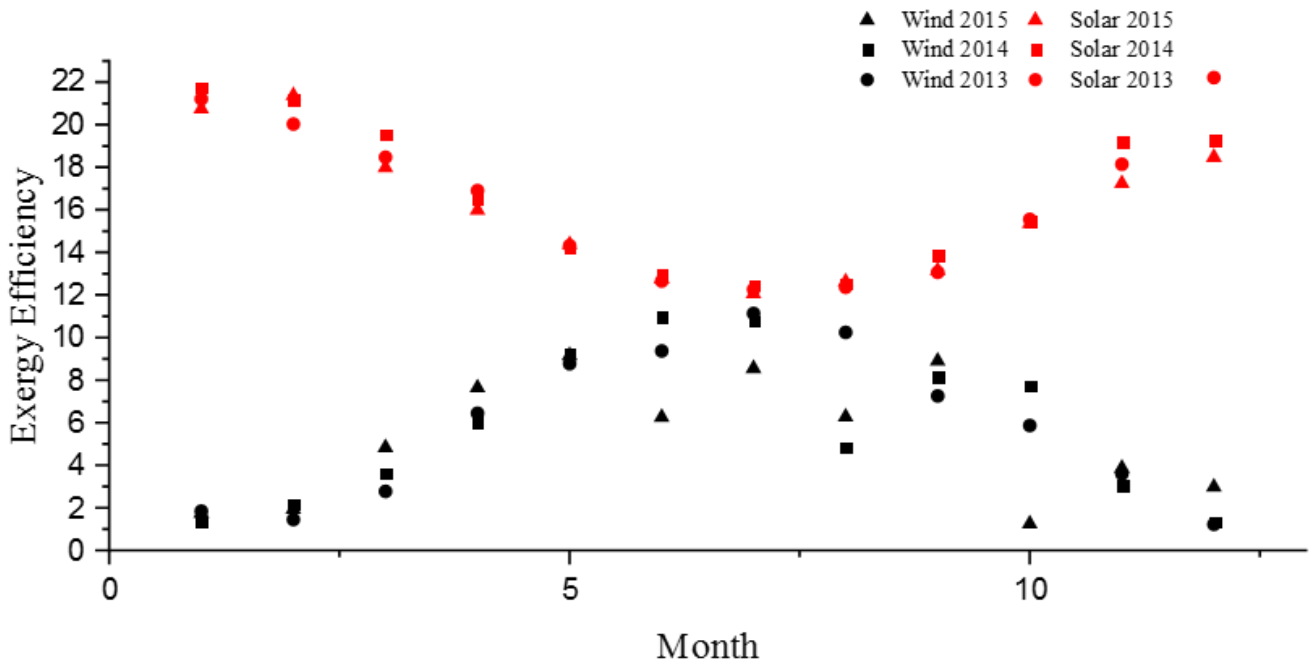
PV Panel Exergy



Hydrogen Generation Based on Excess Grid



Hydrogen Generation Based on Excess Grid



Conclusion

- SMR is still the most common method to produce hydrogen
  - Fossil fuel based
  - Unsustainable
- Other methods such as thermochemical cycles:
  - A cleaner alternative
  - More research is needed