Compressorless Hydrogen Transmission Pipelines

Deliver Large-scale Stranded Renewable Energy at Competitive Cost

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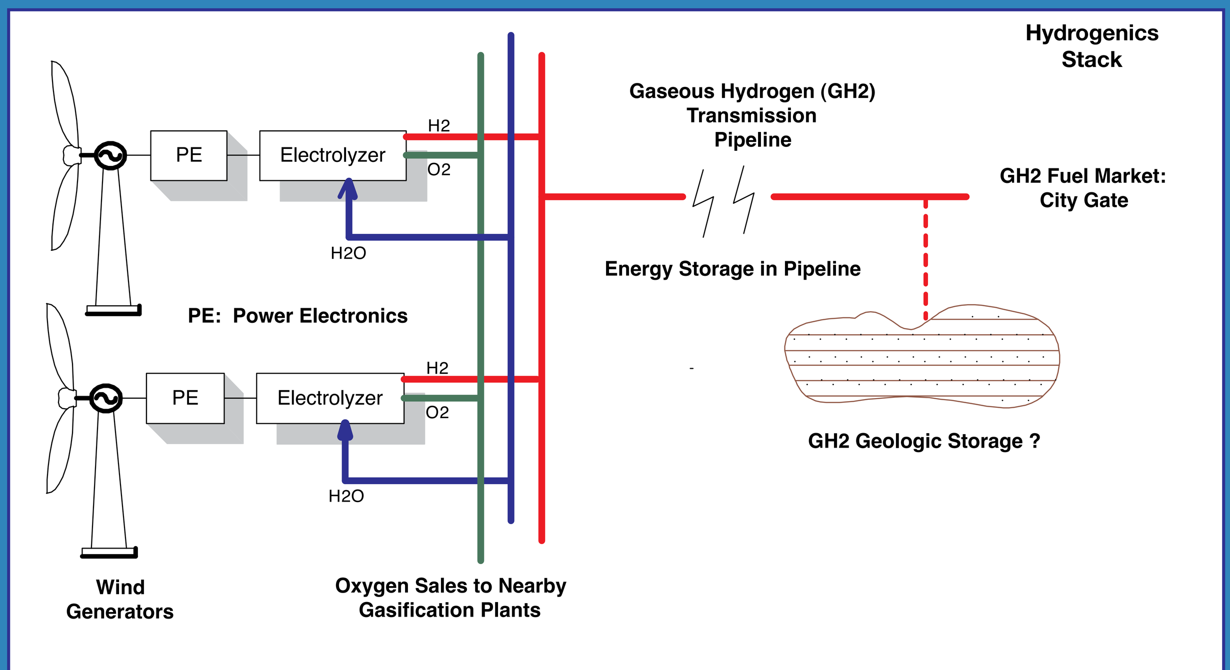
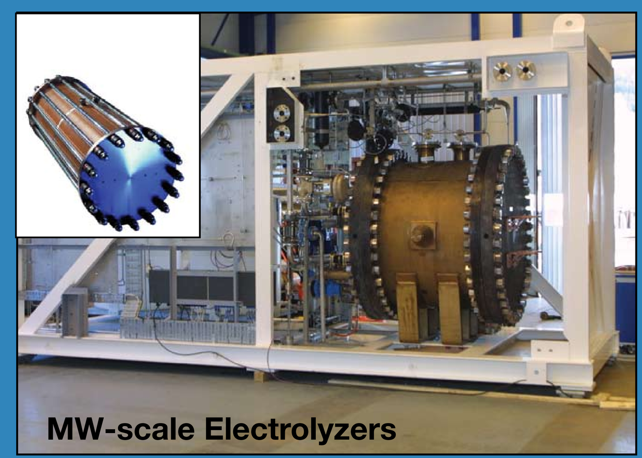
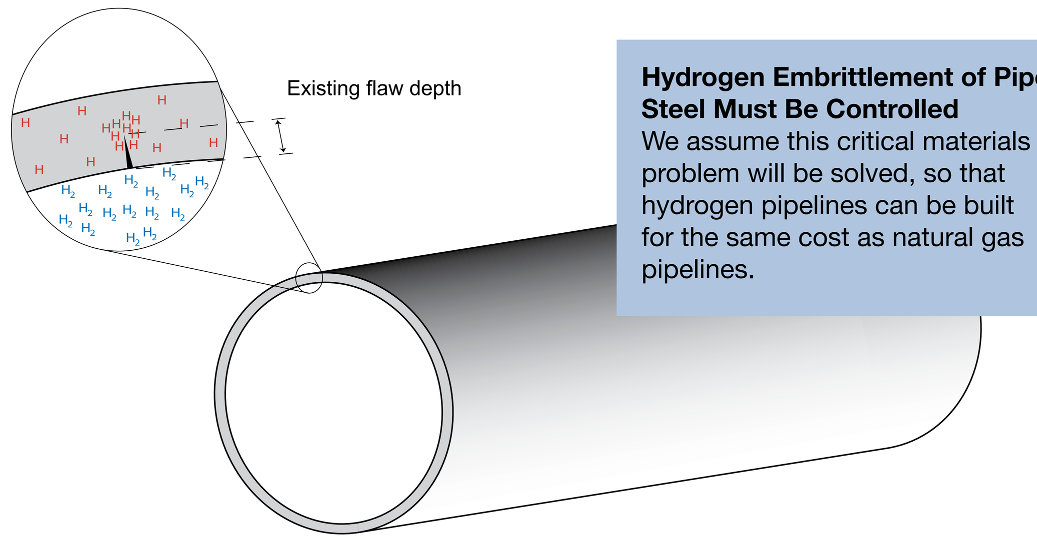




Norsk Hydro complete MW-scale electrolyzer system, less gas cleanup equipment

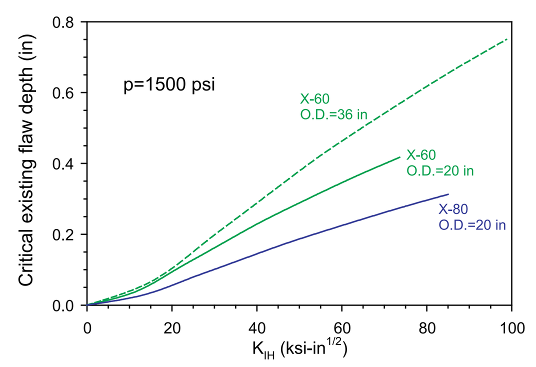
- Input 4.2 - 4.3 kWh per Nm3 = 560 kW
- Output 130 Nm3 per hour at 30 bar g (~450 psi)
- Capital cost goal: ~ $300 - 350 / kW input
- Power electronics sharing with wind generator reduces costs

- **May hydrogen fuel be a bigger market for GW-scale wind than electricity transmitted to the grid?**
- **How far may wind-source hydrogen gas (GH2) fuel be pipelined without costly compressors?**
- **What is the cost of wind-source GH2, pipelined 300 - 1,600 km, at a city-gate market?**



Hydrogen Embrittlement of Pipeline Steel Must Be Controlled
We assume this critical materials problem will be solved, so that hydrogen pipelines can be built for the same cost as natural gas pipelines.

Atomic hydrogen in pipeline steel can cause hydrogen embrittlement: existing flaws will propagate unless restricted below a critical size



Pipeline Parameters Used in Fracture Mechanics Calculations

Material	Yield Strength, S_y (psi)	Pressure, p (psi)	Design Factor, F	OD (in)	Wall Thickness, t (in)
X-60	60,000	1500	.72	20	0.46
X-60	60,000	1500	.72	36	0.83
X-80	80,000	1500	.72	20	0.35

CAPITAL COSTS: 1,000 MW WINDPLANT, ELECTROLYZERS; 20" PIPELINE, 320 km LONG

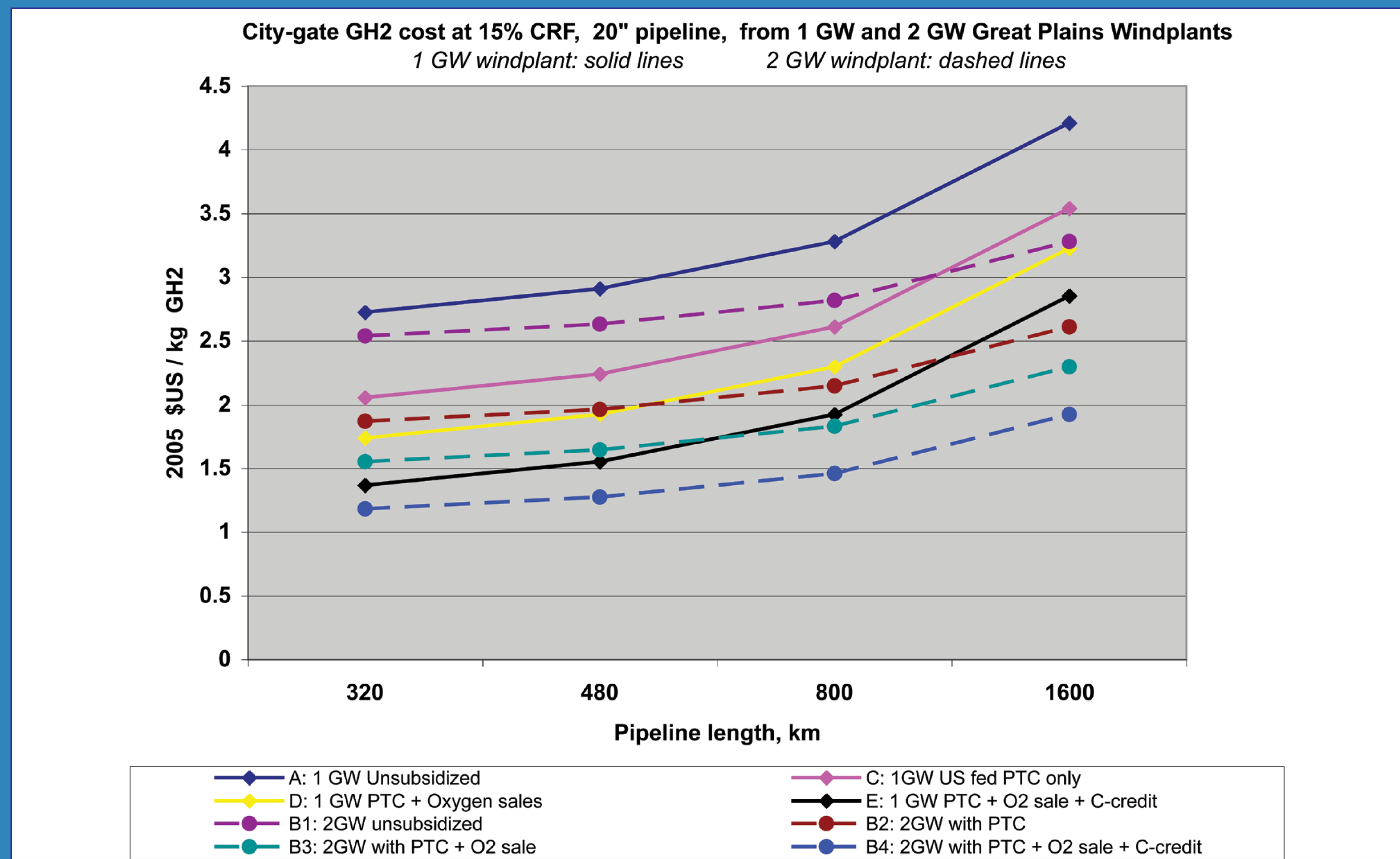
	Total Installed Capital Cost $ / kW in Year 2010	Total (million 2005 $US)
Windplant	800	800
Power electronics incremental cost	30	30
Electrolyzers: 1,500 psi output	330	330
Pipeline: 20", 500 miles (800 km) long	$29 / inch diam / m length	464
TICC (total installed capital cost)		**$1,624**

UNSUBSIDIZED COST OF WIND-SOURCE GH2 FUEL DELIVERED AT END-OF-PIPE AT DISTANT CITY GATE, FOR A RANGE OF CAPITAL RECOVERY FACTOR (CRF)
Assumes no USA Federal Production Tax Credit (PTC) or other subsidy; no byproduct oxygen sales

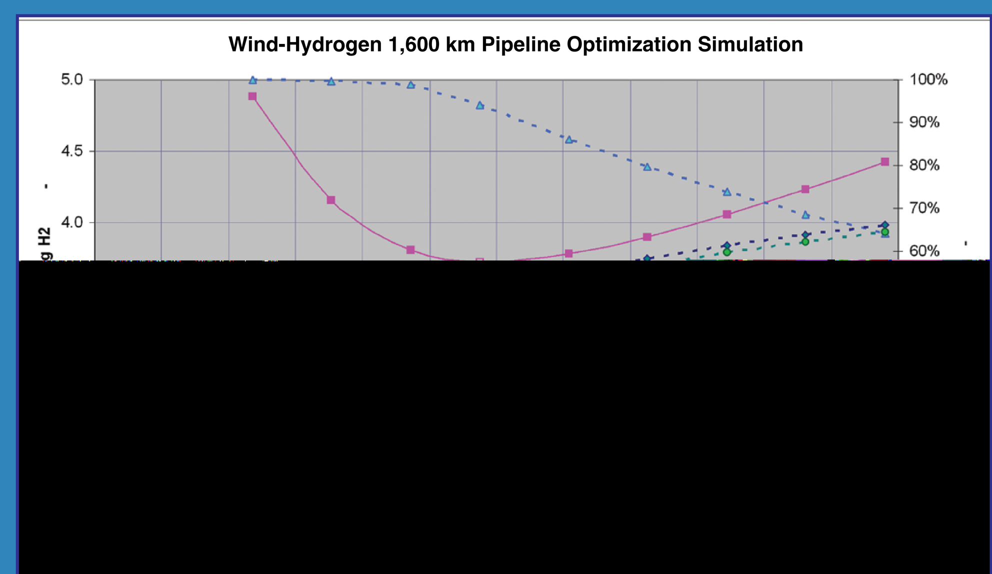
PIPELINE LENGTH	320 km / 200 miles	480 km / 300 miles	800 km / 500 miles	1600km /1000 miles
	Cost / kg	**Cost / kg**	**Cost / kg**	**Cost / kg**
@ CRF = 12%	$2.19	$2.34	$2.64	$3.38
@ CRF = 15%	$2.72	$2.91	$3.28	$4.21
@ CRF = 18%	$3.26	$3.48	$3.93	$5.04
@ CRF = 21%	$3.75	$4.01	$4.53	$5.82

GH2 PIPELINE CAPACITY, WITHOUT INLET OR MIDLINE COMPRESSION
Assume: Inlet pressure 100 bar; outlet pressure 30 bar
"Capacity": Fully turbulent flow achieved "Storage Capacity": Unpack from 100 to 30 bar

Distance, km	Distance, miles	Outside Diameter, inches	Capacity GW	Capacity MMscfd	Capacity Million Nm3 / day	Capacity Tons per day, metric	Storage Capacity, MMscf	Storage Capacity, Tons
480	300	20	2.3	573	14.8	1,526	211	562
480	300	36	10.2	2,580	66.7	6,869	675	1,798
800	500	20	1.8	444	11.5	1,182	352	936
800	500	36	7.9	1,998	51.7	5,319	1,126	2,997
1,600	1,000	20	1.2	313	8.1	833	703	1,872
1,600	1,000	36	5.6	1,413	36.5	3,762	2,251	5,994



We can deliver GW-scale windpower - source gaseous hydrogen (GH2) fuel, hundreds of km by pipeline, at an untaxed cost per unit energy comparable to today's gasoline. But, what will the urban market pay for this un-firm source of hydrogen?



System Capital Cost Component Optimization Simulations

- Unsubsidized cost per kg, 2005 $US
- Cost of delivered (GH2) fuel is minimized when wind generation capacity is ~135% of electrolyzer and pipeline capacity

Pipeline Will Smooth, Not Firm, Windplant Output at Hourly-to-daily Time Scale

- Actual output, Great Plains windplant, first week of September
- 800 km, 20" diameter pipeline
- Hydrogen gas pipeline transit time ~ 22 hours
- 1,700 MW peaks are electrolyzer input power limit; some wind generation is curtailed
- Pipeline energy storage cannot "firm" wind at weekly-to-seasonal scale

Key assumptions:

1. Year 2010 technology and markets: results in 2005 $US
2. A single 1,000 MW (nameplate) windplant in Great Plains achieving maximum economies-of-scale and high windplant capacity factor (CF)
3. No connection to electric transmission grid, which, by 2010:
   - Has become saturated with windpower;
   - Has not been expanded, due to cost and permitting obstacles
4. All wind energy is converted to gaseous hydrogen (GH2), for pipeline transmission
5. Total installed capital costs:
   - Wind generators: $800 / kW
   - Electrolyzers, less transformer-rectifier subsystem: $300 / kW
   - Hydrogen pipeline, 100 bar, 20" diam: $580,000 / km
6. 40% windplant CF; 15% capital recovery factor (CRF)
7. High-pressure-output electrolyzers directly feed pipeline at 100 bar
8. No compressors, either at source nor along pipeline
9. Hydrogen-capable pipelines can be built and safely operated for the same cost as natural gas pipelines of same diameter and pressure
10. Pipeline energy storage by "packing" to 100 bar, "unpacking" to 50 bar:
    - "Packing" stores 16.8 MWh per km of pipeline
    - Provides "smoothing" but not "firming" of windplant output
11. A market for GH2 hydrogen fuel at the pipeline destination city, but competition from "firm" GH2 fuel from natural gas via SMR *
12. Hydrogen transmission pipelines can be built for the same cost as natural gas pipelines of same diameter and pressure. The critical materials problem of hydrogen embrittlement of pipeline steel will be managed.

* SMR: Steam Methane Reforming, a mature industrial process which produces >90% of world annual consumption of 90 million tons of hydrogen

Conclusions:

1. Wind-generated hydrogen fuel can be delivered to a city-gate market, 300 – 1,600 km away by pipeline, for $1.25 – 4.25 per kg, depending primarily on assumed:
   - Subsidies and value-adding features
   - Capital recovery factor (CRF): 15% assumed
   - Pipeline length

   This is competitive with today's price of gasoline.
2. Potential "value-adding" economic features reduce cost of delivered GH2:
   - US federal PTC of $0.019 / kWh
   - Sell oxygen byproduct of electrolysis to adjacent gasification plants for $20 / ton O2
   - Carbon-emission-offset credit, estimated at $0.01 / kWh
3. 20" diam hydrogen pipeline capacity is ~ 1.8 GW at 100 bar input, 30 bar output, 320 km long
4. The pipeline provides valuable energy storage, smoothing windplant output, at minute-to-daily time scale, but is inadequate for seasonal smoothing, for "firming" the wind energy supply. Large-scale, low-cost, GH2 geologic storage, in natural or man-made (solution-mined salt cavern) formations, will be needed to "firm" wind at annual scale.
5. High-pressure-output electrolyzers eliminate costly compressors from the entire system
6. The oxygen byproduct of electrolysis may be sold to nearby biomass or coal gasification plants, adding value and revenue
7. Biomass and other renewable energy sources may synergistically improve pipeline CF. We will need a pilot-scale pipeline system to explore and confirm this benefit.
8. Hydrogen system pipeline and other steel components must be designed to accommodate hydrogen embrittlement in "renewables-hydrogen service".
9. New underground hydrogen pipelines may be more secure and easier to permit than new overhead electric lines.

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