Electronic Supplementary Material (ESI) for Energy Advances.

Supplemental information

S1 Aluminum smelters capital cost

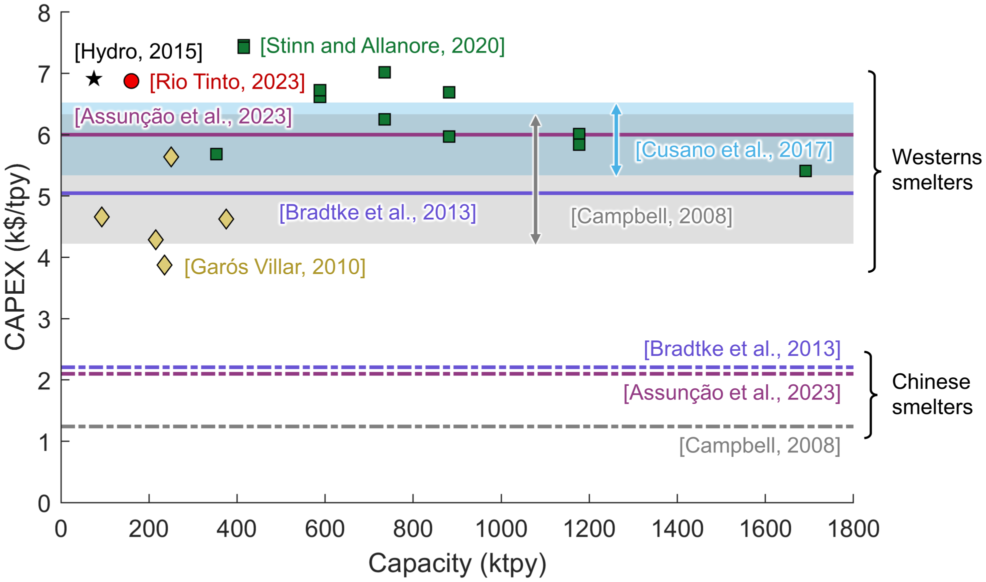

Fig. S1 Capital cost of aluminum smelters retrieved from literature.[1–8]. Data shown as shaded bands[3,5] to represent a range, or as lines[5,6,8] when plant capacity was not specified. Data was adjusted to 2020 USD using the Chemical Engineering Index, except for references from 2023[7,8].

S2 Inert anodes technology potential impact on aluminum production cost

Table S1 Summary of economic impact of inert anodes implementation in aluminum production based on a literature review.

Category	Impact	Decription/Note	Year
Cell productivity	+15%	From Elysis public data	2022[9]
Operating cost	-15%		
Cell productivity	+15%	IA and WC	2007[10]
Operating cost	-15%	IA and WC	
Energy consumption (kWh/kg)	14.4	Baseline carbon anode cell	
	-3.0	WC (ACD drops from 4.5 to 2.0 cm, reducing the bath drop from 1.75 to 0.78 V)	
	+1.7	IA and low overvoltage (from 0.55 to 0.1 V)	
	-1.3	IA, low overvoltage, and WC	
Anode cost - horizontal	-71%	From \$198/t_{Al} for CA to \$57/t_{Al} for horizontal IA	2006[11]
Anode cost - slanted	-76%	From \$198/t_{Al} for CA to \$47/t_{Al} for horizontal IA	
Anode cost - retrofit	-10%	From \$140/t_{Al} for CA to \$128/t_{Al}. for retrofitted IA	2001[12]
Anode cost - new cell	-40%	From \$122/t_{Al}. for CA to \$73/t_{Al}. for vertical IA in new cells	
Anode plant CAPEX	-90%	Reduction from 160 M\$ to 10-15 M\$	
Labor requirement	-34%	Due to anode manufacturing and less anode handling	
Energy consumption (kWh/kg)	13.2	Baseline carbon anode cell	
	+2.5	Retrofitted inert anode cell	
	+0.4	IA, WC, vertical anodes, 90% CE	
Cathode lining cost	+?%	\$150,000 per cell increasing from WC	

Legend: CA: carbon anode, IA: inert anode, WC: wettable cathode, ACD: anode to cathode distance, CE: current efficiency

S3 Alumina market price

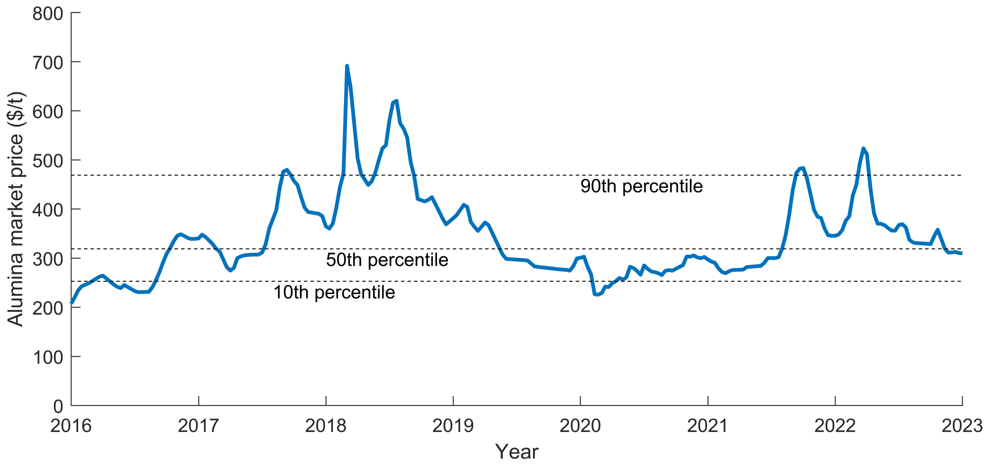

Fig. S2 Alumina market price (data retrieved from Norks Hydro investors reports[13–15]).

S4 Alternative energy carriers: liquefied hydrogen and ammonia

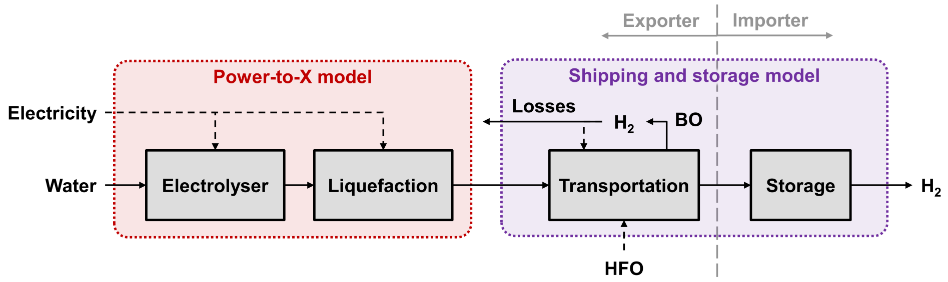

Fig. S3 Liquefied hydrogen Power-to-X, shipping and storage models block diagrams. Regasification was neglected as it represents a minimal CAPEX and energy requirement. No losses were assumed during the discharge of fuel form the carrier vessel to the tanks. The power plant is assumed to consume more than the boil-off losses, therefore avoiding the need for re-liquefaction on-site.

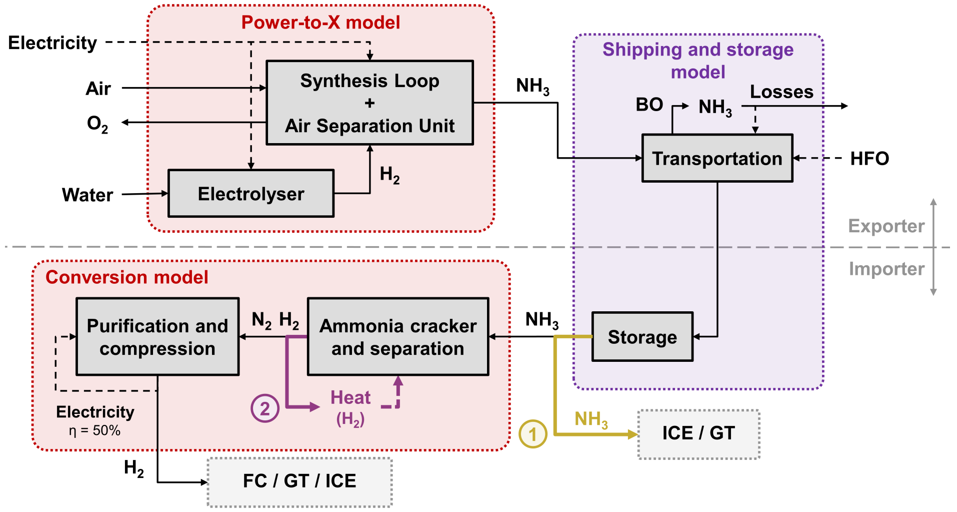

Fig. S4 Ammonia Power-to-X, shipping and storage models block diagrams. No losses were assumed during the discharge of fuel form the carrier vessel to the tanks. Compression and purification required after the cracking process were lumped together to simplify the analysis.

S5 Hydrogen carriers shipping model

Assumptions:

- The shipping cost C_{ship} is calculated per trip (round-trip).
- The vessel travels twice the shipping distance (specialized vessel returns empty).
- To account for boil-off losses, the delivered energy cost is calculated by summing the production (Power-to-X) cost and the shipping cost C_{ship}, and then dividing by the transportation efficiency defined as $\eta_t = 1 - t_{\text{s}} \cdot BOR$.

$$C_{\text{ship}} = \left(\frac{CPX_{\text{V}}(CRF + OPX_{\text{V}})}{365} + L \right) (2t_{\text{s}} + t_{\text{h}}) + \left(F_{\text{c},1} + F_{\text{c},2} + C_{\text{canal}} \right) t_{\text{s}} + C_{\text{port}} \tag{S1}$$

$$CPX_{\text{V}} = \rho \cdot V \cdot CPX_{\text{v}} \tag{S2}$$

$$t_{\text{s}} = \frac{D}{24 \cdot S} \tag{S3}$$

$$F_{\text{c},1} = \left(\frac{P}{S \cdot \eta} - \frac{BOR \cdot V \cdot \rho \cdot E}{1{,}000} \right) HFO \geq 0 \tag{S4}$$

$$F_{\text{c},2} = \frac{P \cdot HFO}{S \cdot \eta} \tag{S5}$$

Table S2 Variables and parameters

Variable	Description	Units	Value	Notes
CPX_{V}	Vessel CAPEX	\$	-	see eqn (S2)
CPX_{v}	Vessel unit CAPEX	\$/kg	-	see Table **??**
V	Vessel cargo capacity	m^3	160,000	-
ρ	Energy carrier density	kg/m^3	-	see Table **??**
OPX_{V}	Vessel operating cost	-	4% of CAPEX	-
L	Labor cost	\$/day	7,000	same as Table **??**
S	Vessel cruising speed	knots	14.5	same as Table **??**
D	Distance	km	-	-
t_{s}	Duration of the trip	days	-	see eqn (S3)
t_{h}	Number of handling days per round trip	days	2	-
$F_{\text{c},1}$	Fuel cost for the outward trip (full)	\$/day	-	see eqn (S4)
$F_{\text{c},2}$	Fuel cost for the return trip (empty)	\$/day	-	see eqn (S5)
P	Vessel continuous power requirement	MW	10	same as the dry bulk carrier
η	Powertrain efficiency	-	50%	same as the dry bulk carrier
BOR	Boil-off rate	%/day	-	see Table **??**
HFO	Heavy fuel oil energy cost	$\text{\$/MWh}_{\text{ch}}$	42	same as the dry bulk carrier
E	Energy carrier specific energy	kWh/kg	-	see Table **??**
C_{canal}	Canal costs	\$/day	10,000	same as Table **??**
C_{port}	Port charges	\$/trip	100,000	same as Table **??**

S6 Stationary continuous power generation equipment cost and efficiency models

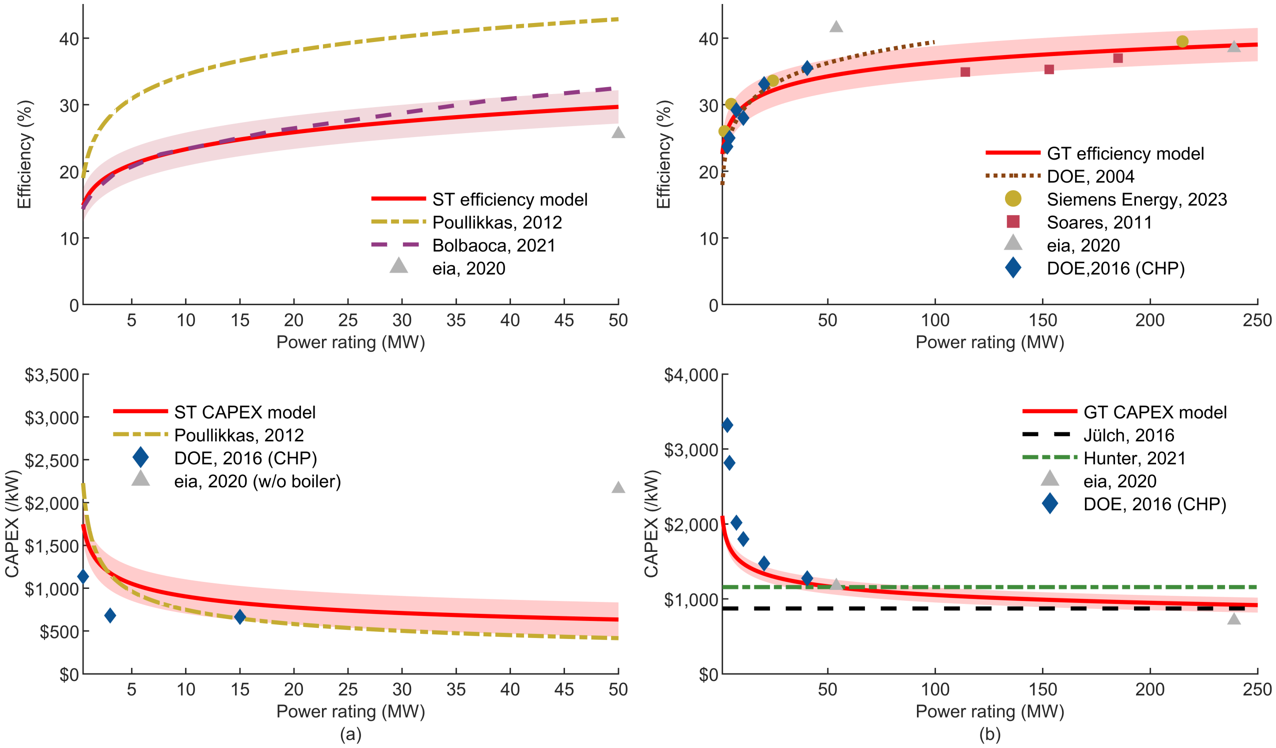

Fig. S5 Cost and efficiency models for (a) steam turbines [16–18], and (b) gas turbines [19–25].

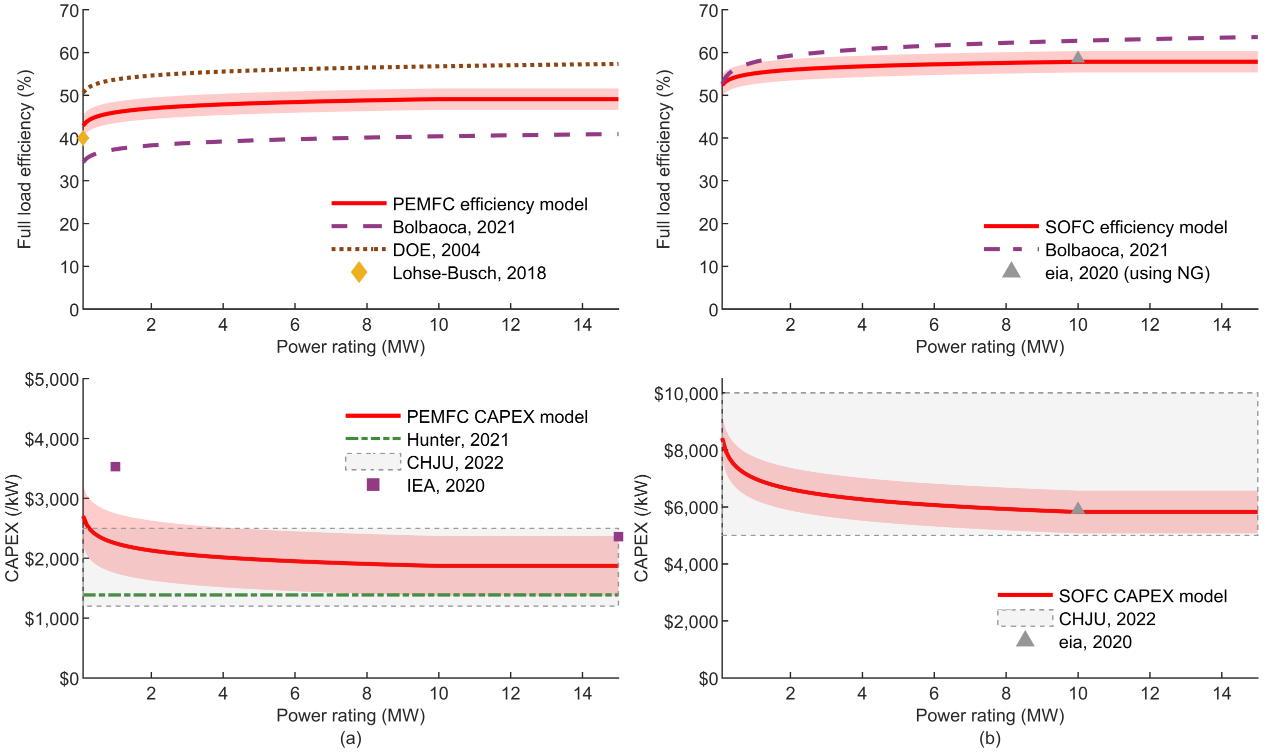

Fig. S6 Cost and efficiency models for (a) proton exchange membrane fuel cells [17,19,25–28], and (b) solid oxide fuel cells [17,27,29].

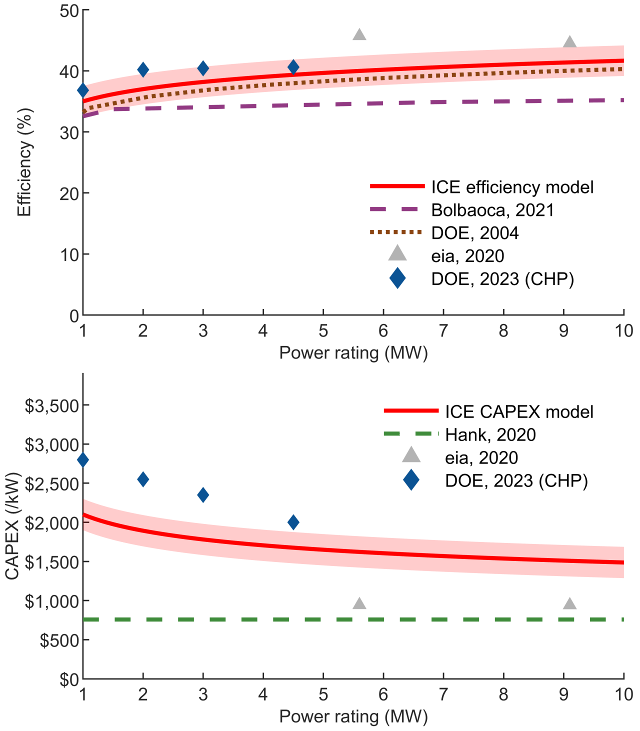

Fig. S7 Cost and efficiency models for internal combustion piston engines[17,19,22,30,31].

Table S3 Power generation equipment assumptions at 25 $\mathrm{MW_e}$

Parameter	Value	Uncertainty
General assumptions		
OPEX (% of CAPEX)	2	-
Equipment life (years)	10	-
Interest rate (%)	8	-
Steam turbine		
CAPEX ($\$/\mathrm{kW_e}$)	739	± 200
Efficiency (%)	26.7	± 2.5
Gas turbine		
CAPEX ($\$/\mathrm{kW_e}$)	1,296	± 100
Efficiency (%)	32.2	± 2.5
Internal combustion engine (modular 10 MW_e units)		
CAPEX ($\$/\mathrm{kW_e}$)	1,487	± 200
Efficiency (%)	41.7	± 2.5
Proton exchange membrane fuel cell (modular 10 MW_e units)		
CAPEX ($\$/\mathrm{kW_e}$)	1,870	± 500
Peak efficiency (%)	61.3	-
Efficiency at full load (% of peak)	80	-
Full load efficiency (%)	49.1	± 2.5
Solid oxide fuel cell (modular 10 MW_e units)		
CAPEX ($\$/\mathrm{kW_e}$)	5,820	± 750
Peak efficiency (%)	66.1	-
Efficiency at full load (% of peak)	87.5	-
Full load efficiency (%)	57.8	± 2.5

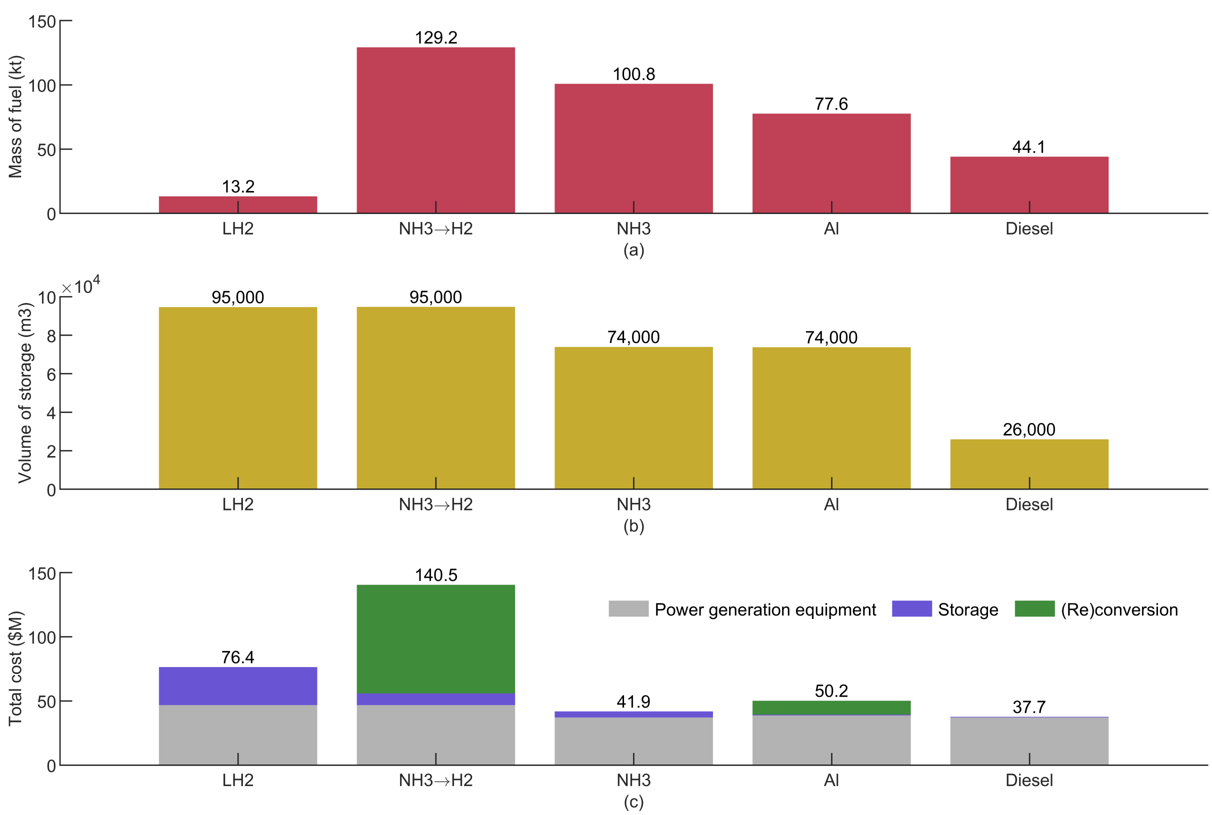

Fig. S8 The (a) total mass of fuel to be shipped to the mine each year, the (b) volume of storage needed at the mine assuming 2 trips per year, and the (c) total CAPEX needed at the mine for a 25 MW_e power generation system for each pathway. The mass and volume are a function of the efficiency of the power generation system and of the specific energy and energy density of each fuel. Aluminum storage also serves to store the alumina reaction products, increasing the overall volume needed.

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