ELECTROLYZER ECONOMICS

THE TOBE ADVANTAGE.

40-55% LOWER LCOH.

A comprehensive comparison of electrolyzer technologies for green hydrogen production. Data-driven analysis shows isothermal electrolysis delivers the lowest levelized cost across all electricity price scenarios, with significant advantages in efficiency, capital cost, and total cost of ownership.

$1.99
LCOH AT $0.04/KWH

40%
BELOW ALKALINE

51%
BELOW PEM

0
PGM DEPENDENCY

Version 1.0 · January 2026

EXECUTIVE SUMMARY

This whitepaper presents a comprehensive comparison of electrolyzer technologies for green hydrogen production. Our analysis demonstrates that Tobe Energy's isothermal electrolysis system delivers the lowest levelized cost of hydrogen (LCOH) across all electricity price scenarios.

$1.99	42.23	$446	10%
LCOH AT $0.04/KWH	KWH/KG EFFICIENCY	CAPEX PER KW	STACK REPLACEMENT COST

KEY FINDINGS

- **Lowest LCOH at any electricity price:** Tobe achieves $1.99/kg H_2 at $0.04/kWh—40% below alkaline, 51% below PEM.
- **Efficiency that compounds:** At 42.23 kWh/kg (94.7% electrical efficiency), Tobe consumes 29% less electricity per kilogram than alkaline and 31% less than PEM.
- **CAPEX advantage persists at scale:** Prototype CAPEX of $446/kW already undercuts alkaline ($850/kW) by 48%; MW-scale projections reach ~$177/kW.
- **Stack replacement costs 80% lower:** Tobe's 304 stainless steel stack requires ~10% of CAPEX for replacement vs. 35-50% for conventional systems.
- **No PGM supply chain risk:** Zero platinum-group metals eliminates the iridium bottleneck that constrains PEM scale-up.
- **Operational flexibility built in:** 10-100% turndown, instant startup, grid-friendly capacitive load behavior.

DECISION FRAMEWORK

IF YOUR PRIORITY IS...	CONSIDER...
Lowest LCOH	Tobe (40-55% lower than alternatives)
Proven TRL 9 at GW scale	Alkaline
Extreme compactness	PEM
Waste heat integration	SOEC

WHY ELECTROLYZER CHOICE MATTERS

The electrolyzer is the economic engine of any green hydrogen project. Its capital cost, efficiency, and lifetime determine whether a project achieves sub-$2/kg hydrogen or struggles above $5/kg.

THE LCOH EQUATION

Levelized cost of hydrogen (LCOH) captures the full economic picture by amortizing capital costs over the project lifetime and adding operating expenses. For most projects:

- **Electricity accounts for 60-80% of LCOH** — making system efficiency the dominant lever
- **CAPEX contribution increases** at low capacity factors or high electricity prices
- **Stack replacement costs can add 15-30%** to lifetime operating expenses for some technologies

THE COMPOUNDING EFFECT OF EFFICIENCY

Every kWh/kg improvement saves money on every kilogram produced, every hour, for the project's 20-year life. Consider a 1 MW system operating at 90% capacity factor (7,884 hours/year):

Tobe at 42.23 kWh/kg

Produces 186,692 kg H_2/year

Uses 7,884 MWh electricity/year

Electricity cost: $315K at $0.04/kWh

Alkaline at 59.43 kWh/kg

Produces 132,660 kg H_2/year

Uses 7,884 MWh electricity/year

Produces 41% less H_2 per MWh

20-YEAR ELECTRICITY SAVINGS

At $0.04/kWh, Tobe's efficiency advantage translates to **$1.0-2.5M in savings** over a 20-year project life for a 1 MW system—before accounting for lower CAPEX and reduced maintenance costs.

WHAT BUYERS ACTUALLY CARE ABOUT

Bankable LCOH
PROJECTIONS FOR FINANCING

Tech Risk
TRL AND TRACK RECORD

Supply Chain
MATERIAL AVAILABILITY

Ops Fit
RENEWABLE COMPATIBILITY

THE COMPETITIVE LANDSCAPE

Five electrolysis technologies compete for green hydrogen projects today. Each has distinct operating principles, cost structures, and application profiles.

Alkaline Electrolysis (AEL)

Uses potassium hydroxide electrolyte with nickel electrodes. Most mature technology with century-long industrial history.

Strengths: Mature (TRL 9), GW-scale proven, lower material costs

Weaknesses: Moderate efficiency (60-65%), slow response, caustic handling

Best fit: Baseload industrial with stable power

Proton Exchange Membrane (PEM)

Solid polymer membrane with platinum-group metal catalysts. Fast response but material constrained.

Strengths: Fast response, compact, high current density

Weaknesses: High CAPEX ($1,100-1,300/kW), PGM dependency

Best fit: Grid-balancing, space-constrained sites

Solid Oxide Electrolysis (SOEC)

Operates at 700-1000°C using ceramic electrolytes. Highest efficiency with external heat.

Strengths: 70-80% efficiency with waste heat

Weaknesses: Very high CAPEX ($4,000+/kW), short stack life, hours-long startup

Best fit: Industrial co-location with high-grade waste heat

Anion Exchange Membrane (AEM)

Aims to combine alkaline cost with PEM flexibility using alkaline membrane.

Strengths: No PGMs, potentially lower cost than PEM

Weaknesses: Very short stack life (~7,000 hrs), membrane stability unproven

Best fit: R&D and pilot projects

TOBE ENERGY: ISOTHERMAL ELECTROLYSIS

Tobe's proprietary isothermal electrolysis eliminates waste heat generation through resonant power electronics and a membrane-free, near-ambient temperature design.

94.7%	$446	304 SS	10-100%
ELECTRICAL EFFICIENCY	CAPEX PER KW	NO EXOTIC MATERIALS	TURNDOWN RANGE

HEAD-TO-HEAD COMPARISON

Comprehensive comparison of key performance metrics across all five technologies. Data for conventional technologies represents industry averages; Tobe data is from prototype testing.

METRIC	TOBE (PROTO)	TOBE (MW)*	ALKALINE	PEM	SOEC	AEM
CAPEX ($/kW)	$446	~$177	$850	$1,200	$4,342	>$931
Elec. Efficiency (%)	94.7%	94.7%	62.0%	61.5%	78.3%	57.3%
System Eff. (kWh/kg)	42.23	42.23	59.43	61.50	45.83	63.00
Stack Lifetime (hrs)	80,000+	80,000+	79,400	62,500	33,333	7,000
Stack Replace (% CAPEX)	10%	10%	35%	50%	60%	40%
Operating Temp	<50°C	<50°C	60-80°C	50-80°C	700-1000°C	40-60°C
Startup Time	Seconds	Seconds	Minutes	Sec-Min	Hours	Minutes
Turndown Range	10-100%	10-100%	20-100%	10-100%	30-100%	20-100%
Critical Materials	304 SS	304 SS	Ni, diaphragm	Ir, Pt, membrane	Ceramics	Membrane
TRL	6-7	6-7	9	8-9	6-7	6-8

*MW-scale pricing is a sensitivity case based on projected manufacturing economics. Stack lifetime for Tobe is estimated (1,000+ hours tested, no degradation observed).

THE TOBE POSITION

Tobe occupies a unique position: **highest efficiency AND lowest CAPEX**. No incumbent technology offers both. This combination drives the LCOH advantage shown in the following analysis.

LCOH ANALYSIS

LCOH is the metric that matters most for project economics. Our model calculates the all-in cost per kilogram over a 20-year project life, including capital recovery, electricity, maintenance, and stack replacement.

MODEL ASSUMPTIONS

8%	20	90%	2-4%
WACC	PROJECT LIFE (YEARS)	CAPACITY FACTOR	ANNUAL MAINTENANCE

LCOH RESULTS BY ELECTRICITY PRICE ($/KG H_2)

TECHNOLOGY	$0.02	$0.03	$0.04	$0.05	$0.06	$0.07	$0.08
Tobe (Prototype)	**$1.15**	**$1.57**	**$1.99**	**$2.41**	**$2.84**	**$3.26**	**$3.68**
Tobe (MW Scale)*	**$0.96**	**$1.39**	**$1.81**	**$2.23**	**$2.65**	**$3.08**	**$3.50**
Alkaline	$2.14	$2.74	$3.33	$3.93	$4.52	$5.12	$5.71
PEM	$2.82	$3.44	$4.05	$4.67	$5.28	$5.90	$6.51
Solid Oxide (SOEC)	$7.32	$7.78	$8.24	$8.70	$9.15	$9.61	$10.07
AEM	$5.53	$6.16	$6.79	$7.42	$8.05	$8.68	$9.31

*Sensitivity case. Electricity prices in $/kWh across top row.

KEY FINDINGS

At $0.04/kWh (Industrial/PPA Rate)

- Tobe Prototype: **$1.99/kg**
- 40% below alkaline ($3.33/kg)
- 51% below PEM ($4.05/kg)

At $0.06/kWh (Grid Rate)

- Tobe Prototype: **$2.84/kg**
- 37% below alkaline ($4.52/kg)
- 46% below PEM ($5.28/kg)

LCOH ADVANTAGE INCREASES AT LOWER PRICES

At low electricity prices, CAPEX and stack replacement become larger shares of LCOH. Tobe's advantages in both metrics compound: at $0.02/kWh, Tobe achieves **$1.15/kg—46% below alkaline**.

TOTAL COST OF OWNERSHIP

While LCOH provides the per-kilogram metric, project developers also need to understand absolute dollar flows over the project lifetime. The following shows 20-year TCO for a 1 MW system at $0.04/kWh.

20-YEAR TCO BREAKDOWN (1 MW SYSTEM)

TECHNOLOGY	CAPEX	ELECTRICITY	MAINTENANCE	REPLACEMENT	TOTAL TCO
Tobe (Prototype)	$446K	$6,307K	$178K	$45K	**$6,976K**
Tobe (MW Scale)*	$177K	$6,307K	$71K	$18K	**$6,573K**
Alkaline	$850K	$6,307K	$510K	$298K	**$7,965K**
PEM	$1,200K	$6,307K	$720K	$1,200K	**$9,427K**
Solid Oxide (SOEC)	$4,342K	$6,307K	$3,474K	$10,421K	**$24,544K**
AEM	$950K	$6,307K	$570K	$8,360K	**$16,187K**

*Sensitivity case. All figures at $0.04/kWh electricity.

KEY INSIGHTS

Electricity Dominates for Efficient Systems

- For Tobe, electricity = 90% of TCO
- Efficiency is the dominant lever
- Tobe's 42.23 kWh/kg drives lowest electricity spend

Stack Replacement is the Hidden Killer

- AEM: $8.4M replacement over 20 years
- SOEC: $10.4M replacement over 20 years
- These costs often underestimated in projections

TOBE'S 10% REPLACEMENT COST IS TRANSFORMATIVE

At **$45K vs. $1.2M for PEM**, the difference in stack replacement alone covers Tobe's entire CAPEX multiple times over. This is possible because Tobe's stack uses 304 stainless steel with no consumable membranes, catalysts, or high-temperature ceramics.

OPERATIONAL FIT

Beyond economics, the right electrolyzer must match your operational profile. Tobe excels in renewable pairing and grid flexibility.

OPERATIONAL COMPARISON

METRIC	TOBE	ALKALINE	PEM	SOEC	AEM
Startup Time	**Seconds**	1-10 min	Sec-1 min	1-24 hrs	1-5 min
Turndown Range	**10-100%**	20-100%	10-100%	30-100%	20-100%
Cold Start Penalty	**None**	Minor	Minor	Severe	Minor
Grid Behavior	**Capacitive**	Resistive	Resistive	Resistive	Resistive
Renewable Pairing	**Excellent**	Good	Excellent	Poor	Good

RENEWABLE INTEGRATION

Tobe's instant startup and wide turndown range (10-100%) make it ideal for direct coupling with solar and wind:

- **No warm-up energy wasted** during cloud transients or wind lulls
- **No thermal cycling stress** from variable operation
- **Capacitive load behavior** provides smoother power draw, reducing grid stress

GRID SERVICES CAPABILITY

Tobe's resonant LLC power electronics enable harmonically neutral operation, allowing participation in demand response programs without operational penalties. The system can ramp from minimum to maximum output in seconds, capturing value from grid services while maintaining hydrogen production.

> **SOEC LIMITATION**
>
> SOEC requires stable, high-temperature operation—poor fit for variable renewables. Cold starts take hours and cause ceramic thermal stress, limiting to baseload-only applications with guaranteed heat supply.

SUPPLY CHAIN & SCALABILITY

Scaling electrolysis to terawatts requires materials that exist at scale. PEM's iridium dependency creates a structural bottleneck that limits deployment potential.

THE IRIDIUM PROBLEM

PEM electrolyzers require iridium as the anode catalyst. Current commercial systems use 0.67-2.0 grams of iridium per kilowatt—a critical constraint at scale.

7-8	80-85%	100+	12+
TONNES IR/YEAR (GLOBAL)	FROM SOUTH AFRICA	TONNES FOR 100 GW PEM	YEARS PRODUCTION REQUIRED

Iridium is a byproduct of platinum mining—production cannot scale independently. Net-zero scenarios requiring terawatt-scale deployment face a fundamental materials constraint that price signals cannot resolve.

SCALABILITY RISK COMPARISON

TECHNOLOGY	CRITICAL MATERIAL	SUPPLY CONSTRAINT	SCALABILITY RISK
Tobe	**304 Stainless Steel**	**None**	**Low**
Alkaline	Nickel, diaphragms	Moderate	Low-Medium
PEM	Iridium, platinum	Severe	High
SOEC	Specialty ceramics	Moderate	Medium
AEM	Specialty membranes	Moderate	Medium

TOBE'S COMMODITY MATERIALS ADVANTAGE

304 stainless steel is produced at **>50 million tonnes/year globally**. Tobe's design eliminates supply chain constraints and enables rapid scaling without materials bottlenecks. No PGMs, no specialty membranes, no exotic ceramics.

WHERE EACH TECHNOLOGY WINS

No technology is optimal for every application. This section provides an honest assessment of where each approach fits best.

Choose Tobe Energy When

- LCOH optimization is the primary driver
- Supply chain resilience matters
- Pairing with variable renewable generation
- Operational simplicity (no caustics, no high temps)
- Domestic manufacturing is valued

Choose Alkaline When

- GW-scale, bank-financed deployment today
- Baseload operation with stable power
- Established service ecosystem essential
- TRL 9 requirement is non-negotiable
- Caustic handling infrastructure exists

Choose PEM When

- Space is extremely constrained
- Sub-second response for grid services
- Higher LCOH acceptable for proven flexibility
- Compactness justifies premium cost

Choose SOEC When

- Abundant high-grade waste heat (>600°C)
- Guaranteed baseload operation
- Industrial co-location (steel, glass, nuclear)
- High CAPEX acceptable for efficiency

HONEST ASSESSMENT: TOBE'S CURRENT LIMITATIONS

- **TRL 6-7:** Prototype proven with 1,000+ hours; MW-scale in development
- **Track record:** Not yet deployed at commercial scale
- **Financing:** May require technology risk premium from conservative lenders

THE RIGHT FIT

If you need a bank-financed, GW-scale project deployed this year, alkaline is the proven choice. If you're planning a project for **2027+** and LCOH is your priority, Tobe offers 40% lower hydrogen cost with a simpler, more operationally flexible system.

FREQUENTLY ASKED QUESTIONS

Q: Your efficiency claims seem too good. How is 94.7% possible?

Conventional electrolyzers lose 20-40% of input energy as heat, which must be removed with cooling systems. Tobe's isothermal design eliminates waste heat generation at the source through resonant power electronics, converting more electricity directly to hydrogen. See our Technology Overview whitepaper for the physics.

Q: What's the catch with the low CAPEX?

No catch—it's a function of materials. We use 304 stainless steel instead of platinum-group metals or specialty ceramics. Our stack design is simpler, with fewer components and no membranes. As we scale to MW production volumes, manufacturing economics push costs even lower.

Q: How confident are you in the 80,000-hour stack life estimate?

We've tested 1,000+ hours with no measurable degradation. The design contains no consumable components—no membranes to fail, no catalysts to poison, no high-temperature ceramics to crack. We estimate 80,000+ hours based on materials science fundamentals, with accelerated life testing underway.

Q: Can you integrate with existing control systems?

Yes. Our systems use standard industrial PLCs with OPC-UA and Modbus TCP protocols. They're SCADA-ready out of the box and integrate with any modern control infrastructure.

Q: What standards does Tobe target for compliance?

We're pursuing product listing under ISO 22734, with installations designed to NFPA 2, NFPA 70, and local AHJ requirements. Our systems are designed with pathways for DOE Clean Hydrogen Production Standard (CHPS) compliance at <2.0 kg CO_2e/kg H_2.

Q: How does the LCOH model handle uncertainty?

All projections use transparent assumptions (8% WACC, 90% CF, 20-year life). We present both prototype pricing and MW-scale sensitivity cases. The model and methodology are available upon request for independent verification.

NEXT STEPS

Ready to explore how Tobe can improve your hydrogen project economics? We offer customized analysis for qualified partners.

ENGAGEMENT OPTIONS

Project Developers	Investors	EPCs	Technical Review
CUSTOM LCOH ANALYSIS WITH YOUR INPUTS	FINANCIAL MODEL AND DILIGENCE PACKAGE	PILOT DEPLOYMENT AND INTEGRATION	DETAILED SPECS FOR QUALIFIED PARTIES

REFERENCES

- International Energy Agency (IEA). *Global Hydrogen Review 2024*.
- International Renewable Energy Agency (IRENA). *Green Hydrogen Cost Reduction*, 2024.
- U.S. Department of Energy. *Technical Targets for PEM Electrolysis*.
- Minke et al. "Is iridium demand a potential bottleneck..." *Int. J. Hydrogen Energy*, 2021.
- NREL. *Manufacturing Cost Analysis for PEM Water Electrolyzers*, 2024.

CONTACT

Ready to explore how Tobe can support your hydrogen strategy?

Email: colby@tobe.energy

Web: tobe.energy

Request: Project-specific LCOH analysis, pilot scoping, or diligence materials

Disclaimer: This document contains forward-looking statements regarding projected performance, costs, and timelines. Actual results may vary. Performance figures represent laboratory measurements under controlled conditions; field performance may differ. Cost projections assume production volumes not yet achieved. LCOH model assumptions documented; methodology available upon request.