

Emission Transitive Emission CL17 Supplemental Investigation

This supplement extends the CL17 chemistry network into an everyday-engine, electrolysis, storage, capture, recycle and manufacturing model. It corrects the treatment of HHO, expands the electrolysis and battery branches, separates process reflux from exhaust gas recirculation, and couples Bubble Butt to reuse and replacement-fuel manufacture.

There is definitely something here, but it is a system rather than a self-sustaining fuel. The strongest configuration keeps hazardous chemistry at a depot, uses separated hydrogen and oxygen as consumed reactants or promoters, recovers heat and water, and converts clean captured carbon into methane, methanol, DME or chemicals. Mixed HHO is not a catalyst, and an engine-driven HHO loop is energy-negative in the screen.^{2,3,6,7}

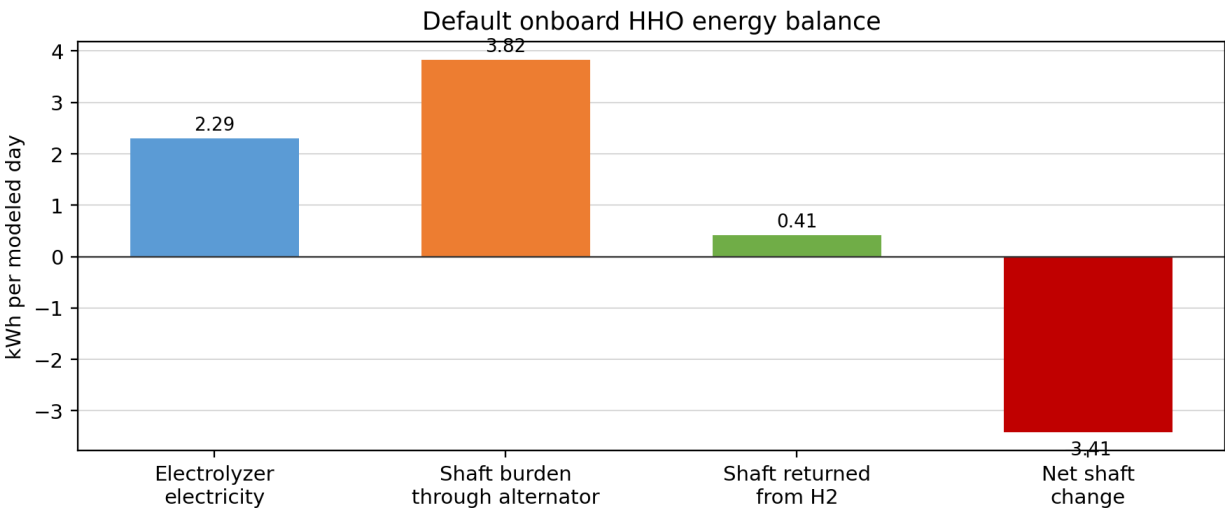
Main simulation results

Investigation	Default result	Meaning
Onboard HHO	Minus 3.41 kWh shaft per day	A 10.4-point absolute efficiency gain is needed for break-even
Bubble Butt	0.08 to 6.93 kg CO2 per day	Plain water is a trim; high capture needs reactive media at a depot
CO2 to fuel	15.5 to 17.1 percent shaft to electric	Carbon can cycle; electricity remains the primary input
Five-pass reflux	66.4 percent conversion	Conversion rises while reactor throughput grows 2.66 times
Combination explorer	1,134 candidate and 6,840 rejected	Compatibility and safety gates remove most permutations

HHO and reaction promotion

A catalyst increases reaction rate without being consumed overall. An oxyhydrogen or HHO mixture is consumed to form water, so it cannot be treated as a catalyst. Depending on placement, hydrogen can be an added fuel, reductant, hydrogenation reactant or flame-kinetic promoter; oxygen can be an oxidant, enrichment stream or partial-oxidation reactant. The distinction is not semantic: it determines the energy balance, gas-separation requirement and hazard analysis.^{2,6}

The default onboard case uses 2.5 kg per day of a gasoline surrogate, 25 percent engine efficiency, a 5 percent added hydrogen energy share, 55 kWh per kg hydrogen electrolysis electricity and 60 percent alternator efficiency. It produces 0.0417 kg hydrogen and 0.331 kg oxygen, draws 2.294 kWh electricity, imposes 3.823 kWh of shaft burden through the alternator, and returns only 0.411 kWh of shaft work from hydrogen combustion. The modeled net change is therefore minus 3.412 kWh per day before auxiliaries or compression. DOE reports 55 kWh per kg hydrogen as a 2022 system-status value for both PEM and liquid alkaline electrolysis.^{3,4,7}



The break-even calculation requires a 10.4 percentage-point absolute improvement in engine efficiency at the 5 percent assist case. That is a screening hurdle, not a universal experimental verdict: hydrogen addition has been shown to extend lean operation and change combustion duration, but NOx and efficiency depend on ignition timing, mixture control, load and engine design. The correct next experiment is an externally supplied, separated-hydrogen dynamometer test with the electrolyzer energy accounted for outside the engine, followed by a full well-to-shaft balance.^{6,7}

- Retain separated external hydrogen addition as an engine-calibration research path.⁶
- Retain separated oxygen enrichment for stationary burners, reformers and gasification research, with explicit NOx and materials limits.²
- Use hydrogen as a manufacturing reactant for acetylene hydrogenation, waste-oil upgrading and CO₂-derived fuels.^{1,30}
- Reject mixed-HHO storage and do not credit an alternator-fed HHO loop with net fuel creation.⁷

Expanded electrolysis matrix

The useful comparison is not one electrolyzer against another in isolation. Each route creates a different set of products, temperature demands, separation problems and downstream matches. PEM and alkaline water electrolysis are the strongest sources of separated hydrogen and oxygen. Solid-oxide electrolysis becomes attractive where high-temperature heat is already available. Chloride routes are industrial chemistry nodes and must not be treated as interchangeable water electrolyzers.^{2,3,4,5}

Electrolysis family	Outputs	Best CL17 role	Boundary
PEM or liquid alkaline	Separated H2 and O2	External H2 assist, fuel synthesis, oxygen use	55 kWh per kg H2 system-status input; water quality and gas crossover
Solid oxide steam	Separated H2 and O2	Heat-integrated depot production	38 kWh electric plus about 9 kWh thermal per kg H2 in the DOE status case
CO2 or steam CO2 co-electrolysis	CO, formate or syngas	Methanol, DME, Fischer Tropsch or CO branch	Selectivity, durability and gas cleanup are still development issues
Chlor alkali	H2, Cl2 and NaOH	Industrial symbiosis and capture reagent	Only where chlorine and caustic have contracted demand
Aqueous LiCl membrane	LiOH, H2 and Cl2	Connect LiOH capture, hydrogen and chlorine loops	Membrane separation, corrosion and chlorine handling
Molten LiCl	Li metal and Cl2	Specialist lithium regeneration for CL17	High-temperature reactive inventory; no onboard use
HCl electrolysis	H2 and Cl2	H2 Cl2 regenerative storage	Stationary closed-loop containment
Ammonia, methanol or urea assisted	H2 plus oxidized feed products	Hybrid electrolysis and waste treatment research	Lower voltage consumes another molecule and may create difficult byproducts

In the CL17 matrix, aqueous LiCl electrolysis is especially interesting because the LiOH can return to capture or lithium processing, hydrogen can feed fuel synthesis, and chlorine can enter a controlled storage or product route. It is also a coproduct trap: per kilogram of hydrogen, stoichiometry produces roughly 23.75 kg lithium hydroxide and 35.17 kg chlorine. A project should proceed only when every output has a qualified outlet and the separator is treated as a safety-critical component.

13,14

Battery chemistry and cycling

Battery chemistry belongs in the investigation because many of the proposed loops require short-duration buffering, regenerative electrolysis, start-up power and capture auxiliaries. The comparison must distinguish commercial storage from chemistry research. LFP and sodium-ion are practical controls; flow systems and regenerative fuel cells suit stationary duration; Li chlorine and Li CO₂ remain specialist experimental branches.^{22,23,24,27,28}

Storage route	Screening round trip	Placement	Decision
LFP lithium ion	90 percent editable default	Vehicle or depot	Commercial benchmark
Sodium ion	85 percent editable default	Vehicle niche or depot	Compare with certified products
Vanadium or iron flow	75 percent editable default	Stationary	Duration benchmark
H ₂ O ₂ regenerative fuel cell	47.4 percent demonstrated case	Stationary	Useful chemical-storage control
H ₂ Cl ₂ regenerative fuel cell	70 percent screening value	Specialist stationary	Partner research only
Zn Cl ₂ flow battery	91 percent laboratory result at low current density	Specialist stationary	Promising but not system-proven
Rechargeable Li Cl ₂	60 percent unvalidated screening input	Specialist cell laboratory	Fundamental research
Li CO ₂	50 percent unvalidated screening input	Specialist cell laboratory	Fundamental research

The chlorine and lithium batteries are not selected merely because they share CL17 species. Rechargeable Li Cl₂ has been demonstrated as a cell chemistry, and membrane-free chlorine flow work has reported 91 percent round-trip energy efficiency at 10 mA per square centimetre. Those results do not erase chlorine containment, metal-anode, crossover, corrosion, scale-up and current-density questions. They justify a specialist comparative cell programme, not a vehicle battery proposal.^{26,27}

Cycling tests should report energy efficiency, coulombic efficiency, capacity retention, self-discharge, standby losses, degradation, gas crossover and failure response over the intended duty cycle. For the integrated system, battery losses must be combined with electrolyzer, compression, synthesis and engine losses; no component-level efficiency should be presented as the total loop efficiency.

Active reflux recycle and engine recirculation

Active reflux has two distinct meanings in this project. Process reflux or recycle condenses or separates unreacted feed and returns it to a reactor, while a controlled purge prevents inert or contaminant accumulation. Exhaust gas recirculation returns a fraction of exhaust to an engine intake to change combustion temperature and NO_x. EGR is not fuel manufacture and should be modeled as an engine-control variable rather than a chemical production loop.

The workbook's finite-pass process model starts with 100 mol fresh feed, 25 percent single-pass conversion, 95 percent recovery of unconverted material, a 5 percent purge from the recovered stream and five active passes. Overall conversion reaches 66.4 percent, compared with 25 percent without recycle. Total reactor throughput rises to 265.5 mol, and the assumed separation and recycle energy is 1.328 kWh. Even infinite passes approach only 77.4 percent conversion because recovery and purge losses remain.

Recycle target	Separation method to investigate	Control variable	Failure mode
H ₂ CO ₂ methanation or methanol	Condensation plus gas separation	H ₂ to CO ₂ ratio and inert purge	Water or sulfur poisoning; inert buildup
Methanol dehydration to DME	Distillation and condensate reflux	Water removal and reflux ratio	Equilibrium loss and catalyst deactivation
CL17 lithium acetylene cycle	Solid liquid and gas separation	Lithium and LiOH recovery	Moisture ingress and reactive carryover
Bubble Butt capture solvent	Desorption, polishing and liquid return	Working capacity and blowdown	Salt accumulation, corrosion and aerosol carryover
Engine EGR	Valve and cooler control	EGR fraction and intake temperature	Soot, instability and aftertreatment mismatch

The key experimental comparison is conversion gain per additional unit of compression, separation and heat duty. Recycle is useful only when the recovered stream is clean enough to return without progressively poisoning the catalyst or concentrating corrosive species. The workbook therefore exposes single-pass conversion, recovery, purge, number of passes and recycle energy as independent inputs.

Manufacturing coproducts

The system becomes more credible when a main fuel process also creates useful materials, but coproduct accounting must be conservative. A stream is not a product until its purity, daily quantity, market demand, treatment burden and regulatory status are established. Otherwise the apparent value is a shifted waste liability.

Main process	Coproduct	Screening ratio	Reuse test
Water electrolysis	Oxygen	7.936 kg per kg H2	Certified oxidant use or no value credit
Methane pyrolysis	Solid carbon	2.979 kg per kg H2	Carbon quality for materials or CL17 carbon feed
Biodiesel	Crude glycerol	0.10 kg per kg biodiesel assumption	Purity and local market saturation
Chlor alkali	Chlorine and sodium hydroxide	35.17 and 39.68 kg per kg H2	Contracted offtake, storage and capture-media demand
Aqueous LiCl electrolysis	Lithium hydroxide	23.75 kg per kg H2	Purity for sorbent regeneration or battery material
CL17 carbide hydrolysis	Lithium hydroxide	1.84 kg per kg acetylene	Closed lithium recovery with low loss
Bubble Butt	Water, sludge and captured PM	Site measured	Water polishing; sludge treated as contaminated until characterized

Oxygen is a particularly easy source of double counting. Water electrolysis generates it, but oxygen sales should not be used to subsidize hydrogen unless the local market can absorb the full quantity at the required purity. Chlorine is more restrictive: chlor-alkali stoichiometry creates about 35 kg chlorine for every kilogram of hydrogen, so energy production must not drive unwanted chlorine manufacture.^{2,11,12}

Captured particulate from real exhaust is not automatically a useful solid-carbon feed. Metals, ash, lubricating-oil additives, salts and polycyclic aromatic hydrocarbons may make it a regulated waste or require costly purification. Characterization by a qualified laboratory is a gate before reuse in the lithium-acetylene branch or any material product.^{8,10}

Bubble Butt capture and reuse

Bubble Butt is most defensible as a modular exhaust-conditioning and pollutant-transfer device, followed by station service. A plain-water contactor can cool exhaust and capture particulate and some soluble gases, but it does not provide material CO2 capture by itself. High CO2 capture requires a reactive sorbent or adsorbent, regeneration, gas cleanup and compression. Wet scrubbing also introduces pressure drop, pump energy, droplet carryover and wastewater management. ^{8,9,10}

Scenario	CO2 captured	Water recovered	Net shaft	Interpretation
Baseline aftertreatment	0.000 kg per day	0.177 kg per day	8.212 kWh	Reference only
Plain water trim	0.077 kg per day	1.064 kg per day	8.089 kWh	Cooling, PM and soluble-pollutant research
Reactive onboard	1.926 kg per day	1.419 kg per day	7.719 kWh	Research only; mass and waste burden
Depot full loop	6.935 kg per day	2.661 kg per day	7.226 kWh	Preferred regeneration and synthesis location

These are deliberately editable scenarios, not performance claims. They use 2.5 kg per day of gasoline surrogate, 7.705 kg carbon dioxide formed, 3.548 kg water formed, 50 km per day, and screening capture and parasitic fractions. The purpose is to expose the tradeoff: the depot case captures far more carbon but consumes more useful engine output and requires storage or immediate transfer of almost 7 kg CO2 per modeled day.

The recommended capture train is:

- exhaust cooling and condensation with water-backflow protection
- certified oxidation catalyst, particulate filter and selective catalytic reduction where the engine requires them
- wet or reactive contactor followed by a mist eliminator
- liquid and solid separation with blowdown and water polishing
- optional CO2 desorption and compression at a depot
- transfer of clean CO2, water and heat to electrolysis or fuel synthesis

Heat should first offset direct thermal loads such as desorption, distillation, steam generation and feed preheating. Recovered water may return to an electrolyzer only after treatment and confirmation that chloride, metals, organics and catalyst poisons are below the receiving equipment's limits. NOx-to-nitrate and particulate-to-carbon-product concepts remain characterization studies rather than assumed products.

Captured carbon to replacement fuel

The carbon-reuse model begins with 5 kg captured CO₂ per day, 90 percent purity and 70 percent conversion yield, leaving 3.15 kg clean CO₂ converted. Hydrogen electricity is set to 55 kWh per kg hydrogen, synthesis and compression to 1 kWh per kg product, and engine efficiency to 30 percent. The resulting shaft-to-electric ratios are optimistic because capture regeneration, feed cleanup, standby and distribution are excluded. ^{3,4,29,30,31}

Product	Product mass	H ₂ mass	Electric plus synthesis	Fuel energy	Shaft to electric
Methane	1.148 kg	0.577 kg	32.89 kWh	17.71 kWh	16.2 percent
Methanol	2.294 kg	0.433 kg	26.10 kWh	14.44 kWh	16.6 percent
DME	1.649 kg	0.433 kg	25.45 kWh	14.52 kWh	17.1 percent
FT liquid surrogate	1.004 kg	0.433 kg	24.81 kWh	12.83 kWh	15.5 percent

DME is marginally highest in this simplified engine-return screen, while methane has the strongest compatibility with existing gas infrastructure and methanol has the simplest liquid-product pathway. The small differences do not justify a winner without real capture energy, catalyst life, plant scale, fuel-distribution and engine-emissions data. The correct decision variable is lifecycle emissions and useful work per unit of renewable electricity, not product mass alone. ^{29,30,31}

Bounded combination exploration

The workbook enumerates 14,400 combinations across six fuels, four hydrogen or oxygen roles, six electrolysis routes, four capture modes, five storage routes and five recovered-output uses. The classification yields 1,134 candidates, 2,124 research-only systems, 4,302 incomplete chains and 6,840 rejected chains. These counts describe the defined design space, not probabilities of success.

The highest-scoring families combine methane, methanol or DME with depot capture, PEM or alkaline electrolysis, LFP buffering and CO₂-to-methanol or CO₂-to-DME reuse. External separated hydrogen remains available as a calibration variable. The rejected set is dominated by mixed onboard HHO and mobile chlorine or lithium inventories. Incomplete rows expose missing product matches, such as a CO₂-to-fuel route without reactive capture or an H₂ chlorine storage route without a matched chlorine electrolysis loop.

Supplemental research programme

The next phase should be a staged request for assistance rather than an attempt to combine every apparatus at once. Each stage should close a mass and energy balance before the next chemistry is added. The work needs laboratory space, certified equipment, analytical capability and engineering supervision that are not presently available within the project.

Priority	Work package	Facility and capability request	Decision evidence
1	Engine and Bubble Butt baseline	Instrumented engine dynamometer, five-gas analysis, particulate measurement, pressure-drop and condensate sampling	Fuel use, useful work, CO ₂ , water, NO _x , CO, HC, PM and backpressure
2	Separated hydrogen promotion	Certified external H ₂ supply, flashback protection, calibrated injection and engine controls	Lean limit, combustion stability, brake efficiency and NO _x with full upstream energy accounting
3	Wet and reactive capture	Corrosion-compatible contactor, mist elimination, sorbent analysis and wastewater treatment	Capture selectivity, working capacity, regeneration duty, aerosol loss and liquid quality
4	CO ₂ to fuel and reflux	Bench methanation or methanol DME partner, gas cleanup and process simulation	Single-pass conversion, recycle energy, catalyst tolerance, purge and product quality
5	Battery and storage comparison	Battery cyclers plus certified LFP and sodium controls; specialist flow and regenerative-cell laboratory	Round trip, degradation, self-discharge and containment performance
6	CL17 specialist electrochemistry	Glovebox, molten-salt or membrane electrolysis expertise, gas analysis and emergency controls	Faradaic efficiency, lithium recovery, chlorine balance, impurities and full energy demand

Measurements that cannot be omitted

- complete carbon, hydrogen, oxygen, chlorine, lithium and water balances with quantified uncertainty
- electrical, shaft, thermal, compression, pumping and separation energy on the same time basis
- gas purity, crossover, unreacted feed, liquid carryover and solid composition
- engine regulated emissions before and after every module, including cold start and transient operation
- pressure drop, corrosion, freeze tolerance, service interval and wastewater or sorbent replacement
- lifecycle source of electricity, hydrogen, carbon and chemical reagents

The first fundable demonstration should avoid lithium, chlorine and mixed HHO. It should pair a conventional engine or stationary generator with instrumented Bubble Butt water trim, heat and condensate recovery, and a depot-side reactive capture skid. In parallel, a university or industrial partner can investigate the CL17 lithium-acetylene and chlorine-storage branches under an existing chemical safety system.

Research request for assistance

Emission Transitive Emission requests collaborative access to laboratory space, engine test facilities, certified separated-gas equipment, electrochemical instrumentation, capture and regeneration rigs, and chemical analysis. The objective is to determine which combinations can provide a measurable transition from fossil fuel use without hiding energy demand, creating uncontrolled hazardous inventories, or moving emissions into an unmeasured waste stream.

The programme is intentionally comparative. It will test direct electrification and commercial batteries as controls; external separated hydrogen as a combustion-promoter variable; PEM, alkaline and heat-integrated electrolysis as hydrogen sources; Bubble Butt water trim and stationary reactive capture as separate functions; and methane, methanol and DME synthesis as competing carbon-reuse routes. Lithium, chlorine, Li CO₂ and CL17 acetylene pathways will be limited to specialist partner laboratories.^{1,2,22,27,28,30}

Decision statement

There is definitely something here. The most promising idea is not to make an engine power its own electrolyzer, but to make the engine one node in a serviced material-and-energy network. A vehicle can use a certified transition fuel and a low-burden capture trim; a depot can recover heat and water, regenerate sorbents, store electricity, and convert clean CO₂ with externally supplied low-carbon hydrogen. The same site can route higher-risk lithium and chlorine research to specialist partners rather than carrying it onboard.

The key is to identify a fuel and process combination that can assist the transition from fossil fuels or replace them through technology while preserving useful work, safety and lifecycle emissions performance. Current limitations are practical: insufficient laboratory space, analytical capability, engine instrumentation, electrochemical equipment and chemical-containment infrastructure. Those limitations justify a structured collaboration request, not a weaker safety boundary.

Immediate decisions

- Proceed with the interactive mass-and-energy workbook as the shared screening baseline.
- Seek an engine-test partner for external separated-H₂ and Bubble Butt control experiments.
- Seek a process partner for depot CO₂ capture, reflux and methane or methanol DME synthesis.
- Keep H₂ chlorine, Li chlorine, Li CO₂ and lithium-acetylene work in specialist stationary laboratories.
- Reject any result that omits upstream electricity, parasitic load, purge, regeneration or waste treatment.

Sources and numbered endnotes

Superscript numbers in the report refer to the numbered sources below. Access dates for live technical pages are 12 September 2026. Screening assumptions are labeled as assumptions in the text and workbook.

1. **McEnaney et al.**. “A cyclic electrochemical strategy to produce acetylene from CO₂, CH₄, or alternative carbon sources.” 2020. [Source link](#) Used for CL17 lithium-mediated acetylene cycle.
2. **U.S. Department of Energy**. “Hydrogen Production Electrolysis.” accessed 2026. [Source link](#) Used for Electrolyzer types, gas separation and system boundary.
3. **U.S. Department of Energy**. “Technical Targets for Proton Exchange Membrane Electrolysis.” 2022 status. [Source link](#) Used for 55 kWh per kg H₂ system status.
4. **U.S. Department of Energy**. “Technical Targets for Liquid Alkaline Electrolysis.” 2022 status. [Source link](#) Used for 55 kWh per kg H₂ system status.
5. **U.S. Department of Energy**. “Technical Targets for High Temperature Electrolysis.” 2022 status. [Source link](#) Used for 38 kWh electrical and 47 kWh total per kg H₂ system status.
6. **Ma et al.**. “Experimental study on thermal efficiency and emission characteristics of a lean burn hydrogen enriched natural gas engine.” 2007. [Source link](#) Used for Hydrogen addition extends lean limit; calibration and NO_x matter.
7. **Karagoz et al.**. “Investigation of the energy requirements for the on-board generation of oxy-hydrogen on vehicles.” 2018. [Source link](#) Used for Required efficiency gain for alternator-fed HHO.
8. **U.S. Environmental Protection Agency**. “Wet Scrubbers for Particulate Matter.” 2020. [Source link](#) Used for PM and acid-gas capture, pressure drop and liquid waste.
9. **Sharma and Maréchal**. “Carbon Dioxide Capture From Internal Combustion Engine Exhaust Using Temperature Swing Adsorption.” 2019. [Source link](#) Used for Mobile capture architecture and thermal integration.
10. **Mardle et al.**. “Underground Diesel Exhaust Wet Scrubbers Current Status and Future Prospects.” 2018. [Source link](#) Used for Water-contact diesel exhaust cooling and pollutant capture.
11. **U.S. Department of Energy**. “Chlor Alkali Industry Energy and Environmental Profile.” 2000. [Source link](#) Used for Chlorine, caustic and hydrogen co-production.
12. **European Commission Joint Research Centre**. “Best Available Techniques Reference Document for Chlor Alkali.” 2014. [Source link](#) Used for Industrial chlor-alkali process and emissions controls.
13. **U.S. Patent 3597340**. “Recovery of Lithium as Lithium Hydroxide Monohydrate From Aqueous Lithium Chloride.” 1971. [Source link](#) Used for LiOH, H₂ and Cl₂ from aqueous LiCl electrolysis.
14. **Su et al.**. “Production of LiOH H₂O from lithium chloride by electrodialysis and crystallisation.” 2024. [Source link](#) Used for Modern LiCl to LiOH membrane route.
15. **U.S. Department of Energy Y 12**. “Low temperature lithium production method eliminates high temperature electrolysis.” 2024. [Source link](#) Used for Conventional molten LiCl context.
16. **U.S. Patent 4617098**. “Continuous electrolysis of lithium chloride into lithium metal.” 1986. [Source link](#) Used for Molten LiCl gives Li metal and chlorine.
17. **Huskinson et al.**. “A High Power Density High Efficiency Hydrogen Chlorine Regenerative Fuel Cell.” 2012. [Source link](#) Used for H₂ Cl₂ reversible storage.
18. **Vitse et al.**. “On the use of ammonia electrolysis for hydrogen production.” 2005. [Source link](#) Used for Ammonia assisted hydrogen production.
19. **Sasaki et al.**. “Hydrogen production by methanol water solution electrolysis.” 2010. [Source link](#) Used for Methanol-assisted electrolysis consumes carbon feed.
20. **U.S. Department of Energy NETL**. “Solid Oxide Electrolysis Cell Research.” accessed 2026. [Source link](#) Used for Steam and CO₂ co-electrolysis research.

21. **Chen et al.**. “Highly selective urea electrooxidation coupled with efficient hydrogen evolution.” 2024. [Source link](#) Used for Wastewater co-electrolysis potential and selectivity limits.
22. **U.S. Department of Energy**. “Storage Futures Study Battery Storage.” 2021. [Source link](#) Used for Commercial battery benchmark context.
23. **International Renewable Energy Agency**. “Sodium ion batteries technology brief.” 2025. [Source link](#) Used for Sodium-ion maturity and use cases.
24. **U.S. Department of Energy**. “Energy Storage Grand Challenge Roadmap.” 2020. [Source link](#) Used for Stationary flow-battery benchmark context.
25. **Bennett et al.**. “Analysis of a 100 W Regenerative Fuel Cell Demonstration.” 2020. [Source link](#) Used for 47.4 percent demonstrated H₂ O₂ round-trip efficiency.
26. **Yu et al.**. “High energy and low cost membrane free chlorine flow battery.” 2022. [Source link](#) Used for 91 percent laboratory round-trip efficiency at 10 mA per cm².
27. **Zhu et al.**. “Rechargeable Na Cl₂ and Li Cl₂ batteries.” 2021. [Source link](#) Used for Rechargeable metal chlorine battery chemistry.
28. **Xu et al.**. “The Li CO₂ battery a novel method for CO₂ capture and utilization.” 2013. [Source link](#) Used for Primary Li CO₂ battery concept.
29. **National Aeronautics and Space Administration**. “Sabatier carbon dioxide methanation reactor resources.” accessed 2026. [Source link](#) Used for CO₂ plus H₂ to methane and water.
30. **International Renewable Energy Agency**. “Innovation Outlook Renewable Methanol.” 2021. [Source link](#) Used for CO₂ H₂ methanol and DME pathways.
31. **Argonne National Laboratory**. “GREET publications and pathway studies.” accessed 2026. [Source link](#) Used for Synthetic liquid fuel lifecycle boundary.
32. **U.S. Department of Energy**. “Hydrogen Shot Summit Methane Pyrolysis Panel.” 2021. [Source link](#) Used for Methane to hydrogen and solid carbon.
33. **U.S. Department of Energy Alternative Fuels Data Center**. “Biodiesel Basics.” accessed 2026. [Source link](#) Used for Biodiesel manufacture and vehicle use context.
34. **Kobayashi et al.**. “Science and technology of ammonia combustion.” 2019. [Source link](#) Used for NO_x N₂O and ammonia slip constraints.
35. **U.S. Department of Energy Alternative Fuels Data Center**. “Hydrogen Basics.” accessed 2026. [Source link](#) Used for Hydrogen as energy carrier and vehicle fuel.
36. **NIST Chemistry WebBook**. “Thermochemistry records for fuels in the model.” accessed 2026. [Source link](#) Used for Molar masses and standard thermochemistry.