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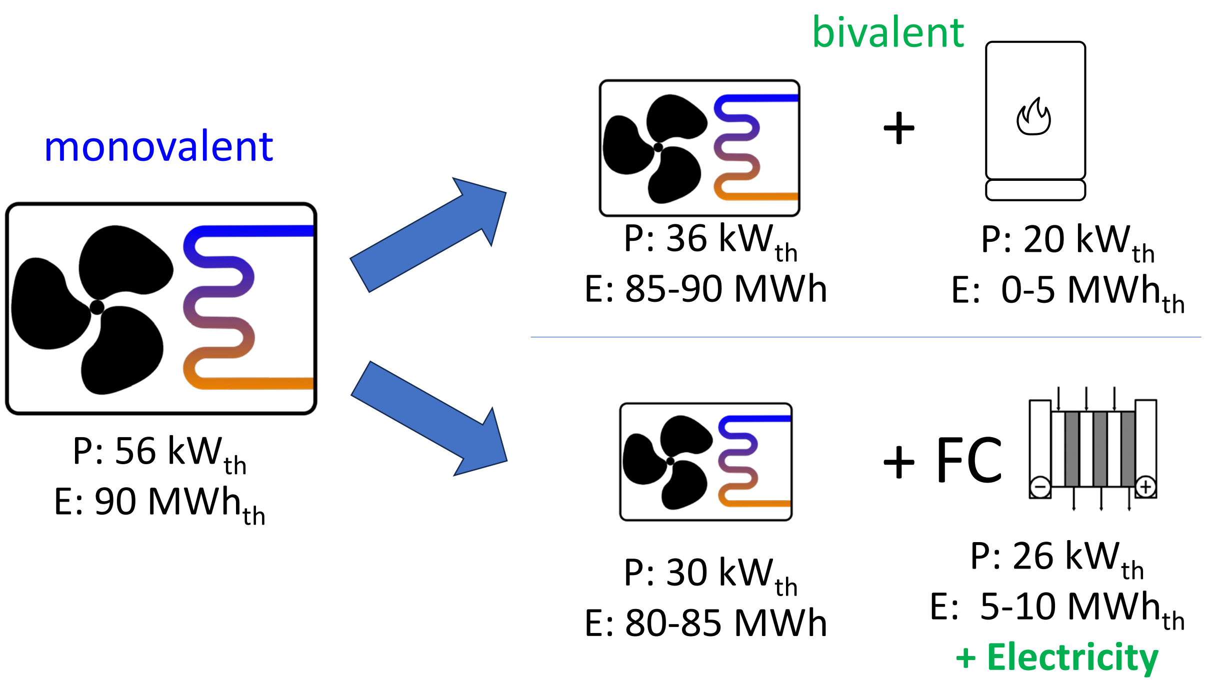
Interim report dated December 2025

ReWAX

Smaller heat pump dimensioning using X-to-Energy for peak load coverage



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Zusammenfassung

Eine vergleichende Bewertung von sieben Power-to-X-Energieträgern – Wasserstoff, Methan, Methanol, Ammoniak, LOHC, Eisen und Aluminium für den Einsatz zur Deckung als Spitzenlast in bivalenten Gebäudeheizsysteme– wurde anhand technischer, wirtschaftlicher, ökologischer und sicherheitsrelevanter Kriterien durchgeführt. ReMEC-Energieträger (Aluminium und Eisen) zeigten für Power-to-Energy (Heat and Power) die höchsten Umwandlungswirkungsgrade und Speicherdichten, während Wasserstoff eine hohe gravimetrische Energiedichte, aber geringe Gesamteffizienz aufwies. Methan erwies sich als kosteneffizient in verschiedenen Produktionsszenarien; bei Ammoniak- und Eisen zeigten die berechneten Energieträgerkosten (Levelized cost of X, LCOX) eine vergleichsweise geringe Sensitivität gegenüber Strompreisschwankungen. Wasserstoff hatte für diese Anwendung den niedrigsten CO_2-Fussabdruck (~18 g CO_2-eq/MJ of electric and thermal energy), dicht gefolgt von Methan und den ReMEC Kandidaten. Kein erneuerbarer Energieträger dominierte in allen Kategorien; die Eignung hängt vom Anwendungsfall ab. Als Nächstes folgen Systemsimulationen und eine Kosten-Nutzen-Analyse zur Integration mit Wärmepumpensystemen.

Résumé

Une évaluation comparative de sept vecteurs énergétiques Power-to-X — hydrogène, méthane, méthanol, ammoniac, LOHC, fer et aluminium — a été menée selon des critères techniques, économiques, environnementaux et de sécurité. Les ReMEC (alu et fer) ont présenté la meilleure efficacité de conversion et densité de stockage, tandis que l'hydrogène offrait une densité massique élevée mais une faible efficacité globale. Le méthane s'est révélé robuste en coût à différentes échelles ; l'ammoniac et le fer étaient peu sensibles au prix de l'électricité. L'hydrogène a montré la plus faible empreinte carbone (~18 g CO_2-éq/MJ), suivi du méthane et des ReMEC. Aucun vecteur ne domine toutes les catégories ; le choix dépend du contexte. La suite du projet inclut des simulations système et une analyse coûts-bénéfices pour leur intégration avec des pompes à chaleur.

Summary

A comparative evaluation of seven Power-to-X energy carriers —hydrogen, methane, methanol, ammonia, LOHC, iron, and aluminium —was conducted across technical, economic, environmental, and safety criteria. ReMECs (aluminium and iron) showed the highest process efficiency and storage density, while hydrogen offered high gravimetric energy but low round-trip efficiency. Methane emerged as a cost-resilient option at various scales; ammonia and iron showed low sensitivity to electricity prices. Hydrogen had the lowest carbon footprint (~18 g CO_2-eq/MJ), with methane and ReMECs close behind. No single option dominated all categories; application context determines suitability. Next, system simulations and cost–benefit analysis will assess integration with heat pump systems.

Contents

Abbreviations

AF – Annuity Factor
BFE – Bundesamt für Energie (Swiss Federal Office of Energy)
CAPEX – Capital Expenditure
CO_2-eq – Carbon Dioxide Equivalent
CORE – Federal Energy Research Concept (2021–2024)
CTRANS – Specific transport cost
EC – European Commission
Energieperspektiven 2050+ – Swiss national energy scenarios toward net zero
GWP_{100} – Global Warming Potential (100-year time horizon)
IEA – International Energy Agency
LCOX – Levelized Cost of Energy Carrier Supply X
LHV – Lower Heating Value
LOHC – Liquid Organic Hydrogen Carrier
MCDA – Multi-Criteria Decision Analysis
OPEX – Operational Expenditure
PtH_2 – Power-to-Hydrogen
$PtCH_4$ – Power-to-Methane
PtMeOH – Power-to-Methanol
$PtNH_3$ – Power-to-Ammonia
PtX – Power-to-X (conversion of renewable electricity into another energy carrier)
ReMEC – Renewable Metal Energy Carrier
TRL – Technology Readiness Level
WP – Work Package

1 Introduction

1.1 Background information and current situation

1.1.1 Transition towards renewable and flexible heating systems

The decarbonisation of Switzerland's building sector is a cornerstone of the Energiestrategie 2050 and the Net-Zero 2050 target. Space and water heating are historically dominated by fossil fuels and account for over one third of the country's final energy consumption. The *Energieperspektiven 2050+* scenarios foresee a strong electrification of heat supply, primarily through heat pumps and complemented by renewable district-heating networks [1].

According to the *FWS Statistiken 2023*, the Swiss heat-pump market has expanded steadily to more than 30 000 units per year [2]. The research project *OptiPower* [3] confirmed that systems are frequently oversized: in over 600 multi-family buildings, the median oversizing was ≈ 40%, while in office buildings it reached 100–300% [4]. Oversizing of heat pumps increases investment cost, might reduce lifetime through frequent cycling, and can lower efficiency. It also reinforces electricity peaks during cold weather periods, stressing the grid when renewable generation is limited. These findings highlight the need for flexible and bivalent heating systems that ensure comfort while lowering winter electricity demand.

1.1.2 Power-to-X technologies and renewable energy carriers

To ensure a secure and low-carbon energy supply in winter, Switzerland requires storable and dispatchable **renewable energy carriers**. **Power-to-X (PtX)** technologies convert renewable electricity into chemical energy carriers that can be stored and later reconverted into heat and/or electricity when required.

Typical PtX energy carriers include:

- **Hydrogen (Power-to-H_2):** A mature technology (TRL 8–9) and the basis for most other PtX chains. Domestic production capacity is limited (potential annual production approx. 20 000 t), supplied mainly by industrial electrolysis (≈ 10-15%), while the majority stems from by-product hydrogen generated in chlor-alkali and petrochemical, typically used internally within industry. Distribution and storage infrastructure exists at local industrial and mobility sites but remains **fragmented and regionally concentrated**, with no national large-scale storage and transmission network established yet [5,6].
- **Methane and Methanol (Power-to-CH_4 / Power-to-MeOH)**: Synthetic hydrocarbons produced by combining renewable hydrogen with captured CO_2 through catalytic (Sabatier) or chemical synthesis processes. Both, CH_4 and MeOH, are **fully compatible with existing gas and liquid-fuel infrastructure**, enabling relatively straightforward distribution and use. Methane offers **high infrastructure readiness** and is suited for decentralised CHP or boiler applications, while methanol can serve as a **liquid hydrogen carrier or feedstock** for chemical industries. Typical overall PtX-to-end-use efficiencies range between **45–60%**, depending on process design and utilisation [7].

- **Ammonia (Power-to-NH_3)**: A carbon-free **hydrogen carrier** produced from renewable hydrogen and nitrogen via the Haber–Bosch process. It offers relatively **high volumetric energy density** and can be **stored and transported using existing infrastructure** from the chemical and fertiliser industries. Ammonia is therefore considered a promising option for **large-scale and long duration energy storage**. However, its **toxicity**, **handling requirements**, and the **energy losses** associated with synthesis and reconversion to hydrogen or heat remain key challenges [8].
- **Liquid Organic Hydrogen Carriers (LOHCs)**: Organic liquids that **reversibly store and release hydrogen** under ambient conditions, enabling **safe and compact storage**. The **hydrogenation (charging) process is exothermic**, while the **dehydrogenation (discharging) process is endothermic** and requires high-temperature heat input. This limits their **net energy contribution for winter supply** unless renewable or waste heat is available for the discharge step.
- **Renewable Metal Energy Carriers (ReMEC):** An emerging class of **PtX technologies**, where metals such as aluminium or iron are produced from their oxides using renewable electricity. They offer **carbon-free, high-density, and loss-free long-duration energy storage**. During discharge, the metals react with water or oxygen while producing hydrogen and/or heat in an exothermic reaction, providing useful energy for winter demand. The resulting metal hydroxides or oxides can be re-oxidised in a **closed circular process**, enabling repeated seasonal metal cycling.

These renewable energy carriers complement direct electrification by enabling **seasonal or long duration energy storage** and **peak-load coverage** during cold and cloudy winter periods.

1.1.3 Existing challenges

Despite their potential, PtX and renewable energy carriers face several challenges:

- High production cost depending on electricity price and full-load hours of the facility
- Efficiency losses in multi-step conversion chains (35-65% overall).
- Infrastructure and regulation gaps, including limited hydrogen pipelines, storage capacity, and safety standards [6].
- Market immaturity, with limited PtX production and fragmented supply chains
- Integration complexity when coupling intermittent XtE operation with continuous heat-pump demand.

Consequently, PtX systems are presently not competitive for continuous baseload operation but can be **economically viable for renewable peak-load coverage**, where the higher specific energy carrier cost plays a minor role due to limited operating hours and therefore low annual demand.

1.2 Purpose of the project

Building on the challenges described above, the project investigates **how PtX energy carriers can enhance the flexibility and resilience of heat supply** in Swiss buildings and district-heating networks. The analysis focuses on **bivalent heating concepts** that combine a heat pump with a compact **X-to-Energy unit** capable of providing **renewable peak-load coverage** during cold weather periods.

This approach enables the **heat pump to be dimensioned for base-load conditions**, reducing oversizing, lowering capital and operational costs, and minimising winter electricity peaks. At the same time, it replaces conventional oil- or gas-fired backup systems with **carbon-neutral, renewable energy carriers** that can be **produced from renewable excess electricity** - or in places where renewable energy is available at low cost all year around - and transported over long distances and stored easily for long duration.

The project systematically analyses various PtX options, including hydrogen, methane, methanol, ReMEC (aluminium, iron), to determine their **technical, economic, ecological, and safety characteristics**.

Through this, ReWAX aims to:

- provide a **scientifically validated basis** for integrating renewable energy carriers into building heating systems,
- quantify **cost and efficiency advantages** of bivalent PtX-assisted configurations, and
- contribute to reducing **Switzerland's winter energy gap** and **dependence on fossil fuels**.

The project directly supports the goals of the *Energieperspektiven 2050+* and the Federal Energy Research Concept (CORE 2021–2024)[1], the Swiss government's strategic framework that defines national priorities for energy research, by advancing **seasonal storage technologies** and improving **security of energy supply**.

1.3 Objectives

The **ReWAX project** pursues five main objectives that address the technical, economic, and practical feasibility of using **X-to-Energy technologies** for renewable peak-load coverage in buildings and district-heating networks.

Each objective is linked to specific research questions guiding the analyses and expected findings.

Objective 1 – Technology overview and comparison: Prepare a comprehensive overview of **Power-to-X (PtX) and X-to-Energy technologies** suitable for covering peak heat demand.

Objective 2 – Technical impact on heat-pump systems: Analyse the **technical consequences of integrating an X-to-Energy unit** into a heat-pump system. Simulations will quantify how much the installed capacity of air-to-water, brine-to-water, or lake-water heat pumps can be reduced when peak heat is supplied by an X-to-Energy technology, and how this affects seasonal performance and grid interaction.

[1] The Federal Energy Research Concept (CORE 2021–2024) is Switzerland's four-year strategic framework for national energy research. It defines federal priorities for efficiency, renewable integration, storage, and system flexibility, and guides research funding by the Swiss Federal Office of Energy (SFOE/BFE).

Objective 3 – Economic impact on heat-pump systems: Evaluate the **economic effects** of using an X-to-Energy peak-load unit. The analysis will determine how reduced sizing influences **investment costs**, **operating costs**, and **service life** of heat pumps, and assess the overall cost balance between additional PtX components and savings on the heat-pump side.

Objective 4 – Economic viability and contribution to supply security: Assess the **overall cost-effectiveness** of X-to-Energy peak-load systems under current and future framework conditions. This includes analysing boundary conditions such as energy prices and utilisation rates, estimating the **potential to improve energy-supply security**, and identifying **policy or incentive measures** that could support market introduction.

Objective 5 – Experimental demonstration: Select a **promising technology combination** and demonstrate it experimentally at the SPF laboratory test stand. Measurements will confirm the technical feasibility, efficiency, and control behaviour of a bivalent system and validate simulation results from the previous objectives.[2]

Through these objectives, ReWAX will provide a scientific and practical foundation for applying renewable X-to-Energy technologies in building and district-heating systems. The results will show how such systems can reduce heat-pump oversizing, investment cost, and winter electricity peak demand, while enhancing supply security and supporting Switzerland's transition to a climate-neutral heat supply.

2 Procedures and methodology

2.1 General approach

The ReWAX project follows a structured, multi-stage research approach, as illustrated in Figure 1. The workflow combines the identification and comparison of X-to-Energy options (WP2) with system modelling and simulation (WP3), cost–benefit analysis (WP4), and experimental validation (WP5).[2]

The work packages are interlinked: results from WP2 provide input data for simulations in WP3; these, in turn, feed into the economic evaluation in WP4.

[2] *Due to budget reductions announced during the project, it is currently under discussion whether this part of the work can or will be carried out as originally planned.*

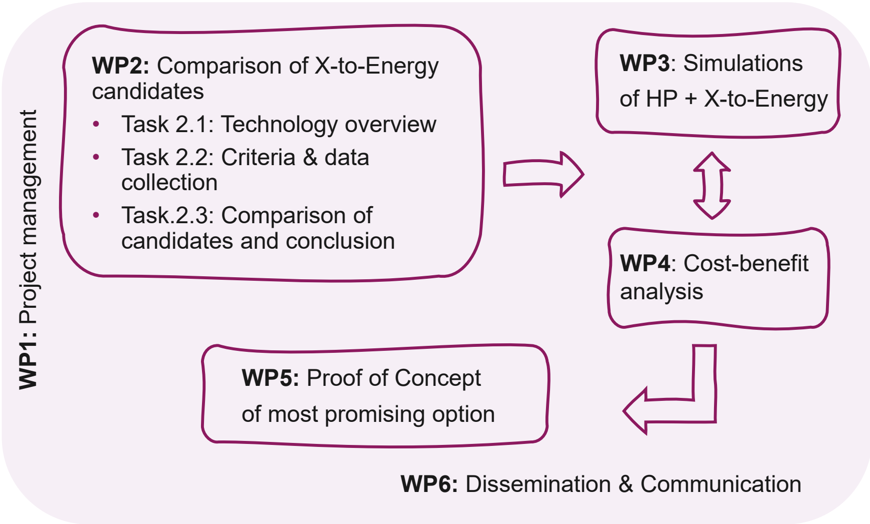

Figure 1: Overview of the ReWAX work packages (WP).

A **project advisory board (Begleitgruppe)** comprising representatives from the **SFOE**, **IWB**, **sgsw**, **IWK**, Romande Energie with Realstone SA (first phase) and the **project partners tend** and **Vaillant Group** provide regular feedback to ensure practical relevance and alignment with current developments in the Swiss energy sector.

Overall, ReWAX aims to establish a coherent framework linking **technology assessment, system modelling, and experimental validation** to evaluate how PtX energy carriers can enable renewable peak-load coverage in heating systems.

2.2 Implementation within this interim report

During the first project period (October 2024 - October 2025), the methodological framework described above has been implemented as planned.

- **WP 2 - Evaluation of PtX energy carriers**: This work package has been completed, including data collection, development of the multi-criteria comparison matrix, and preliminary ranking of hydrogen, methane, methanol, iron, and aluminium. The advisory board recommended the inclusion of **Liquid Organic Hydrogen Carriers (LOHC)** and **ammonia** as additional candidates, with ammonia as an option for applications in district-heating networks.
- **WP 3 - Task 3.1: Definition of reference systems and modelling framework**: The reference systems have been defined and discussed with the advisory board, providing the basis for subsequent simulation studies in WP3.

3 Activities and results

3.1 WP2 – Evaluation of PtX energy carriers

A **structured technology comparison** was carried out based on three main groups of criteria: **Technical Performance**, **Resource & Supply**, and **Economics & Environment**, supplemented by aspects of **Safety & Handling**.

Key indicators include feasibility and system efficiency, storage density, technology readiness level (TRL), fuel availability, supply resilience, capital and operating cost, and overall greenhouse-gas potential (GWP_{100}). The **selection of these criteria was defined in collaboration with the project advisory board**.

For each investigated energy carrier (hydrogen, methane, methanol, ammonia, LOHC, iron, and aluminium), a dedicated **two-page factsheet** summarises the **key technical, economic, environmental, and safety aspects.** These factsheets are published on the project website: www.ost.ch/spf/rewax to provide harmonised data on conversion efficiencies, storage density, technology maturity, infrastructure readiness, and open challenges. A **transparent cost comparison** was also performed by calculating the **levelized cost of energy-carrier supply (LCOX)**, which represents the cost of the delivered energy carrier per unit of energy output (CHF/MWh of energy). In this project, “energy” refers to the chemical energy content of the carrier (heat and electricity), based on the lower heating value (LHV). The cost indicator accounts for the **complete delivery chain**, including **production, central storage, and transportation** to the end user, but excludes end-user storage and conversion equipment (e.g., boilers, fuel cells, or CHP units). These additional costs will be considered separately in WP4: Cost-benefit analysis.

The following sections describe the evaluation with its assumption and comparison of the investigated energy carriers in further detail.

3.1.1 Technical performance

The **Technical Performance** evaluation included both quantitative and qualitative indicators describing the efficiency, energy density, maturity, and system complexity of each energy carrier along the Power-to-X-to-Energy chain. The following parameters were considered:

- **Power-to-X-to-Storage efficiency (LHV basis):** represents the cumulative conversion efficiency from electricity input to stored energy. Metals achieved the highest efficiencies (alu ≈ 63 %, Fe ≈ 57 %), indicating low conversion losses during storage. Hydrogen showed the lowest efficiency (≈ 44 %) due to additional compression or liquefaction energy demand.
- **Power-to-X conversion complexity:** reflects the number of conversion steps and major components required for production and storage. Fewer steps correspond to simpler process integration, higher efficiency, and lower cost, whereas multiple stages imply higher equipment demand and greater losses.
- **Technology readiness level (TRL):** assessed separately for the **Power-to-X (production)** and **X-to-Energy (utilisation)** processes. For X-to-Energy, both for boiler and fuel cell technology were considered in this comparison. However, for cost-benefit analysis also CHP conversion, such as combustion engine, and gas turbine for district heating applications will be considered. The TRL scale ranges from 1 (laboratory research) to 9 (commercial deployment), as illustrated in Figure 2. Hydrogen and methane technologies show the highest maturity levels for both production and utilisation. Ammonia, methanol, and LOHC systems are at intermediate stages of development, while the ReMEC carriers (aluminium and iron) remain at an early stage.
- **CHP system complexity:** evaluated according to the number of subsystems required for the **X-to-Energy** conversion. A lower number of subsystems indicates a simpler and more

integrated system. For example, hydrogen requires only a single component (fuel cell) and was therefore ranked as least complex.

- **Energy density:** assessed on both **volumetric** (kWh/m³, LHV) and **gravimetric** (kWh/kg, LHV) bases. Solids demonstrate a strong volumetric advantage (aluminium ≈ 23 300 kWh/m³; Fe ≈ 11 300 Wh/m³) compared with liquids such as methanol and ammonia (≈ 4 000 kWh/m³), while hydrogen has the lowest volumetric density (~1 100 kWh/m³). In contrast, hydrogen exhibits the highest gravimetric energy density (33 kWh/kg), followed by liquids in the mid-range (5–14 kWh/kg) and solids at lower levels (aluminium ≈ 8.6 kWh/kg; Fe ≈ 2 kWh/kg).

Figure 2: Definition of Technology Readiness Levels (TRL) [9].

All indicators were harmonised and normalised for use in the Multi Criteria Decision Analysis (MCDA), providing a consistent and transparent dataset of technical performance across all evaluated energy carriers.

Figure 3 and Figure 4 present the normalized technical performance results of all evaluated energy carriers. Metals (Al and Fe) exhibit the highest process efficiencies and volumetric energy densities, while hydrogen shows the best gravimetric density but lower efficiency when stored into winter due to compression and liquefaction losses. Methane, methanol, ammonia, and LOHCs achieve intermediate positions, benefiting from established synthesis routes but limited by lower energy densities or additional process steps. In terms of technology maturity (TRL), hydrogen and methane systems are currently the most developed, followed by ammonia, methanol, and LOHC. The ReMECs (aluminium and iron) are less mature but technologically promising, offering high storage density and low complexity once fully developed.

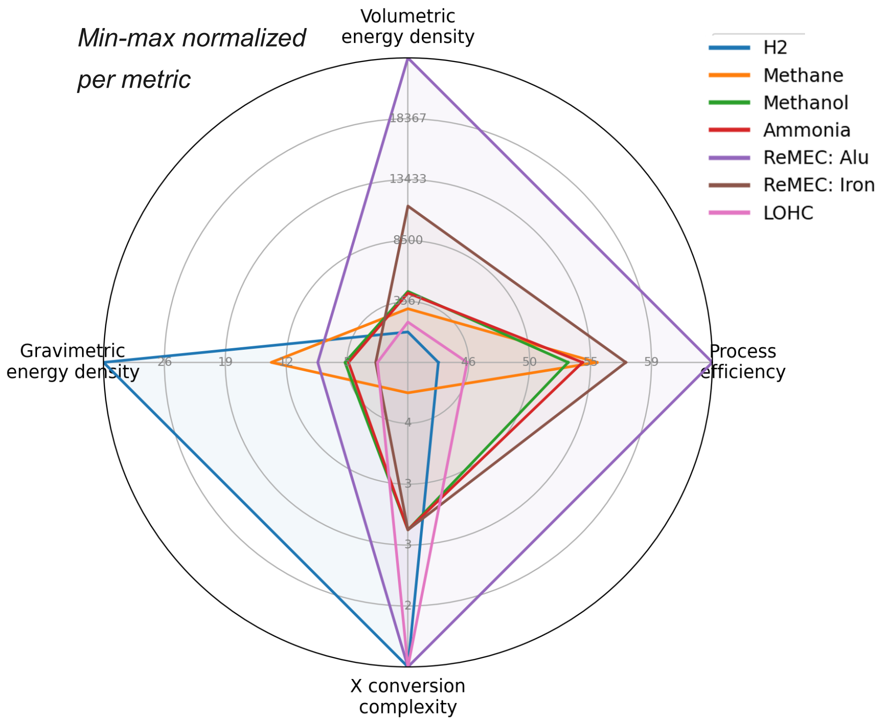

Figure 3: Normalized technical performance indicators (efficiency, energy density, and conversion complexity) for all investigated energy carriers (Annex A.1).

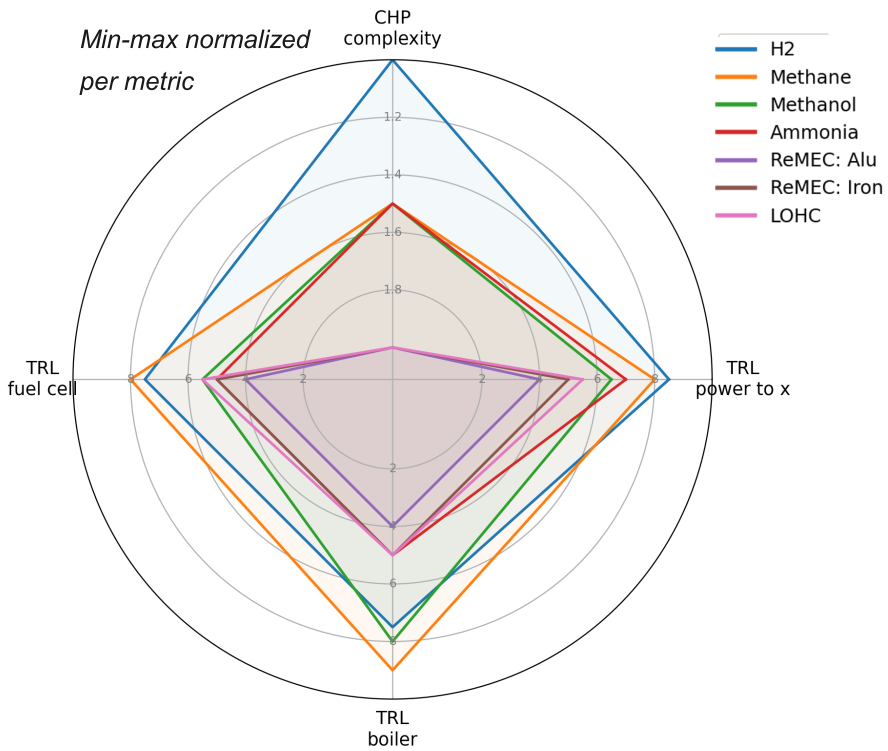

Figure 4: Normalized indicator of technology maturity and system complexity (TRL for Power-to-X, fuel cell, boiler; and CHP system complexity). For parameters with a TRL range, the mean value was used – for example, hydrogen fuel cells range from TRL 7-9, so an average value of 8 was applied (Annex A.2).

3.1.2 Resource and supply

The resource and supply assessment examined the availability, resilience, and feedstock requirements of each energy carrier within the Power-to-X framework. Three key parameters were considered:

- Availability of energy carrier: the estimated production potential or existing domestic supply within Switzerland and selected international reference regions (e.g. Germany, Denmark, Iceland). Current and planned production capacities were compiled from literature, project databases, and industrial sources.
- Resiliency of supply: defined as the robustness and security of the energy carrier supply chain, considering feedstock dependence, geographic diversity, and infrastructure maturity. However, since large-scale production and distribution systems for most Power-to-X carriers are still at an early development stage, a meaningful ranking could not yet be established. Available data on supply-chain maturity and geographic diversification remain too limited to support a consistent assessment. Consequently, this indicator was considered in the evaluation framework for completeness but not included in the MCDA scoring.
- CO_2 source requirement: indicates whether a carbon source is needed for synthesis. Hydrogen, ammonia, and the ReMEC carriers do not require CO_2, while methane and

methanol depend on biogenic or captured CO_2, and LOHC systems vary depending on the carrier liquid used.

Hydrogen supply in Switzerland remains limited and mainly fossil-based: total production is about 21,500 t H_2/yr, with only a small share from electrolysis. The largest Swiss PtH_2 site is Monthey (two 750 Nm³/h alkaline units, with one of them in operation at the time of writing) [5].

Power-to-Methane is further along: biological methanation has been operating at Limeco (Dietikon) since March 2022, and internationally the Werlte $PtCH_4$ plant has run since 2013; $PtCH_4$ is early commercial [10].

Methanol and ammonia are globally available commodities, but their Power-to-X (green) variants are not yet widespread: Switzerland has no e-MeOH production, while global e-MeOH capacity is growing from a few pioneering plants toward larger projects. For ammonia, there are no Power-to-Ammonia installations in Switzerland; Power-to-NH_3 is pre-commercial, with ~10 pilot plants worldwide according to the International Energy Agency, Hydrogen Technology collaboration Programme (IEA Hydrogen TCP) [11].

LOHC remains at pilot/early demonstration with the first large European plant targeting 2027; no Swiss production yet.

ReMEC (Al & Fe) have high raw-material availability and mature recycling chains [12]. Power-to-Iron is at TRL 6–8 with industrial pilots by HYBRIT and Boston Metal, while Power-to-Aluminium is at TRL 4–5, demonstrated by Arctus Aluminium and ELYSIS (Alcoa / Rio Tinto) aiming for commercialization by 2030.

3.1.3 Economic and environment

The cost analysis applies uniform boundary conditions and economic assumptions across all carriers. Table 1 summarises the general economic parameters, while Table 2 lists carrier-specific technical assumptions applied for the cost analysis.

Table 1 General economic assumptions

Parameter	*Symbol*	*Value / Range*	*Unit*	*Note*
Discount rate	i	5	%	Used for the annuity factor
Economic lifetime	n	25 (plants, storage) / 40 (caverns)	years	Technology dependent
Electricity price	-	50 (base); 5–150 (sensitivity)	CHF/MWh	Uniform assumption
Operating hours	-	3000 / 8600	h per year	Intermittent vs baseload
CAPEX scaling	-	$\propto$ Capacity$^{-0.2}$ … $^{-0.4}$	-	Economies of scale based on literature
OPEX	-	2–5% of CAPEX	%/y	Technology dependent, excluding electricity input cost
Currency year	-	2024	-	Nominal CHF values

Table 2 Carrier-specific technical assumptions

Carrier	*Main Process*	*Efficiency (LHV), %*	*Key Storage Type*	*Typical Cost Driver*
H_2	PEM electrolysis	70	500 bar / liquid / cavern	Compression and liquefaction
CH_4	Catalytic methanation (Sabatier process)	80	Gas or cavern storage	Methanation CAPEX
MeOH	Catalytic CO_2 conversion via H_2	56	Liquid storage (ambient conditions)	CO_2 feedstock and process energy
NH_3	Haber–Bosch Synthesis (H_2 + N_2)	70–75	Pressurised or refrigerated tanks	Electrolysis electricity cost
LOHC	Hydrogenation/ dehydrogenation	49	Liquid media	Plant CAPEX, carrier material cost
Aluminium	Electrolysis (CO_2 free inert anode)	65	Bulk solid	Electricity cost and smelter CAPEX
Iron	Reduction of iron oxide with H_2	85	Bulk solid	Hydrogen feed cost

The **Levelized Cost of Energy Carrier Supply X (LCOX)** was calculated for each energy carrier using the following relations:

$$AF_j = \frac{i}{(1+i)^{-n_j} - 1} \quad (1)$$

$$LCOX = \frac{\sum j\{production, storge\}\, CAPEX_j \cdot AF + OPEX_j}{W} + c_{transport} \quad (2)$$

Where:

- $CAPEX_j$ and $OPEX_j$ are, respectively, the investment and annual operating cost of subsystem j (production including electricity use and storage)
- AF is the annuity factor, and
- W is the annual useful energy output (MWh).
- $c_{transport}$ represents the specific transport cost (CHF/MWh of energy delivered to end users before X-to-Energy conversion). It accounts for the logistics required to move the energy carrier from the production site to the point of use.

It should be noted that for hydrogen, methane, methanol, ammonia, LOHC, and iron, production was assumed to be located within Switzerland, with domestic distribution to end users by road. For aluminium, the production site was assumed to be in Iceland according to the Horizon Europe REVEAL project concept, with intermodal logistics consisting of cargo shipping to EU port in Rotterdam, rail transport from Rotterdam to Zurich, and final road distribution to end users [13].

All cost data represent indicative estimates based on current technology data and literature sources and are therefore subject to high uncertainty. They primarily serve to illustrate relative trends and cost sensitivities rather than absolute market prices.

At small scale and partial load (10 MW / 3 000 h, Figure 5), LCOX of all carriers rise sharply with increasing electricity prices, starting between 200 and 650 CHF/MWh, depending on the carrier, roughly 150 – 250 CHF/MWh higher than under full-load operation. With increasing electricity prices, most carriers converge toward ≈600 CHF/MWh, indicating that at low utilization, fixed investment dominates total cost. CH_4 remains the most resilient option, starting around 200 CHF/MWh and staying among the lowest-cost carriers, while NH_3 and Fe are the least sensitive to electricity price.

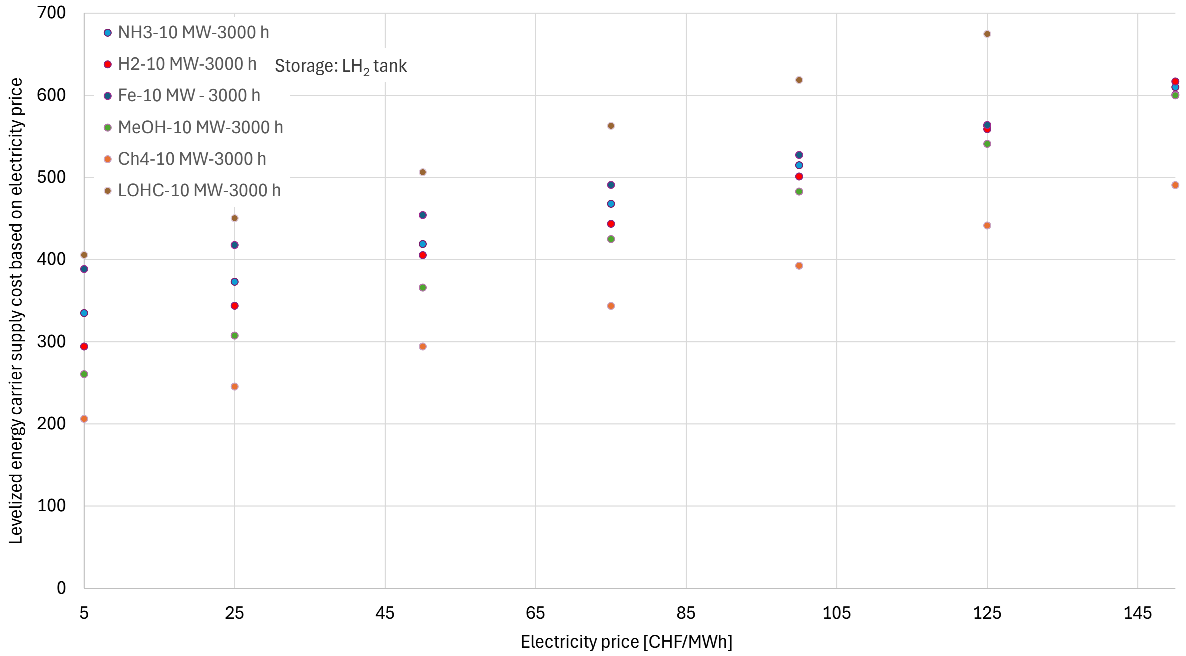

Figure 5: *LCOX (CHF/MWh) as a function of electricity price for different Power-to-X energy carriers at 10 MW scale of the PtX plant and partial-load reduced operation time throughout the year (3000 hours/yr). The cost includes production, storage, and transport to end user (Annex A.3).*

H_2, MeOH, and especially LOHC show the steepest cost slopes at small scale, indicating high sensitivity to electricity price and utilization. In contrast, CH_4, NH_3, and Fe remain comparatively robust, confirming that gas- and metal-based carriers are less affected by electricity cost fluctuations. In turn, complex liquid carriers such as methanol and LOHC become uncompetitive at low operating hours despite their storage advantages.

At a small scale (1-10 MW), aluminium electrolysis is not competitive because of its high specific capital intensity and the strong economies of scale inherent to smelting technology. Inert-anode smelting plants require large, molten-salt cells connected in series with shared infrastructure for power supply, gas handling, and casting. At commercial scales of around 500 kt aluminium per year (≈ 2.5–3 GW electrical input), the specific investment cost for conventional Hall-Héroult cells is roughly 3 000–4 000 USD per tonne of annual aluminium capacity and rises steeply with smaller capacities, as fixed plant components cannot be downsized proportionally [14]. The introduction of inert-anode technology can reduce investment costs by roughly 40% compared with conventional cells, yet this improvement does not offset the strong scale dependency. Even the smallest aluminium smelters operating today have capacities near 50 kt aluminium per year (≈ 250–300 MW electrical input).

However, secondary aluminium production from recycling streams, which involves remelting scrap metal rather than electrolytic reduction, can be carried out economically at small scales (5–20 kt alu per year) due to its low energy demand and simple infrastructure. This process, however, differs fundamentally from Power-to-Aluminium, as it does not enable the storage of renewable electricity but only recovers existing material.

Therefore, aluminium production becomes economical only at very large, full-load industrial scales (≥500 MW; 325–650 kt per year), where process efficiency and specific investment costs improve. At such scales, high and steady utilization of capacity also reduces the impact of electricity price fluctuations on overall production cost (Figure 6).

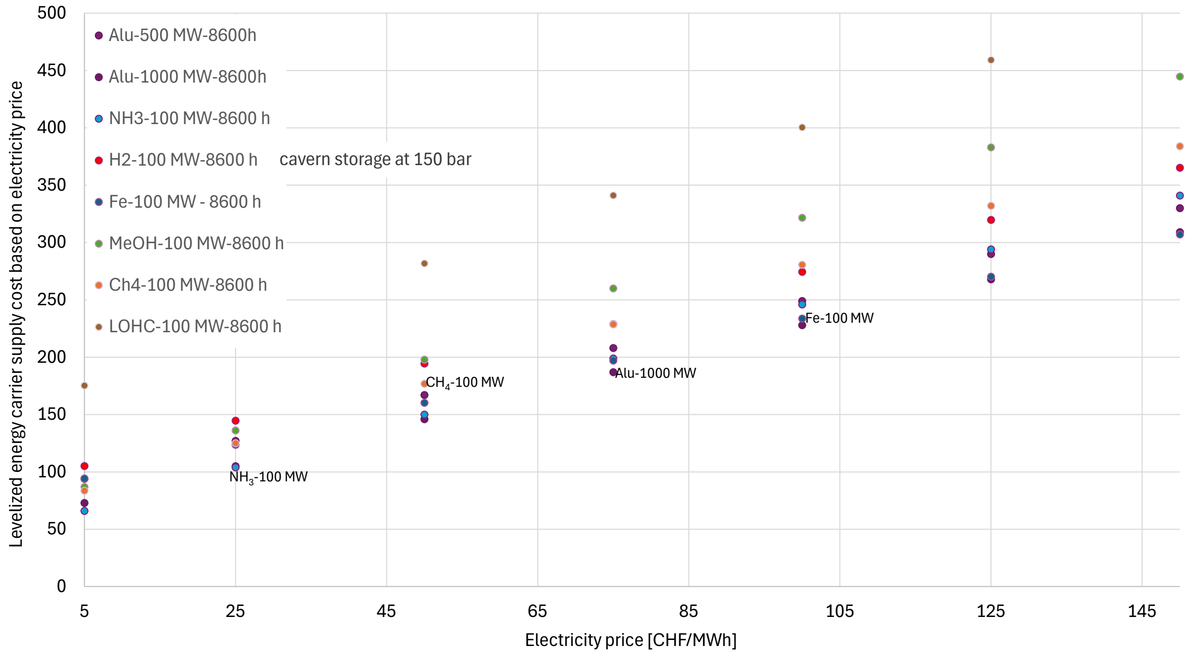

Figure 6: *LCOX (CHF/MWh) as a function of electricity price for different Power-to-X energy carriers and scales of the PtX plant (100/500/1000 MW, 8600 full-load hours per year). The cost includes production, storage, and transport to end user. For hydrogen, salt cavern storage at 150 bar was assumed (Annex A.4).*

In general, economies of scale markedly improve competitiveness across all Power-to-X carriers at production capacities ≥ 100 MW, both for high and low number of operating hours per year. Ammonia (NH_3) and iron remain the overall lowest-cost and most robust options at high capacities, while hydrogen becomes increasingly competitive at large scale only when seasonal salt-cavern storages are available. These significantly lower total supply cost compared to compressed gas containers or liquefied storage. Aluminium achieves some of the lowest specific energy-carrier costs in the comparison due to its high energy density and thus low transport and storage costs. Methanol (MeOH) performs well at high utilization ((8600 h/year)) but loses competitiveness at lower operating hours, showing high sensitivity to utilization. LOHC exhibits the steepest cost increase and the highest absolute values (> 600 CHF/MWh at high electricity prices).

Note: Hydrogen costs were estimated using the Levelised Cost of Hydrogen (LCOH) Calculator of the Clean Hydrogen Observatory [15]. Methane, methanol, ammonia, and iron pathways are highly dependent on the hydrogen feedstock price, while hydrogen cost is mainly driven by storage costs, for seasonal storage, where the use of salt caverns markedly improves competitiveness. Aluminium production costs were derived from *EU REVEAL* project data.

The **Global Warming Potential (GWP100a)** of the analysed Power-to-X energy carriers (Figure 7) was evaluated from literature and own LCA analysis from PeakMetal project for ReMEC candidates, assuming renewable electricity supply [16].

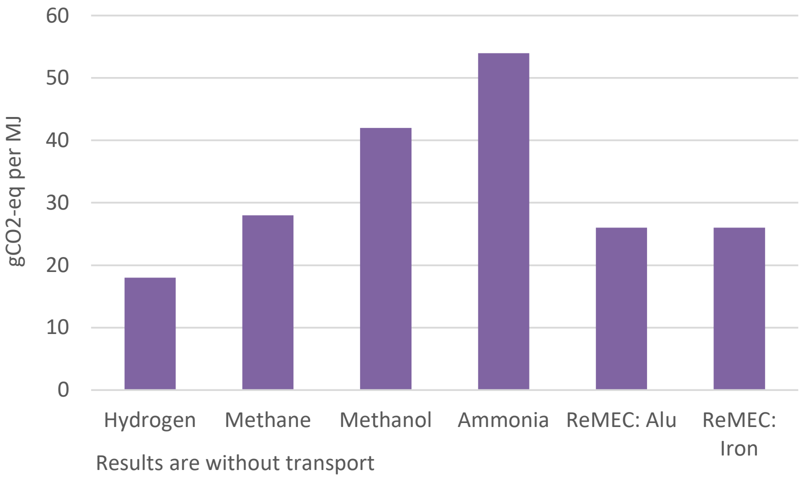

Figure 7: Direct GWP100a Power-to-X energy carriers without transport (Annex A.5).

The results indicate clear differences between production routes and conversion complexity. Hydrogen shows the lowest specific carbon footprint of around 18 g CO_2-eq/MJ, reflecting the short process chain and high conversion efficiency of electrolysis. Methane and metal-based carriers (ReMEC–alu and ReMEC–iron) show similarly low footprints of approximately 26–28 g CO_2-eq/MJ. Methanol and ammonia exhibit higher emissions—around 42 g CO_2-eq/MJ and 54 g CO_2-eq/MJ, respectively—mainly due to their more complex synthesis routes and additional process energy requirements. For LOHC, no reliable data are currently available.

Overall, hydrogen and the metal-based carriers achieve the lowest life-cycle CO_2 emissions, whereas methanol and ammonia show higher GWP values because of multi-step conversion chains and additional synthesis inputs. When powered entirely by renewable electricity, all pathways remain well below fossil benchmarks, confirming their potential for deep decarbonization of long-term energy storage and transport.

Note: Results are cradle-to-gate and exclude transport and end-use process. Values are indicative estimates subject to high uncertainty due to limited primary data and methodological variability in LCA studies.

3.1.4 Safety and handling

The safety and handling criteria combine both regulatory and operational aspects to assess the relative safety of each energy carrier during transport, storage, and use.

The evaluation considered five main criteria:

Hazard classification: Based on EU Regulation (EC) No. 1272/2008 (CLP), indicating whether the substance is officially listed as a hazardous material and the number of associated **Hazard (H)** and **Precautionary (P)** statements.

Ignition behaviour: Derived from the auto-ignition temperature and flashpoint of each carrier. Substances with higher ignition temperatures and lower flammability risks received better (lower) scores.

Transport: Ranked according to the typical transport mode and dangerous goods classification of each energy carrier, reflecting the infrastructure and vehicle requirements for safe carrier distribution. Pipelines (1) were rated safest, as they enable continuous transport with fully enclosed infrastructure and minimal loading or unloading operations. Ambient liquid or solid material tanks (2) were considered moderately safe, requiring sealed vehicles, spill-prevention systems, and adherence to road or rail regulations. Pressurised vessels (3) involve elevated pressures and reinforced cylinders or tube trailers, which require periodic inspection and compliance with transport regulations for dangerous goods. Cryogenic transport (4) was rated most demanding, relying on insulated tankers and boil-off management systems to maintain low temperatures and prevent vapour release during transport.

Handling: Evaluated according to the physical form of the energy carrier, representing the relative effort, technical complexity, and safety precautions required during operation and transfer. Solids (1) are the easiest to handle because they are chemically stable, non-volatile, and can be managed without pressurised or sealed systems. Liquids (2) require controlled transfer systems such as pumps and closed lines to avoid spills or vapour release, resulting in moderate handling complexity. Gases (3) are the most demanding to handle due to their compressibility and tendency to escape through small leaks, necessitating pressurised connections, specialised fittings, and higher operational safety measures.

Storage: Ranked considering that solids require no specific containment, liquids require dedicated tanks and more complex infrastructure, and gases are the most demanding and safety-critical due to high-pressure storage in vessels. Corresponding rank values were assigned as solid (1) < liquid (2) < underground methane storage (3) < compressed gas (4), capturing differences in containment requirements and associated safety risks.

Each energy carrier was assigned a qualitative score for each safety & handling criterion, where lower point values indicate safer conditions and easier handling. For the Transportation / Handling / Storage indicator, the four sub-scores for ignition behaviour, transport mode, handling effort, and storage concept were added together to form a single composite value.

The resulting four safety & handling indicators: **hazard classification (H-statements)**, **precautionary classification (P-statements)**, **air-purity regulation (LRV / CAQ index)**, and **transportation / handling / storage** ranking were determined for each energy carrier. Figure 8 shows the results of these indicators: considering min–max normalization per metric. A **larger plotted area** indicates **better overall safety and easier handling** performance.

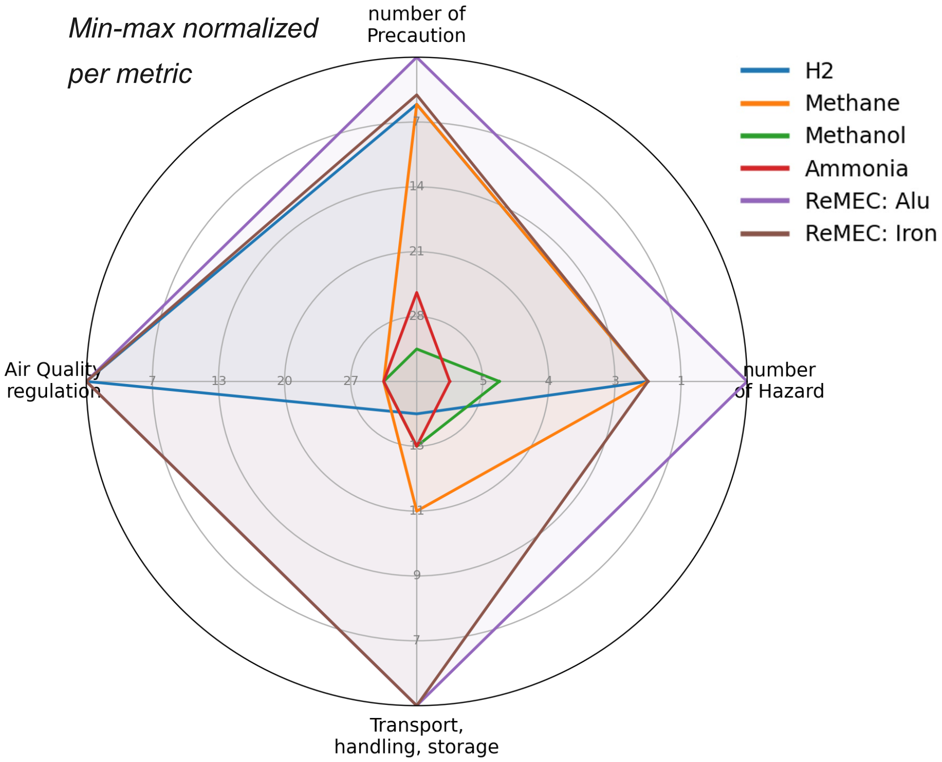

Figure 8: Normalized safety and handling indicators for all energy carriers (Annex A.6).

4 Evaluation of results to date

The comparative analysis across technical, economic, environmental, and safety dimensions highlights distinct trade-offs between Power-to-X energy carriers. No single carrier dominates across all criteria; instead, suitability depends on application context and boundary conditions.

ReMEC (aluminium and iron) stand out for their high system efficiency (up to 63%), excellent volumetric energy density, and superior safety performance. While their TRL is lower, particularly for aluminium, they offer strong long-term potential for seasonal storage where volume, robustness, and low operational risk are critical.

Hydrogen, despite being technologically mature and lightweight, exhibits the lowest Power-to-Storage efficiency due to energy-intensive storage (compression or liquefaction) and presents the highest handling complexity. Its competitiveness improves significantly at large scale and with geological storage options like salt caverns.

Methane offers a balanced profile: it combines good efficiency, established infrastructure, moderate GHG emissions (~26 gCO_2-eq/MJ), and relatively low LCOX at small and medium scale. It remains one of the most robust and cost-resilient options under varying electricity prices.

Methanol and ammonia perform well in terms of infrastructure compatibility and energy density but face trade-offs: methanol has moderate GWP and cost sensitivity, while ammonia shows higher emissions (~54 gCO_2-eq/MJ) and requires cautious handling due to toxicity, despite its carbon-free nature.

LOHC, although promising for liquid-phase hydrogen storage, remains the least competitive across almost all metrics—low efficiency, high cost sensitivity, and limited maturity—restricting its short-term relevance.

Overall, the evaluation confirms that solid carriers (alu, iron) are strong candidates for safe, dense, and efficient long-duration energy storage. Gaseous and liquid fuels offer versatility but require careful alignment of scale, safety measures, and energy sourcing to deliver meaningful climate and cost benefits.

5 Next steps

Building on the comparative assessment of energy carriers in WP2, the project will now advance to system-level modelling in WP3. This phase focuses on simulating hybrid heating systems that combine heat pumps with selected X-to-Energy conversion systems using Power-to-X options as analysed in this report. For the different options, seasonal performance, system sizing, and load-shifting potential will be analysed. The simulations will help identify optimal integration strategies for peak load coverage using renewable fuels. In parallel, WP4 will carry out a detailed cost–benefit analysis, quantifying the economic viability of different technology combinations across varying energy price scenarios, system scales, and operating profiles.

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Annex A: Tables representing ReWAX results of WP2

A.1 Technical performance indicators (efficiency, energy density, and conversion complexity)

Metric	H2	CH4	MeOH	NH3	LOHC	ReMEC: Alu	ReMEC: Iro
Power-to-X storage form	*liquid*	*gas, 300 bar*	*liquid*	*liquid 9 bar or -33°C*	*liquid*	*solid*	*solid*
Power-to-X-to-Storage efficiency (%)	44	55	53	54	46	63	57
Storage density incl. container at 300 bar for gases (kWh/m³) (LHV)	1100	2982	4382	4250	~1900	23300	11300
Storage density incl. container (kWh/kg) (LHV)	33	13.9	5.53	5.1	1.8	8.6	2
X conversion complexity (conversion stages)	2	4	3	3	2	2	3

A.2 Technology maturity and system complexity (TRL for Power-to-X, fuel cell, boiler, and CHP system complexity)

Metric	H2	CH4	MeOH	NH3	LOHC	ReMEC: Alu	ReMEC: Iro
Power-to-X storage form	*liquid*	*gas, 300 bar*	*liquid*	*liquid 9 bar or -33°C*	*liquid*	*solid*	*solid*
Technology Readiness Level: Power-to-X (TRL: 1-9)	8-9	8	8-9	7	5-6	4	5
Conversion complexity (CHP)	1	1-2	1-2	1-2	2	2	2
Technology readiness level (TRL) for X converter	Fuel cell: 6-9; boiler: 7-8	fuel cell: 7-9; boiler: 9	DMFC: 5-6; boiler 7-9	fuel cell: 4-6; boiler: 4-6	fuel cell: 5-6 boiler: 4-6	Alu-H2 converter: 4	Fe-boiler: 5

A.3 LCOX (CHF/MWh) as a function of electricity price for different Power-to-X energy carriers at 10 MW scale of the PtX plant and partial-load reduced operation time throughout the year (3000 hours/yr)

El. price, CHF	NH_3-10 MW-3000 h	H_2-10 MW-3000 h	Fe-10 MW-3000 h	MeOH-10 MW-3000 h	CH_4-10 MW-3000 h	LOHC-10 MW-3000 h
5	335	294	389	261	206	406
25	373	344	418	308	245	451
50	419	406	454	366	294	506
75	468	444	491	415	344	563
100	515	501	528	483	383	619
125	563	559	564	541	442	675
150	610	617	610	600	491	731

A.4 *LCOX (CHF/MWh) as a function of electricity price for different Power-to-X energy carriers and scales of the PtX plant (100/500/1000 MW, 8600 full-load hours per year).*

El. price, CHF	Alu-500 MW-8600 h	Alu-1000 MW-8600 h	NH_3-100 MW-8600 h	H_2-100 MW-8600 h	Fe-100 MW-8600 h	MeOH-100 MW-8600 h	CH_4-100 MW-8600 h	LOHC-100 MW-8600 h
5	94	73	66	105	94	87	84	175
25	127	105	104	145	124	136	125	223
50	167	146	150	194	160	198	177	282
75	208	187	199	229	197	260	229	341
100	249	228	246	274	234	322	281	400
125	290	268	294	320	270	383	332	459
150	330	309	341	365	307	445	384	519

A.5 Direct GWP100a Power-to-X energy carriers (without transport)

Metric	H2	CH4	MeOH	NH3	LOHC	ReMEC: Alu	ReMEC: Iro
Power-to-X storage form	*liquid*	*gas, 300 bar*	*liquid*	*liquid 9 bar or -33°C*	*liquid*	*solid*	*solid*
Direct GWP100a (gCO2-eq/MJ X produced without transport)	18	28	42	54	-	26	26

A.6 Safety and handling indicators for all energy carriers

Metric	H2	CH4	MeOH	NH3	LOHC	ReMEC: Alu	ReMEC: Iro
Power-to-X storage form	*liquid*	*gas, 300 bar*	*liquid*	*liquid 9 bar or -33°C*	*liquid*	*solid*	*solid*
Safety (hazard based on EU Regulation, number of H)	2	2	5	6	depending on carrier	0	2
Safety (precaution based on EU Regulation, number of P)	5	5	31	25	depending on carrier	0	4
Air purity regulation (LRV, Index CAQI)	-	30 mg/m3	30 mg/m3	30 mg/m3	-	-	-
Transportation / handling / storage *1	14	11	13	13	11	5	5

Annex B: Factsheets on PtX energy carriers

The pdf version of all factsheets are attached in the following order:

B.1 Power-to-Hydrogen

B.2 Power-to-Methane

B.3 Power-to-Methanol

B.4 Power-to-Ammonia

B.5 Power-to-LOHC

B.6 Power-to-Aluminium

B.7 Power-to-Iron

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Power-to-Hydrogen

Seasonal energy carrier – Power-to-X technology

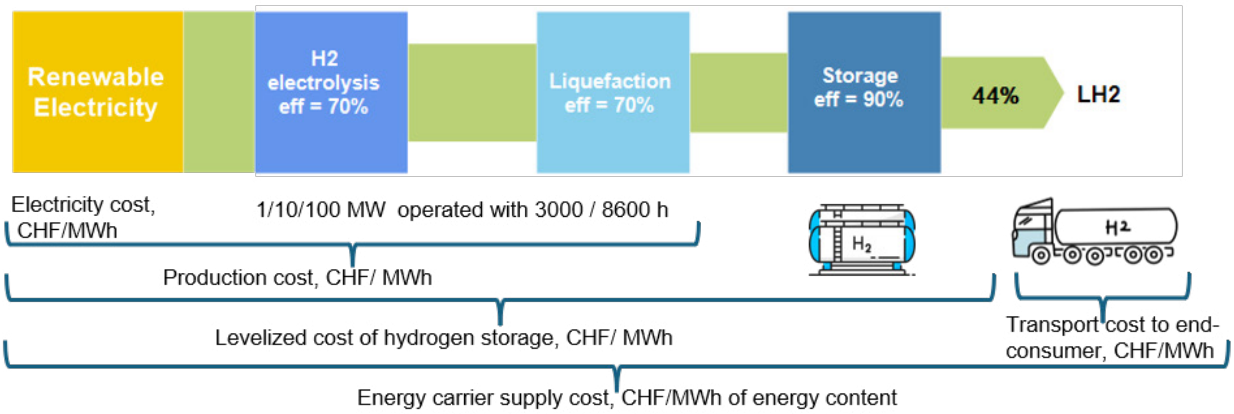
Hydrogen, produced through water electrolysis ($2\ H_2O \rightarrow 2\ H_2 + O_2$) powered by renewable electricity sources such as solar, wind, or hydropower, represents a clean energy technology. It is a crucial alternative for decarbonising sectors that are challenging to electrify directly, such as heavy industry, aviation, and long-haul transport, where hydrogen can be used either directly as a fuel or indirectly to produce fossil-free kerosene and other synthetic fuels.

Hydrogen electrolysis plant in the canton of Graubün-den, located next to the Reichenau hydropower plant in Domat/Ems. Photo: Axpo

A key advantage of renewable hydrogen is the flexibility in electrolysis operation. However, the widespread adoption of renewable hydrogen faces significant hurdles, including high production costs and the need for extensive distribution infrastructure. The latter involves developing efficient transportation and storage systems to move hydrogen from production sites to endusers, which can be particularly challenging, given hydrogen´s low volumetric energy density. The InfraMap (https://www.h2in-framap.eu/#introduction) tracks the development of hydrogen infrastructure across Europe.

Renewable hydrogen production in Switzerland faces key challenges and opportunities. A major barrier is the high upfront investment, given current market scale limitations. The absence of specific goals in the national hydrogen strategy creates uncertainty about system implementation and regulatory clarity. Switzerland´s limited domestic renewable energy resources increase reliance on hydrogen imports, particularly in winter. Therefore, if hydrogen is used as an energy carrier to cover winter energy demand, long-term hydrogen storage is required. However, the low volumetric energy density of hydrogen, even as a liquid or at high compression, poses major technical and economic barriers to large-scale seasonal storage.

Considering hydrogen production with liquefaction for storage, a Power-to-Hydrogen-to-Storage efficiency of 44% can be achieved, as illustrated below [1].



The total cost of supplying hydrogen as an energy carrier encompasses production expenses (including the Power-to-H_2 process), long-term storage costs, and transportation costs to the end consumer. Together, these components represent the complete supply cost of utilizing hydrogen as a storable and transportable medium for renewable energy. Switzerland currently has no hydrogen backbone; integration with the planned European Hydrogen Backbone (EHB) is under discussion but not yet implemented.

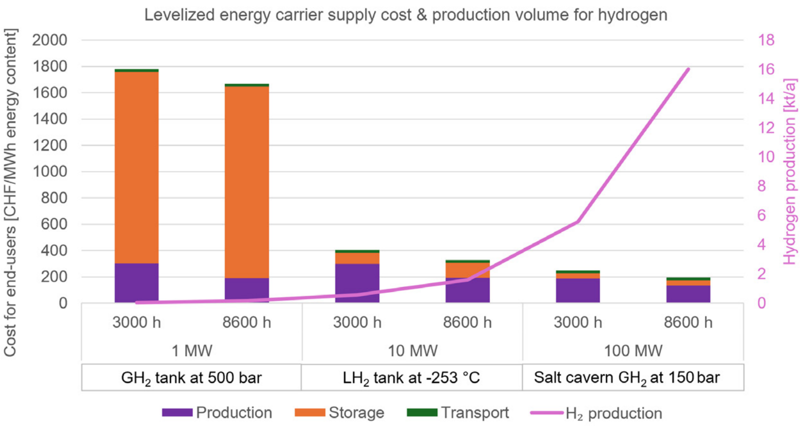
Availability

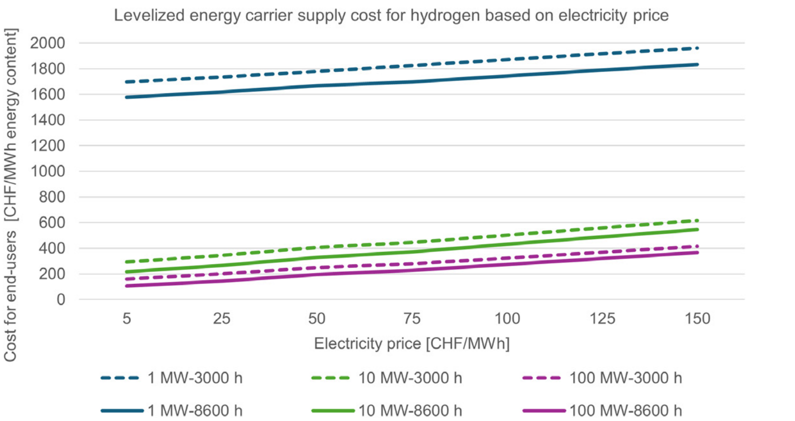
Total global hydrogen production in 2025	97 Mio. tonne [2]
Global production of renewable hydrogen in 2025	< 1 Mio. tonne [2]
CH production of renewable hydrogen in 2025	Max. 1500 tonne [3]

Chemical properties

Volumetric energy density (LHV): Net calorific value	LHV: ~3.0 kWh/m³ (1 bar, 0 °C), ~1100 kWh/m³ (500 bar, 15 °C), Liquid 2,360 kWh/m³ (-253 °C) [4]
Gravimetric energy density: Net calorific value	LHV: ~33 kWh/kg, HHV: ~39 kWh/kg
Melting point / Boiling point	-259 /-253 °C at standard atmospheric pressure
Auto ignition	535 °C
Flammability limits	Highly flammable from 4 to 75 vol.%
Explosive limits	4 to 75 vol.% [5]

Cost analysis





The upper graph on the left illustrates the relationship between levelized hydrogen supply cost to end-users (bars) and production volume (pink line) across installed electricity capacity scenarios for 1 MW, 10 MW, and 100 MW. Calculations are based on an electricity price of 50 CHF/MWh, a 5% interest rate, and a 25-year economic lifetime. Hydrogen production and storage costs depend strongly on system scale, storage technology, and utilization hours.

Small-scale systems using compressed hydrogen tanks at 500 bar (1 MW) have the highest supply costs per MWh of hydrogen due to very high storage CAPEX and limited utilization due to longterm storage. Liquid hydrogen storage at mid-scale (10 MW) achieves lower costs despite liquefaction energy penalties, while large-scale systems (100 MW) with salt cavern storage offer the lowest costs thanks to minimal storage CAPEX and strong scale effects. However, the use of salt caverns is limited to locations with suitable geological formations.

The lower left graph shows that levelized hydrogen supply cost increases linearly with electricity price, with larger systems and high utilization (8600 h/year) achieving substantially lower costs. Overall, high annual operating hours and large-scale deployments are essential for delivering cost-competitive hydrogen, while storage technology choices depend on site-specific conditions.

Projects

Switzerland is actively advancing its renewable hydrogen production capabilities through a diverse range of projects, from small-scale demonstrations to large industrial facilities. These initiatives target various sectors, including mobility, industry, and district heating. Most projects primarily utilize renewable hydropower as their energy source, with several already operational or soon to be commissioned. However, the production capacity, so far, is still in its infancy.

For most applications, hydrogen is currently transported using compressed gas tube trailers, each capable of carrying several hundred kilograms of hydrogen. While this method offers the greatest flexibility, it is also quite costly, particularly when dealing with low volumes.

Location	Capacity	Production	Status/Start	Main Use Cases
Domat/Ems GR	2.5 MW	350 t/year	Opened 2024	Mobility, industry
Bürglen UR	2 MW	260 t/year	End of 2025	Mobility, industry, shipping
Freienbach SZ	10 MW	1200 t/year	Planning	Trucks, gas grid, district heating
Gerlafingen SO	30 MW	4700 t/year	≥2027	Steel, industry, district heating
Schiffenen FR	2 MW	300 t/year	Opened 2023	Freight transport
Aigle VD		20 t/year	2025	Local industry (steel/metallurgy)
Glovelier JU		720 kg/day	July 2026	Industry, mobility (biomass-based)
Gösgen SO	2 MW	300 t/year	2024	Regional mobility
Bulle, FR	2 MW		2024	Industry, mobility
St. Gallen SG	2 MW		2023	Local buses, municipal vehicles, demo

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Power-to-Methane

Seasonal energy carrier – Power-to-X technology

Methane is a critical energy carrier with diverse applications across multiple sectors. As a primary component of fossil-derived natural gas, it supplies heat, electricity, and fuel for a wide range of industrial processes. In addition, methane is a versatile chemical feedstock, essential for producing hydrogen, ammonia, and various petrochemicals.

Traditionally, methane supply has relied heavily on fossil fuel extraction through natural gas production and conventional methods. However, renewable methane production offers sustainable alternatives through two primary pathways: bio-methane production and Power-to-Methane ($PtCH_4$) processes. Biomethane production involves converting biomass into biogas through anaerobic digestion, followed by CO_2 removal to obtain pure methane. This method is already widespread but faces limitations due to biomass availability. Switzerland still has untapped biomass resources that could be utilized for energy purposes [6]. The biomass with the greatest additional usable potential is farmyard manure with 24 PJ (equivalent to 6.67 TWh) of primary energy, which could be used for biomethane production.

The $PtCH_4$ production relies on hydrogen production through water electrolysis, which then reacts with CO or CO_2 in a methanation reactor to form synthetic methane (SNG, Figure 1).

The process follows the Sabatier reaction:
$$4\,H_2O + CO_2 \leftrightarrow \; CH_4 + 2\,H_2O + 2\,O_2 .$$

This methanation process can be achieved through a) catalytic methanation, which uses chemical catalysts (typically nickel-based) at high temperatures (300 to 400°C) and pressures to convert CO_2 and hydrogen into methane.

This method offers high conversion rates and rapid reaction kinetics b) biological methanation, which, unlike biomass-based biogas production, uses methanogenic microorganisms (archaea) to convert externally supplied CO_2 and hydrogen into methane at lower temperatures and pressures, mimicking natural biogas production processes.

While biological methanation operates under milder conditions and can be more flexible in handling varying feed compositions, it typically requires longer reaction times compared to catalytic processes.

If this methanol is burned, the same amount of CO_2 is released as was used in its production for synthesis. If the used CO_2 is taken from Direct Air Capture (DAC) or from renewable exhaust gases (CO_2 from biogas), the carbon cycle is thus closed the process chain is carbon neutral.

In Switzerland, the first industrial-scale $PtCH_4$ facility using biological methanation has been operating since March 2022 at Limeco in Dietikon. Globally, the world´s largest $PtCH_4$ plant has been in operation in Werlte, Germany, since 2013 [4]. However, the production of $PtCH_4$ is still in its infancy but is being expanded, e.g., in Japan.

For large-scale applications, key challenges include the high energy demand of the production process, cost disadvantages compared to conventional natural gas, and the requirement for reliable CO_2 sources to sustain methanation.

Technology readiness: $PtCH_4$ is currently at an early commercial stage. Catalytic methanation is well established, whereas biological methanation is less mature. Electrolysers (alkaline and PEM) are commercially available, while the TRL of CO_2 capture technologies varies depending on the source of CO_2.

The overall efficiency of $PtCH_4$ processes is in the range of 35–60% (LHV-based), with electrolysis efficiencies of 50–70% for PEM, 56–61% for alkaline, and 70–80% for SOEC, while methanation efficiencies lie between 70–85% [2,4,7]. Methane can be stored either as compressed gas in pressure vessels or as liquefied synthetic gas (SNG), which is obtained by cooling methane to –162 °C. For transport, gaseous methane is typically distributed via pipelines, whereas liquefied methane can be shipped by sea, rail, or truck.

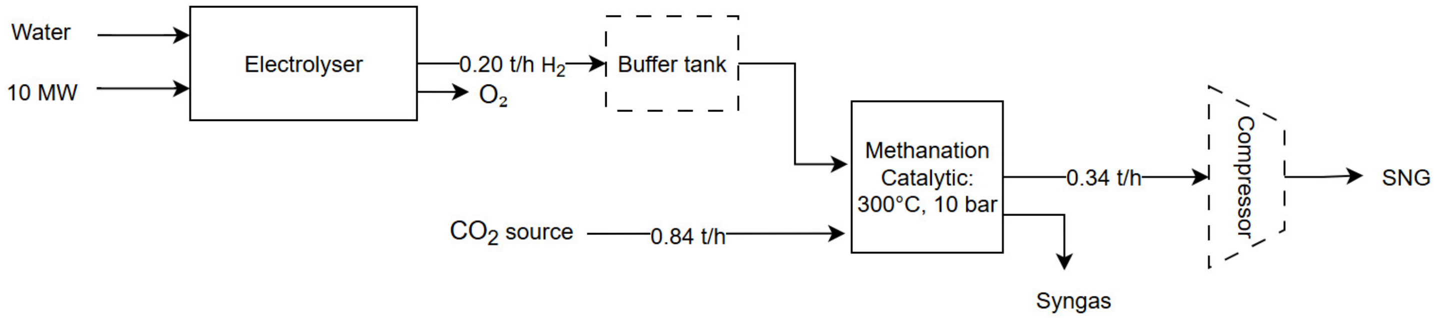


Figure 1: $PtCH_4$ (SNG) synthesis process flow diagram for a 10 MW electrolyser. Dashed units are the ones that can be installed but are not necessary. The CO_2 can come from different sources and can be extracted in different ways.

Availability

Global production of $PtCH_4$	116 MWe of installed electrolysers [8]
Swiss production of $PtCH_4$	6 PJ (5.5% of consumption with 1.4% being biomethane) [5] 3.35 MWe of installed electrolysers [8]
CO_2 source	biogas production, waste incineration, wastewater treatment, direct air capture

Chemical properties & Safety

Volumetric energy density (LHV): Net calorific value	9.94 kWh/m_3 @standard conditions: 273.15 K, 1.013 bar
Gravimetric energy density: Net calorific value	13.9 kWh/kg
Melting point / boiling point	-182 / -161 °C
Flash point / Auto ignition	-188 °C / 537 °C
Explosive / flammability limits in air	Highly flammable (4.4-17%)
Health safety	Not toxic, but can cause severe skin burns and eye damage
Safety (hazard based on EU Regulation	H220, H280
Safety (precaution based on EU Regulation	P210, P377, P381, P403

PtCH4 installations in Switzerland

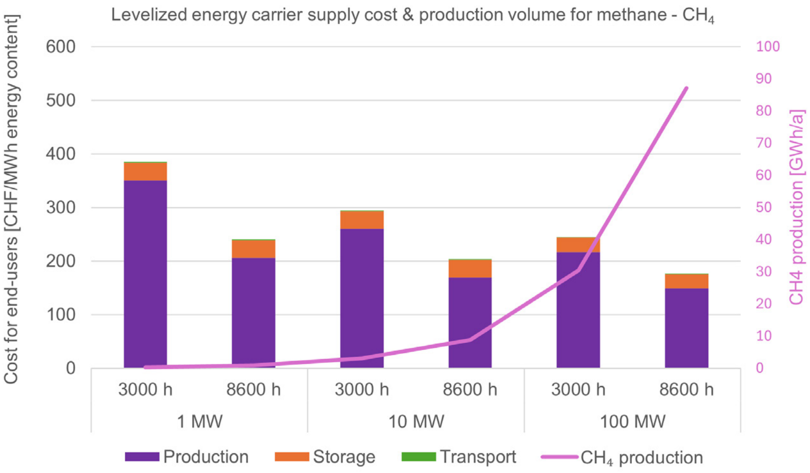
Limeco: Commercial $PtCH_4$ plant. It uses the renewable electricity of Limeco's waste incineration plant to produce hydrogen. Then it is mixed with sewage gas and converted into methane which can be fed into the natural gas grid. Capacity: 2.5 MW electrolysers. Location: Dietikon

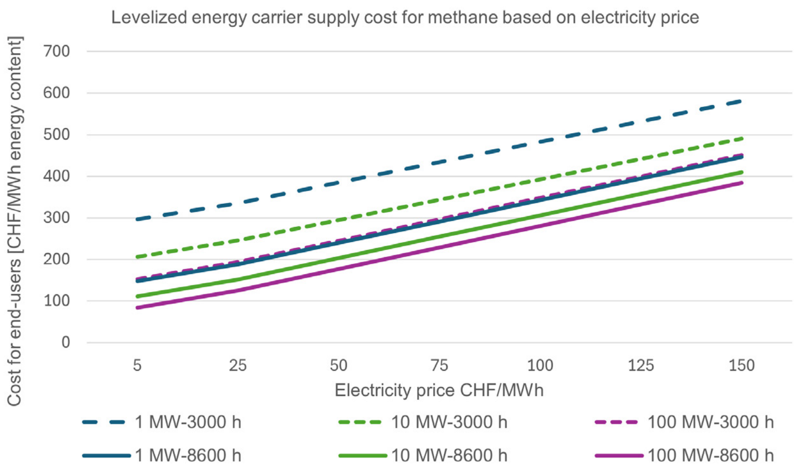
Gaznat: Testing of a methane reactor integrated into a $PtCH_4$ system. The synthetic methane is injected into the local distribution grid. Capacity: 11 kW SNG. Location: Sion.

Ostschweizer Fachhochschule: 1st $PtCH_4$ demonstration plant in Switzerland. Location: Rapperswil.

Cost analysis

The production costs take into account the hydrogen production and the methanation process. The costs were calculated for a PEM electrolyser; more information on the hydrogen costs can be found in the corresponding factsheet. A fixed cost on CO_2 with 0.05 CHF/kg has been applied, taking the average unit cost for different CO_2 sources and technologies.





For methane synthesis, the specific costs for each size were derived from different studies [1,3]. All assumptions and values can be found in the Sources/additional information section.

Three different sizes of electrolysers have been analysed, and for each, a half-year and a full year operation have been analyzed. The storage investment is based on a study where seasonal gas storage in caverns was analyzed [9]. The levelized cost of methane ranges from 145–210 CHF/MWh under full-year operation and 235–370 CHF/MWh under half-year operation, compared to 20–50 CHF/MWh for fossil-based fuels.

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EMPOWERING EXPERTISE.

OST
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Power to Methanol

Seasonal energy carrier – Power-to-X technology

Methanol is a raw material for the chemical industry, but it is also used as a solvent or as an energy source. The reported global methanol capacity in 2023 was around 170 Mio. tonne, and it is expected to grow by >9% until 2028 [1]. The production is facing an environmental challenge, as most methanol is currently produced via steam reforming of natural gas. In recent years, progress has been made in using CO_2 from either direct air capture or exhaust gases from processes, such as biogas production, waste incineration, or wastewater treatment plants.

When CO_2 is combined with hydrogen, it can be converted into methanol. The reaction path is described in the following chemical equation:

$$CO_2 + 3\,H_2 \leftrightarrow 2\,CH_3OH + H_2O$$

Hydrogen is produced through the process of water splitting via electrolysis (see corresponding factsheet). For the Power-to-Methanol (PtMeOH) process, the electrolyser can be powered by excess electricity generated from solar (PV), hydro power, or wind energy.

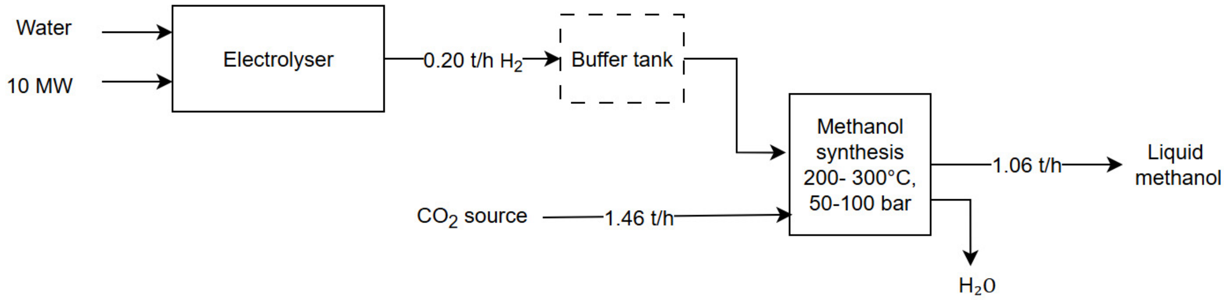
If this methanol is burned, the same amount of CO_2 is released as was used in its production for synthesis. If the used CO_2 is taken from Direct Air Capture (DAC) or from renewable exhaust gases (CO_2 from Biogas), the carbon cycle is thus closed, the process chain is carbon neutral. Methanol from renewable sources cuts CO_2 emissions by up to 95% compared to conventional fuels [2].

The first company that started producing PtMeOH is in Iceland and is still operational with an annual production capacity of 4000 t. Other companies in China, Chile, and India followed with an additional production capacity of around 5400 t/a [2]. In May 2025, a plant in Denmark was inaugurated with a production capacity of 42 kt/a. This Methanol will support the decarbonisation of sectors that are difficult to electrify and will be sold to companies such as Maersk, LEGO, and Novo Nordisk [3].

The biggest plant, which is currently in the engineering phase, is located in the USA and owned by HIF Global and will have a capacity of 1.4 Mio. tonne per year. The announced PtMeOH projects have a projected total capacity of 10.1 Mio. tonne by 2030 [2].

The PtMeOH-to-Storage efficiency is around 56% [4], assuming a hydrogen electrolysis efficiency of 70%, a CO_2 from biogas fermentation (0.43 kWh per kg CO_2, and a MeOH synthesis efficiency of 85%. If CO_2 DAC is used instead, with an estimated energy requirement of 3.44 kWh per kg CO_2, then the PtMeOH-to-Storage efficiency decreases to 35%.

In general, methanol synthesis itself is well established; its integration with electrolysers is relatively new, with the technology readiness level (TRL) estimated at 6–7 [12].



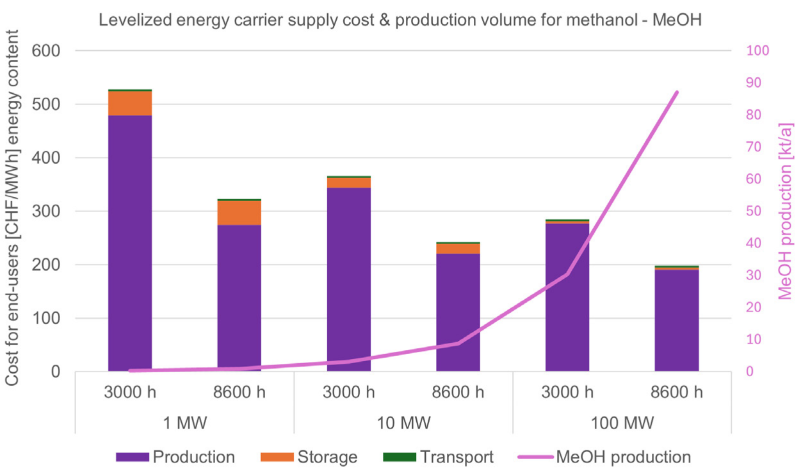
Availability & ressources

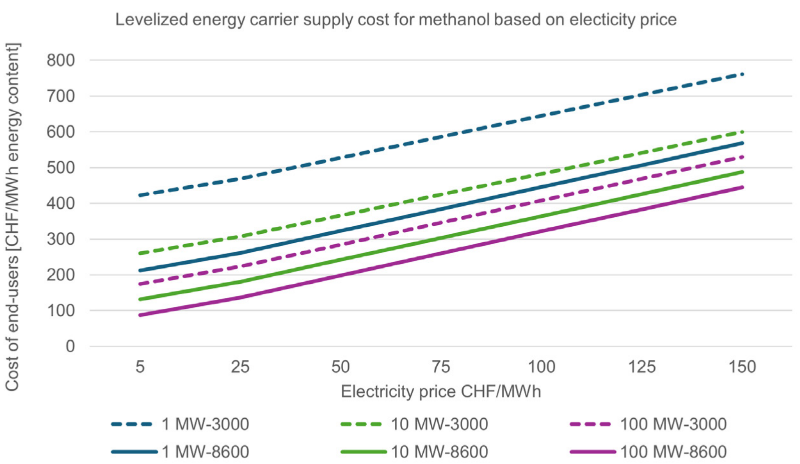
Global production of methanol in 2023	170 Mio tonne [1]
Global production of PtMeOH	38 000 tonne [2]
CH production of PtMeOH in 2024	0
CO_2 source	Wastewater treatment plant, biogas, Direct air capture (DAC)

Chemical properties & Safety

Volumetric energy density (LHV): Net calorific value	4380 kWh/m3 [5] @ standard conditions: 273.15 K, 1.013 bar
Gravimetric energy density	5.53 kWh/kg [5]
Melting point / boiling point	-98 / 65 °C
Flash point / Auto ignition	11 / 464 °C
Explosive / flammability limits in air	Highly flammable (6.7-36.5%)
Health safety	Toxic if swallowed, inhaled or skin contact. May cause cancer
Safety (hazard based on EU Regulation)	H225, H301, H311, H331, H370
Safety (precaution based on EU Regulation)	P210, P233, P240, P241, P242, P243, P260, P280, P301+P310, P303+P361+P353, P304+P340, P305+P351+P338, P307+P311, P403+P235, P501

Cost analysis





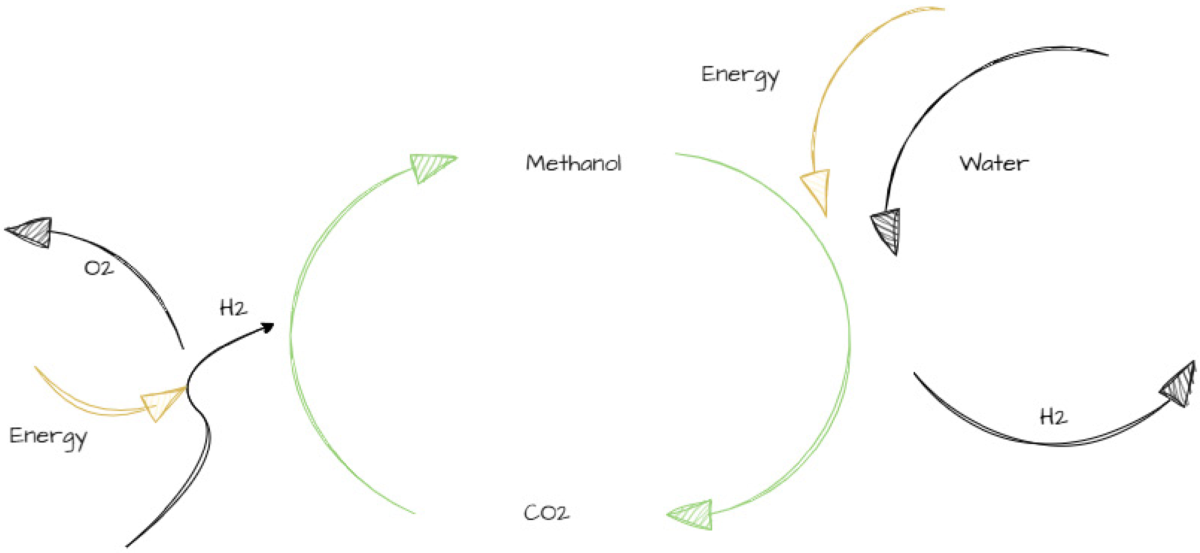
The upper left graph presents the cost distribution for installed MeOH capacities of 1 MW, 10 MW, and 100 MW under two operational modes (3000 and 8600 h). A fixed cost on CO_2 with 0.05 CHF/kg has been applied, taking the average unit cost for different CO_2 sources and technologies. Larger installed capacities result in lower carrier supply cost, while the pink line indicates the corresponding annual production volume in kilotons.

The lower left graph shows how the overall MeOH carrier price depends on the electricity price, with an increase of about 100 CHF/MWh-MeOH for every 25 CHF/MWh rise in electricity cost.

Production cost is the main cost driver, while transport and storage account for a small portion of the cost [6]. The calculation on the transport cost is based on a transport distance of 50 km by truck for 0.64 CHF/tkm [10]. The cost drivers in production are the hydrogen electrolysers and the MeOH synthesis plant. [7,8]. With higher installation capacity and more annual operating hours, the cost per unit of the energy carrier decreases. The cost of fuel (OPEX) ranges between 100 and 600 CHF/MWh, depending on plant size and electricity cost. Transport and logistics add between 3 and 10 CHF/MWh for truck deliveries over distances of 50 to 150 km.

For detailed cost information on hydrogen, refer to the corresponding Power-to-Hydrogen factsheet.

Simplified MeOH concept



Above a simplyfied concept of PtMeOH production. Water serves as an input and is split into hydrogen and oxygen. The hydrogen is then combined with CO_2 to produce methanol.

To retrieve hydrogen, a reforming process of methanol is required, releasing hydrogen and CO2. The hydrogen is then introduced into a fuel cell to generate energy, while the CO_2 is reused for methanol production.

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EMPOWERING EXPERTISE.

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University of Applied Sciences

Power-to-Ammonia

Seasonal energy carrier – Power-to-X technology

About 70% of global ammonia production is used in agriculture, primarily as a base for fertilizers like urea and ammonium nitrate [5]. In industry, ammonia is used in the production of textiles, plastics, and various chemicals.

Traditionally, ammonia production has relied heavily on fossil fuel-based processes. Conventional ammonia production methods include steam methane reforming (SMR) of natural gas, 70% of ammonia production [1], and coal gasification, 30% of the global production [1]. These carbon-intensive methods contribute significantly to global CO_2 emissions – approximately 1.2% of total global emissions [3].

China is the largest producer, accounting for 30% of the total production, followed by the United States and the EU [5]. The transition to sustainable ammonia production represents a crucial shift in the energy landscape. Power-to-X (PtX) technologies offer an alternative pathway through electrolytic hydrogen production. In this process (described in Figure 1), nitrogen is obtained via Air Separation Unit (ASU) or Pressure Swing Adsorption (PSA), while hydrogen is produced through electrolysis. Both molecules then react in the Haber-Bosch process following this equation:

$$N_2 + 3\,H_2 \rightarrow NH_3$$

When both hydrogen and nitrogen are produced using renewable energy and sustainable methods, the resulting product is known as green ammonia or e-ammonia. Unlike methane or methanol, $PtNH_3$ is a carbon-free energy carrier, offering a significant advantage when used in gas turbines, fuel cells, and other energy systems. It also benefits from a high energy density, offering significant advantages for energy storage and transport. In this context, $PtNH_3$ also offers a promising solution for seasonal energy management.

During summer, when renewable electricity supply often exceeds demand, surplus electricity can be used to synthesize ammonia, which is then stored and reconverted to electricity in winter using gas turbines or fuel cells. This seasonal arbitrage not only optimizes the use of renewable energy but also allows for integration with thermal systems in Power-to-Heat or Power-to-Cool applications. By reducing dependence on fossil fuel imports and allowing strategic energy reserves to be built up, it strengthens energy resilience and independence.

While there are currently no Power-to-Ammonia installations in Switzerland, ammonia is imported and used in a variety of applications, particularly in agriculture for fertilizer production and spreading, in industrial processes such as chemical manufacturing and refrigeration. Although the global deployment of Power-to-Ammonia remains limited – only ten plants are currently operational worldwide according to the IEA hydrogen database – numerous projects are in development, indicating increasing momentum for this technology.

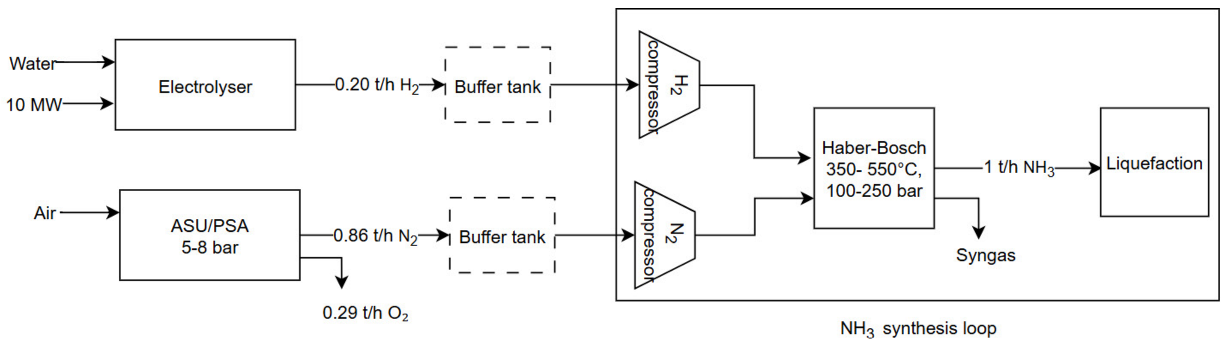


Figure 1: $PtNH_3$ synthesis process flow diagram for a 10 MW electrolyser. Dashed units are the ones that can be installed but are not necessary. ASU: Cryogenic air separation unit. PSA: Pressure swing adsorption.

Pre-commercial state

The Haber-Bosch process for ammonia synthesis is fully mature, having been developed for more than a century. Electrolysis technologies are less mature, and their integration with Haber-Bosch is still under development.

Efficiency (LHV basis)

Overall PtH$_2$to-NH$_3$ efficiencies are in the range of 52–62 % [6]. Electrolysis efficiencies are 50–70% for PEM and 56–61% for alkaline [2]. Additional energy requirements include ASU/PSA consumption below 0.9 GJ per tonne NH$_3$ [6,8] and an ammonia synthesis loop demand of about 2 GJ per tonne NH$_3$ [6].

Storage and transport

In its state at atmospheric conditions, ammonia exists as a gas. It can be stored as compressed gas in pressure vessels, as liquid in semi-refrigerated tanks (~0 °C) or at low temperatures (–33 °C), and less commonly in solid-state storage. Transport options include pipelines, maritime shipping, rail, and trucks.

PtNH$_3$ is compatible with existing infrastructure, and handling expertise further supports its potential role in decarbonized energy systems. However, challenges remain, including the high energy consumption of the production process, safety concerns due to its toxicity and corrosiveness, current cost disadvantages compared to conventional ammonia, and the lack of a fully developed regulatory framework for large-scale deployment.

Despite these limitations, the broad applicability and energy security benefits of PtNH$_3$ make it a key element in the transition to a more sustainable and resilient energy system.

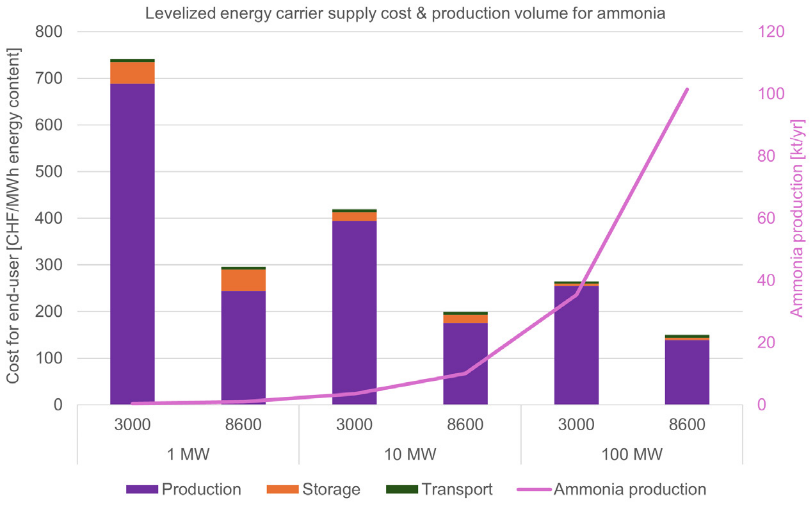
Availability

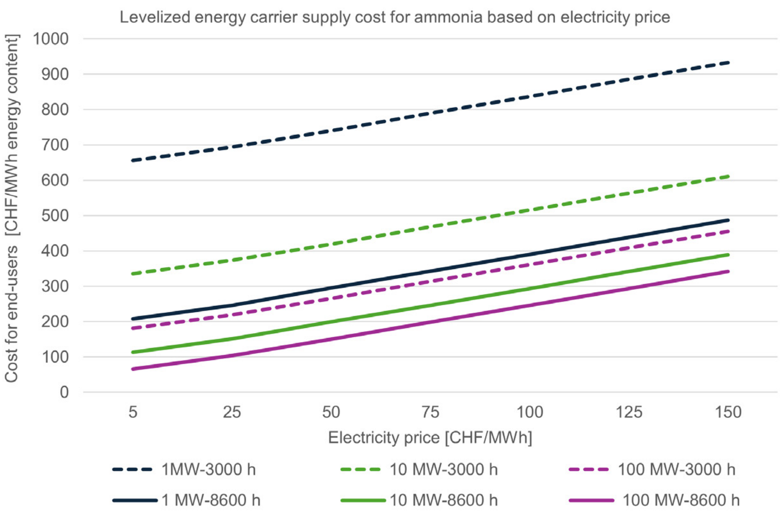
Global production of ammonia in 2023	240 Mio. tonne [3]
Swiss production capacity of PtNH$_3$ in 2024	-

Chemical properties & Safety

Volumetric energy density (LHV): Net calorific value	8.56 kWh/m³ @standard conditions: 273.15 K, 1.013 bar 3596 kWh/m³ @ (-33°C, 1 bar), (20°C, 8.6 bar) Durch die Vorfertigung der Fassadenmodule wird die Bauzeit minimiert.
Gravimetric energy density:Net calorific value	6.25 kWh/kg
Melting point / boiling point	-78 / -33 °C
Flash point / Auto ignition	11 / 651 °C
Ammonia is a colorless gas with a pungent odor. It is toxic and corrosive at high concentrations. Exposure to concentrations above 300 ppm can pose an immediate danger to life and health. It causes severe irritation to the eyes, respiratory system, and skin. Proper handling, storage, and ventilation are essential in all applications.	
Safety (hazard based on EU Regulation)	H221, H280, H314, H331, H400, H410 / H411
Safety (precaution based on EU Regulation)	P210, P260, P271, P303 + P361 + P353, P304 + P340, P305 + P351 + P338, P310, P377, P403 + P233, P405
Explosive / flammability in air	15-28% (slightly flammable)
Corrosion	Causes severe skin burns and eye damage
Toxicity	Toxic if inhaled and very toxic to aquatic life
Air purity regulation	30 mg/m³

Cost analysis





The production costs take into account the hydrogen production encompassing the electrolyser and all external costs, the air separation unit for N_2 extraction, and the NH_3 synthesis. For both N_2 and NH_3 synthesis, the cost functions have been derived from two studies [8], [7]. The bigger the size of the ammonia production, the higher the impact of the electricity cost. The same is observed with the number of operation hours. For the 100 MW scenario with full-year operation, the total cost is multiplied by five between the lowest and highest electricity cost. The levelized cost of ammonia ranges from 120-250 CHF/t under full operation and 180-700 CHF/t under half-year operation, compared to 260-4410 CHF/t for fossil-based fuels [4].

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EMPOWERING EXPERTISE.

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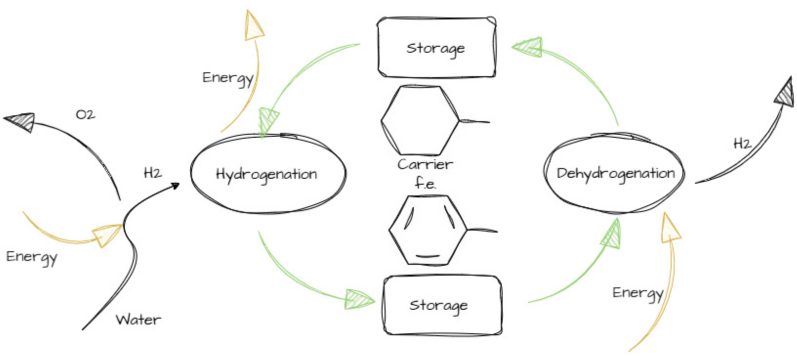
Liquid Organic Hydrogen Carriers

Seasonal energy carrier – Power-to-X technology

A Liquid Organic Hydrogen Carrier (LOHC) is a specific type of chemical compound or substance (carrier material) that serves as a medium for safe and efficient storage and transport of hydrogen. LOHCs are composed of organic molecules that can chemically bond with hydrogen and release hydrogen reversibly. This allows for the secure storage of hydrogen in a liquid form at moderate temperatures and pressures, mitigating the challenges associated with handling gaseous hydrogen. The Power-to-H_2-LOHC system is a promising technology with a high energy density.



Simplified LOHC principles

Hydrogen is produced through the process of water splitting via electrolysis. The details of hydrogen production via electrolysis can be found in the corresponding factsheet. The produced hydrogen is bonded to an organic liquid carrier material. In principle, any unsaturated compound (organic molecules with C-C double or triple bonds) can adsorb hydrogen during hydrogenation. But for the LOHC mostly aromatic compounds are used [2].
The bonding of hydrogen is called hydrogenation. It is an exothermic process that takes place between 30 and 50 bar. On the contrary, heat needs to be applied to release the hydrogen (dehydrogenation step). For both reaction steps, a catalyst is needed to get the reaction running.

When using LOHC, no CO_2 is released, and the carrier material is kept in circulation. The degradation of the carrier per cycle is around 0.1% but may vary depending on the type of carrier [5].

As shown on the left, the concept of LOHC production utilizes water as an input which is split into hydrogen and oxygen. The hydrogen is then combined with the carrier medium, this hydrogenation step releases heat. To retrieve hydrogen, a dehydration step is required. This step requires heat. The hydrogen is then introduced into a fuel cell to generate energy. The carrier is kept in the circuit and may be hydrogenated several times.

Several projects located worldwide are investing in the LOHC technology. The biggest plant is in Germany and its commissioning is planned in 2027 with an overall hydrogen storage capacity of 1800 tons. This amount is loaded in 40 000 m³ of carrier material [1].

The efficiency of Power-to-LOHC-to-H_2 is around 49% [2]. The technology readiness level (TRL) of LOHC systems is estimated at 5–6 [8], indicating pilot to early demonstration stage.

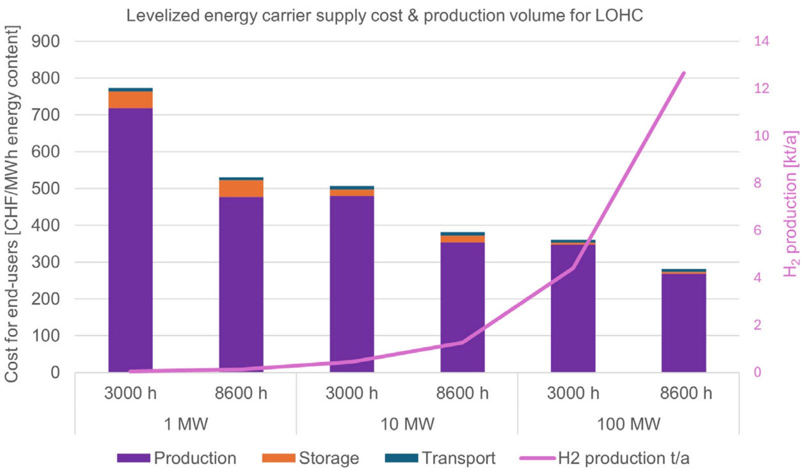
Availability

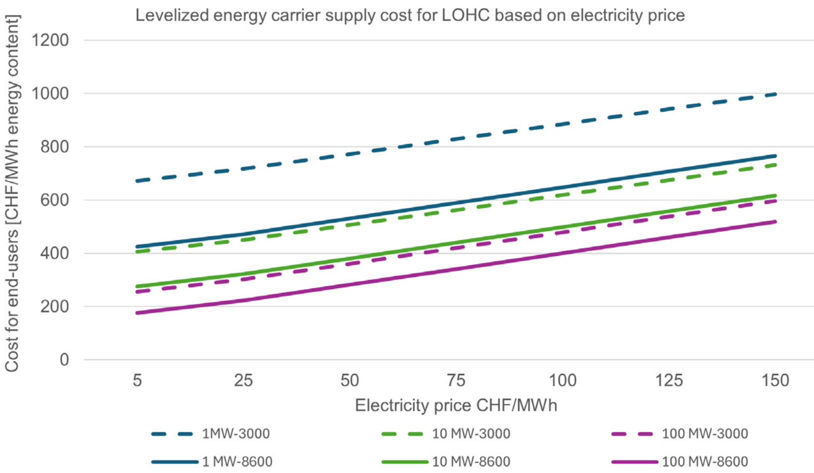
Global production of LOHC	38 000 tonne [3]
CH production of LOHC	0

Chemical properties (aromatic compounds)

Volumetric energy density	1700-2 200 kWh/m³ [9]
Gravimetric energy density	1.7-1.9 kWh/kg [9]
Flammability/air	Depending on the carrier used, it could be flammable or a combustible material which will not ignite readily.
Health safety	Depending on the carrier used, from aspiration hazards to toxic

Cost analysis





The upper left graph shows the cost distribution for installed capacities of 1 MW, 10 MW, and 100 MW under two operational modes (3000 h and 8600 h), with the pink line indicating annual production volume in kilotons.

The lower left graph illustrates the dependency of the overall carrier price on electricity, showing steep increases for smaller, low-utilization plants (e.g., 1 MW at 3000 h: 618 to 943 CHF/MWh as electricity rises from 5 to 150 CHF/MWh) and significantly lower, flatter costs for larger plants with high utilization (e.g., 100 MW at 8600 h: 162 to 505 CHF/MWh). Overall, production cost is the main driver, ranging between 160 and 950 CHF/MWh depending on the electricity price, while transport and logistics add only 8 to 26 CHF/MWh for truck deliveries over 50 to 150 km. Storage needs are assumed to be covered by existing methanol or oil tank infrastructure. The cost driver in production is the hydrogen electrolyser, hydrogenation, and dehydrogenation plant. [5].

For detailed cost information on hydrogen, refer to the corresponding Power-to-Hydrogen factsheet.
The cost calculation assumes an economic lifetime of 25 years, maintenance costs at 2% of investment, a 5% discount rate, an electricity price of 50 CHF/MWh, and a carrier price of 2–4 CHF/kg.

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EMPOWERING EXPERTISE.

OST
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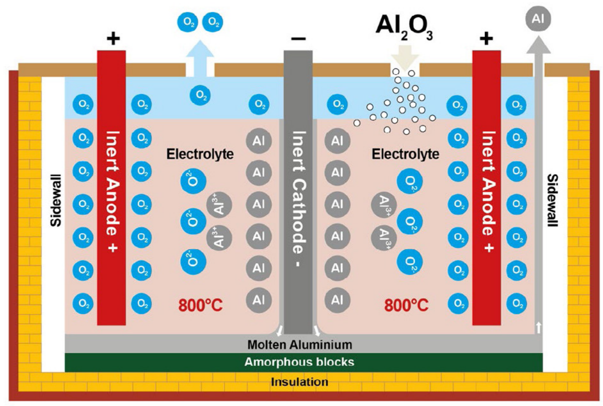
University of Applied Sciences

Renewable Metal Energy Carrier: Power-to-Aluminium

Seasonal energy carrier – Power-to-X technology

The global primary aluminium sector produced approximately 72.7 million tonnes of aluminium in 2024 [1]. Current primary aluminium production relies on the Hall-Héroult process, which electrolytically reduces aluminium oxide (alumina) using carbon anodes as the reducing agent, generating substantial direct CO_2 emissions. Reducing these emissions has become a key priority for the industry.

$2\ Al_2O_3 + e^- \rightarrow 4\ Al + 3\ O_2$



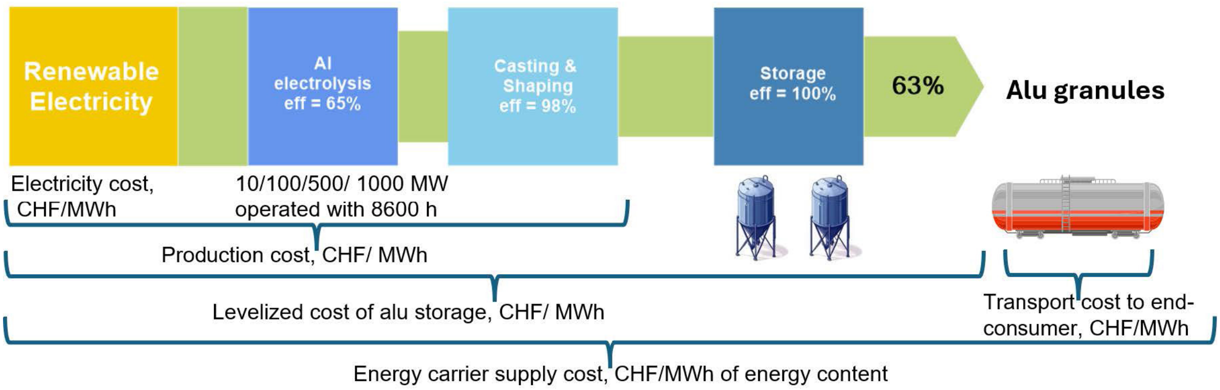
Schematic of the vertical inert anodes and cathodes in low-temperature electrolyte for aluminium production without direct CO_2 emission from Arctus Aluminium. Illustration: Copyright © Arctus 2025; printed with permission.

In recent years, progress has been made in developing smelting technologies with no direct carbon emissions. Companies like Trimet Aluminium, ELYSIS, and RUSAL are advancing the creation of inert anodes and are currently constructing demonstration plants on an industrial scale, with an expected full commercialisation in 2030.

Arctus Aluminium, in collaboration with an Icelandic research organization, has developed a vertical electrode cell that incorporates inert anodes and wettable cathodes, operating at a relatively low temperature of 800 °C (schematic on the right) [2].

In 2025, a 500 A inert anode pilot cell has successfully produced aluminium with a commercial purity of 99.8%, emitting one tonne of oxygen for every tonne of aluminium, and achieving a reduction of over 98% in direct CO_2 emissions compared to the Hall-Héroult process.

Considering aluminium granule production with the Arctus Aluminium technology (Technology Readiness Level, TRL4 of 9 in 2025), a Power-to-Aluminium-to-Storage efficiency of 63% can be achieved, as shown in the illustration below [3].



The total energy carrier supply cost for aluminium includes production costs (covering Power-to-Alu process), storage costs, and transport costs to the end consumer. Combined, these cost components reflect the full supply cost of using aluminium as a storable and transportable medium for renewable energy.

Availability

Abundance/World reserves	Third most abundant element / 7425 Mio. tonne [4]
Global production of aluminium in 2024	72.7 Mio. tonne [1]
Total global production (accumulated)	1517 Mio. tonne [3]
CH production of renewable aluminium in 2024	0

Chemical properties

Volumetric bulk energy density	>23 000 kWh/m3 for bulk material / 15 000 kWh/m^3 for granules
Gravimetric energy density	8.6 kWh/kg
Melting point / Boiling point	660 / 2470 °C
Auto ignition	Bulk aluminium is not self-igniting, but fine powder can ignite at 400–600 °C.
Flammability in air as bulk or granules	Not flammable for granule sizes < 500 um
Flammability in air as powder	Combustible as fine powder (<100 um); dust explosion risk class St1-St2 depending on fineness

Circular economy concept

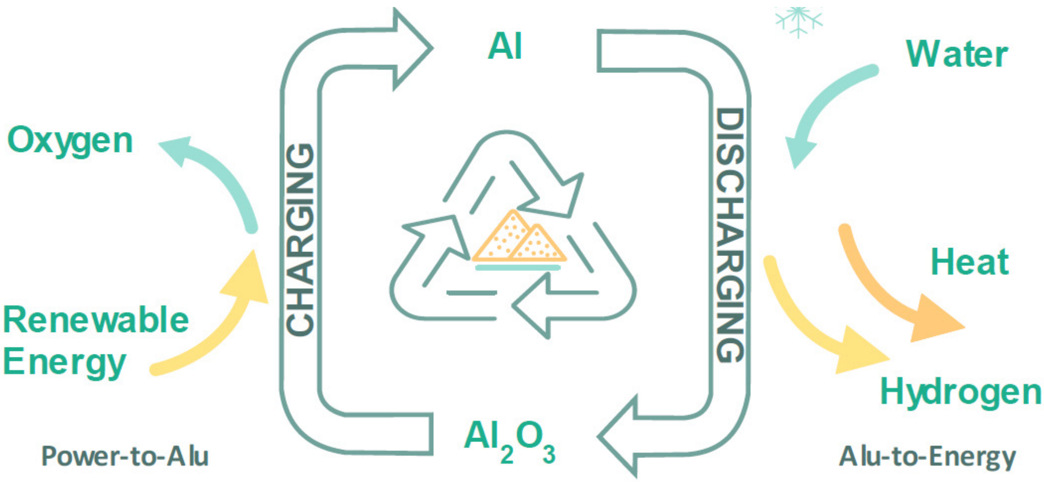
Renewable electricity can be stored by producing aluminium in centralized facilities (Power-to-Alu, charging process). In this process, renewable energy is used to reduce alumina (Al_2O_3) into aluminium metal using the above-described inert anode technology that emits only oxygen.

The resulting aluminium acts as a renewable metal energy carrier (ReMEC), storing up to 23 MWh per m^3 of energy for bulk material or up to 15 MWh/m^3 as granules without losses over time [2]. Like wood chips or pellets, aluminium can be transported using existing infrastructure to buildings or industries to meet peak energy demands during winter.

Simplified concept of aluminium ReMeC storage cycle

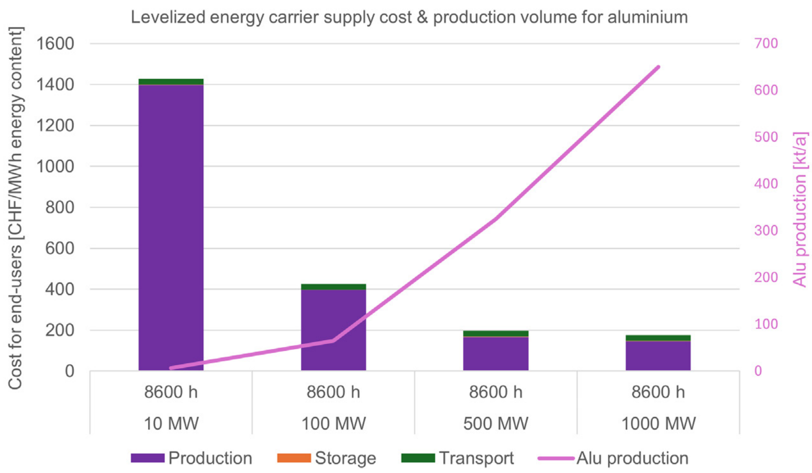
When energy is needed, aluminium reacts with water in the Alu-to-Energy or discharging process, releasing hydrogen and heat. The hydrogen can be used in H_2 boilers to produce more heat, or it can be converted in fuel cells to generate both electricity and heat in a combined heat and power (CHP) system, enabling grid stabilization during high-demand periods.

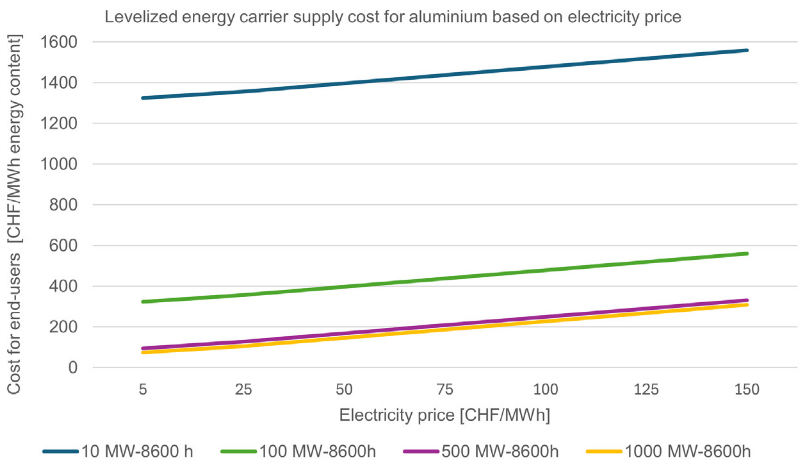
At reaction temperatures below 280 °C, the byproduct of this process is aluminium hydroxide, which is collected when new aluminium is delivered and returned to the Power-to-Alu facility [2]. There, it is converted back into aluminium oxide for recharging, creating a closed-loop material cycle. Aluminium shows high potential for integration as a ReMEC into buildings and district heating networks in Switzerland, supporting winter heat and electricity demand coverage and contributing to reduced electricity imports and external dependencies.



Simplified concept of aluminium ReMeC storage cycle.

Cost analysis





The upper left graph illustrates the relationship between aluminium levelized supply costs (bars) and production volumes (pink line) across installed Power-to-Alu capacity scenarios for 10 MW, 100 MW, 500 MW, and 1000 MW, considering an electricity price of 50 CHF/MWh, 5% interest rate and 40 years economic lifetime. It is important to note that aluminium production is assumed to operate at full-load hours only (8600 h), as the Power-to-Alu process cannot be interrupted without significant effort and cost. The observed economies of scale are derived using the capacity-scaling relationship reported by Stinn and Allanore, where capital expenditures (CAPEX) are estimated as $CAPEX = \alpha \cdot Capacity^{\beta}$ with scaling exponent β of 0.7, indicating that investment costs grow sublinearly with capacity [5]. Consequently, as production capacity increases, the overall production cost per tonne of aluminium decreases sharply, demonstrating strong economies of scale.

While production costs remain the largest share of total supply costs, storage and transport costs remain comparatively minor across all scenarios. The pink line overlay shows the aluminium production volume, highlighting the significant output benefits of large-scale systems.

The lower left graph shows how levelized aluminium supply costs respond to different electricity price levels, ranging from 5 to 150 CHF/MWh for each of the four capacity scenarios. The results indicate that supply costs increase linearly with rising electricity prices, demonstrating consistent price sensitivity across all capacities.

Together, these cost analysis shows that increasing production capacity can significantly lower the cost of producing aluminium per tonne. However, all production scales remain affected by changes in electricity prices.

This highlights the importance of combining **large-scale production** with strategies that **protect against electricity price fluctuations** to keep aluminium production costs competitive and stable. Therefore, locations with low-cost, abundant renewable electricity available year-round, such as Iceland - which already produces about 1 Mio. tonne of aluminium per year - are very promising sites for the Power-to-Alu process.

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EMPOWERING EXPERTISE.

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Renewable Metal: Iron

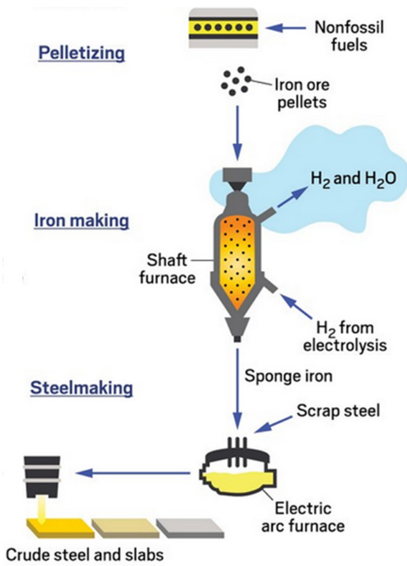
Seasonal energy carrier – Power-to-X technology

The Direct Reduction of Iron via hydrogen (DRI-H2) uses hydrogen to reduce iron oxide pellets at 700–900°C, eliminating CO_2 emissions typical of conventional ironmaking. The feedstock is regenerated iron oxide collected after combustion cycles, formed into uniform pellets via agglomeration and sintering.

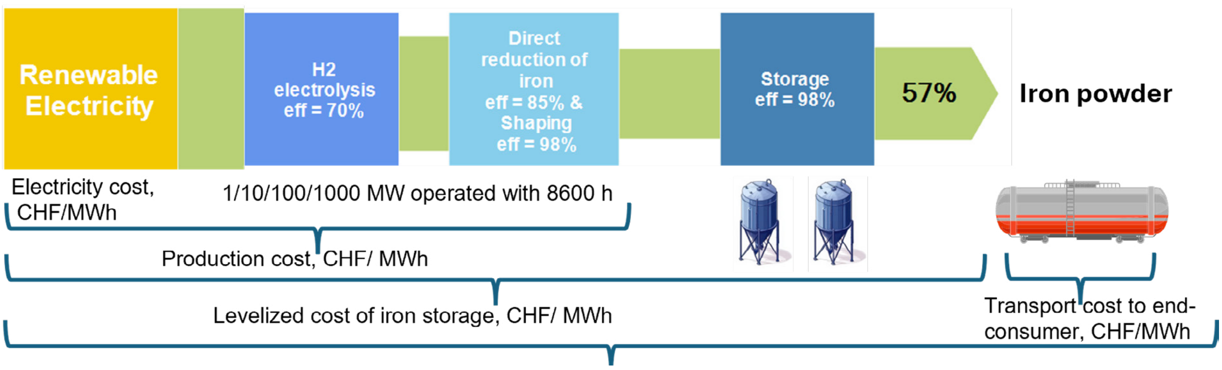
In hydrogen direct reduction, the chemical reaction $Fe_2O_3 + 3\ H_2 \rightarrow 2\ Fe + 3\ H_2O$ occurs within shaft furnaces or fluidised bed reactors, producing metallic iron (sponge iron) and water vapour. The resulting sponge iron retains its pellet shape but becomes porous because oxygen atoms are removed from the iron oxide lattice during reduction, leaving voids and cavities where they were previously located. This porosity (typically 85–95% metallic iron) increases surface area, making sponge iron suitable for further processing into iron powder via grinding or milling for energy storage applications.

Production can be scaled as needed, and by reusing regenerated iron oxide, virgin iron ore extraction is avoided. To produce steel, sponge iron (direct reduced iron, DRI) is melted in an electric arc furnace (EAF) together with scrap steel to form crude steel and steel slabs. The EAF process uses electricity as its primary energy source, meaning no direct CO_2 emissions are generated during melting, unlike traditional blast furnace routes that rely on coal-based reduction. In terms of technology development, hydrogen-based direct reduction is already at an advanced stage, with technology readiness level (TRL) 6–8. Major industrial initiatives, such as HYBRIT in Sweden (SSAB, LKAB, Vattenfall), currently at TRL 7, are demonstrating pilot and demonstration plants, with full industrial deployment expected by 2030 to enable fossil-free iron and steel production.

Considering iron production via hydrogen-based direct reduction, a Power-to-Iron-to-Storage efficiency of approximately 57% can be achieved.



Process steps of steel production with DRI-H_2 to produce sponge iron in the iron-making process step [1].



Availability

Abundance / World reserves	Fourth most abundant element / 85 000 Mio. tonne iron content [1]
Global production of iron in 2024	2500 Mio. tonne [1]
Total cumulative global production	68 831 Mio. tonne [2]
CH production of renewable iron in 2024	-

Chemical properties

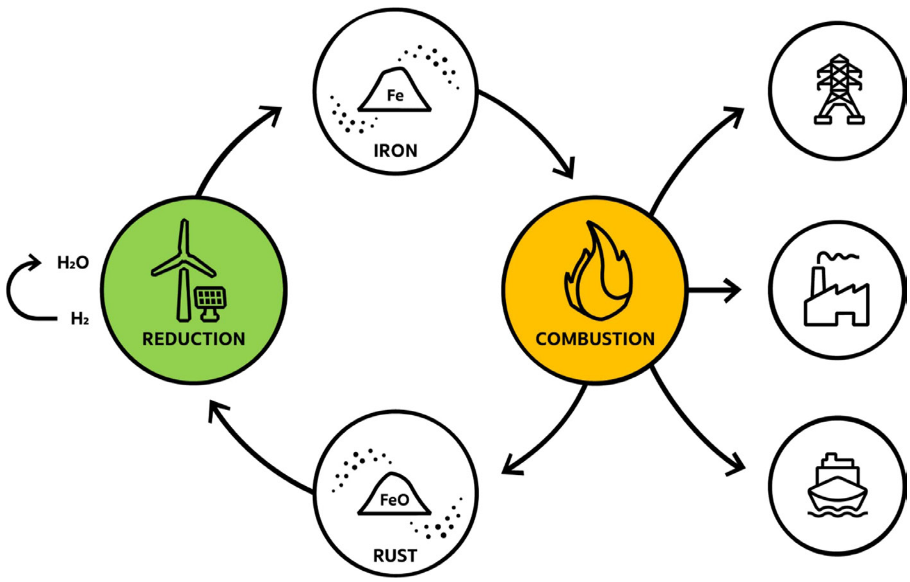
Volumetric bulk energy density	14 900 kWh/m³ for bulk material / ~7000 kWh/m³ for powder [3]
Gravimetric energy density	~2 kWh/kg
Melting point / Boiling point	1538 / 2862 °C
Auto ignition	Varies by form: bulk solid ion is not self-igniting, but fine powder can ignite at 350-500 °C depending on particle size [4]
Flammability in air as bulk	Non-flammable in bulk solid or coarse granules
Flammability in air as powder	Combustible as fine powder (<100 um); dust explosion risk class St1-St2 depending on fineness

Circular economy concept

Iron powder serves as an energy carrier in a circular Power-to-Iron system. Iron oxide undergoes direct reduction using hydrogen generated via electrolysis from renewable electricity, converting electrical energy into chemical energy stored within iron powder without any direct CO_2 emissions.

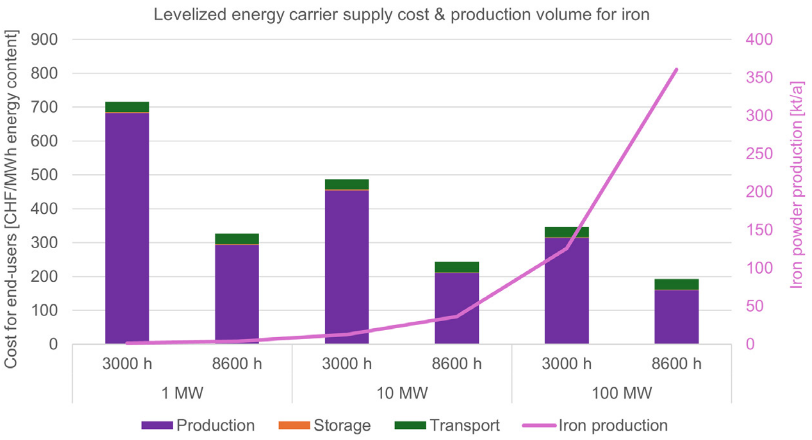
The iron powder provides high volumetric energy density with stable, non-toxic properties for safe transport and storage. Energy release occurs through combustion, producing high-temperature heat for power generation, industrial processes, and district heating. Iron powder can also be applied as a CO_2-free fuel in ships, particularly for short-sea or service vessels, though its high mass requirement limits use to weighttolerant applications. Iron oxide (rust) is the sole byproduct. Additionally, oxidation with water or steam is a current focus of R&D.

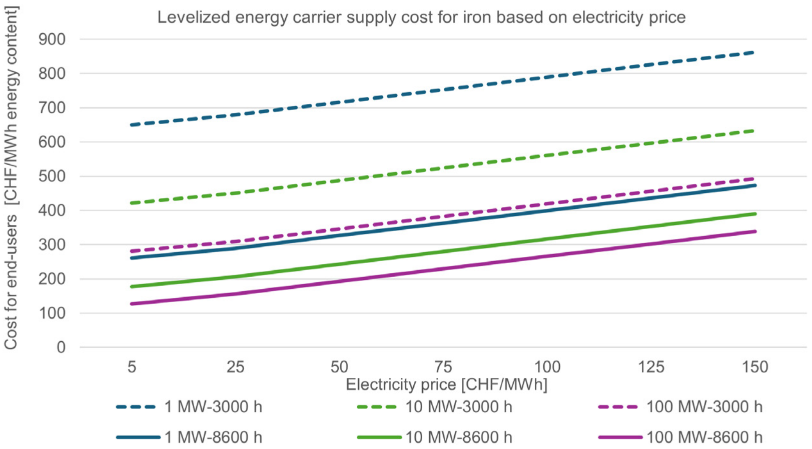
The circular system is completed by collecting the iron oxide and returning it to the Power-to-Iron facility for regeneration. This creates a closed-loop material cycle with complete recyclability. Iron powder's high volumetric energy density exceeds that of ammonia or compressed hydrogen, while offering minimal NOx and particle emissions when combusted, making it a safe, low-cost, and environmentally friendly solution for large-scale, long-term energy storage.



Simplified concept of iron powder ReMeC storage cycle [3].

Cost analysis





The two graphs illustrate iron's cost dynamics as an energy carrier, focusing on levelized supply cost structure and electricity price sensitivity. The upper left graph compares supply costs for three system sizes – 1 MW, 10 MW, and 100 MW – at two utilization levels: 3000 and 8600 full-load hours per year. Calculations are based on an electricity price of 50 CHF/MWh, a 5% interest rate, and a 25-year economic lifetime.

Costs decline substantially with increasing system size and operational hours: a 1 MW plant operating 3000 hours an-nually exceeds 700 CHF/MWh, while a 100 MW plant at 8600 hours delivers energy at below 200 CHF/MWh. Production accounts for most total supply costs, with storage and transportation contributing only marginally. This underscores that securing low-cost renewable electricity is the key lever for competitiveness.

The lower left graph shows a near-linear relationship between electricity price and levelized supply cost for each system. Smaller, low-utilization plants face steep cost increases with rising electricity prices, making them more exposed to market volatility. In contrast, larger, highly utilized plants maintain lower base costs and flatter cost curves, reflecting greater resilience.

At an electricity price of around 100 CHF/MWh, supply costs range from roughly 800 CHF/MWh for a 1 MW plant operating at 3000 hours to around 250 CHF/MWh for a 100 MW plant operating at 8600 hours, highlighting the substantial benefits of scale and high utilization. Still, these estimates are subject to high uncertainty, as they rely on assumptions and literature values, and reflect a market that is only at an early stage, with few operational projects worldwide.

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