CLIMATE AND POLLUTION COMPARISON

Hydrogen, batteries and a cleaner Earth

From production and use to recycling. Where ZENIT can contribute.

Winner for everyday road travel

For most new cars and other uses that can charge directly, choose **battery-electric power supplied by low-emissions electricity**. The same supply can serve more vehicles, and the technology can be deployed today. Avoiding unnecessary car trips and making walking, cycling and public transport practical can cut traffic pollution further. [1] [12] [13]

Life-cycle climate emissions by powertrain

Medium EU cars and the ZENIT ZC-1 concept / g CO_2e per kilometre / lower is better



ICCT benchmarks cover manufacture, fuel or electricity supply, driving, maintenance and recycling. The projected EU grid case covers 2025–2044. *ZC-1 rows are provisional estimates based on published data from comparable vehicles. See page 5 for the calculation and evidence gaps. [1] [19] [20] [21]

Why 50 versus 52 changes little

Renewable hydrogen scores slightly lower in this study scenario. ICCT also estimates the fuel-cell route uses roughly **three times as much renewable electricity** for the same travel. A two-gram difference depends heavily on the vehicle and supply assumptions. Direct charging is the stronger default when clean power is limited. [1]

ZENIT's ZC-1 estimate. The renewable-hydrogen case is about 68% below the gasoline benchmark. The estimate rises above gasoline with unabated natural-gas hydrogen. [1] [19] [20]

How the hydrogen is made

Hydrogen carries energy from its production source. The full supply chain determines the climate result.

Production route	What the plant does	Climate and local pollution
Natural gas, no carbon capture	Steam reforming converts methane and steam into hydrogen. Further treatment separates the hydrogen and produces CO_2.	**10–12 kg CO_2e/kg H_2** in the IEA benchmark. Includes upstream impacts such as gas-supply methane. [2]
Coal, no carbon capture	Coal reacts with steam and oxygen to make a gas mixture. The hydrogen is then separated.	**22–26 kg CO_2e/kg H_2** in the IEA benchmark. Mining and plant pollution add local burdens. [2]
Fossil fuels with carbon capture	CO_2 is captured from selected streams and can be transported for permanent storage.	The total depends on which streams are captured, additional energy, residual plant CO_2 and upstream methane. Report measured life-cycle intensity. [2]
Water electrolysis	An electrolyser uses electricity to split treated water into hydrogen and oxygen. Hydrogen is conditioned and delivered to the user.	Electricity dominates many cases. Water demand also includes treatment and cooling. Assess effects on the local water supply. [2] [3] [5]

What changes when the power supply changes?

At **55 kWh per kg of H_2**, DOE's 2022 PEM electrolyser system benchmark, the four example electricity supplies give these production-power emissions. [3]

Power intensity (g CO_2e/kWh)	20	50	200	400
Electricity emissions (kg CO_2e/kg H_2)	1.10	2.75	11.00	22.00

Calculation multiplies each power intensity by 55 and divides by 1,000. It excludes plant manufacture, water services outside the electricity benchmark, distribution and leakage. IEA's fossil figures above have a broader production boundary. [2] [3]

Check the route from plant to use. Compression, liquefaction where used, and delivery increase the energy bill. Escaped hydrogen indirectly warms the climate through atmospheric chemistry. Leak accounting matters even when production power is clean. [2] [6]

Check the exhaust separately. A fuel cell makes electricity and water. Burning hydrogen in air can create nitrogen oxides (NO_x), even though the hydrogen fuel contains no carbon. Road tyres and brakes still contribute particles with either drivetrain. [7] [13]

The IEA reports that unabated fossil fuels still dominated hydrogen production in 2025. [4]

What happens to old batteries?

A durable pack spreads its manufacturing burden over more service. Repair and material recovery each have a place.

Manufacture and use. Mining and refining supply lithium, graphite and copper. Some chemistries use nickel and cobalt. Count cell-making energy, charging and any replacement packs. [1] [10]

Collection and assessment. A specialist checks a pack’s condition and history before repair, reuse or stationary second life. Damaged or unsuitable packs need controlled processing to manage fire risk. [8]

Recycling routes for lithium-ion packs [8]

Route	How material is recovered	Trade-off
Mechanical sorting	Facilities dismantle or preprocess packs and can shred cells under controlled conditions. They separate foils, casings and electrode-rich black mass.	An intermediate stage. The black mass still needs refining, while copper and aluminium can enter separate recovery streams.
Heat-based recovery	Smelting separates metals such as nickel and cobalt.	Heat is energy-intensive. Lithium may require additional recovery from residues.
Liquid-based recovery	Leaching and separation recover selected metals from black mass.	Can recover lithium and other metals. Reagents, wastewater and residues require treatment.
Direct recycling	Recover or recondition electrode materials while preserving more of their structure.	Promising for suitable, well-sorted chemistry streams. Application and scale vary.

Two percentages with different meanings

EU rules set lithium-based battery recycling efficiency targets of **65% by average weight by the end of 2025** and **70% by the end of 2030**. Separate targets for recovery of the lithium itself are **50% by the end of 2027** and **80% by the end of 2031**. These are regulatory targets. Actual collection and recovery vary. [9]

Electrical waste is broader than spent battery packs. ITU and UNITAR estimated **62 million tonnes** of global e-waste in 2022, of which **22.3%** was documented as formally collected and recycled. That percentage represents e-waste overall. [11]

Extend the useful life of devices and batteries. Require documented take-back and recovery when they reach end of life. [8] [10] [11]

Where ZENIT can help

A useful ZENIT result would be a measured reduction in energy use or pollution against the best available option for the same job.

Two ZENIT Earth proposals to evaluate

ZC-1 hydrogen combustion. Provisional estimates are **74 g CO_2e/km** with renewable hydrogen and **296 g CO_2e/km** with unabated natural-gas hydrogen. A pilot should measure hydrogen use and on-road NO_x separately and obtain supplier data for delivered hydrogen and the tank. [1] [7] [19] [20]

SERAT, heat recovery and optional electrolysis. An existing facility could test lower power demand, useful heat delivered and essential-service reliability with today's electricity supply. ZENIT fusion remains a research proposal. A climate claim for a fusion plant requires measured net electricity at the site boundary over a representative operating cycle and an independent life-cycle assessment. [16] [17]

The most useful comparison

For 100 km, ICCT's model uses **20.2 kWh** for a battery car and **1.0 kg H_2** for a fuel-cell car. At DOE's benchmark, making that hydrogen takes **55 kWh** before separate delivery and dispensing energy, about **2.7 times** the battery car's electricity use. For a ZENIT ferry or other route, compare the same operating schedule, occupancy, payload and charging or refuelling constraints. [1] [3] [16]

Additional ways to reduce pollution now

Where	What to do	What it addresses
Streets and local travel	Improve public transport, walking and cycling. Use appropriately sized electric vehicles for trips that still need a car.	Fewer vehicle kilometres can cut greenhouse gases, congestion and tyre and road wear. [12] [13]
Buildings and heat	Reduce heat demand with insulation. Use efficient heat pumps where suitable and reuse waste heat when it displaces a real demand.	Less fuel burning and lower electricity demand per unit of useful heat, depending on the installation and power mix. [12] [15]
Methane and industry	Repair oil and gas methane leaks, cut food waste, and improve landfill and wastewater gas control. Use verified low-emissions hydrogen where hydrogen is already a necessary industrial input, such as ammonia production.	Cuts methane and the ozone it helps form, and replaces part of today's fossil-based hydrogen demand. [4] [14] [18]

How the ZC-1 scores were calculated

The two estimates use the same vehicle assumptions and change the source of hydrogen.

Data used	Value	Basis
Lifetime distance	240,000 km	ICCT medium EU car over 20 years. [1]
Base car and recycling	7.2 t CO_2e	ICCT gasoline combustion-car proxy. It includes conventional fuel hardware. [1]
Hydrogen tank assembly	4.21 t CO_2e	Tank manufacture from a comparable lower-medium passenger car. [20]
Maintenance	5 g CO_2e/km	ICCT gasoline and CNG combustion-car estimate. [1]
Hydrogen consumption	1.79 kg H_2/100 km	Simulated drive cycle for a hydrogen-combustion passenger car. [19]
Direct lubricant emissions	0.2 g CO_2/km	Estimate from a separate hydrogen-engine simulation. [21]
Hydrogen supply	1.2 or 13.6 kg CO_2e/kg H_2	Renewable electrolysis or unabated gas hydrogen. Both factors cover compression and short-distance transport. [1]

Calculation. Spread the base car and tank over 240,000 km, then add maintenance, lubricant CO_2 and hydrogen supply emissions per kilometre. The rounded totals are 74 g CO_2e/km for renewable hydrogen and 296 g CO_2e/km for unabated natural-gas hydrogen.

What to measure. A ZC-1 drive cycle and supplier records can replace the borrowed fuel-use and supply factors. The tank’s eventual retirement and any additional hydrogen leakage are unquantified. Measure nitrogen oxides separately from the climate score. [6] [7]

Include equipment on both sides

A hydrogen vehicle consumes its fuel. The tanks, stacks, catalysts and electronics still need recovery or disposal. Count those components, plus the electrolyser on the supply side, alongside the packs and electronics used for direct charging. [1] [3] [10]

Method and references

The car chart compares the same transport service. The production table compares a kilogram of hydrogen. Waste figures track material recovery on their own terms.

Scope. The EU car data are modelled estimates for comparable new vehicles, with uncertainty from lifetime mileage, electricity and fuel sources, pack size, manufacturing and recycling. A project-specific study would use a defined functional unit, such as grams CO_2e per passenger-kilometre, with a separately reported inventory for NO_x, particulate matter, water, material recovery and hazardous waste.

Sources

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[3] U.S. Department of Energy
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A multi-model assessment of the Global Warming Potential of hydrogen ↗

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Lithium-ion battery recycling and reuse ↗

[9] European Union
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[10] IEA (2024)
EV Battery Supply Chain Sustainability ↗

[11] ITU and UNITAR (2024)
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[13] European Environment Agency (2025)
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