HYDROGEN TURBINES

1. A new economic optimum for wind energy

Wind turbines are currently designed using an economic optimisation to generate electricity at the highest electricity prices and at the lowest costs. Therefore, wind turbines are not utilising all the available wind energy nor reaching the technical limits of the potential wind energy yield.

By producing hydrogen directly from the wind turbine, significantly more wind energy can be produced. As a result, a larger energy yield per wind turbine is achieved.

So, a whole new economic optimum of wind energy yield is created by integrating electrolysis in wind turbines and connecting it to hydrogen pipelines. This makes it possible to generate more wind energy per available space (/km^2), per wind turbine and deliver it at lower costs to an end user.

2. Twice the energy, delivered at lower cost

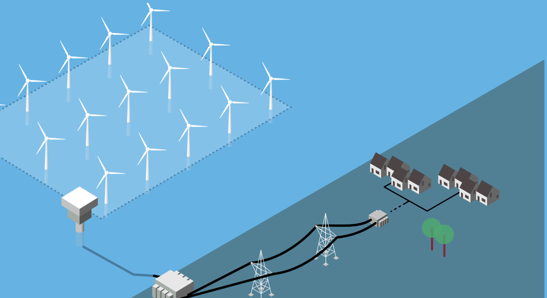
Twice the energy, delivered at lower cost

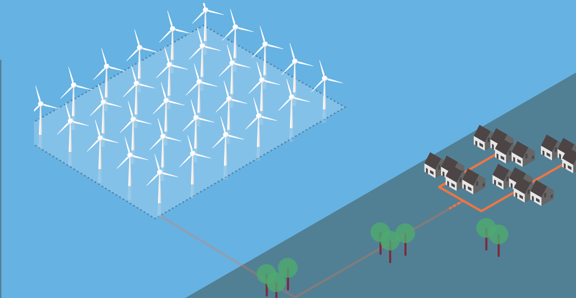
Synergy leading to new economic optimum for

1) farm design ›› 60% more energy
2) turbine design ›› 30% more energy

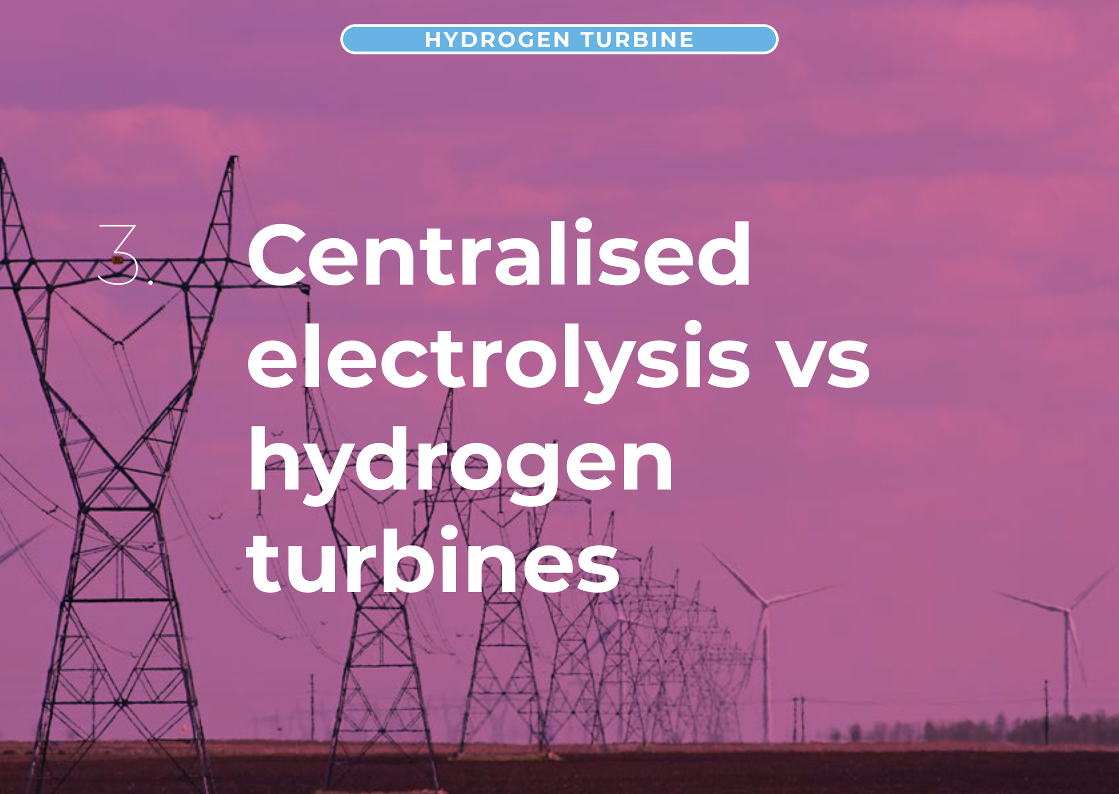
Regular wind farm
electricity

Hydrogen wind farm
2x more energy





3. Centralised electrolysis vs hydrogen turbines



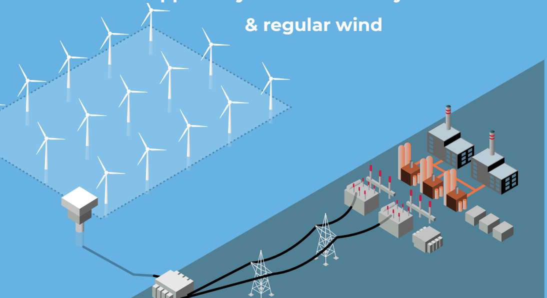
Centralised electrolysis vs Hydrogen turbines

Central electrolysis =
combining disadvantages of hydrogen and electricity

- By definition more costly per MWh than electricity from wind
- Split incentive / paradox between wind park and electrolysis
- No synergy possibilities between turbine, electrolysis & pipeline

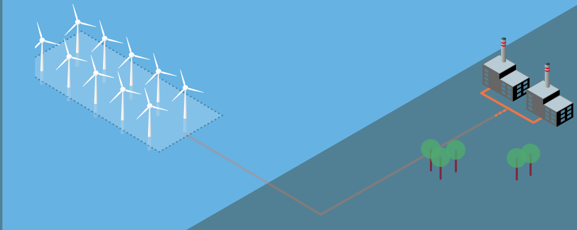
Industrial H_2 demand

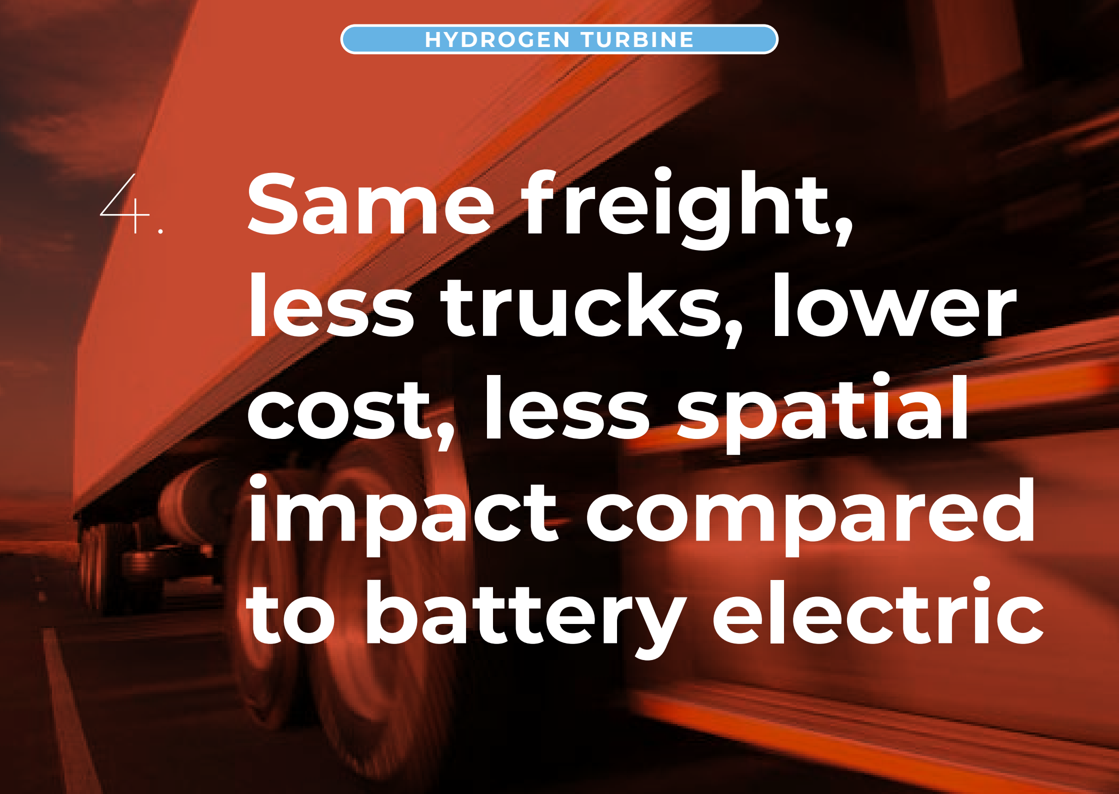
supplied by central electrolysis & regular wind



Industrial H_2 demand

supplied by hydrogen farm





4. Same freight, less trucks, lower cost, less spatial impact compared to battery electric

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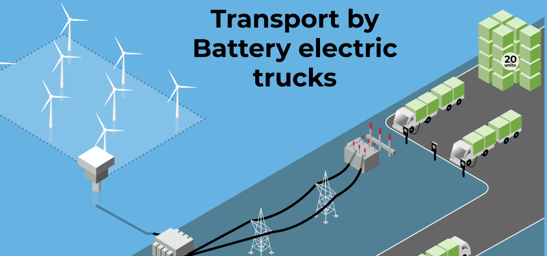
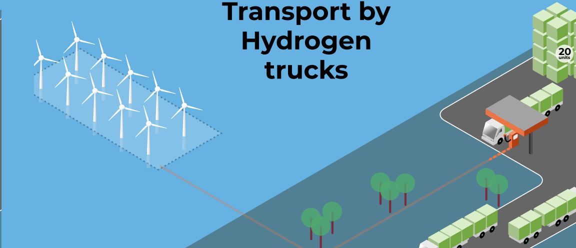
Same freight

less trucks, lower cost, less spatial impact compared to battery electric

- Efficiency of transported useful weight (MJ/ton-km) is the important denominator, not vehicle efficiency (MJ/km)
- Battery vehicle heavier than fuel cell vehicle, hence
  - More vehicles to transport same amount of goods
  - A relative lower vehicle efficiency per useful transported freight
- Time (of driver) important cost factor in transport
  - Requires fast charging/ refilling impacting efficiency & cost of infrastructure
- Wind to wheel by H_2
  - Requires less space on road and in landscape
  - Has much lower cost of energy infrastructure (pipelines & filling station)
  - Have a higher value by payload and availability





A Wind > B Turbine > C Generator > D Energy

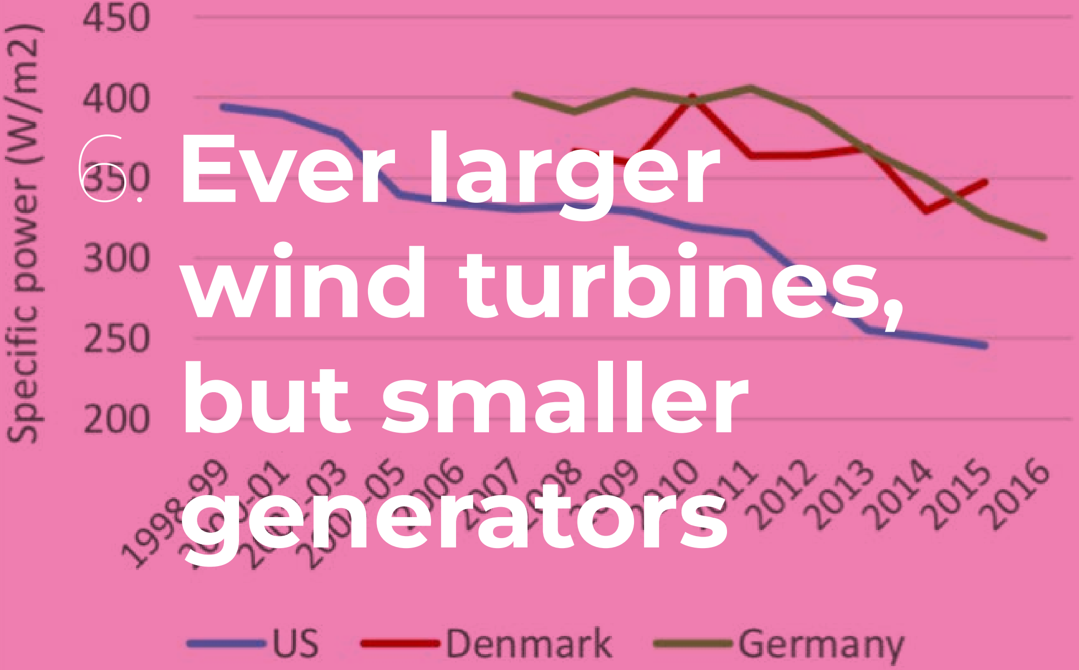
5. More full load hours, but less electricity in strong winds

REGULAR WIND TURBINES

There is more wind at higher altitude, longer blades can capture more wind. Wind turbines are therefore becoming increasingly larger. The stronger the wind blows, the bigger the generator has to be to convert all the energy into electricity.
So, wind turbines can generate more energy with strong winds. But those strong winds occur less hours per year. A larger generator with all the underlying electrical components and necessary cables, lead to increasingly more expensive electricity at a certain point. With a smaller generator, many more so-called full load hours can be achieved, which keeps costs per kWh low.
With modern wind turbines, the number of full load hours is therefore increasing, making wind energy more and more affordable. However, these wind turbines yield less power than is technically possible, especially when there is a strong wind.

REGULAR WIND TURBINES

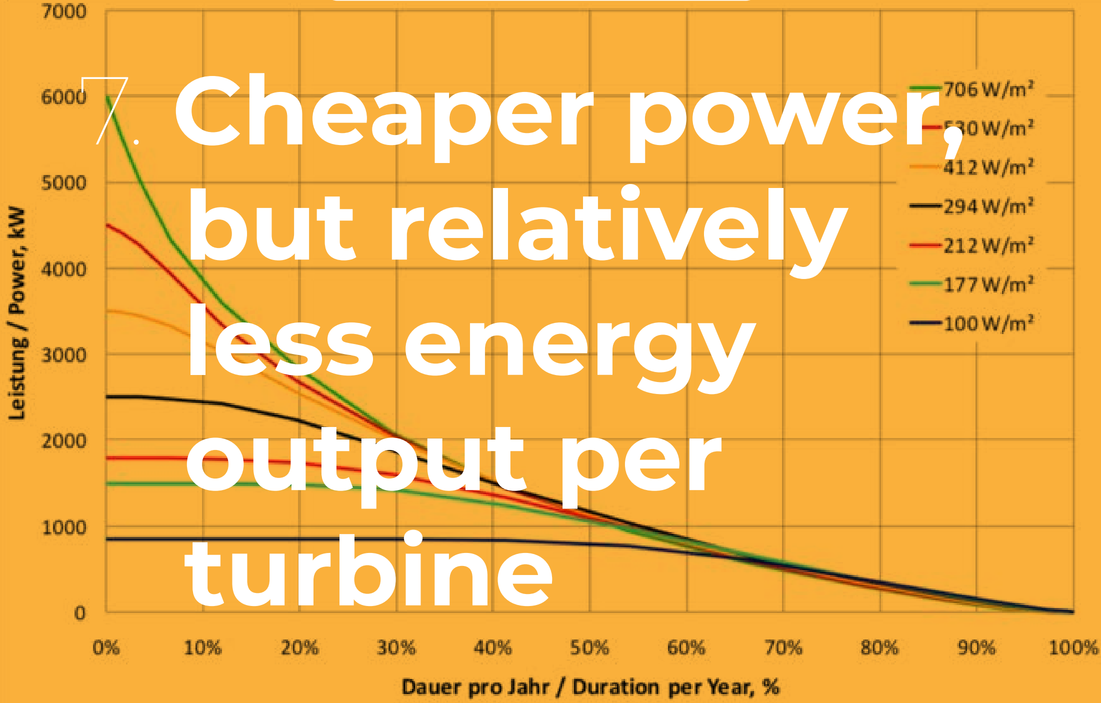
6. Ever larger wind turbines, but smaller generators



A larger generator, with the same blade length, supplies more electricity with increasing wind power. But when the wind is strong, the market price of electricity decreases. For relatively larger generators it is also more difficult to predict the production in advance, increasing the so-called imbalance (cost). Dutch governmental statistics shows that the average value of onshore wind was 21.5% below the average electricity price in 2020. The coming years more wind farms will come on line, putting more pressure on the electricity market at windy days.
The contradiction is that at windy days more energy can be yielded, but that due to increasing cost of the required electrical components and infrastructure, the costs per kWh increases and the market value drops.
Wind turbines are becoming larger, but the generator is becoming smaller (in relation to the length of the blades). Therefore, modern turbines and wind farms produce less electricity than technically possible.

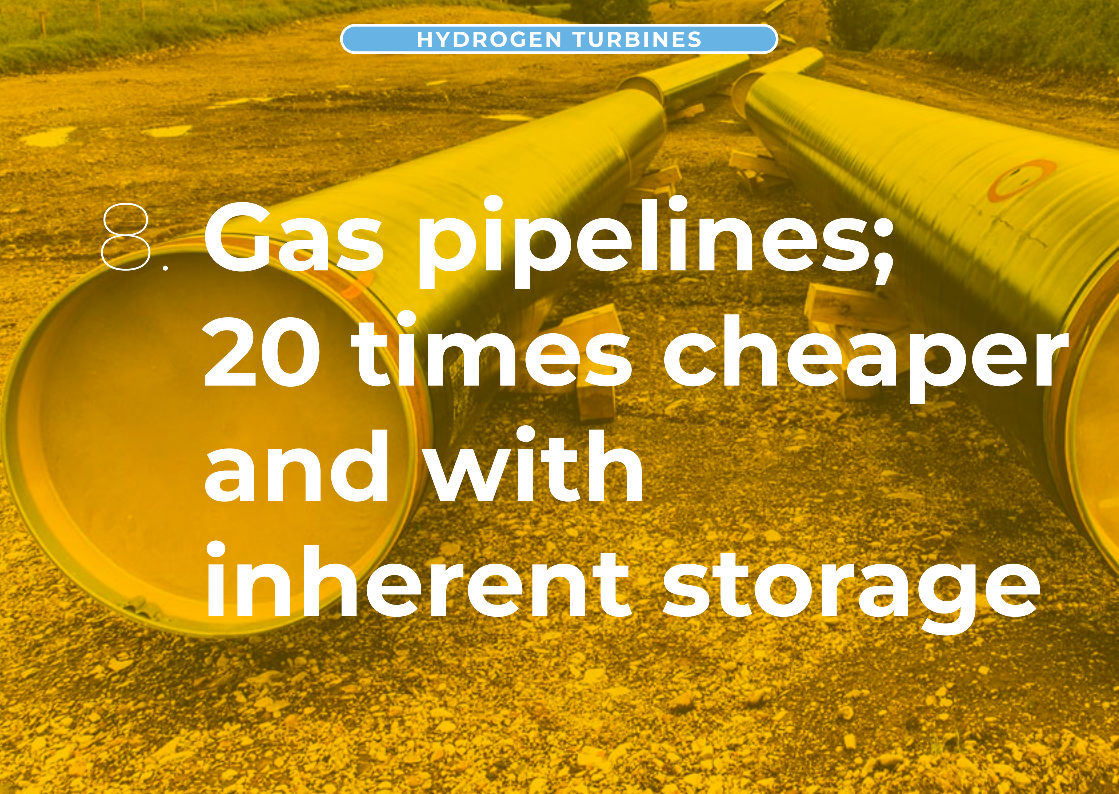
REGULAR WIND TURBINES

7. Cheaper power, but relatively less energy output per turbine



Since 2016, the expected cost price of onshore wind has decreased by +/- 37%. 31% of this cost reduction is due to the assumption that new wind turbines achieve 24% more full load hours with average wind conditions. 28% of the cost decrease is due to decreased costs of investments and maintenance, the rest of the decrease is due to lower interest rates.

Higher full load hours can mainly be achieved by making the generator relatively small compared to the length of the blades. This reduces the average cost price of the generated energy, but the wind turbine delivers less power than is technically possible at that location. The relatively expensive electrical components (generator, power electronics, transformers and cabling) play an important role in the economic optimisation of a wind turbine and wind farm.



8. Gas pipelines; 20 times cheaper and with inherent storage

Transporting energy in the form of gas is cheaper than transporting electricity. This becomes apparent when natural gas is compared with electricity making use of regulated tariffs. A gas grid connection is cheaper by a factor 20 for a comparable connection (peak) capacity.

In case of a wind turbine or whole wind farms, the peak capacity of the electricity connection is only used for a limited number of hours per year. A gas pipeline with the same connection capacity is much cheaper.

In addition, gas pipelines can be used as a storage system by playing with the pressure in the pipe (“line-packaging”), reducing the impact of imbalance or oversupply due to strong winds on the market value of the energy. Hydrogen gas pipelines, therefore, offer new economic opportunities for wind energy.

9. What is the best place to store 'surplus' electricity?

Energy losses during the transport of electricity increase quadratically with the power to be transported. This means a power cable at an offshore wind farm that produces at maximum power loses at the same time more than 10% of its energy through heat generation in the cable.

Storing electricity at a great distance from wind or solar farms at peak times, not only requires costly electrical infrastructure, but also leads to much more energy being lost than when it is converted directly at the source. The same phenomenon occurs with fast chargers for battery-electric vehicles. In order to control the heat generation at high charging speeds, liquid-cooled fast charging stations are being launched on the market. Electricity is not ideal when it comes to peak loads, such as with wind, solar, fast charging or heat demand in winter times.

10. Wind integrated with hydrogen reduces costs in many ways

Before electricity from the generator is fed into the grid, it has already been converted and transformed several times. For example, the (alternating) current from the generator is converted into direct current and then back into alternating current for the grid.

Electrolysis works on direct current. When connecting to the electricity grid, the current must therefore first be transformed and then converted to direct current.

However, electrolysis can also be connected directly to the direct current part of the wind turbine. This integration prevents both high component costs and high energy losses. This and the much cheaper pipeline connection changes the economics of wind energy.

11. Hydrogen wind farms: double the yield at lower cost per MWh

The more turbines per km^2, the higher the energy yield of a wind farm per year. But the lower the average yield per turbine, due to so-called wake-effects.
The more turbines in a farm, the higher cost of infield and export cables so, at some point the average cost per MWh increases faster than the extra yield. Offshore farm infrastructure adds up to 40% of the cost per MWh.
The optimal distance between turbines is ±7 times the rotordiameter.
Pipelines are much cheaper, the optimal economic distance is 3 times the rotordiameter. By using technology available today, 60% more yield can be generated at a lower cost per MWh.
By optimising the generator capacity, 30% more yield is economic viable.
Therefore doubling the yield per km^2 of available space at a lower cost per MWh than possible with electricity.

12. Will innovation and large scale lead to affordable hydrogen?

In 2022, many reports state that hydrogen will play a very important role in the energy transition. Large-scale grid-connected electrolysis plants and innovation should lead to the necessary cost reductions. But generating more and cheaper wind energy with a hydrogen turbine is already possible with current technology. This only requires system integration and upscaling of the serial production of electrolysis stacks.

Since electrolysis fits into the wind turbine itself, no large-scale factories are needed and the electricity grid is immediately relieved. Scaling up can only be achieved by a growing demand for hydrogen. Organise a clear legal framework for hydrogen and stimulate the demand for hydrogen, then the costs will decrease automatically; even to a lower level than with wind energy producing electricity.

13. Hydrogen produces more and cheaper wind energy

The maximum economically viable wind energy with electricity is limited by the high cost of the electrical components and infrastructure required at higher wind forces. In addition, with strong winds the market value of electricity decreases. The integration of electrolysis in a wind turbine connected to pipelines changes these economic limitations. The cost of the hydrogen components scale differently at peak loads. And hydrogen is inherently stored energy.

A hydrogen turbine differs from a regular turbine by having a larger generator, relative to the length of the blades. Hydrogen wind farms differ from regular farms by the distance between turbines. As a result, in strong winds the yield is higher, but the number of full load hours is lower. Thanks to the low transport costs of gas and inherent storage, the energy can be delivered cost-effectively to the end user.

14. Hydrogen as a competitive alternative for diesel

Hub

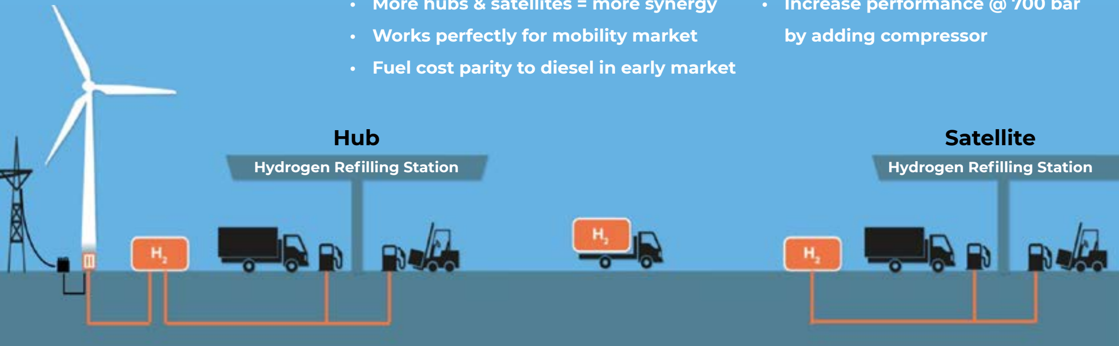
- Hybrid turbine
- Compression4storage
- Distribution by swappable high pressure storage
- Fast refilling station
  - No kg/day capacity limit
  - Heavy duty 350 bar
  - Light duty 700 bar

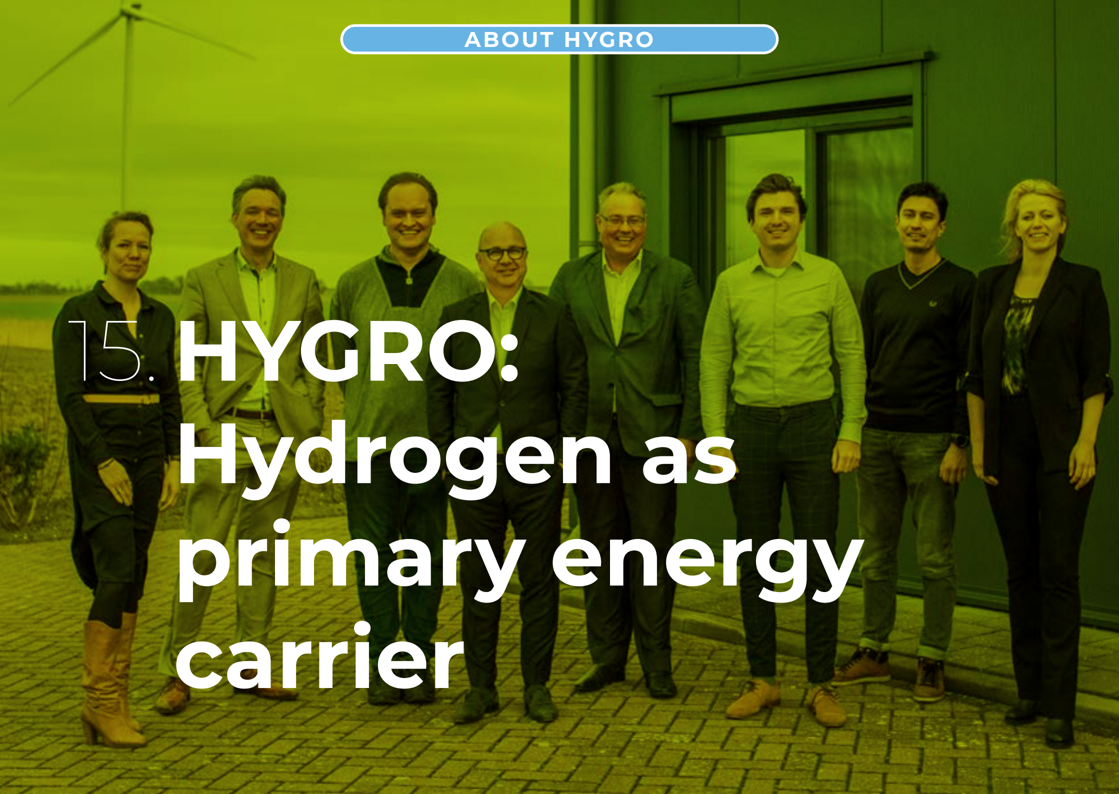
Hub & satellite

- Maximal synergy & cost savings in chain:
  - Wind ◂▸ H2 ◂▸ compression ◂▸ storage ◂▸ logistics ◂▸ filling station ◂▸ vehicles
- Storage as pivot point, optimising:
  - (Wind) flexibility
  - Logistics
  - Compression & filling stations
- More hubs & satellites = more synergy
- Works perfectly for mobility market
- Fuel cost parity to diesel in early market

Satellite

- No compressor ▸▸ low cost station
- Fast refilling
- Heavy duty 350 bar
- Light duty 700 bar, limited @ 350 bar
- kg/day adjustable to demand
  - Increase capacity by adding more swappable storage
- Increase performance @ 700 bar by adding compressor





15. HYGRO: Hydrogen as primary energy carrier

HYGRO wants to accelerate the energy transition with green hydrogen. Our proven vision is that the synergy between wind, solar, direct electrolysis and pipelines can double the yield of sustainable energy and at lower cost compared to electricity.

When we use hydrogen as the primary energy carrier throughout the value chain, we can deliver that hydrogen, at the right time, in the right place, in the right quantities and at the lowest possible cost to the end user. That is why HYGRO develops, builds, and operates a sustainable and integrated supply chain. This way we ensure efficient production, smart distribution, and satisfied end users of green hydrogen.

16. International activities

Due to the expertise gained in the last 5 years with the corresponding calculation models and due to the type of projects HYGRO is developing for the time being only in the Netherlands, HYGRO can also add significant value to projects outside the Netherlands. HYGRO prefers to work in partnerships, this way chain knowledge and involvement is immediately secured.

For example: HYGRO is the knowledge partner for Giner, Plugpower & GE in a long term research project supported by the American government. NREL is involved in this process in order to validate the results, among other things.

17. Expertise & Products

With our experience and knowledge, we offer amongst others:

- (Co)-development of projects
- Design & approach services
- Quick scans
- Green hydrogen and related equipment
- Rental of (small) hydrogen fuel stations

HYGRO

hydrogen as primary energy carrier

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