Large parts of Canada are ideal for future hydrogen production, global analysis suggests

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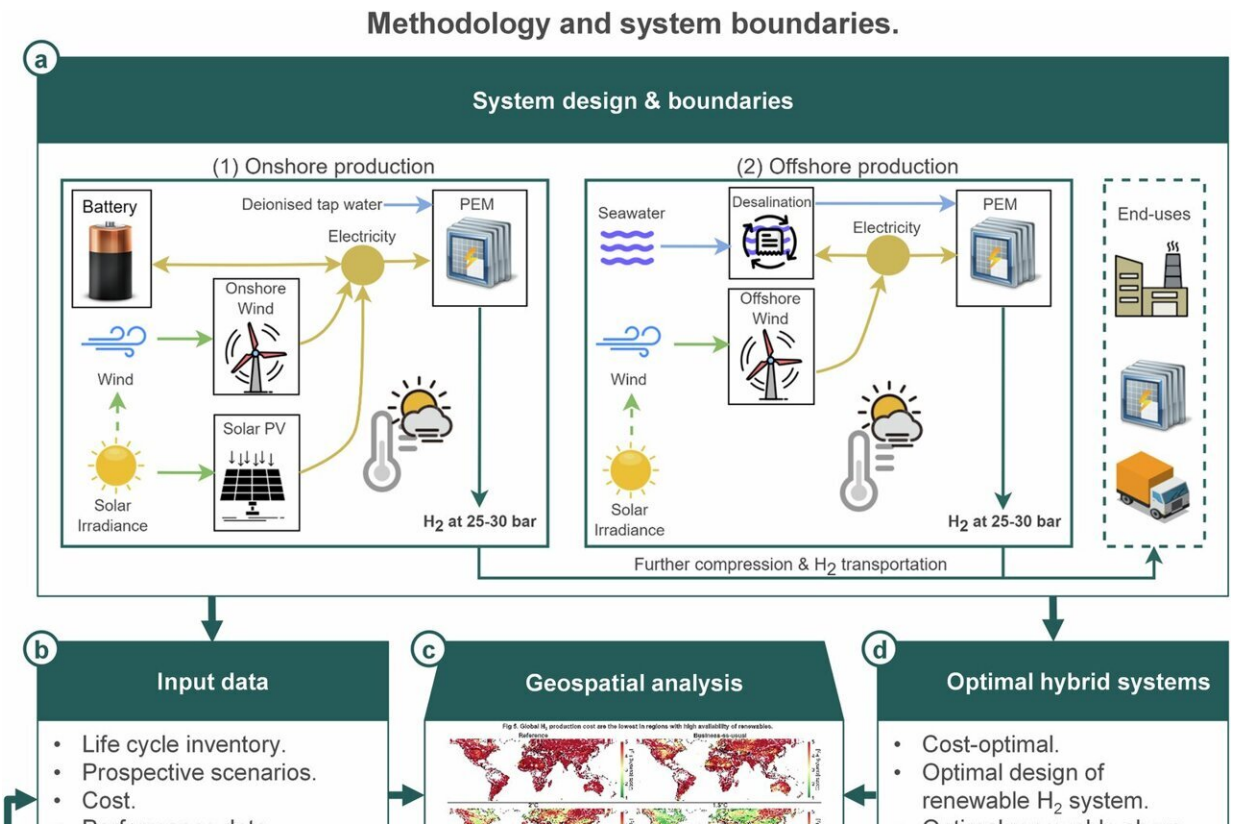

Graphical overview of the methodology. Credit: *Nature Communications* (2024). DOI: 10.1038/s41467-024-51251-7

Researchers at the Paul Scherrer Institute PSI have analyzed which regions of the world could produce hydrogen most cost-effectively in

order to build an economy based on this alternative energy carrier rather than fossil-fuel based alternatives.

One of their findings is that simply replacing fossil fuels by electricity and hydrogen will not put an end to greenhouse gas emissions. The study is published in the journal *Nature Communications*.

Switzerland aims to become climate-neutral by 2050. This means that from this year onward, no net additional greenhouse gases should be released into the atmosphere in order to slow down climate change. The electrification of transport, industry and households, while at the same time switching to renewable sources of electricity, such as hydroelectric, wind and solar power, is one of the key building blocks for achieving this goal.

However, electricity cannot be employed everywhere as a source of energy—for specific applications, its energy storage density is insufficient. When higher demands need to be met, hydrogen needs to step up. Aviation, agriculture and the steel industry, for example, represent applications which could reduce their climate impacts by a lot using hydrogen—sometimes further converted to produce fertilizer or synthetic hydrocarbons.

The researchers, led by principal author Tom Terlouw and project leader Christian Bauer from the Laboratory for Energy Systems Analysis at PSI, collected geographical and economic data and forecasts to describe the development of a hydrogen economy in four different scenarios.

Depending on the scenario, they predict that the demand for hydrogen will lie between 111 and 614 megatons per year in 2050. In the first scenario, the world continues with business as usual, still relying on fossil fuels. In the fourth and most optimistic scenario, it adopts rigorous climate protection measures and is able to meet the 1.5 degree target. At

the moment, approximately 90 megatons of hydrogen are produced worldwide every year.

Where is there enough space for electrolysis?

Hydrogen can be produced by various processes. Steam methane reforming, in which the element is extracted from natural gas, oil or coal—i.e. fossil fuels—under conditions of high pressure and temperature, is currently the dominant method. The more optimistic scenarios assume that PEM electrolysers will increasingly be used instead.

These devices use electricity and a polymer electrolyte membrane to split water into hydrogen and oxygen. If only green electricity from renewable sources is used, the process can run without fossil fuels. It produces up to 90% less greenhouse gases than steam methane reforming.

The central question, however, was in which parts of the world the hydrogen should be produced using this technology. "We primarily applied economic criteria," says Terlouw, "in other words, we looked at where production would be most inexpensive."

Two factors proved decisive: where can the huge demand for green electricity needed for electrolysis be met most efficiently—thanks to an abundance of alternative energy sources, such as wind and solar? And where is there enough suitable land to build the necessary production facilities?

Canada is ideal, Switzerland less so

Large parts of Canada, for example, turned out to be one of the best

regions for future hydrogen production. "There are lots of open spaces which are very windy and therefore ideal for putting up wind turbines," says Terlouw.

"On top of this, there's plenty of water around and the political situation is stable—although we didn't consider these two criteria in great detail in our study. But of course, the availability of water for electrolysis also plays a role, as does the question of whether the country concerned is one from which hydrogen can be reliably imported."

Leaving aside these criteria, the central United States also offers good conditions, as do parts of Australia, the Sahara, northern China and northwestern Europe. Either because there's plenty of sun for solar energy or lots of wind and open spaces for building wind turbines—and hydrogen factories.

Central European industrialized countries, such as Switzerland or Germany, are less suitable for hydrogen production because scarcely any land is available for wind turbines, and solar radiation levels are relatively low. Other densely populated regions and countries, such as Japan or large coastal areas of the US and China, could only produce hydrogen at a comparatively high cost.

"We have identified a certain discrepancy between regions with a high demand for hydrogen and regions with a high capacity to produce it efficiently," Terlouw concludes.

A hydrogen economy would have to overcome this discrepancy through global trade, but this requires additional energy—as well as political cooperation. Ultimately, the energy requirements arise because hydrogen is usually transported as a compound—for example, in the form of ammonia or methanol. The volume of the pure gas is much too large, while the far more compact liquid form requires massive cooling.

The ecological downsides of green hydrogen

The study also looks at other environmental side effects of a potential hydrogen economy, which are often ignored by the public. "Firstly, it is important to emphasize that even a functioning hydrogen economy will continue to produce residual greenhouse gas emissions," says Terlouw.

The study puts these residual emissions at almost one gigaton of CO_2 equivalents per year. Total emissions are currently around 40 gigatons. "It will not be possible to reduce the climate impact to zero," Bauer confirms.

This is mainly because the production and distribution of hydrogen are themselves associated with emissions.

On the one hand, an estimated 2.5% of the hydrogen is released into the atmosphere through leaks, whereby the hydrogen itself acts indirectly as a greenhouse gas by promoting the formation of potent greenhouse gases such as methane and ozone.

On the other hand, electrolysis systems exhibit so-called embodied emissions, which occur during the production and transport of the required materials, even if the final systems run on green electricity.

"Many of the systems and machines used in a hydrogen economy are manufactured in countries where, for the foreseeable future, their production will largely rely on fossil fuels," reports Terlouw. "Most solar panels come from China nowadays, for example, where the bulk of the electricity is still produced by coal-fired power stations."

Anyone serious about becoming climate-neutral needs to compensate for such residual emissions by capturing and removing equivalent amounts of carbon dioxide from the atmosphere. Technologies such as direct air

capture, in which special equipment removes CO_2 from the air, could be used for this purpose. Or reforestation, where planting additional trees binds certain amounts of carbon from the air.

Critical materials

According to Terlouw and Bauer, other environmental effects of a hydrogen economy also need to be taken into consideration beyond its impact on our climate. The machines and systems use a range of materials that are either harmful to the environment themselves or whose production is detrimental to the environment.

Wind turbines, for example, contain permanent magnets based on rare earth metals whose extraction in China does not meet European environmental standards. The catalyst used in PEM electrolysis is iridium, a metal that is considered problematic simply because it is so rare. And the large amounts of land and water needed to produce hydrogen might also constitute a negative environmental factor.

"Last but not least, there is the big issue of social acceptance," as Terlouw points out. "Will people accept coastal landscapes being occupied by large hydrogen production plants, for example?" In water-scarce areas, before being electrolyzed, seawater would first have to be desalinated, which requires additional energy and land.

"In the current study, we have not yet taken such factors into account," admits Bauer. "Further studies are to follow. We want to point out possible means of achieving the energy transition. Whether we go on to pursue them, and how rigorously we do, is ultimately a socio-political question."

More information: Tom Terlouw et al, Future hydrogen economies imply environmental trade-offs and a supply-demand mismatch, *Nature*

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