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Golden hydrogen

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Abstract

Hydrogen is a colorless compound to which symbolic colors are attributed to classify it according to the resources used in production, production processes, such as electrolysis, and energy vectors, such as solar radiation. Green hydrogen is produced mainly by electrolysis of water using renewable electricity from an electricity grid powered by wind, geothermal, solar or hydroelectric power plants. For grid-powered electrolyzers the tendency is to go larger to reach the gigawatt-scale. An evolution in the opposite direction is the integration of the photophysics of sunlight harvesting and the electrochemistry of water molecule splitting in solar hydrogen generator units, with each unit working at kilowatt-scale, or less. Solar hydrogen generators are intrinsically modular, needing multiplication of units to reach gigawatt-scale. To differentiate these two fundamentally different technologies the term 'golden hydrogen' is proposed, referring to hydrogen produced by modular solar hydrogen generators. Decentralized modular production of golden hydrogen is complementary to centralized, energy-intensive green hydrogen production. The differentiation between green hydrogen and golden hydrogen will facilitate the introduction of the additionality principle in clean hydrogen policy.

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The colors of hydrogen

Focus on hydrogen as an energy vector is growing and its ability to facilitate large scale implementation of renewable energy is gaining interest [1–5]. Renewable hydrogen offers solutions especially for hard-to-decarbonize industrial sectors [2,6–11]. This intense focus on hydrogen at the policy and regulatory level, as well as in industry, explains the need to differentiate categories of hydrogen based on their usefulness towards decarbonization goals. A standardized color code system is handy.

In environmental science and engineering color codes are often used to represent levels of cleanliness of a specific resource. The term 'greywater', for example, is regularly used to distinguish less polluted domestic wastewater from 'blackwater', which contains higher levels of contaminants and generally poses a grave risk to the environment [12]. In a similar sense, the hydrogen color classification system has been introduced to assist policy-makers, project developers and consumers to differentiate the different hydrogen production processes and technologies on their merits towards a renewable energy future. Within the dynamic hydrogen landscape new colors come into being and add to the global hydrogen vocabulary.

Policy documents around the world directly or implicitly refer to green, grey, blue, turquoise, pink and black hydrogen [2,3,6,8,13–16]. It is important to note that some hydrogen colors have established definitions, while inconsistent definitions can be found for others. DNV, for example, defines yellow hydrogen as produced through water electrolysis using grid electricity, while National Grid uses a definition stating that it is being produced using solar power exclusively [17,18]. Both definitions could fall under the European CertifHy guarantee of origin (GO) definition of green hydrogen. Furthermore, different definitions of renewable energy are used around the world, leading to differing definitions for green hydrogen [19]. It is clear that green hydrogen carries a broad definition and calls have been made for its standardization on an international level [16,19].

Bracker [20], Agora Verkehrswende, Agora Energiewende, and Frontier Economics [21] have developed sustainability criteria for green hydrogen. These criteria are based on additionality, sustainable use of space, sustainable economic development in production countries, sustainability of water supply, and greenhouse gas emissions [20,21]. A considerable debate is ongoing about the importance of additionality in the determination of the 'cleanliness', or 'greenness', of renewables-based hydrogen [22]. Additionality refers to the requirement that renewable electricity used for the production of renewable hydrogen should come from plants that are additional to those required to achieve the renewable energy penetration target for final electricity consumption [22]. This requirement is important to ensure that the production of green hydrogen directly serves the goal of decarbonization, instead of just adding inefficiencies to the renewable energy system, which indirectly leads to an increase in fossil fuel in the energy mix. It is nevertheless difficult to define and measure additionality in practice within an integrated energy system [23].

The European Commission's '*NextGenerationEU*' economic recovery package aims to rapidly upscale clean hydrogen production and use in Europe [24]. The EU Hydrogen strategy states that it is preferred that the renewable electricity used to produce renewable hydrogen is additional [1]. The Prefecture of Aichi in Japan requires that in the long term renewable electricity installations for hydrogen production should be new, or unused [19]. The German TÜV SÜD CMS 70 Standard states that certified clean hydrogen production should at least partly be powered by additional plants [25].

The CertifHy GO certification scheme for green hydrogen and 'low-carbon hydrogen' is considered to be the most advanced in the world [16,26]. CertifHy Green Hydrogen is defined as originating from renewable sources and having a greenhouse gas balance less than 60% below the production of hydrogen through state-of-the-art steam reforming of natural gas, which has a benchmark greenhouse gas footprint of 91 g CO2eq/MJ. CertifHy defines 'low-carbon hydrogen' as originating from non-renewable energy sources, including nuclear, with carbon capture and storage (CCS) or potentially also carbon capture and utilization (CCU), with a greenhouse gas balance being as low as that of green hydrogen [26]. Blue hydrogen is commonly defined as being produced through steam methane reforming with CCS and pink hydrogen as being produced through water electrolysis with nuclear energy. Blue and pink hydrogen could, therefore, both fall under CertifHy's 'low carbon hydrogen', but low carbon hydrogen is not necessarily blue or pink. Several other certification schemes are in development around the world, with the aim of supporting consumer disclosure and enabling market growth for hydrogen [16,19,27]. As an example serves the discussion paper published by the Australian Federal Government which is aimed at establishing a national GO certification scheme [16]. It proposes a 'cradle to gate' methodology for hydrogen certification and aims to focus on production-side emissions from steam methane reforming with CCS, coal gasification with CCS, and electrolysis. It is important that there is an international standardization of the methodology used to certify hydrogen [16,19]. For an overview of current certification schemes around the world, the reader is referred to other reports reviewing such schemes [19,23].

Although CertifHy defines green hydrogen and 'low carbon hydrogen' based on its energy source and carbon footprint, other colors of hydrogen require the production process to be specified. Turquoise hydrogen, produced through methane pyrolysis, is mainly distinguished from blue hydrogen (steam methane reforming with CCS) based on the production process. In some cases, such as coal gasification for black hydrogen, the color also implicitly specifies the feedstock.

The H-atom and energy source, the production process and the direct greenhouse gas emission of the different colors of hydrogen are listed in Table 1. Based on an analysis of Google search trends globally between 2020 and 2022, the hydrogen colors that have been used as search-terms most are green, white, blue, black, and yellow.

Given the broad penetration of the colors of hydrogen in society, the classification should be transparent and consistent. Solar hydrogen generators are overlooked by the hydrogen color palette and tend to be categorized implicitly in the green hydrogen category. In the next section arguments will be developed for the separate category of golden hydrogen (Table 1).

Solar hydrogen generators

The use of sunlight and appropriate photocatalysts to produce solar fuel has already been proposed in 1912, but fundamental research in the field was not undertaken in earnest until the 1970s [30,31]. There are many ways to combine the semiconductor photophysics of charge carrier generation with the electrocatalytic splitting of water molecules. Nielander et al. have developed a taxonomy and nomenclature for solar fuel generators to allow for clear comparison between devices. Based on the fundamental principles underlying designs, four categories and ten device names can be distinguished [32]. Although this list is not exhaustive, devices that produce hydrogen are listed in Table 2, together with the taxonomy. The devices listed in Table 2 are expected to reach commercialization on the medium to long term [33]. For an overview of photocatalytic water splitting the reader is referred to Maeda and Domen [34] as well as Wang et al. [35]. For an overview of both photocatalytic and photoelectrochemical water splitting, the reader is referred to Bosserez et al. [36].

Integration of physical and chemical phenomena in solar hydrogen generators, such as listed in Table 2, is scientifically very challenging and scaling of laboratory level integrated solar hydrogen systems is not trivial

Table 1

The colors of hydrogen.

Color	Hydrogen atom source	Energy source and production process	Direct greenhouse gas emission (kg CO2eq/kg H2)	Reference
Colors that are established in academic literature and policy documents				
Black	Water	Coal gasification	18–20	[17]
Brown	Water	Lignite gasification	18–20	[17]
Grey	Methane	Steam methane reforming	9–11	[17]
Blue	Methane	Steam methane reforming with CCS	0.5–4	[17]
Turquoise	Methane	Pyrolysis	0	[17]
Green	Water or biomass	Water electrolysis powered by renewable energy, and biomass gasification	0	[17,26]
Pink	Water	Water electrolysis powered by nuclear energy	0	[17]
New color class proposed in this paper				
Golden	Water	Direct solar water splitting	0	
Less common colors, which are not always consistently used				
Yellow	Water	Grid-powered electrolysis or solar powered electrolysis	Dependent on energy mix	[17,18]
Red	Water	Thermolysis using nuclear heat or solar heat	0	[17,28]
Purple	Water	Thermolysis and electrolysis using nuclear heat and electricity	0	[17]
Orange	Water	Biomass gasification or municipal waste electrolysis	0	[28,29]
White	Naturally occurring	Fracking	0	[18,28]

Table 2

Taxonomy and nomenclature of solar fuels generators according to Nielander et al. [32].

Defining characteristics (n = total number of junctions, l = number of solid state junctions)				Device name (TRL level 1 to 4)	Category
Junctions	Light absorber material dissolved or suspended in solution.	More than one PEC cell integrated in the device.	Chemicals formed at semiconductor electrolyte interface.		
n = l	NO	NO		PV-biased electrosynthetic cell	PV cell
n ≠ l l > 0	NO	YES	YES	PEC- and PV-biased photoelectrosynthetic cell	PV-biased PEC cell
n ≠ l l > 0	NO	NO	YES	PV-biased photoelectrosynthetic cell	PV-biased PEC cell
n ≠ l l > 0	NO		NO	Regenerative PEC-biased and PV-biased electrosynthetic cell	PV-biased PEC cell
n ≠ l	NO	YES	YES	PEC-biased photoelectrosynthetic cell	PEC cell
n ≠ l	NO	NO	YES	Photoelectrosynthetic cell	PEC cell
n ≠ l	NO		NO	PEC-biased electrosynthetic cell	PEC cell
	YES			Photoelectrosynthetic particulate/molecular photocatalysts	Photoelectrosynthetic particulate/ molecular photocatalysts

[36]. Concepts for particle suspension photocatalytic water splitting devices (photoelectrosynthetic particulate/molecular photocatalysts, according to the taxonomy of Nielander et al. [32]) have been analyzed and discussed by Nandy et al. [37]. The EU-funded CONDOR-project is focused on developing a modular device for the production of solar fuels, including hydrogen, with sunlight as the only energy source [38,39]. The Sun-To-X project, also funded by the EU, aims to use solar energy and ambient moisture to produce hydrogen via photoelectrochemistry [40,41]. Advanced photoelectrosynthetically active heterostructures are also implemented in modular hydrogen production units, which could be implemented in small-scale, distributed setups [42]. Hydrogen panels producing hydrogen by capturing and splitting water molecules from the atmosphere upon solar illumination is another example [43].

Green hydrogen as a category has become very broad, including virtually all renewable hydrogen technologies. Given the growing importance of the additionality principle, we propose here to distinguish golden hydrogen produced with solar hydrogen generators as a distinct category.

Golden hydrogen

Golden hydrogen is produced in dedicated solar hydrogen generators. Solar hydrogen generators serve the sole purpose of producing hydrogen using solar energy. The captured solar energy cannot be used for other purposes and the hydrogen cannot be produced by other energy sources. All chemical and physical processes needed to produce hydrogen from water by solar illumination are integrated in a single device. This intimate integration of functions is typically at sub-meter scale and often at centimeter down to nanometer scale. The golden hydrogen production capacity per square meter of illuminated surface is capped by the intensity of solar energy reaching the surface of the earth.

> Golden hydrogen is produced by dedicated solar hydrogen generators, defined as devices integrating all physical and chemical processes needed to directly produce hydrogen from water by solar illumination. This intimate integration of functions is typically at the sub-meter scale.

Golden hydrogen production favors modular devices and enables a form of autonomy. This is because the intimate integration of functions allows for smaller functional units. There is a tendency to go smaller and develop decentralized autonomous solar hydrogen generators with all functionalities for solar water splitting integrated at ever smaller scale to minimize energy losses in the systems. The functional unit containing all necessary components is typically at or below the m^2-scale in golden hydrogen systems. Small production units could be more dependent on micro-climate conditions [44]. Such devices are, however, suited for applications at any scale, ranging from distributed systems at kilowatt-scale up to gigawatt-size solar hydrogen farms, combining a large amount of modular units.

Within an uncertain energy future modularity could reduce the financial risk involved with golden hydrogen projects, as it could allow for functional golden hydrogen plants at lower capex, which can then be scaled up gradually by adding more modules as the need arises [45,46]. Modular scaling also facilitates a learning process that can lead to cost reductions and performance improvements as the project becomes larger [45]. Granular energy technology is also typically less complex, stimulating faster innovation cycles and potentially offering larger efficiency gains [45]. Energy supply technologies with lower unit investment cost have been shown to diffuse faster, with lower investment barriers [45,47]. It has also been found that granular energy technologies create more jobs over their lifetime than 'lumpy' technologies [45].

Modular units could also be placed close to end-users, enabling the establishment of hydrogen prosumers. The distributed generation of hydrogen is coordinated within a diminished scope of control, due to its modularity, increasing resilience of the energy system as a whole [11]. The diminished scope of control also limits the interference of golden hydrogen production with established green electricity production. Furthermore, due to its additionality, golden hydrogen production is driven by hydrogen demand rather than oversupply in the power market, and could thus incentivize energy efficiency at the end-user. The co-location of hydrogen production and usage could also simplify balance of plant needs. According to the International Energy Agency's Global Hydrogen Review 2022, energy system robustness will become increasingly important — especially in the light of recent geopolitical developments [48]. The employment of Golden hydrogen within the energy system could aid in improving the system's robustness.

Conclusion

Solar hydrogen generators are a new renewable energy technology. They produce solar fuel without consuming energy from the grid and are intrinsically additional. Golden hydrogen shifts the limit in hydrogen production away from electricity availability. Spatial limitations could be diminished by the integrated nature of the golden hydrogen production process and associated technologies. The modularity associated with golden hydrogen production devices also brings an array of possible advantages in the quest to achieve a successful energy transition.

A case has therefore been put forward for the introduction of the term golden hydrogen. By distinguishing between green hydrogen and golden hydrogen, the origin of the energy and the principle of additionality can easily be accommodated in policy discussions, project plans, and consumer disclosure programs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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