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Redefining the Hydrogen "Colours" based on Carbon Dioxide Emissions: A New Evidence-Based Colour Code

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Abstract. *This paper redefines hydrogen colour codes based on carbon dioxide emissions. It highlights that there are several colour codes, which disregard the carbon dioxide emitted in the hydrogen production process (e.g., electrolysis with renewable energy, steam reforming of natural gas, coal gasification, etc.). Some colours are used interchangeably for different technologies, while many colour codes do not assign a colour for all possible production pathways. Therefore, the existent framework is misleading and lacks scientific underpinning of colour labelling (e.g., green, blue, grey, black, yellow, purple, turquoise, etc.). This paper builds upon the work of Nikolaidis and Poullikkas and provides a qualitative assessment of the colour codes used to label various technologies. Based on a comparative analysis of the latest research and analysing hydrogen colour codes, this paper inquires whether there is or not, a common understanding of the hydrogen production pathways that lie behind each hydrogen "colour". This paper finds that there are major inconsistencies regarding the colours used, especially for technologies using fossil fuels as an energy source, but nuclear energy has also been found to have discrepancies in labelling. At the same time, there is only one colour used to describe a wide range of technologies using renewable energy (i.e., green). However, if carbon dioxide emissions of the corresponding production technology were visually represented using a predefined colour-code, the hydrogen produced with fossil fuels would have a less diverse colour range, than current colour palettes would suggest. Rather than being "grey" and "blue", coal, oil and gas-based hydrogen appear to be different shades of "brown" and "black". This finding illustrates that these technologies emit more carbon dioxide emissions than an initial labelling would suggest, which raises the question whether any colours of hydrogen, other than its "green" versions, is compliant with the objectives of the Paris Agreement.*

Keywords: hydrogen, green, black, grey, colour, carbon dioxide emissions, Paris Agreement.

Introduction

This paper redefines hydrogen colour codes based on carbon dioxide emissions. The objective of this paper is to propose a new colour code, labelling hydrogen based on the scientific evidence of the carbon dioxide emissions released in the production process depending on the fuel and technology used (e.g. electrolysis with renewable energy, electrolysis with nuclear power, steam reforming of natural gas, coal gasification, etc.), instead of the current colour code which is based on technology and fuel.

The present paper also aims to evaluate the effectiveness of the existent colour codes in the decarbonization process. Additionally, the new proposed colour code aims to provide transparency to researchers, industrial actors, policymakers, as well as helping them make informed decisions about the hydrogen they consume (or plan to consume) with the aim of promoting the use of more sustainable hydrogen production methods.

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Furthermore, this paper also suggests a potential solution for a simple harmonised colour code for hydrogen production technologies. Ultimately, this research aims to contribute to the ongoing discussions and efforts towards a sustainable hydrogen economy at global level.

Since hydrogen production – and especially its "green" version – has regained and continues to gain interest among practitioners, policy makers and researchers in the decarbonisation process of various sectors of the economy as per Paris Agreement, it is important to have a common understanding of the various hydrogen production pathways (Raman et al., 2022).

Colour codes have many benefits in the hydrogen debate. First, colour labelling could simplify the categorisation of a wide range of available technological pathways to produce hydrogen (e.g., "green" versus "grey" versus "black"). Second, it could help identify the quantity of emitted carbon dioxide emissions per technology via a simple predefined labelling (e.g., "green" represents the technology with the lowest emissions, while "black" represents the technology that has the highest quantity of emissions in the hydrogen production process). Third, a colour code could help with visually representing the various hydrogen production technologies (e.g., mapping relationships between technologies).

This paper adopts a qualitative approach to answer the question of whether there is a commonly agreed and harmonised colour code to produce hydrogen. The first hypothesis is that there is a conventional, commonly agreed, and harmonised colour code for hydrogen production technologies, while the second hypothesis is that there is no commonly agreed and harmonised colour code for hydrogen production technologies.

This paper builds upon the work "A comparative overview of hydrogen production processes" of Nikolaidis and Poullikkas (Nikolaidis & Poullikkas, 2017), which is the "topmost cited publication" on hydrogen production processes (Raman et al., 2022). This widely cited study provides a qualitative assessment of the colour codes used in recent literature to label various hydrogen production technologies.

Based on a comparative analysis of the latest research and analysing hydrogen colour codes, the present paper inquires whether there is or not a common understanding of the hydrogen production pathways that lie behind each hydrogen "colour".

The information about the common understanding of the hydrogen production pathways and the use of colour codes to label them can be relevant for managerial practices and businesses in the hydrogen industry for several reasons.

First, a common understanding of the hydrogen production pathways and the colours used to label them can facilitate communication and collaboration within the industry. This can lead to a harmonised and standardised approach to labelling hydrogen production pathways, which can help businesses and stakeholders to compare and understand the production methods and their corresponding environmental impacts.

Second, a harmonised colour code can support the marketing and promotion of hydrogen as a sustainable energy source by enabling clear and consistent communication of the production methods and their corresponding environmental impact to the public and stakeholders.

Third, understanding the various production methods and their corresponding colours can inform businesses and managers about the most environmentally friendly production pathways and help them make informed decisions about their production processes and feedstocks, as well as making informed decisions about future investments in research, development, and innovation.

Overall, having a common understanding of the hydrogen production pathways and their corresponding colour codes can contribute to the growth and sustainability of the hydrogen industry and support the transition to a low-carbon energy economy.

At first sight, researchers, policy makers and industrial actors seem to use a logical and well-defined colour code based on the hydrogen production technology employed and the source of energy, which serves as input. However, as this paper shows, the colours used to label hydrogen are rather confusing. Moreover, there is no common agreement of the technology and fuel that should lie behind each colour, if a predefined colour code is used, based on the commonly agreed principle that "green" means fewer carbon dioxide emissions, while "black" means higher emissions.

The authors are planning to expand the present paper to include a glossary with definitions of each of the technological pathways. The purpose is to provide readers with the necessary technical knowledge to understand the text clearly, even if they do not work in the energy industry (or related industries). This would significantly ease readability.

Moreover, to guide the interested readers, the authors will provide a chart with the key hydrogen colours currently used. A simple illustration envisaged is shown in Figure 1.

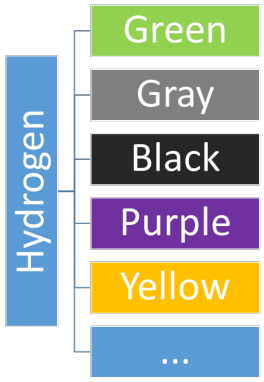


Figure 1. Key hydrogen colours currently used by businesses and researchers
Source: Authors' own research results.

Literature review

Hydrogen production pathways

Currently 98% of the hydrogen is produced at global level thanks to fossil fuels (IRENA Coalition for Action, 2022). However, hydrogen, especially the one produced via water electrolysis with renewable energy sources (water, solar, wind, etc.), i.e. "green" hydrogen, is commonly understood to play a significant role in the global energy transition, since it would play a role in the decarbonisation of various economic sectors, and especially those that are considered to be hard-to-decarbonize like the iron and steel industry or aviation, to name just two examples (Howarth & Jacobson, 2021; IRENA, 2020).

There are several useful overviews of the various hydrogen production pathways in the academic literature, with one standing out as being comprehensive. Nikolaidis and Poullikkas offer an overview of the various hydrogen production processes by providing a comparative overview, including both production pathways with fossil fuels like oil, gas and coal, as well as renewable energy sources, like solar, wind and bioenergy. They also include a well-illustrated map of these technologies (Nikolaidis & Poullikkas, 2017).

However, the hydrogen production methods visually illustrated in their widely cited article, has some gaps, especially when compared to the current state of the literature. There are main gaps: first, their visualisation does not contain nuclear energy – although nuclear energy falls within the

scope of their research; second, the illustration lacks more recent hydrogen production pathways which have gained interest among academics, like advanced microwave plasma (Pocha et al., 2023); and third, the overview lacks to provide a comprehensive definition of "green" hydrogen, although the term is used in the abstract.

Hydrogen colours: from green to black, through brown, grey, blue, turquoise, yellow, orange, purple, pink and red hydrogen

Since hydrogen is a naturally-occurring and colourless gas, it can be seen as "ironic" - as one professional in the hydrogen industry said - that the various technological pathways to produce it, are labelled using a wide spectrum of colours (Giard, 2022), including white, green, black, brown, grey, blue, turquoise, yellow, purple, pink, orange and red hydrogen.

There are several attempts to define the various colours allocated to the various technological pathways in the scientific literature, but none has reached consensus. This lack of common understanding of a unique colour code is observed both among industry and policy makers and among international organisations. For example, the International Energy Agency and the Hydrogen Council usually avoid using any colour labels per technology (IEA, 2021), while the International Renewable Energy Agency defines grey, blue, turquoise and green hydrogen (IRENA, 2021).

In scientific literature, Ringsgwandl *et al.* define "green" hydrogen as being hydrogen produced through water electrolysis with electricity from renewable sources. In this process, the authors also provide other possible technological pathways to produce hydrogen to which a colour is assigned, indicating whether these technologies are available at industrial scale.

In providing such an overview, the authors also allocate a colour for the various other technologies (e.g. pink for hydrogen produced via electrolysis with electricity sources from nuclear energy and yellow for hydrogen produced via electrolysis with electricity sources from various sources, both fossil-based and renewable) (Ringsgwandl et al., 2022).

However, there are several flaws with such an overview: First, it omits other hydrogen colours that are widely used in the scientific literature or among industrial players, like "brown" (Howarth & Jacobson, 2021) or "black" hydrogen (Osselin et al., 2022), which refers to fossil fuel-based hydrogen. Thereby, it gives only a partial image of the technological pathways available for hydrogen production.

Second, the colours attributed to the various technological pathways do not match with the colour labels found in other research papers or industry position papers. E.g. they label as "pink" the hydrogen produced via electrolysis with nuclear energy and "yellow" the hydrogen produced via electrolysis from an electricity mix (Ringsgwandl et al., 2022).

However, in other research papers, "pink" is defined as hydrogen produced via electrolysis with nuclear power (Ajanovic et al., 2022) and in other industry communication items, "yellow" is defined as hydrogen produced via electrolysis with solar energy (Acciona, 2022).

Methodology

This paper builds upon the work of Nikolaidis and Poullikkas and provides a qualitative assessment of the "colours", which are currently used to label the various technological pathways available to produce hydrogen. Based on a comparative analysis of the latest research and analysing hydrogen colour codes, this paper inquires whether there is or not, a common understanding of the hydrogen production pathways that lie behind each hydrogen "colour".

The research question is the following: Is there a commonly agreed and harmonised colour code to label the various technological pathways available to produce hydrogen?

The first hypothesis is that there is a conventional, commonly agreed, and harmonised colour code, while the second hypothesis is that there is no commonly agreed and harmonised colour code to label the various hydrogen production pathways.

In this context, the first objective of this paper is to demonstrate, using a comparative analysis of the latest literature, whether there is or not, a common understanding of the technologies that lie behind each colour used next to the word hydrogen.

As such, the research endeavour employs a methodology, which follows the following steps:

In the first phase, a literature review is conducted, including academic literature and reports from major international organisations having hydrogen as part of their mission from governments around the world.

In the second phase, a comparison is conducted between the literature that contains comprehensive descriptions and graphical illustrations of the various hydrogen production pathways, including both the fuel used (e.g. coal) and the production method (e.g. gasification). In some cases, where a colour code is available, a comparison of the colour labels used for various hydrogen production methods is also conducted.

In a third phase, building on the work of Nikolaidis and Poullikkas, the graphical illustration of the hydrogen production methods was created from scratch by enriching the initial graphical illustration thanks to the work of other researchers (Akubo et al., 2019; Okeke et al., 2023; Osselin et al., 2022; Pocha et al., 2023). Concretely, the authors have added additional hydrogen production routes and have restructured the visual representation, based on the literature review. A detailed table with the elements that are new, compared to the initial work of Nikolaidis and Poullikkas can be added in the expanded version of the abstract, if the present proposal is accepted (as part of the additional 40% of the content) to add more clarity to the methodology. A source for each new element can be provided.

In a fourth phase, each of the technological pathways is allotted a colour, based on the literature review. In case one technology is assigned a different colour in different research papers, this is visually illustrated by showing all colours identified in the literature review thanks to a gradient of the 2, 3, 4 or more colours identified.

Therefore, after following these steps, a more comprehensive overview of the various technological pathways can be drawn. At the same time, if there are no inconsistencies with regards to the colour labels (i.e., if the same colour is assigned to the same overarching technological category), the first hypothesis is confirmed. If, however, a technological pathway has various colours allotted in the scientific literature or if one colour is used to describe different technological pathways to produce hydrogen, then the first hypothesis is rejected and, concomitantly, the second hypothesis is confirmed.

The objective of the research is to demonstrate whether there is a common understanding of the technologies behind each colour used next to the word hydrogen and to redefine the hydrogen "colours" based on the amount of carbon dioxide emitted in the hydrogen production process.

In conclusion, we have followed a systematic and transparent methodology that includes a literature review, comparison, and visual representation of the hydrogen production pathways to address the research question. We have also described the steps we took to assign colours to the technological pathways and explained the rationale behind our methodology.

Results and discussions

The results presented in Figure 2 are obtained by creating from the beginning a visual illustration, based on the initial hydrogen production methods by Nikolaidis and Poullikkas. The illustration was enriched with new technological pathways that were found in the literature review, but which were not considered initially by Nikolaidis and Poullikkas.

After having added all relevant technological pathways, each of the technological pathways is allotted a colour, based on the literature review. In case one technology is assigned a different colour in different research papers, this is visually illustrated by showing all colours identified in the literature review for that particular technology thanks to a gradient of the 2, 3, 4 or more colours identified.

As illustrated in Figure 2, following the methodology elaborated in the present paper, there are major inconsistencies with regards to the hydrogen "colours" used to describe the various technological pathways, especially when it comes to those methods which are using fossil fuels as an energy source, although nuclear energy has been also found to have discrepancies.

At first sight, researchers, policy makers and industrial actors seem to use a well-defined colour code based on the hydrogen production technology employed and the source of energy which serves as input. E.g. "green" hydrogen for the one sourced with renewable energy, "black" for hydrogen sourced from fossil fuels and "pink" for hydrogen produced with nuclear power.

While coherent labelling might be used within individual papers, the present research shows that the colours used to label hydrogen are confusing and misleading across the literature.

While there seems to be a consensus that "pink" hydrogen refers to the one produced thanks to nuclear energy, for the same technological pathway the colour "red", "purple" and "yellow" is also used. This leads to huge confusion since researchers have assigned the colour "yellow" to the hydrogen produced via electrolysis with electricity from the grid (Ringsgwandl et al., 2022), meaning it is sourced from various energy sources, including both fossil fuels and renewable energy sources, while "yellow" has been used by some industrial actors to describe a subcategory of "green" hydrogen, i.e. "yellow" hydrogen is the one produced via electrolysis with solar energy (Acciona, 2022).

While "green" hydrogen was initially used to refer exclusively to hydrogen produced via electrolysis using renewable-sourced electricity, the label "green" has been extended to all methods of hydrogen production with renewable energy, including biomass processes (as opposed to splitting water into hydrogen (H_2) and oxygen (O)). The only exception to the rule that "green" hydrogen is the one produced thanks to renewable energy sources irrespective of the method employed, seemed to be the hydrogen produced via electrolysis with solar energy, which was singled out and labelled as "yellow" by some industrial actors (Acciona, 2022).

At the international level, among policy makers and governments, there is also no clear taxonomy in this respect. For example, the hydrogen strategy for a climate-neutral Europe avoids using any colour codes and defines "renewable hydrogen" as the "hydrogen produced through the electrolysis of water (in an electrolyser, powered by electricity), and with the electricity generated from renewable energy sources", with close to zero greenhouse gas emissions. At the same time, it acknowledges that "renewable hydrogen may also be produced through the reforming of biogas (instead of natural gas) or biochemical conversion of biomass, if in compliance with sustainability requirements" (European Commission, 2020).

The discussion about the colours attributed to the hydrogen produced with fossil fuels as energy source and feedstock raises even more questions, adds to the confusion, and lacks total clarity. Specifically, what some call "black" hydrogen, is rather "grey" or "brown" for others. Similarly,

hydrogen produced through hydrocarbon pyrolysis is either labelled as "grey" (as often gas-sourced hydrogen is labelled) or is labelled as "turquoise", without any logical or evidence-based reasoning.

However, there seems to be a consensus that – if carbon capture technologies are deployed in the hydrogen production process – the fossil fuel-based hydrogen can be labelled as "blue".

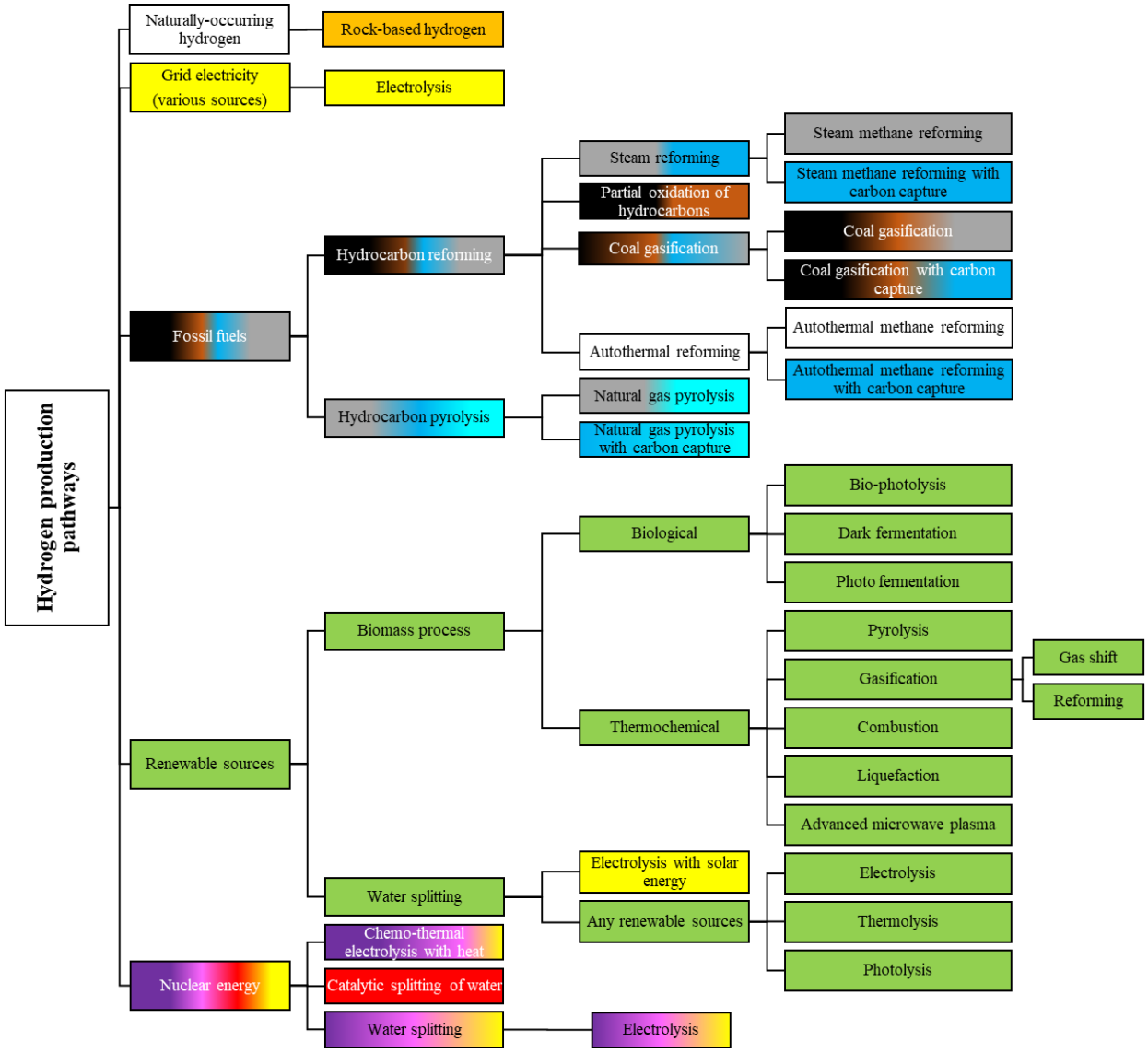


Figure 2. Technological pathways to produce hydrogen, including existing colour codes

Source: Authors' own research results.

When it comes to naturally occurring hydrogen, researchers label it as "white" – although hydrogen is a colourless gas. Interestingly, a passive exploitation of naturally occurring hydrogen was proposed as an alternative to active hydrogen production methods (like the ones discussed in this paper). The process of obtaining hydrogen by inserting water into ferrous iron formations in the ground is labelled as "orange" hydrogen, because it is associated with the colour of rusting iron (Osselin).

There is also the problem that not all available or future possible hydrogen production technologies have a distinct colour allocated.

Since there is no logical, theoretical, or empirical basis for allocating colours, new hydrogen production pathways might run out of "colours".

For example, hydrogen produced through autothermal methane reforming does not have a clearly identified "colour" (although it could be argued that it could be anything among the colours attributed to fossil fuel-based hydrogen).

Moreover, when carbon dioxide emissions from the corresponding production technology are visually represented using a predefined colour-code, based the commonly agreed principle that "green" hydrogen means that little to no carbon dioxide was emitted in the production process, while "black" means that a significant amount of carbon dioxide was emitted into the atmosphere, the hydrogen produced with fossil fuels have a less diverse colour range, than current colour palettes would suggest, as schematically represented in Figure 2.



Figure 2. Proposed 3-colour code for hydrogen production technologies based on carbon dioxide emitted in the process

Source: Authors' own visual representation

Rather than being "grey" and "blue", coal, oil and gas-based hydrogen would appear to be different shades of "brown" and "black". The proposed carbon dioxide emissions scale would illustrate visually that fossil-fuel based hydrogen emits more carbon dioxide emissions than an initial colour labelling would suggest.

Since the current hydrogen debate is sparked by the necessity to reduce carbon dioxide emissions throughout various economic sectors of the economy around the world, the implication of this finding is of utmost importance for the scientific, economic, and political debate. This paper questions whether any "colours" of hydrogen, other than its "green" versions, i.e., produced via electrolysis with renewable energy (sourced from water, solar, wind, etc.) is compliant with the objectives of the Paris Agreement.

Therefore, the proposal of this paper would be to completely disregard these chaotic and ever-more complex colour codes which are confusing and follow no logic, since colours are used without any respect to colour theories. As such, current colour labels of hydrogen include in an uncoordinated way both primary (red, yellow, blue), secondary (orange, green and purple), as well as tertiary colours (turquoise, brown), in addition to tints of primary colours (pink), as well as white, grey and black (Albert Henry Munsell, 1905).

Instead, the authors propose to use a simple 3-colour code, namely "green", "grey" and "black" hydrogen, based on the scale of carbon dioxide emitted in the production process of hydrogen, expressed in tons of carbon dioxide emitted per kilogram of hydrogen produced (irrespective of the deployment of carbon capture technologies, since their benefits would be captured as less carbon dioxide emitted in the atmosphere).

As per to Munshell colour system, the scale would be from "black" to "green", with "grey" as a transition between the two hues (black, green). Arranging hydrogen production technologies on such a coloured carbon-dioxide scale would allow for a better understanding and visual representation of how the various hydrogen production technologies relate to each other in the

global energy transition from a fossil-fuelled economy to a climate-neutral economy. It would also provide hydrogen produced with nuclear energy with a more coherent point of comparison with other technological pathways.

According to the proposed new 3-colour code, "green" would be assigned to the lowest emitting technologies (i.e. based on renewable energy sources), "black" would be assigned to the highest emitting ones (i.e. based on fossil fuels), while "grey" would be everything in-between (e.g. those technologies producing hydrogen from fossil fuels, but using carbon capture techniques).

The specific carbon dioxide emission threshold for each colour has yet to be defined in future research.

Conclusion

There are three major findings in the present research paper.

First, there is no unified, harmonised and commonly agreed colour code allocated to the various technological pathways to produce hydrogen – although at first sight it might seem that way. There is a common understanding that "green" hydrogen is produced thanks to renewable energy via different methods.

However, when it comes to nuclear energy and fossil fuels used to produce hydrogen via different techniques, the multitude of colours used by academia and industry is rather confusing to say the least.

Second, this paper has come forward with a more comprehensive graphical illustration of the various technological pathways available to produce hydrogen, based on a comparative approach of the latest scientific literature in this field. Therefore, it proposes a more comprehensive visual representation of the technological pathways to produce hydrogen. In addition to its far-reaching inclusion of technologies available, it also contains a visual illustration of the existing colour codes employed in scientific research papers and among relevant industry actors.

Third, the authors refute the complex colour codes as being misleading, confusing, unharmonized and lacking any scientific underpinning. Instead a simple, 3-colour code is proposed to be used based on the carbon dioxide emitted in the hydrogen production process, based on Munshell's colour theory (green, grey and black).

The results obtained in our research paper contribute to the existing literature by refuting the complex and confusing colour codes used to classify the various technological pathways to produce hydrogen. By proposing a simple, 3-colour code based on the carbon dioxide emitted during the hydrogen production process, the authors aim to provide a more harmonised and unified approach to classifying hydrogen production pathways.

In terms of theoretical value, the paper contributes to the advancement of knowledge in the field of hydrogen production by offering a comparative analysis of the latest scientific literature and providing a more comprehensive visual representation of the technological pathways available. This can serve as a valuable resource for business leaders in industrial sectors, policy makers, academics, and other stakeholders in the hydrogen production sector.

In terms of managerial practice, the simple, 3-colour code you propose has the potential to improve decision-making and investment in the hydrogen production sector. By providing a more straightforward and unified approach to classifying hydrogen production pathways, the present proposal can help stakeholders to better understand the carbon footprint of various hydrogen production technologies and make informed choices about which pathways to invest in and support.

However, as with any research work, there is room for improvement since it has its own limitations. One limitation is that this paper does not define actual carbon dioxide parameters to be used together with the 3-colour code for hydrogen production technologies. Another limitation is that it is based on a literature review and has not been validated by experts. For example, future research could include the validation of the above-mentioned findings via a brief questionnaire to be sent to hydrogen experts both to validate the present findings and to obtain comprehensive feedback on the practical usefulness of the new proposed 3-colour code.

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