Why hydrogen's carbon past matters for hydrogen futures

Recent calls for critical social science research on hydrogen have largely focused on "green" hydrogen produced from renewable energy sources. What these calls have not fully considered is that hydrogen is a substance that has been used and produced at scale by hydrocarbon industries for decades. The fossil-based knowledge, technology, and infrastructure of this carbon past remain at the heart of the future hydrogen economy, as exemplified by the socially and environmentally problematic rise of "blue" hydrogen. To achieve a socio-ecological hydrogen transition, social science research on hydrogen needs to start from hydrogen's carbon past in order to identify and contribute to the active reworking of hydrocarbon path dependencies.

Johannes Hollenhorst

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Hydrogen futures from the carbon past

Climate change is central to the current materialisation of hydrogen: it assigns the material a new role as a crucial energy vector in the global energy system. While hydrogen has previously been used primarily as a feedstock for petroleum refining and fertiliser production, the International Energy Agency (IEA) recently outlined that hydrogen "offers ways to decarbonise a range of sectors – including long-haul transport, chemicals, and iron and steel – where it is proving difficult to meaningfully reduce emissions" (IEA 2019, p. 13). This shift in the use of hydrogen – from highly carbon intensive situations in the past to an important component for decarbonisation and the mitigation of climate change in the future – raises the question of whether and how the knowledge, technology, and infrastructure of hydrogen's carbon past are implicated in the making of climate neutral hydrogen futures.

Previous calls for critical social science research on hydrogen (Kalt and Tunn 2022, Müller et al. 2022, Hanusch and Schad 2021) have not problematised the hydrocarbon path dependency of hydrogen and have instead focused on the novelty of green hydrogen production at scale. Based on my research on the emergence of the global hydrogen economy, especially within the UK, I am pointing to the continued importance of the hydrocarbon industry in hydrogen production and use. Drawing upon Karen Barad's concept of materialisation (Barad 2007) and building on previous substance culture research (Hahn and Soentgen 2011, Ertl and Soentgen 2015), I propose that studying hydrogen from a pluralist and historicising substance-focused perspective is vital for social researchers to make meaningful interventions into the making of hydrogen futures.

The relevance of grey and blue hydrogen for hydrogen futures research

Most hydrogen currently produced is derived from natural gas and is commonly referred to as "grey" hydrogen. The technology used to produce grey hydrogen is called steam methane reforming (SMR). SMR played a decisive role in overcoming food shortages in the early 20th century in concatenation with the Haber-Bosch process. In combination, these technologies enabled the industrial production of fertilisers, leading to the conclusion that today we are "eating fossil fuels" (Pfeiffer 2006). SMR emits about 9.1 kilograms of carbon dioxide for every kilogram of hydrogen produced. This means that the refining and chemical industries, which use large quantities of grey hydrogen as a feed, are among the world's most polluting industries.

To abate the carbon emissions of SMR and turn grey hydrogen into "blue" hydrogen, SMR is combined with carbon capture and storage (CCS).[1] Next to electrolytically produced "green" hydrogen, blue hydrogen is now considered one of the two major ways of producing climate neutral hydrogen. CCS is thereby the key to continuing to produce hydrogen using the methods of the hydrocarbon past – and has itself been the subject of substantial critical social science research. This includes research on the >

1 Next to SMR, hydrogen is also produced from coal and oil through gasification, a technology which is even more carbon dioxide intensive, technologically challenging, and expensive. These technologies are therefore currently not considered for large-scale blue hydrogen production.

Johannes Hollenhorst, MSc | London School of Economics and Political Science | Department of Sociology | London | UK | j.hollenhorst@lse.ac.uk

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TABLE 1: Definitions of hydrogen (H_2).

HYDROGEN DEFINITION	ENERGY SOURCE	TECHNOLOGY	kg CO_2e per kg H_2
grey	natural gas	SMR	10–14
blue	natural gas	SMR + CCS	1.5–6.2
green	renewable electricity	electrolysis	0
EU: green	variable	variable	< 3.4
US: clean	variable	variable	< 4
UK: low-carbon	variable	variable	< 2.4

SMR: steam methane reforming
CCS: carbon capture and storage
CO_2e: CO_2 equivalent

Sources: Grey, blue, and green hydrogen (IEA 2022, pp. 8–9, 40) based on International Partnership for Hydrogen and Fuel Cells in the Economy (2022), EU: Green (European Commission 2023 a, 2023 b), US: Clean (U.S. Department of Energy 2023, pp. 2–3), UK: Low-Carbon (Department for Energy Security and Net Zero 2023).

varying perceptions of, and responses to, the risks associated with CCS (Evar 2013, 2011, Einsiedel et al. 2013, Oltra et al. 2012), conflicts over its role in international climate governance (Krüger 2017, 2015), and its delaying effect on meaningful decarbonisation (Low and Boettcher 2020).

Due to these concerns with CCS, as well the long-winded process of identifying and surveying appropriate storage geologies for storing captured carbon, some countries with significant hydrogen ambitions, such as Germany and Sweden, had originally intended to focus on producing, importing, and using green hydrogen only, effectively excluding blue hydrogen from their hydrogen strategies (Federal Government of Germany 2020, p. 3, Swedish Energy Agency 2021). In addition, these countries also pledged to only use hydrogen in applications for which no other decarbonisation pathways exists – a step justified by the substantial thermodynamic energy losses occurring during the electrolytic production of green hydrogen.

Since the Russian military invaded Ukraine in 2022, however, commitments to green hydrogen in Sweden and Germany have started to falter. In part, this is because blue hydrogen has provided a long-term rationale for investing in new liquefied natural gas (LNG) infrastructure, allowing for the short-term replacement of Russian gas imports into Europe (Geitmann 2022). While the European energy crisis is arguably a singular event, its effects highlight the fragility of the highly integrated global energy system and the respective negotiability of climate-related commitments in the context of unforeseen events that have put energy security at risk. In addition, countries like the United Kingdom, Japan, and the United States never ruled out the use of blue hydrogen to begin with and are already investing heavily in this technology (e. g., de la Garza 2022).

The primary focus on green hydrogen in hydrogen futures research is therefore not appropriate for analysing and problematising the emergence and dynamics of the global hydrogen economy. Instead, hydrogen futures research needs to consider the emergence of green and blue hydrogen in an integrated way, highlighting the varying socio-ecological implications by analysing the knowledge, technologies, and infrastructures underpinning respective hydrogen futures. This is particularly important as new standardisations of hydrogen, such as "clean" or "low carbon" hydrogen (table 1) increasingly blur the boundaries between blue and green hydrogen in ways that make it harder to distinguish between the different social and ecological effects of this material. The social and ecological effects should however be a significant consideration for hydrogen futures in relation to green hydrogen, as has been previously reported (see, e. g., Hanusch and Schad 2021).

Knowledge, technology, and infrastructure extend the past to the future

The classification society DNV forecasted in their recent outlook that unabated grey and CCS-reliant blue hydrogen will make up slightly more than half of all the hydrogen produced in 2040, and slightly less than half of the hydrogen produced in 2050 (DNV 2022). Currently, unabated hydrogen still accounts for almost all the hydrogen produced globally (figure 1). Next to researching the emergence of international green hydrogen trade relationships (Kalt and Tunn 2022), and assessing questions of justice in this context (Müller et al. 2022), a critical social science approach to hydrogen futures research therefore needs to consider the non-renewable part of hydrogen futures, which remains heavily reliant on the hydrocarbon industry.

To do so, we might start by inquiring into authoritative knowledge claims about the different hydrogen production pathways, such as DNV's projection of the hydrogen future itself. Forecasts can have decisive performative effects on the unfolding of the future (Beckert 2016). This is particularly important since many of the organisations creating influential reports on hydrogen futures like the IEA or DNV have historic and contemporary ties to the hydrocarbon industry and continue to prioritise the future use of oil and gas assets over their accelerated phase-out. Counter knowledge production, like the widely discussed article *How green is blue hydrogen?* (Howarth and Jacobson 2021) or the Tyndall report on pathways for a rapid and just phase-out of oil and gas (Calverley and Anderson 2022) can help to unravel underlying forecasting assumptions in relation to their socio-ecological effects by juxtaposing these conflicting knowledge claims.

Next to the importance of mapping knowledge controversies, researching hydrogen futures also requires situating hydrogen technologies in local energy transition landscapes. This is particularly true for the application of hydrogen in the many contexts in which hydrogen futures are disputed. While the IEA (2019)

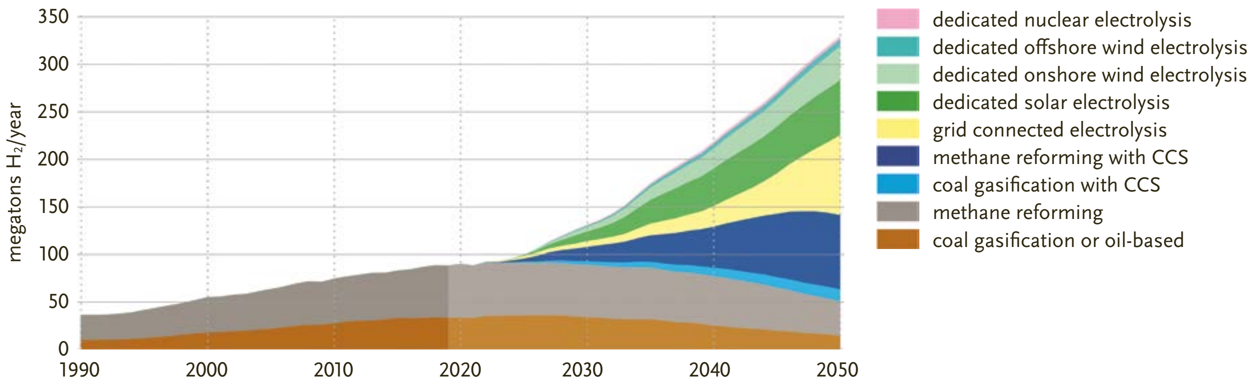

FIGURE 1: World hydrogen production by production route (DNV 2022, p. 73).

foresees a limited role for hydrogen futures in the broader energy transition landscape, gas companies and related organisations, like the European Hydrogen Backbone initiative (EHB 2022), as well as organisations like the global Hydrogen Council (2021) are pushing for a much wider use of hydrogen by foreseeing a wide variety of hydrogen technologies, such as residential heating.

Examples of the local materialisation of a more extensive global hydrogen economy are the envisaged replacement of natural gas boilers with hydrogen boilers in homes in the UK (Lowes et al. 2020), or the installation of hydrogen powered combined heat and power (CHP) technology in Japan (Uriu 2021). Interests of well-established national energy and technology industries are in these contexts overriding concerns of thermodynamic efficiency in the political decision-making processes. This can be in the interest of safeguarding jobs in established parts of the energy industry, or strengthening local industries for future hydrogen technology and service exports. Trying to analyse the politics for or against the use of hydrogen in applications like heating therefore requires attention to the system boundaries defined and potential dichotomies between underlying interests and actual thermodynamic conditions.

Decisions related to hydrogen technology consequentially question which future infrastructures should be invested in. As oil and gas companies are currently striving to protect their hydrocarbon assets and respective knowledge, technology, and skills acquired over decades of hydrocarbon production from energy transition risks (e.g., Van der Ploeg and Rezai 2020), blue hydrogen has been identified as a key way to enable the repurposing of existing oil and gas assets. The reutilisation of existing natural gas technologies (SMR), or the repurposing of natural gas fields and existing pipeline infrastructures at the end of their lifecycle (CCS) keep the hydrocarbon past at the heart of the hydrogen future and minimise the pressure in reinventing the energy industry.

In the UK, this is exemplified by plans to convert the National Transmission System (NTS) to hydrogen. Originally designed to transport natural gas from the North Sea to consumers across the UK, these plans foresee the repurposing of pipelines for blue hydrogen transmission, which could potentially be used to heat homes and power industries (Dodds and McDowall 2013, National Grid 2022). Even though heating with hydrogen is more inefficient and costly than heating homes with heat pumps (Rosenow 2022), the execution of grid conversion plans would ease the transition pressure on the oil and gas sector in the North East of Scotland and therefore also the pressure on tens of thousands of people working directly and indirectly in oil and gas in this region and elsewhere. Accordingly, CCS enabled blue hydrogen plans are backed by an unforeseen and influential coalition between oil and gas companies and respective trade unions, making a decision against blue hydrogen politically challenging in the UK. The amount of blue hydrogen that these plans would require in turn provides the central pillar for justifying de-risking of the UK government's investment in CCS infrastructures in Scotland, which would otherwise not have enough capturable carbon emissions due to the small number of industrial emitters.

These path dependencies need to be thoroughly analysed in order to prevent repetition of the hydrocarbon past by the means of CCS and blue hydrogen and to enable meaningful socio-ecological hydrogen futures in response.

Reworking the hydrocarbon past for socio-ecological hydrogen futures

To overcome the shortcomings of the hydrogen futures literature as outlined above, I suggest that critical social science research should take a different conceptual starting point: hydrogen should be understood as a substance with a multiplicity of possible substance cultures shaped by the variety of historically contingent ways in which it has become part of a cultural context and practice (Hahn and Soentgen 2011, Papadopoulos et al. 2021). This contrasts with understanding it as a formed matter with a singular function (Hahn and Soentgen 2011, pp. 19 f.), which invisibilises the historical contingency of its assumed future use as a climate-neutral energy carrier. Beginning from a substance perspective may highlight the significance of the historic and present entanglement of hydrogen with hydrocarbon industries, and allows the study of its materialisation in the context of climate change against the background of hydrocarbon practices. >

The merit of this substance-focused approach has already been demonstrated, for instance, in the case of nitrogen by Ertl and Soentgen (2015). Throughout their edited volume, the partially conflicting, partially enabling materialisation of nitrogen as a war resource during World War I (Fehr 2015) as a basis for the industrialisation of food production (Uekötter 2015) and the adverse effects of food production on the environment (Matschullat et al. 2015) have all been laid out. Against this backdrop, it would be inappropriate to highlight only the positive effects of industrial nitrogen production on stabilising global food supplies, as this would render invisible the long-term eutrophication effects of fertiliser use and its fatal effects as a war resource.

Bringing this example of – different but linked – nitrogen substance cultures back to hydrogen futures research, it would be equally inappropriate to highlight only the positive effects that green hydrogen futures could have on the decarbonisation of industries. This is because the industrial production of hydrogen has so far been one of the most important sources of carbon emissions globally, and provides a justification for continued hydrocarbon extraction in combination with reutilisation of oil and gas industry knowledge, technology, and infrastructure through CCS. Furthermore, even in the case of green hydrogen, one must consider in which ways its production and use are contributing to decarbonising the future in a meaningful way. For instance, the largest green hydrogen production plant currently under construction in Europe is co-located within the Shell petroleum refinery in Rotterdam (Shell 2022). While the 200-MW electrolyser effectively displaces carbon emissions from grey hydrogen production, it is used to remove the direct carbon emissions of an inherently carbon-intensive industry. In this case, green hydrogen prolongs the existence of the hydrocarbon industry, rather than contributing to a transition away from hydrocarbons. As such, it reflects the retarding effect that CCS is already having on meaningful decarbonisation (Low and Boettcher 2020).

In response, a critical social science perspective driven by a substance culture understanding can facilitate the reworking of hydrogen's hydrocarbon past for a socio-ecological future. In agreement with the principle of the multiplicity of possible elemental futures (Papadopoulos et al. 2021) and the insight that achieving future justice requires a return to the injustices of the past (Barad 2017) to formulate adequate responses, the exploration of socio-ecological hydrogen futures thereby starts from the hydrocarbon realities of hydrogen's past. Based on this widened perspective, we can then map out what a just transition away from past knowledge, technologies, and infrastructures could look like, without running the risk of repeating past injustices by other means.

Crucially, this process of transforming hydrogen's hydrocarbon past into socio-ecological hydrogen futures needs to include the political and economic practices with which hydrogen is associated and justified. The entanglement of energy with political and economic practices has previously been demonstrated for the case of coal and oil (e.g., Mitchell 2011). Building on these insights, the achievement of socio-ecological hydrogen futures requires a rethinking of the politics of net zero and the economics of green growth that has been underpinning the increase in the relevance of hydrogen as an energy vector since 2019. National net zero plans are oftentimes entailing hydrogen as part of a new green growth regime, attempting to combine the reduction of carbon emissions with future economic growth. The underlying need to position contributions to climate change mitigation as economic is problematic. This is because it distracts from the importance of thoroughly reconfiguring the hydrocarbon past, and redirects the focus on short-term fixes rather than long-term strategies for a circular and climate-neutral economy.

Conclusion

Going forward, critical social science research on hydrogen futures needs to take into close consideration the knowledge, technology, and infrastructure that enables the emergence of the global hydrogen economy. Doing so, the partially contradicting, partially complementing pathways for producing and using hydrogen can be included in the evaluation of the socio-ecological qualities of hydrogen futures. In this article, I have suggested that a substance culture approach to studying hydrogen could effectively overcome the pre-emptive framing of hydrogen as a climate neutral energy vector and facilitate an integrated understanding of the past and future entanglements for grey, green, and blue hydrogen from the hydrocarbon past.

On this basis, meaningful interventions can be designed for the future of hydrogen. Furthermore, questions such as whether heating homes with blue hydrogen provide positive socio-ecological outcomes can be addressed by considering the different types of hydrogen and their non-hydrogen alternatives, and analysing the extent to which the hydrocarbon past has been reworked in the interest of a just transition to a circular and climate neutral economy. The interventions based on the outcome of this integrated hydrogen futures analysis could thereby take different forms, such as proposing changes in policy, participation in democratic decision-making processes, or support for issue-based public campaigns.

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Johannes Hollenhorst
Studies in sociology, anthropology, and international relations in Erfurt, DE, Budapest, HU, London, UK. Since 2021 PhD candidate at the Department of Sociology at London School of Economics and Political Science, UK. Research interests: energy transition, materiality of climate change, alternative futures.