The Power of Hydrogen

The emergent eco-social relations of the capitalist hydrogen economy

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Abstract:

The production, use and trade of hydrogen fuels as an energy medium across different sectors – the hydrogen economy – is being articulated as a vision of the future by various global energy actors. Hydrogen's spatio-temporal profile makes it suitable to integrate into the fossil fuel landscape and reproducing the economic power embedded within it. Through a thematic analysis of documents shaping the emergent hydrogen economy, we can see the integration of fossil fuels and their infrastructure into this economy, producing a dynamic of mitigation deterrence, as well as an entrenchment of relations of ecologically unequal exchange in the global distribution of the economy. Ultimately, the hydrogen economy is understood to embody extractivist eco-social relations. Building a political movement and alternative economic vision through ecosocialism is argued as key to challenging the power of this emergent economy.

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Abbreviation list

CCS – Carbon capture and storage

CCUS – Carbon capture utilization and storage

ETC – Energy Transitions Council

EU – European Union

IAMs – Integrated assessment models

IEA – International Energy Agency

IPCC – International Panel on Climate Change

IRENA – International Renewable Energy Agency

LNG – Liquid natural gas

WTO – World Trade Organization

1. Introduction: Igniting the hydrogen economy

As the climate crisis accelerates, driven by the progressive expansion of capitalist industrial production, those same progressive forces churn out new technological innovations purported to be able to resolve the crisis. Those of us who simultaneously see the urgent necessity of emissions abatement, while also recognizing the structural impetus against such a change in capitalism - as well as the multiple social and ecological violences that capitalism enacts beyond climate change – are faced with the difficult task of balancing a pragmatic evaluation of the tools available to us and rigorously critiquing the pitfalls and contradictions of such tools and the system that produces them. Finding this balance is crucial. A rejection of any kind of change from within present conditions locks us into waiting for the future to bring itself about. However, accepting capitalist techno-solutions as necessary, even reluctantly, means not only accepting their consequences as necessary and but also failing to recognize that, due to the deeply structural character of capitalism's ecological contradiction, these technologies are often non-solutions. In recent years, hydrogen as an energy carrier has emerged as one of many capitalist techno-solutions for reducing greenhouse gas emissions. Hydrogen is touted as being able to decarbonize the "hard to decarbonize" sectors like long distance shipping and steel production, and international agencies, oil companies, and new business ventures push forward the idea of a hydrogen economy, in which hydrogen acts as the energetic medium fueling significant parts of the global economy. But how do we interpret such a vision, and can it really help us decarbonize? Is hydrogen another dubious techno-capitalist solution, or does it have key function to play in global emissions mitigation and in creating an environmental just world?

The original concept of the hydrogen economy dates back to the 1970s[1], first articulate by J. O'M. Bockris, who imagined nuclear reactors on floating platforms converting the water below them into hydrogen, which from there would flow outward to fuel the rest of the economy. Although climate change

[1] Alexandra M. Oliveira, Rebecca R. Beswick, and Yushan Yan, "A Green Hydrogen Economy for a Renewable Energy Society," *Current Opinion in Chemical Engineering* 33 (2021/09/01/ 2021), https://dx.doi.org/https://doi.org/10.1016/j.coche.2021.100701, John O' M. Bockris, "The Hydrogen Economy: Its History," *International Journal of Hydrogen Energy* 38, no. 6 (2013/02/27/ 2013), https://dx.doi.org/https://doi.org/10.1016/j.ijhydene.2012.12.026.

had not yet become a significant public concern, Bockris saw this economy as addressing the problems of "heat and air pollution" and that it would "not imply a pollutional limit on growth."[2] The first wave of hydrogen hype began in the 1990s, with significant enthusiasm around the development of fuel cell electric vehicles, but the industry failed to materialize[3]. Now, fifty years since the birth of the concept, the foundation of the economy finally seems to be taking shape, and if it is to scale to the level to which it aspires, the next few years are critical for developing the technology, infrastructure, and market[4]. Hydrogen features as a key technology in the most recent report by Working Group Three of the Intergovernmental Panel on Climate Change[5]. According to the IEA, 26 governments have released hydrogen plans, and electrolyser production and research and development funding have grown significantly[6]; according to the Hydrogen Council 680 large-scale projects have been announced by the industry[7].

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[2] J. O'M. Bockris, "A Hydrogen Economy," *Science* 176, no. 4041 (1972), https://dx.doi.org/doi:10.1126/science.176.4041.1323.

[3] Michael Ball, and Marcel Weeda, "The Hydrogen Economy – Vision or Reality?11this Paper Is Also Published as Chapter 11 'the Hydrogen Economy – Vision or Reality?' in Compendium of Hydrogen Energy Volume 4: Hydrogen Use, Safety and the Hydrogen Economy, Edited by Michael Ball, Angelo Basile and T. Nejat Veziroglu, Published by Elsevier in 2015, Isbn: 978-1-78242-364-5. For Further Details See: Http://Www.Elsevier.Com/Books/Compendium-of-Hydrogen-Energy/Ball/978-1-78242-364-5," *International Journal of Hydrogen Energy* 40, no. 25 (2015/07/06/ 2015), https://dx.doi.org/https://doi.org/10.1016/j.ijhydene.2015.04.032.

[4] Adrian Odenweller et al., "Probabilistic Feasibility Space of Scaling up Green Hydrogen Supply," *Nature Energy* 7, no. 9 (2022/09/01 2022), https://dx.doi.org/10.1038/s41560-022-01097-4.

[5] L. Clarke, Y.-M. Wei, A. De La Vega Navarro, A. Garg, A.N. Hahmann, S. Khennas, I.M.L. Azevedo, A. Löschel, A.K. Singh, L. Steg,, and K. Wada G. Strbac, *Energy Systems. In Ipcc, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group Iii to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* (Cambridge, UK and New York, NY, USA: 2022), https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf, P. Jaramillo, S. Kahn Ribeiro, P. Newman, S. Dhar, O.E. Diemuodeke, T. Kajino, D.S. Lee, S.B. Nugroho, X. Ou,, and J. Whitehead A. Hammer Strømman, *Transport. In Ipcc, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group Iii to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, Cambridge, UK and New York, NY, USA. : 2022), https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf.

[6] IEA, *Global Hydrogen Review 2022* (Paris: 2022), https://www.iea.org/reports/global-hydrogen-review-2022

[7] Hydrogen Council, *Hydrogen Insights* (2022), https://hydrogencouncil.com/wp-content/uploads/2022/09/Hydrogen-Insights-2022-2.pdf.

Most existing hydrogen production – around 90%[8] - is produced using fossil fuels, mostly through steam reforming using natural gas, specifically methane[9]. This is referred to as grey hydrogen. When fossil-based hydrogen production is coupled with carbon capture and storage (CCS), hydrogen is considered blue hydrogen. There are currently few blue hydrogen production facilities, only seven as of 2022[10], and as of 2020 blue hydrogen made up only 0.7% of hydrogen production[11]. When hydrogen is produced through the use of renewable energy, it is considered green hydrogen. This is generally done through electrolysis, the splitting of water into its based components with electricity. Current green hydrogen production is also almost non-existent, making up only 0.03% of global hydrogen production as of 2020[12]. However, if implement, it has the technical potential to be a completely emissions free fuel, as long as all upstream associated emissions are eliminated[13].

The environmental considerations of hydrogen are not limited to production, but must be extended to consumption. Currently, hydrogen is primarily used in chemical manufacturing processes, specifically ammonia for fertilizer, ethanol, and crude oil refining[14]. However, hydrogen is being explored as a fuel for many other industries. It is generally recognized for its ability to decarbonize the "hard to decarbonize" sectors, like long distance transport and heavy industry. Hydrogen is being considered for its applications in long distance maritime shipping and aviation[15] and as an option for green steel manufacturing[16] and

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[8] Norazlianie Sazali, "Emerging Technologies by Hydrogen: A Review," *International Journal of Hydrogen Energy* 45, no. 38 (2020/07/31/ 2020), https://dx.doi.org/https://doi.org/10.1016/j.ijhydene.2020.05.021.
[9] Sema Z. Baykara, "Hydrogen: A Brief Overview on Its Sources, Production and Environmental Impact," *International Journal of Hydrogen Energy* 43, no. 23 (2018/06/07/ 2018), https://dx.doi.org/https://doi.org/10.1016/j.ijhydene.2018.02.022, Sazali.
[10] Global CCS Institute, *Global Status of Ccs* (Global CCS Institute, 2022), https://status22.globalccsinstitute.com/.
[11] Mona Wappler et al., "Building the Green Hydrogen Market – Current State and Outlook on Green Hydrogen Demand and Electrolyzer Manufacturing," *International Journal of Hydrogen Energy* 47, no. 79 (2022/09/15/ 2022), https://dx.doi.org/https://doi.org/10.1016/j.ijhydene.2022.07.253.
[12] Wappler et al.
[13] Furat Dawood, Martin Anda, and G. M. Shafiullah, "Hydrogen Production for Energy: An Overview," *International Journal of Hydrogen Energy* 45, no. 7 (2020/02/07/ 2020), https://dx.doi.org/https://doi.org/10.1016/j.ijhydene.2019.12.059.
[14] Sazali.
[15] Talal Yusaf et al., "Sustainable Aviation&Mdash;Hydrogen Is the Future," *Sustainability* 14, no. 1 (2022), https://www.mdpi.com/2071-1050/14/1/548, P. Gunasekar, S. Manigandan, and Praveen Kumar T.R, "Hydrogen as the Futuristic Fuel for the Aviation and Aerospace Industry – Review," *Aircraft Engineering and Aerospace Technology* 93,

other heat or energy intensive industrial processes[17]. Outside of the hard to decarbonize sectors, hydrogen is being explored as an option for road transport, domestic heating, and backup energy generation[18].

While climate and environmental concerns are cited as reason for rapidly developing a hydrogen economy, such an economy is not without climate and environmental risks. While burning hydrogen does not produce greenhouse gases, hydrogen itself can have indirect warming effects. This happens in three ways: hydrogen bonds with hydroxyl radicals (OH) which would otherwise react with methane, increasing the atmospheric lifetime of methane; hydrogen produces chain reactions resulting in an increase in tropospheric O_3, a potent greenhouse gas; and hydrogen oxidizing in the stratosphere produces water vapour which increases the stratosphere's radiative capability. Due to the small size of hydrogen molecules and hydrogen's ability to cause metal embrittlement, hydrogen is prone to leakage. If deployed at a large scale, hydrogen is estimated to potentially cause between 0.01-0.1 degrees of warming by the 2050[19]. The full significance of hydrogen's climate impacts also depends on the degree to which it allows us to decarbonize by replacing more emissions intensive fuels. This is not only a matter of how widely hydrogen is adopted but by which sectors; while hydrogen can compete against fossil fuels, it can also compete against direct electrification, delaying changes that might help decarbonize more radically and efficiently, while also locking us into fossil fuel infrastructure if hydrogen production falls short[20]. This is particularly true for road transportation – while there is a push by different actors in the industry to develop hydrogen fuel cell vehicles, electric vehicles are more cost and energy effective for small and

no. 3 (2021), accessed 2023/04/14, https://dx.doi.org/10.1108/AEAT-07-2020-0145, Jaramillo, and A. Hammer Strømman, Selma Atilhan et al., "Green Hydrogen as an Alternative Fuel for the Shipping Industry," *Current Opinion in Chemical Engineering* 31 (2021/03/01/ 2021), https://dx.doi.org/https://doi.org/10.1016/j.coche.2020.100668.

[16] Floris Swennenhuis, Vincent de Gooyert, and Heleen de Coninck, "Towards a Co2-Neutral Steel Industry: Justice Aspects of Co2 Capture and Storage, Biomass- and Green Hydrogen-Based Emission Reductions," *Energy Research & Social Science* 88 (2022/06/01/ 2022), https://dx.doi.org/https://doi.org/10.1016/j.erss.2022.102598, Wenguo Liu et al., "The Production and Application of Hydrogen in Steel Industry," *International Journal of Hydrogen Energy* 46, no. 17 (2021/03/08/ 2021), https://dx.doi.org/https://doi.org/10.1016/j.ijhydene.2020.12.123.

[17] Clarke, and G. Strbac.

[18] Clarke, and G. Strbac.

[19] I. B. Ocko, and S. P. Hamburg, "Climate Consequences of Hydrogen Emissions," *Atmos. Chem. Phys.* 22, no. 14 (2022), https://dx.doi.org/10.5194/acp-22-9349-2022.

[20] Falko Ueckerdt et al., "Potential and Risks of Hydrogen-Based E-Fuels in Climate Change Mitigation," *Nature Climate Change* 11, no. 5 (2021/05/01 2021), https://dx.doi.org/10.1038/s41558-021-01032-7.

medium duty vehicles, and are emerging as more promising for heavy duty vehicles[21]. Blue hydrogen is seen as a viable option by the industry, but its full decarbonization potential has yet to be proven, since blue hydrogen production using natural gas yields higher emissions than simply burning natural gas for heat[22].

Hydrogen also comes with other ecological and social challenges. Hydrogen production requires water, land, and metals. If green hydrogen is produced using renewables, then all the eco-social complexities of renewable energy will become entangled in hydrogen. The same goes for shipping, aviation, steel production, mining, and any other industries in which hydrogen may be applied. So far, however, there has been little academic engagement with the eco-social dimensions of the hydrogen economy. The majority of it comes from the environmental and energy justice tradition and builds on the work of Sovacool and others[23]. Most work has offered preliminary examinations of justice considerations for hydrogen. Some scholars have examined hydrogen abstractly to highlight potential injustices that might emerge[24], while others examine specific hydrogen projects, mainly in the global south in partnership with European nations, to explore potential or existing injustices[25].

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[21] Patrick Plötz, "Hydrogen Technology Is Unlikely to Play a Major Role in Sustainable Road Transport," *Nature Electronics* 5, no. 1 (2022/01/01 2022), https://dx.doi.org/10.1038/s41928-021-00706-6, Ueckerdt et al.

[22] Robert W. Howarth, and Mark Z. Jacobson, "How Green Is Blue Hydrogen?," *Energy Science & Engineering* 9, no. 10 (2021), https://dx.doi.org/https://doi.org/10.1002/ese3.956.

[23] Benjamin K. Sovacool et al., "New Frontiers and Conceptual Frameworks for Energy Justice," *Energy Policy* 105 (2017/06/01/ 2017), https://dx.doi.org/https://doi.org/10.1016/j.enpol.2017.03.005, Benjamin K. Sovacool, and Michael H. Dworkin, "Energy Justice: Conceptual Insights and Practical Applications," *Applied Energy* 142 (2015/03/15/ 2015), https://dx.doi.org/https://doi.org/10.1016/j.apenergy.2015.01.002.

[24] K. J. Dillman, and J. Heinonen, "A ?Just? Hydrogen Economy: A Normative Energy Justice Assessment of the Hydrogen Economy," *Renewable & Sustainable Energy Reviews* 167 (Oct 2022), https://dx.doi.org/10.1016/j.rser.2022.112648, Tobias Kalt, and Johanna Tunn, "Shipping the Sunshine? A Critical Research Agenda on the Global Hydrogen Transition," *Gaia* 31, no. 2 (2022 2022), https://dx.doi.org/10.14512/gaia.31.2.2.

[25] Robert Lindner, "Green Hydrogen Partnerships with the Global South. Advancing an Energy Justice Perspective on “Tomorrow's Oil”," *Sustainable Development* n/a, no. n/a (2022), https://dx.doi.org/https://doi.org/10.1002/sd.2439, Franziska Müller, Johanna Tunn, and Tobias Kalt, "Hydrogen Justice," *Environmental Research Letters* 17, no. 11 (2022/11/02 2022), https://dx.doi.org/10.1088/1748-9326/ac991a, Amanda N. Ullman, and Noah Kittner, "Environmental Impacts Associated with Hydrogen Production in La Guajira, Colombia," *Environmental Research Communications* 4, no. 5 (2022/05/06 2022), https://dx.doi.org/10.1088/2515-7620/ac68c8, Katharina Löhr et al., "Just Energy Transition: Learning from the Past for a More Just and Sustainable

Kalt and Tunn call for an ecosocialist engagement with the emerging hydrogen economy, and indeed there appears to be no existing ecosocialist or ecological Marxist academic engagement with hydrogen[26]. This paper attempts to fill the gap in this literature by applying an ecological Marxist analysis to the emerging capitalist hydrogen economy, as well as by proposing considerations for an ecosocialist vision of a hydrogen economy. Both of these aims build on a conceptual foundation of understanding fuel and energy systems as embodied eco-social relations. The purpose of this paper is to understand how a future capitalist hydrogen economy might interact with, and potentially reproduce, the existing fossil fuel economy. To understand this, I examine documents which outline and seek to shape this emergent hydrogen economy.

My questions in analyzing these documents are:

1. What is the envisioned role of fossil fuels and related technologies in the emerging hydrogen economy?
2. What are the ecological and social relations embodied by the physical organization and spatial distribution of the emerging hydrogen economy?
3. How do the eco-social relations of the emerging capitalist hydrogen economy inform the possibility of an alternative hydrogen economy?

This paper is divided into three parts. In the first part, I engage with theories of the real subsumption of nature, ecologically unequal exchange, mitigation deterrence and energy landscapes to develop an eco-socialist approach to conceptualizing the hydrogen economy. In the second part, I analyze documents from various international actors to understand the global dynamics of the emergent hydrogen economy, specifically focusing the use of fossil fuels and associated infrastructure and the global distribution of the economy. In the third part, I discuss the potential and considerations for an ecosocialist hydrogen economy.

Hydrogen Transition in West Africa," *Land* 11, no. 12 (2022), https://www.mdpi.com/2073-445X/11/12/2193.

[26] Searches in google scholar and web of science for "hydrogen" or "hydrogen economy" combined with "ecosocialism," "ecological marxism," "marxism," "historical materialism," or "political ecology" only revealed the few justice related papers which were already found in earlier searches, which are also cited in this section.

2. A critical theory of fuels as eco-social relations

Understanding the function of hydrogen in capitalism and assessing the ecological and social implications of the hydrogen economy requires understanding the role that energy sources and fuels play within capitalist society. To do so, I employ an ecosocialist theoretical approach of understanding fuels as materially embedded social relations. This approach builds on an understanding of capitalist fossil fuels use as the real subsumption of nature, of global trade dynamics as ecologically unequal exchange, of capitalist techno-solutions as forms of mitigation deterrence, and of economic power as embedded in fossil fuel landscapes. Taken together, these theoretical perspectives allow us to examine how existing forms of economic power structure the development of the hydrogen economy, and what kinds of ecological and social arrangements the hydrogen economy might (re)produce.

What would be the eco-social significance of adopting hydrogen as a main energy carrier for certain sectors of the economy? As one of the reports by the International Renewable Energy Agency (IRENA) states, "there is a change from energy stocks (i.e. fossil fuels reserves) to energy flows"[27]. Stocks and flows denote the spatio-temporal profile of an energy source, where stocks are a source of materially accumulated energy which, once extracted, is mobile through space and time, whereas flows denote energy which moves through and across the earth, part of climatic and geological processes that are spatially and temporally specific. Oil is a stock: it can be drilled, shipped around the globe, and burned at varying rates. Wind is a flow: the wind blows at changing speeds in different, but specific, locations; the energy it generates can be captured through windmills and transported through cables, but storing it and controlling the rate at which it is available is more difficult.

However, the development of hydrogen fuels complicates this distinction somewhat. Hydrogen is an energy carrier, meaning it is not found as a source of energy awaiting to be tapped but rather is produced from other forms of energy at a net loss. What hydrogen allows for is the conversion of energy sources, either renewables or fossil fuels, into a new and common medium, one which shares many of the physical properties of fossil fuels. Understanding what kind

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[27]IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and the Way Forward* (Abu Dhabi: 2022), 19, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Global_hydrogen_trade_part_1_2022_.pdf?rev=f70cfbdcf3d34b40bc256383f54dbe73.

of change a hydrogen economy would bring involves understanding the significance of being able to endow renewable energy sources with the spatio-temporal mobility of fossil fuels.

2.1 Ecosocialism: Socio-ecological metabolism and real subsumption of nature

Ecosocialism, or ecological Marxism, has made key contributions to understanding how fossil fuel have enabled the exploitation of labour and nature, specifically through the mediation of the socio-ecological metabolism. As John Bellamy Foster has shown, the concept of metabolism was key for Marx in developing his concept of labour. Marx understood labour, in its general form, as a metabolic relationship between nature and society, in which materials and energy are exchanged, and both nature and the worker are changed by the interaction[28]. A metabolic understanding of labour reveals that the means of production and reproduction are at the same time external and integral to human beings: tools and social system function as natural extensions to the human body, and the movement of the human body itself is conceptualized as a natural force put into motion. Being both part of the human and external to it, the specific ways in which humans metabolize nature are liable to intervention and appropriation, and as Andreas Malm and Søren Mau argue, this is what makes exploitation and economic domination possible[29]. The appropriation of the product of another's labour happens not only through force, but also through the material and social structures through which human beings interact with nature to produce and reproduce themselves.

The historically specific transformation of humanity's metabolic relationship with nature under capitalism is well captured by the concepts of formal and real subsumption of labour and nature. For capitalists to appropriate the value produced by workers, they must insert themselves into the process of production. This is generally done through ownership of the means of production, a social institution through which capitalists can lay claim to the goods a worker has produced. When the self-insertion of the capitalist into the

[28] John Bellamy Foster, *Marx's Ecology* (New York: Monthly Review Press, 2000).
[29] A. Malm, "Fossil Capital: The Energy Basis of Bourgeois Property Relations," in *Fossil Capital: The Rise of Steam Power and the Roots of Global Warming* (Verso, 2016), Søren Mau, *Mute Compulsion: A Marxist Theory of the Economic Power of Capital* (Verso Books, 2023).

process is performed without a transformation of the production process itself, the subsumption of labour is *formal*. However, competition and the pressure to extract surplus value push the capitalists towards the *real* subsumption of labour – the transformation and intensification of the labour process with the goal of facilitating further capital accumulation. This change is captured, for instance, in the shift from artisanal production to industrial factory production. For nature, formal subsumption refers to the appropriation of natural resources in the process of capital accumulation, while real subsumption refers to the transformation of natural processes themselves to suit the needs of capital accumulation[30].

As Malm argues in *Fossil Capital*, capitalism's adoption of fossil fuels can be understood as part of the real subsumption of nature. Energy sources have been central to capitalist production and accumulation. The competitive pressures to increase productive capacities and to increase the rate of exploitation of workers lead to the substitution of human or animal energy to other "prime movers" that could be attached to the labour process, like water, wind, steam, oil, or electricity. This, according to Malm, is where fossil fuels enter the picture. In his historical examination of the integration of fossil fuels into capitalism, Malm shows that coal was preferable to water because it facilitated the exploitation of workers. Fossil fuels like coal are a stock, source of energy mobile in space and time, and their use allowed production to be moved from a specific location based on the availability of running water to a city where there was a larger pool of workers and more competition between them. The ability to control the time and rate at which energy was used also meant that production was more resilient to strikes and less dependent on skilled workers. The intensification and mechanization of production meant that workers could be reduced to mere appendages of a machine, and thus more easily replaceable[31].

But is the use of fossil fuels actually the real subsumption of nature rather than just formal; that is, could it not be considered an appropriation of natural resources rather than a transformation of natural processes themselves? The answer is that it depends on the frame of analysis. While the original concept of the subsumption of nature referred to the intensification to biological processes in "nature based industries" like agriculture, I agree with Mau's assessment that

[30] Malm, in *Fossil Capital: The Rise of Steam Power and the Roots of Global Warming*.
[31] Ibid.

such a definition remains too narrow[32]. Taking a global and geo-historical perspective, unearthing and consuming fossil fuels is not simply an appropriation of resources but a transformation of how the energy of the sun interacts with surface of the earth across time and a transformation of the carbon cycle. Renewables can be similarly understood; they are a transformation of how the energy from the sun, manifest in either direct sunlight or wind, interacts with the surface of the planet. Viewing society and nature as unified through the concept of the socio-ecological metabolism, we see that fossil fuels and renewables change how humans metabolize the energy of the sun, as well as how they harvest, cultivate, and produce other forms of energy. Ultimately, the concept of the real subsumption of nature derives its value from what it can reveal: that in a capitalist society, the movement of energy and organic compounds across the earth and through human societies becomes altered to suit the needs of capital accumulation. The specific nature of the alteration that fossil fuels bring about is the appropriation of materialized energy which becomes spatially and temporally mobile; this mobility in turn facilitates the exploitation of nature and labour by extending competitive pressures across space and enforcing extraction on "peripheral" populations. As Malm emphasizes, the real subsumption of labour happens via the real subsumption of nature[33]. In examining hydrogen, we should be attentive to the ways in which the technology organizes the social-ecological metabolism of energy to suit the needs of capital accumulation.

2.2 Ecologically unequal exchange

One way of understanding the global exploitation that fossil fuels have facilitated is through the concept of ecologically unequal exchange. Ecologically unequal exchange builds on the ecological Marxist concept of the metabolic rift and the World Systems Theory insight that there is an asymmetric flow of resources between global "core" regions and "peripheries"[34]. The concept of ecologically unequal exchange argues that global trade consists of net transfers of embodied materials, energy, land and labour, concealed through the use of

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[32] Mau, 255.
[33] Malm, in *Fossil Capital: The Rise of Steam Power and the Roots of Global Warming*, 309-14.
[34] Martin Oulu, "Core Tenets of the Theory of Ecologically Unequal Exchange," *Journal of Political Ecology* 23 (2016), http://www.scopus.com/inward/record.url?scp=85012034072&partnerID=8YFLogxK.

general-purpose money. Ecologically unequal exchange can be understood as a form of environmental load displacement, where the environmental (and labour) requirements, as well as consequences, of industrial production are sourced from outside a country's borders. This theory has been empirically tested: Alf Hornborg shows how the growth of the British economy during the industrial revolution was not the result of the inherent productivity of the steam engines, but rather that steam engines were made productive by a flow of embodied land and labour from abroad, particularly slave labour and land for cotton production in the United states[35]. A more recent study by Hornborg, Christian Dorninger, and others has shown that there is a net flow of embodied land, labour, energy and materials from upper middle, lower middle, and low-income countries towards high income countries, and that there is also a concentration of added value accumulating in high income countries[36]. This work reveals that economic development in the wealthiest parts of the world is, and has historically been, dependent on the appropriation of embodied land, labour, energy and materials.

In applying a theory of ecologically unequal exchange to the hydrogen economy, there are three key dimensions to consider. The first is the role of technology; as Hornborg argues, technology in a capitalist society is seen as having inherent productive capacities, meaning that innovations and objects themselves are seen as generating economic value. Hornborg challenges such an understanding by seeing technologies as embodied social relations of exchange. The steam engine and the power loom are not productive in their own right but are made productive by the labour, cotton, and coal (and the land and resources they embody) to pass through them. Technologies are both dependent on and reinforce the particularly social relations that sustain them[37]. In this case of hydrogen, the question for my analysis is "what kind of social relations of production does hydrogen technology embody?"

The second dimension is the role of general-purpose money. Money, according to Hornborg, is a way of concealing asymmetries in exchange.

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[35] Alf Hornborg, *Global Ecology and Unequal Exchange: Fetishism in a Zero-Sum World* (New York: Routledge, 2011).
[36] Christian Dorninger et al., "Global Patterns of Ecologically Unequal Exchange: Implications for Sustainability in the 21st Century," *Ecological Economics* 179 (2021/01/01/ 2021), https://dx.doi.org/https://doi.org/10.1016/j.ecolecon.2020.106824.
[37] Hornborg, 40-41.

Assigned monetary values allow for the appearance of equal exchange, while further analysis shows that at an aggregate global level, these exchanges are materially unequal. Dorninger et al. show that poorer nations generate lower added value and richer nations generate higher added value, the result of which is that high income nations are the only group with a net trade surplus. The lower added value produced by low income countries is partly attributed to different productive capacities of labour due to technology, but also to different values ascribed to labour and land. Goods with higher added value produced by high income countries are "commodities representing lower remaining productive potential," or high embodied entropy, whereas poorer countries typically produce goods with higher remaining productive capacity, or lower embodied entropy (meaning higher potential exergy, i.e. more capacity to do work) which "inexorably leads to asymmetric transfers of resources"[38]. In other words, poorer countries pay high prices for commodities that will generate less exchange value, and richer countries pay low prices for commodities that will generate more exchange value. Unequal exchange thus partly occurs through the unequal valuation of land, labour, energy, and materials, and the positions that countries occupy in global supply chains are reinforced by this valuation. For hydrogen, we should examine how different hydrogen technologies, resources required for its production, and hydrogen itself, are valued.

The third dimension is the concept of environmental load displacement. Environmental load displacement refers to the transfers of environmental costs and harms from wealthy countries to poorer countries. This is done by locating industries with harmful environmental impacts or with space requirements that exceed what a country is able or willing to meet in another country. What makes this concept distinct from that of ecologically unequal exchange is its qualitative character. Ecologically unequal exchange posits a quantitative imbalance in global trade. Environmental load displacement highlights that this asymmetric flow is one that privileges the comfort and wellbeing of certain populations while imposing environmental and social consequences on others. This concept thus primes us to look for injustices; in the case of hydrogen, we should ask what kinds of environmental and social harms the industry produces, and which populations will be subjected to them.

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[38] Dorninger et al.

2.3 Mitigation deterrence

One of the primary harms produced by all kinds of economic and industrial activity is climate change, brought on by the emissions of greenhouse gases, primarily from carbon dioxide emissions produced from the burning of fossil fuels. While hydrogen is often lauded for its decarbonization potential[39], the reality of the technology is that it intersects with many aspects of the fossil fuel industry. Almost all of current hydrogen is produced using fossil fuels, mostly through steam reforming of methane[40]. One of the current uses of hydrogen is in crude oil refining. Blue hydrogen, considered a viable alternative by many actors, is made using fossil fuels, specifically natural gas and coal. Blue hydrogen also relies on CCS and allows for the continued use of fossil fuels in various sectors. Hydrogen, having the same spatio-temporal mobility as fossil fuels, is also compatible with various forms of fossil fuel infrastructure, potentially extending their use into the future. While hydrogen fuels technically having the potential to be completely emissions free if all upstream emissions are eliminated[41], their potential compatibility with certain aspects of fossil fuel usage should prompt us to examine the ways in which they might actually hinder decarbonization.

We should, for instance, consider that hydrogen compatibility with fossil fuel infrastructure might hinder or slow the transition to new, less carbon intensive infrastructure. As Ueckerdt et al. argue, attempting to apply hydrogen to certain sectors, like heating for homes or for small passenger vehicles, could compete against direct electrification, which is cheaper and more efficient in such end-use sectors. If hydrogen production then falls short, we then run the risk of being locked into fossil fuel infrastructure[42]. Further, if capitalists invest in new infrastructure that is both hydrogen and fossil fuel friendly, they will be interested in using and retrieving the full value invested into this infrastructure, regardless of whether or not hydrogen has scaled up to meet demand. This kind of economic lock in produced by the risk of stranded assets connects to a broader risk that hydrogen poses – the risk of mitigation deterrence. The concept of mitigation deterrence comes on the economic concept of moral hazard, which refers to when an economic tool creates a situation where actors

[39] Dawood, Anda, and Shafiullah.
[40] Baykara, Sazali.
[41] Dawood, Anda, and Shafiullah.
[42] Ueckerdt et al.

have a reason to act against the original purpose of the tool itself, either because they have the potential to make a profit or because they are economically protected from the costs of their actions[43]. In the context of mitigation, moral hazard identifies the risk that certain technologies or policies that are supposedly intended to mitigate climate change may, for one reason or another, act against mitigation, often because these policies and technologies are more cost effective[44]. Some scholars have argued that carbon capture and storage or geoengineering technologies like solar-radiation management are forms of mitigation deterrence[45]. The anticipated potential of these technologies, relying on discourses of technological optimism, becomes built into climate change mitigation strategies and integrated assessment models (IAMs), even at the level of the International Panel on Climate Change (IPCC)[46]. The effect of this is to displace mitigation into the future, while authorizing continued extraction of fossil fuels in the present. These technologies can be thought of as part of a future making process, one which articulates a vision for what is to come and also prescribes what can and should be done in the present. As the hydrogen economy involves the potential use of carbon capture and storage as well as other fossil fuel related technologies, we should look closely at how it might act as a form of mitigation deterrence.

From an ecological Marxist perspective, we should also consider mitigation deterrence more expansively then the specific attachment to profitability of fossil fuels. While this is a real and important dimension, there is also more to it. Understanding the role that fossil fuels have played and continue to play in capital accumulation, we must also understand that fossil fuels are not only valuable as a commodity off of which a specific portion of the capitalist class

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[43] Wim Carton et al., "Is Carbon Removal Delaying Emission Reductions?," *WIREs Climate Change* n/a, no. n/a (2023), https://dx.doi.org/https://doi.org/10.1002/wcc.826.
[44] Nils Markusson, Duncan McLaren, and David Tyfield, "Towards a Cultural Political Economy of Mitigation Deterrence by Negative Emissions Technologies (Nets)," *Global Sustainability* 1 (2018), https://dx.doi.org/10.1017/sus.2018.10.
[45] Markusson, McLaren, and Tyfield, Duncan McLaren, "Mitigation Deterrence and the "Moral Hazard" of Solar Radiation Management," *Earth's Future* 4, no. 12 (2016), https://dx.doi.org/https://doi.org/10.1002/2016EF000445, Andreas Malm, and Wim Carton, "Seize the Means of Carbon Removal: The Political Economy of Direct Air Capture," *Historical Materialism* 29, no. 1 (16 Mar. 2021 2021), https://dx.doi.org/https://doi.org/10.1163/1569206X-29012021, Carton et al.
[46] R. Slade M. Pathak, P.R. Shukla, J. Skea, R. Pichs-Madruga, D. Ürge-Vorsatz, *Technical Summary. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group Iii to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, UK and New York, NY, USA: 2022).

profits. As Malm argues, fossil fuels are unique as a commodity because they are used "across the spectrum of commodity production" and have thus become "the general lever for surplus-value production"[47]. Fossil fuels are a condition of possibility for the current system of capital accumulation, meaning that capitalists are not only invested in their specific profitability but also in the entire global economy for which they allow. The interrelation of fossil fuels, carbon capture and storage, renewable energies, and hydrogen must be understood not only through the profitability of fossil fuels but also through the social and economic arrangements which have been constructed around them.

2.4 The mute compulsion of the fossil fuel landscape

The deep systemic investment in the social and economic relations that have been built upon the energic foundation of fossil fuels is well captured by Wim Carton's concept of the fossil fuel landscape[48]. The concept, which Carton defines as the "historical, socio-ecological legacy of fossil capitalism" refers to both the physical and social structuring of society around fossil fuels. Denoting all the infrastructure dedicated to producing, shipping and consuming fossil fuels, as well as the "everyday geography" of fossil fuel consumption - all the ways in which our daily lives have been structured by these fuels - it reveals the deep entrenchment of these fuel in the contemporary world. This entrenchment not only structures the present but the future; as fossil fuels compose so much of our current reality their continuation seems like a necessary or natural part of the future. The landscape thus possesses an "inertia" which make it resistant to change. As Carton stresses however, resistance to change does not mean the impossibility of change, and the concept of the fossil fuel landscape does not imply capitalism's inability to decarbonize but rather suggests that decarbonization will be a delayed and extended process.

What Carton describes as the "inertia" of the fossil fuel landscape could also be seen as the "mute compulsion of economic relations" as articulated by Marx and further developed by Søren Mau[49]. The mute compulsion of economic relations refers to the way in which power becomes embedded in economic processes (rather than only being exerted through violence or ideology). The

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[47] Malm, in *Fossil Capital: The Rise of Steam Power and the Roots of Global Warming*, 288.
[48] Wim Carton, "Dancing to the Rhythms of the Fossil Fuel Landscape: Landscape Inertia and the Temporal Limits to Market-Based Climate Policy," *Antipode* 49, no. 1 (2017), https://dx.doi.org/https://doi.org/10.1111/anti.12262.
[49] Mau.

possibility of economic power emerges both from the creation of the proletariat - the separation of some humans from their means of subsistence - as well as through the subordination of production to profit and competition, in other words to the market. Through both of these phenomena, economic structures exert power and act out the logic of capital, through which all economic activity becomes structured towards the extraction of surplus value, or as Mau refers to it, the valorization of value. Workers are compelled to sell their labour out of material necessity, and capitalists are compelled to exploit the worker by the pressures of competition. Once this economic reality is in place, it also lays the groundwork for its own reproduction; competition dictates the reinvestment of profits into more fixed capital, and the immanent necessity of capitalism for social reproduction presents itself as eternal necessity. Capitalism exerts economic power by the application of a material and social logic which is self-reinforcing.

It is on the level of the fossil fuel landscape and the mute compulsion of its economic relations that we can connect the concepts of the real subsumption of nature, ecologically unequal exchange, and mitigation deterrence. What is most significant about the concept of a fossil fuel landscape is that it allows us to see fuels like oil or hydrogen not as discreet objects but rather as sets of social relations. As Matthew T. Huber argues, there is "no such thing as oil-in-itself. Oil is better understood as a social relation," meaning that the productive capacity of oil, its societal impact, and the immense power it seems to exert are not intrinsic, self-contained properties of the fuel, but rather emergent properties of the social relations in which is oil embedded[50]. This view aligns with Hornborg's understanding of technology as embodied social relations. Further, a fossil fuel *landscape* — which as Carton emphasizes implies both the physical and cultural characteristics of space — signifies nature reshaped to suit the extraction, movement and consumption of fossil fuels. It also calls forward the specifically spatial character of this economic regime, that it relies on the production of distance — through appropriation and fragmentation of production processes - and annihilation of distance — through the creation of mobility, specifically of energy and material resources. The inertia, or mute compulsion, of a fuel landscapes reflects the reproduction of the particular economic and social

[50] Matthew T. Huber, *Lifeblood: Oil, Freedom, and the Forces of Capital* (University of Minnesota Press, 2013), 4.

relations which this landscape embodies, and its resistance to certain kinds of changes, like decarbonization.

What a concept of landscape allows us to see is the power that is exercised by the material organization of the economy, and how the logic of economic relations, which present themselves as necessary, facilitate their self-reproduction. Fossil fuels have structured the current economic system by instituting massive separations in the physical and social processes of production and consumption. The production of cheap energy is both an outcome and a condition of the globally unequal appropriation of resources and allocation of environmental consequences. Decarbonization poses a challenge to the continued use of fossil fuels; technological "solutions" are brought in not only to sustain their use but to sustain the relations of production they allow for. A major force shaping the development of new energy technology is the *mute compulsion of the fossil fuel landscape*, the economic and social logic that is embodied by existing energy infrastructure, politics, and culture. The fossil fuel landscape can thus be seen as the physical and social space into which fuels are being deployed, and the mute compulsion/inertia of these landscapes as the forces that shape their concrete manifestation. The eventual development of a hydrogen economy, through its specific technologies of production, transportation, and consumption, as well as the social relations which accompany them, can thus be conceptualized as a the "hydrogen landscape".

3. Methods

The hydrogen economy, or hydrogen landscape, does not yet exist – most current hydrogen production is for limited industrial uses and is produced using unabated fossil fuels. The hydrogen economy is not an economic, political, or material reality but rather a vision for the future, one that is being actively created and shaped by those who articulate it. I am interested in examining what kind of future this is, and what kind of change the advent of the hydrogen economy as articulated by state and private actors would be.

Without a real-world case to analyze, I examine reports and policy documents produced by various international organizations that are engaged in articulating this vision of a hydrogen economy in the future. These organizations are the International Energy Association (IEA), the International Renewable Energy Association (IRENA), the Hydrogen Council, Bloomberg Financial, the Energy Transition Council (ETC), the Rhodium Group, the European Investment Bank, and the European Union, Dii Desert Energy. In selecting specific documents for my document stock, I focused on (1) documents which give a general overview of the hydrogen economy and (2) documents that specifically dealt with the trade or global distribution of hydrogen or hydrogen as a tool for decarbonization. As a result, I collected a document stock of fifteen documents by nine different organizations, listed in Table 1.

IRENA is comprised of 168 member countries, so most of the countries on the planet[51]. The IEA is comprised mostly of affluent European, North American, and East Asian countries[52]. The Hydrogen Council and the Energy Transitions Council (ETC) are groups formed by a number of private actors, primarily in the energy, chemical, automotive and industrial sectors, including some of the largest fossil fuel corporations in the world such as Shell, ExxonMobil, Aramco, BP, Equinor, Sinopec, TotalEnergie, Chevron, Petronas, and others[53]. The reports and agencies referenced here interreference each other – for example, the ETC report discusses the role of hydrogen in the 1.5C scenarios of IEA, IRENA, the Hydrogen Council, and Bloomberg Financial. Short posts on the websites of large financial and political institutions link back to these documents; a post on the World Bank Blogs website includes reference to the Bloomberg report, the Future of Hydrogen IEA report, reports by IRENA and the Energy Transitions Commission report[54], and an article on the International Monetary Fund website was authored by the lead of author of IRENA Geopolitics of the Energy Transformation Report[55]. I take the selected articles, and the organizations that prepared them, to represent the interests of dominant political and economic forces. The contents of the documents differ, revealing some variations in vision of the hydrogen economy, and in my analysis, I consider these variations in relation to the specific compositions of positions of the actors. But generally, these documents can be understood as articulating the imagined and desired

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[51] IRENA, "Membership," (accessed 2023/5/9, https://www.irena.org/About/Membership.
[52] IEA, "Countries & Regions," (accessed 2023/5/9, https://www.iea.org/countries.
[53] Hydrogen Council, "Members," (2022/10/3 2022), accessed 2023/5/9, https://hydrogencouncil.com/en/members/.
[54] Michael Kobina Kane, and Stephanie Gil, "Green Hydrogen: A Key Investment for the Energy Transition," *World Bank Group*, 2023/5/9, 2022, https://blogs.worldbank.org/ppps/green-hydrogen-key-investment-energy-transition.
[55] Thijs Van de Graaf, "Hydrogen's Decade," (2022/12 2022), accessed 2023/5/9, https://www.imf.org/en/Publications/fandd/issues/2022/12/hydrogen-decade-van-de-graaf.

role of hydrogen technologies, as well as the future global distribution of energy and resource production and consumption.

Table 1: Document stock for thematic analysis

Publishing Organization	Title	Year published	Purpose	Scope	Page Count	URL
IEA	The Future of Hydrogen	2019	Assesses current state of hydrogen, examination of potential, recommendations policy to accelerate development.	International; prepared for the G20 summit in Japan.	203	https://www.iea.org/reports/the-future-of-hydrogen
	Global Hydrogen Review	2022	Examines current state of hydrogen, as well as infrastructure, trade, and policy trends. Examines hydrogen's potential role in global energy supply.	International	284	https://www.iea.org/reports/global-hydrogen-review-2022
IRENA	Global hydrogen trade to meet the 1.5°C climate goal Part I	2022	Provides an overview of potential hydrogen trade, assess how that trade might look by 2050.	International	114	https://www.irena.org/publications/2022/Jul/Global-Hydrogen-Trade-Outlook
	Global hydrogen trade to meet the 1.5°C climate goal Part III	2022	Investigates potential and costs of producing hydrogen in different parts of the world.	International	45	https://www.irena.org/publications/2022/May/Global-hydrogen-trade-Cost
	Green Hydrogen for Industry: A Guide to Policy Making	2022	Examines challenges for green hydrogen in the industrial sector and explores policy options for dealing with them.	International	68	https://www.irena.org/publications/2022/Mar/Green-Hydrogen-for-Industry
	Geopolitics of the Energy Transformation: The Hydrogen Factor	2022	Focuses on how hydrogen might change or "disrupt" the geopolitics of energy, examines policy options.	International	118	https://www.irena.org/publications/2022/Jan/Geopolitics-of-the-Energy-Transformation-Hydrogen
Hydrogen Council	Hydrogen Insights	2022	Gives updates of new developments in the industry, an overview of the industry in the present, suggest policies and actions for developing the industry.	International	12	https://hydrogencouncil.com/en/hydrogen-insights-2022/
	Global Hydrogen Flows	2022	Examines the opportunities, challenges, and potential solutions for coordinating the global trade of hydrogen.	International	40	https://hydrogencouncil.com/en/global-hydrogen-flows/
	Hydrogen For Net Zero	2021	Examines the present and future demand of hydrogen, how hydrogen might scale, the current moment of the industry and current investments, and recommends policies and actions from industry.	International	56	https://hydrogencouncil.com/en/hydrogen-for-net-zero/

Publishing Organization	Title	Year Published	Purpose	Scope	Page Count	URL
BloombergNEF	Hydrogen Economy Outlook	2020	Offers an overview of the hydrogen economy, specifically of potential prices and costs, and recommends policies, investments and funding for different aspects of the hydrogen economy, with the goal of driving down hydrogen cost.	International	14	https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf
Energy Transitions Commission	Making the Hydrogen Economy Possible	2021	Examines the potential role of hydrogen in a "deeply electrified" economy, how hydrogen might be scaled up, and recommends policies and actions from industry.	International	92	https://energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Hydrogen-Report.pdf
European Commission	A Hydrogen Strategy for Europe	2020	Develops of strategy for developing hydrogen in the EU, specifically in increasing electrolyser capacity by 2030 .	Europe	24	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301
European Investment Bank	Unlocking the Hydrogen Economy	2022	Examines the hydrogen market to support investment decisions by the European Commission.	Europe	40	https://www.eib.org/attachments/publications/unlocking_the_hydrogen_economy_en.pdf.
Dii Desert Energy	A North Africa - Europe Hydrogen Manifesto	2019	Examines the role that hydrogen could play in both Europe and Africa, arguing for the development of a hydrogen trade from North Africa to Europe based on existing natural gas networks.	North Africa and Europe	32	https://www.menaenergymeet.com/wp-content/uploads/A-North-Africa_Europe-Hydrogen-Manifesto.pdf
Rhodium Group	Clean Hydrogen	2021	Gives an overview of the potential of hydrogen to decarbonize, argues for the economic benefit, and suggests policies and investments for scaling up hydrogen, specifically in the United States.	United States	9	https://rhg.com/research/clean-hydrogen-decarbonization/

I use a deductive-inductive thematic analysis, as articulated by Braun and Clarke (2006), to examine my document stock. Thematic analysis is a broadly defined research approach for analyzing qualitative data; data is organized through coding, and codes are examined to produce themes, categories of meaning that reveal relationships and logics on a higher level of abstraction[56]. My approach is partly a deductive - or theoretical - thematic analysis in the sense that it is theory guided: my conceptualization of the hydrogen landscape, along with the more specific concepts of the real subsumption of nature, ecologically unequal exchange, and mitigation deterrence, guide my reading of the documents. I developed a set of guiding questions based on my theoretical framework, listed in Table 2, which focused my initial reading. It is also partly inductive because, through multiple readings of these documents, I inductively developed my own codes and, through an iterative process of organizing and re-organizing, identified themes and sub-themes which emerged from them.

[56]Virginia Braun, and Victoria Clarke, "Using Thematic Analysis in Psychology," *Qualitative Research in Psychology* 3, no. 2 (2006/01/01 2006), https://dx.doi.org/10.1191/1478088706qp063oa, Paul Mihas, "Qualitative Research Methods: Approaches to Qualitative Data Analysis," in *International Encyclopedia of Education (Fourth Edition)*, ed. Robert J. Tierney, Fazal Rizvi, and Kadriye Ercikan (Oxford: Elsevier, 2023).

Table 2: Guiding questions for document analysis

Theoretical departure	General Guiding Question	Sub-questions
Real subsumption of labour and nature through the spatio-temporal mobility of fuels	What is the value and utility of hydrogen as expressed by these documents?	How do these documents value hydrogen's… … the spatial mobility? … the temporal mobility? … versatility of production pathways? … versatility of end uses? … decarbonization potential?
Ecologically unequal exchange	What are the spatial and geographic arrangements of the hydrogen economy articulated by these documents?	Which countries are seen as exporters, importers, or self sufficient? By what criteria is the role of a given country determined? What are the reasons given for the geo-spatial distribution of the economy? How are land and places determined suitable for hydrogen production? How is resource consumption portrayed?
Mitigation deterrence	What role does the existing fossil fuel economy play in the hydrogen economy as envisioned by these documents?	How does hydrogen interact with… …existing fossil fuel usage? … existing fossil fuel infrastructure? … fossil fuel dependent industries and activities?
Non-theory-specific	What are the envisioned functions of hydrogen and the hydrogen economy?	What industries will it be used in? What end uses are being developed?
	What is the timeline of the hydrogen economy?	What are the short and long term visions of the hydrogen economy? How are green and blue hydrogen seen as developing over time? What applications are being prioritized?
	What are the challenges of building the hydrogen economy?	What solutions are recommended? What are the barriers to scaling?

I identify three types of themes, each belonging to a different function of the hydrogen economy documents. The first is concrete themes, which refers to claims and visions about how the hydrogen economy will be and how it will function. The second is discursive themes, which refers to discourses or narratives which structure or shape perceptions. The third is logical themes, which refer to implicit or explicit logics which justify particular courses of action or the deployment of hydrogen itself. Themes and sub-themes are organized by category in Table 3. As I seek to reveal the underlying material dynamics, construction of discourses, and operative logics within the hydrogen economy, my analysis can be characterized as *latent* (rather than *semantic*) thematic analysis, an approach which integrates an analysis of underlying meaning into the determination of themes themselves[57]. While the phenomena which these three themes describe can often overlap, there is value in distinguishing between them. For example, the discussion of using vacant land in North Africa to produce cheap hydrogen can be understood as containing themes in all three categories: we can distinguish between a) the concrete aim to develop hydrogen in North Africa, b) the discursive portrayal of land in North Africa as vacant, and c) the logic of value which authorizes this trade relationship based on price. Each category of theme speaks to a different function, and each category must be evaluated, and possibly challenged, differently. Themes are determined as belonging to a particular category not only by their function within the document but also their relation to other themes. For example, blue hydrogen as a transitional technology is considered a discursive theme because it stands in contradiction to the concrete theme of generally scaling up blue hydrogen production. The categories of themes can be seen as reflecting three functions of the hydrogen economy documents: a) shaping the concrete development of the hydrogen economy, b) constructing a future-making discourse that authorizes this economy, and c) enacting the economic and social logic of "green" capitalism.

The limitation of this approach is that it examines the hydrogen economy from above, through documents created by large international organizations, and it misses the "on ground" development of the economy through specific firms and projects. While these documents and reports do discuss the concrete development of the industry, such as existing and planned projects, infrastructure, and agreements, they do so in the context of their own analysis, discussion, and recommendations. While this has the value of showing how

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[57] Braun, and Clarke.

these actors would like the hydrogen economy to develop, it undermines the ability of this study to say how it is actually developing. I argue that the visions laid out in these documents will shape the material reality as it develops and thus, are an important entry point to the underlying logic of the hydrogen economy. The study also examines English language documents, and while those documents are issued by organizations that are made up of member companies and corporations from around the world, they may still disproportionately reflect the priorities of Europe or the Anglosphere. Further, as the hydrogen economy by and large does not exist yet, but is at a critical stage in its development, the development of the hydrogen economy may still move in a number of new directions, potentially making certain aspects of this analysis irrelevant in the future.

Table 3: Concrete, Discursive and Logical Themes and Sub themes

Concrete themes	Discursive themes	Logical Themes
Sustaining global relations of extraction - Wealthy nations as importers, poorer nations/regions as exporters - Europe as leader electrolyser exporter Building on the foundations of the fossil fuel landscape. - Continued use of fossil fuels through blue hydrogen - Overall increase in blue hydrogen production - Continued use and expansion of fossil fuel (compatible) infrastructure - Sustaining of everyday relations of fossil fuels - Sustaining the mobility of industry	Hydrogen as a decarbonizing technology - Blue hydrogen as a short-term/transitional technology - Blue hydrogen as clean hydrogen Perception of land as available	Challenge of coordination Energy security Market logic - High prices green energy and technology as barrier - Deploying technologies to reduce cost - Trading energy – bringing supply to meet demand - Carbon price and other market based policies - Economic productivity

4. Results and Analysis

The hydrogen economy documents paint the picture of an ideal green capitalist future: advanced industrial activity and economic growth without the associated emissions, a smooth transition from fossil fuels into renewables. The purpose of this analysis is to pierce the capitalist optimism around hydrogen fuels and to reveal how a capitalist hydrogen economy might actually materialize. I critically analyse the hydrogen economy documents by examining the relations between themes, evaluating them in light of academic literature, and by examining them through my theoretical framework. My analysis is divided into an examination of how hydrogen is generally valued, how hydrogen intersects with the fossil fuel economy, and how hydrogen maps onto patterns of global trade. I conclude with a discussion of the extractive social relations which would be embedded in the hydrogen landscape.

4.1 The Value of Hydrogen

Why hydrogen? Hydrogen is generally portrayed as a **technology of decarbonization** for the "hard to decarbonize sectors", a virtue of its versatility and mobility[58]. The "hard to decarbonize" sectors are those that rely on the mobility of fossil fuels and those in which direct electrification is seen as infeasible, mostly long-distance transportation and heavy industry such as steelmaking[59]. Hydrogen is estimated as abating between 10%[60] and 20%[61] of CO_2 emissions by 2050. This is tied to hydrogen's mobility; hydrogen can be used for transport where direct electrification isn't feasible; it can bring energy from areas with high supply to high demand, as well as to sites of industry that are far removed from energy infrastructure. It can store energy and be used to balance

[58] BloombergNEF, *Hydrogen Economy Outlook* (2020), https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf, Council, Hydrogen Council, *Hydrogen for Net Zero* (2021), https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero.pdf, Galen Hiltbrand et al., *Clean Hydrogen: A Versatile Tool for Decarbonization* (2021), https://rhg.com/research/clean-hydrogen-decarbonization/, IEA, *The Future of Hydrogen* (Paris: 2019), https://www.iea.org/reports/the-future-of-hydrogen, IRENA, *Geopolitics of the Energy Transformation: The Hydrogen Factor* (Abu Dhabi: 2022), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jan/IRENA_Geopolitics_Hydrogen_2022.pdf?rev=1cfe49eee979409686f101ce24ffd71a, IRENA, *Green Hydrogen for Industry: A Guide to Policy Making* (Abu Dhabi: 2022), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Mar/IRENA_Green_Hydrogen_Industry_2022_.pdf?rev=720f138dbfc44e30a2224b476b6dfb77.

[59] BloombergNEF, Hydrogen Council, *Hydrogen for Net Zero*, IEA, *Global Hydrogen Review 2022*.

[60] IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and the Way Forward*.

[61] Hydrogen Council, *Hydrogen for Net Zero*.

out energy grids and reduce intermittencies[62]. Hydrogen is valuable because its mobility and versatility give it a similar spatio-temporal profile as fossil fuels, but potentially without the associated carbon emissions.

A key theme related to hydrogen's mobility and versatility is its provision of **energy security**. Versatile production pathways mean that, for those purchasing hydrogen, there is also a greater versatility of suppliers. This is seen as contributing to energy security; greater supply diversity means that importing countries are not depending on a small group of suppliers[63], making it more unlikely that "cartels" will form[64], and reducing price spikes that are characteristic of fossil fuels[65]. Energy security is placed in the context of the Russia invasion of the Ukraine, and hydrogen is seen a way to reduce dependency on Russian natural gas and oil[66]. We can thus see that the documents recognize an economic and political value for having a globally diffuse economy of fuel production.

A fossil fuel substitute without greenhouse gas emissions, which would shake off some of the geopolitical constraints of the fossil fuel industry and encourage global market competition: a green capitalist dream come true. But hydrogen's mobility and versatility also allow it to intersect with the fossil fuel industry and to build a globally distributed fuel economy, and which come with the risks of mitigation deterrence and ecologically unequal exchange.

4.2 Hydrogen in time: Mitigation deterrence

While hydrogen is framed as being a key technology for decarbonization, the industry is entangled with the fossil fuel industry; some of the main fossil fuel actors are significantly involved in shaping the emergent hydrogen industry, and its production, transportation and consumption would involve the use of fossil fuels and fossil fuel infrastructure, particularly natural gas and carbon capture and storage. Looking at exactly how fossil fuels are entangled with hydrogen is key to understanding to what extent hydrogen economy, as envisioned by the

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[62] Hydrogen Council, *Hydrogen for Net Zero*, Ad van Wijk et al., *A North Africa - Europe Hydrogen Manifesto* (Berlin: 2019), https://dii-desertenergy.org/wp-content/uploads/2019/12/Dii-hydrogen-study-November-2019.pdf.
[63] Wijk et al.
[64] IRENA, *Geopolitics of the Energy Transformation: The Hydrogen Factor*.
[65] IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and the Way Forward*.
[66] Hydrogen Council, *Hydrogen Insights*, IEA, *Global Hydrogen Review 2022*.

analyzed documents, is actually moving towards decarbonization, and to what extent it is acts as a form of mitigation deterrence. This section examines the use of fossil fuels, fossil fuel infrastructure, and fossil fuel social arrangements in the envisioned hydrogen economy. Generally, we can see that hydrogen **builds on the foundations of the fossil fuel landscape** and that this is generally rationalized through **market logic**, in which cost, profit and price act as ultimate determinants of what is desirable and possible**.** As Carton stresses, the concept of the fossil fuel landscape's inertia does not suggest the impossibility of decarbonization, but rather that it will be a slow and extended process. In that light, this section examines the roles that time and temporalities play across these three categories, specifically the timeline of decarbonization proposed and which kinds of technologies belong to the present, and which to the future. Through this, we see that the development of the hydrogen economy works to extend fossil fuel consumption into the future, creating a dynamic of mitigation deterrence rather than decarbonization.

4.2.1 Blue-washing: hydrogen from fossil fuels and CCS

The first thing that must be pointed out about the hydrogen economy is that it would still involve a significant consumption of fossil fuels, specifically natural gas and coal, in the production of blue hydrogen. A consistent theme in the hydrogen economy documents is the **continued use of fossil fuels through the production of blue hydrogen**. Blue hydrogen figures as a major component of both long- and short-term hydrogen supply, particularly for countries rich in oil and gas reserves[67]. We see a range of supply mixtures proposed, from 30/70 percent split between blue and green hydrogen[68], or a 33/66 split[69], to a 40/60 split[70]. All of these figures are for long-term supply mixes, around the 2050 mark. While green hydrogen would then make up the bulk of eventual hydrogen production, blue hydrogen would also comprise a significant portion. In the long-term green hydrogen is also argued to have a greater potential for price decrease relative to grey hydrogen than blue hydrogen, since blue hydrogen by definition involves the same process as grey but with added steps, and therefore

[67] BloombergNEF.
[68] Hydrogen Council, *Global Hydrogen Flows* (2022), https://hydrogencouncil.com/wp-content/uploads/2022/10/Global-Hydrogen-Flows.pdf.
[69] IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and the Way Forward*.
[70] Hydrogen Council, *Hydrogen Insights*.

costs[71]. It should also be noted that there are differences between specific actors in how they see the role of green and blue hydrogen, and this can partly be attributed to their particular positions within the global energy economy: IRENA, an international agency focused on the development of renewable energy, sees very little role for blue hydrogen in the long term and sees green hydrogen as the most viable option[72], whereas the Hydrogen Council, composed of fossil fuel companies, sees a significant role for blue hydrogen in the long term[73].

In their short-term vision however, most actors are significantly more aligned: **blue hydrogen is generally described as a short-term option which would play a transitional role**[74]. Generally, green hydrogen is seen as coming to scale after 2030, when decreases in prices of renewable energy will make investments in production and consumption more attractive. In the period before then, green hydrogen projects will be limited, serving to lay the groundwork of the industry and to start driving down prices, whereas blue hydrogen will be used to decarbonize existing applications, decarbonize existing production so as to phase out grey hydrogen, and create increased demand for hydrogen[75]. Blue hydrogen is also seen as a more realistic and cost-effective option, one that can be deployed in the present, whereas the "overhaul" of transitioning to green hydrogen is a shift reserved for the future[76].

The discursive theme of blue hydrogen as a transitional technology is however in tension with the concrete theme of **increasing blue hydrogen production**. In the short term, carbon capture and storage would not only be used to decarbonize existing grey hydrogen production, but also to create new blue hydrogen facilities[77], meaning blue hydrogen production would grow at least into the 2030s, surpassing existing grey production by over 200%[78]. This

[71] Energy Transitions Commission, *Making the Hydrogen Economy Possible* (2021), https://energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Hydrogen-Report.pdf.
[72] IRENA, *Green Hydrogen for Industry: A Guide to Policy Making*.
[73] Hydrogen Council, *Hydrogen for Net Zero*.
[74]European Commission, Directorate-General for Energy European Commission, *A Hydrogen Strategy for Climate Neutral Europe* (Brussels: European Commission, 2020), https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52020DC0301, Hiltbrand et al, Wijk et al.
[75] Energy Transitions Commission, European Commission, Hydrogen Council, *Hydrogen for Net Zero*.
[76] Hiltbrand et al, Wijk et al.
[77] Energy Transitions Commission, European Commission, Hiltbrand et al.
[78] Energy Transitions Commission, Hydrogen Council, *Hydrogen for Net Zero*.

would mean a net increase in the amount of fossil fuels used in hydrogen production, at least during the next decade.

But does more fossil fuel use in hydrogen production mean more greenhouse gas emissions? The hydrogen economy documents claim that it does not. This is partly done by **characterizing blue hydrogen as a clean technology**; blue hydrogen is often bundled together with green under the label of "clean"[79] or low-carbon[80] with renewable based hydrogen often appearing as the example of the more general category[81], and blue hydrogen and fossil fuels generally appearing later in documents, after lengthy discussions of decarbonization potential[82]. Blue hydrogen's effectiveness for decarbonization depends on the effectiveness of CSS. Generally, CCS is assumed to have a capture rate of 90%[83], with a technical potential of reaching 99% with significant further investment[84].

While 90% is seen by the scientific literature as a technically feasible capture rate, in practice capture rates are generally lower, mainly due to upstream methane emissions, including those from methane used for powering CCS. A study which *does* include upstream emissions finds current blue hydrogen emissions to be higher than if the methane were simply burnt for heat[85]. In general, existing capture rates often fall somewhere between 50% and 90%[86]. There is also the related issue of carbon capture *utilization* and storage (CCUS). If captured carbon is reused, then there is still a net flow of fossil carbon into the atmosphere. One way in which carbon is used is the production of e-fuels, and hydrogen is seen as a potential input for e-fuel production for decarbonizing. If carbon is captured by blue hydrogen production then used again in e-fuel production, the emissions reductions of both technologies have been reduced, if

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[79] Hydrogen Council, *Hydrogen Insights*, Hiltbrand et al, IRENA, *Geopolitics of the Energy Transformation: The Hydrogen Factor*, 19.
[80] European Investment Bank, *Unlocking the Hydrogen Economy — Stimulating Investment across the Hydrogen Value Chain* (Luxembourg: 2022), https://www.eib.org/attachments/publications/unlocking_the_hydrogen_economy_en.pdf.
[81] Bank, Hiltbrand et al.
[82] BloombergNEF, Wijk et al.
[83] Hiltbrand et al, IEA, *Global Hydrogen Review 2022*.
[84] IEA, *Global Hydrogen Review 2022*.
[85]Howarth, and Jacobson.
[86]Minli Yu, Ke Wang, and Harrie Vredenburg, "Insights into Low-Carbon Hydrogen Production Methods: Green, Blue and Aqua Hydrogen," *International Journal of Hydrogen Energy* 46, no. 41 (2021/06/15/ 2021), https://dx.doi.org/https://doi.org/10.1016/j.ijhydene.2021.04.016, Howarth, and Jacobson, Christian Bauer et al., "On the Climate Impacts of Blue Hydrogen Production," 10.1039/D1SE01508G, *Sustainable Energy & Fuels* 6, no. 1 (2022), https://dx.doi.org/10.1039/D1SE01508G.

not eliminated. E-fuels have the highest mitigation potential when they are produced from renewable energy sources and non-fossil CO_2[87], so the degree to which capture carbon from blue hydrogen production is used in e-fuel production impacts blue hydrogen's overall mitigation potential. So, while technology of CCS holds some technical potential, there are still many barriers to scaling it[88], and the emissions reductions that are promised are far from guaranteed.

Another factor influencing hydrogen's ability to decarbonize is the ability of the hydrogen industry to scale and replace emissions intensive fuels. The challenge of scaling is captured by two themes: the **challenge of coordinating the industry** and **high costs as a barrier**. Hydrogen faces significant challenges to scaling, particularly in the short term: two key challenges identified by the industry are the so called "three-sided chicken and egg problem" of simultaneously scaling up supply, transportation, and demand[89], and the high costs of hydrogen in comparison to fossil fuels. Part of the three-sided chicken and egg problem is the investment risk that comes from "demand invisibility"[90], meaning that while there might be significant potential demand for hydrogen fuels in the future, such demand remains invisible since the industry does not yet exist. There is thus a risk for those developing and investing in hydrogen products, since there are high investment costs for producing hydrogen and those who invest do not know if there will be market for their products[91]. Even if there is a market, hydrogen, as a conversion rather than extraction business, is expected to have generally low profit margins[92]. Uncertainty exists on the demand side as well; hydrogen applications also require infrastructure changes for end use industries, thus reliability of supply is critical for scaling up demand[93]. The challenge of scaling up is not just one of coordinating investment, but coordinating infrastructure; developing a hydrogen economy requires the development of complete and functional supply chains, with parts of the supply

[87]Vedant Ballal et al., "Climate Change Impacts of E-Fuels for Aviation in Europe under Present-Day Conditions and Future Policy Scenarios," *Fuel* 338 (2023/04/15/ 2023), https://dx.doi.org/https://doi.org/10.1016/j.fuel.2022.127316, Ueckerdt et al.
[88] Energy Transitions Commission.
[89] Odenweller et al.
[90] Hydrogen Council, *Hydrogen Insights*.
[91] IRENA, *Green Hydrogen for Industry: A Guide to Policy Making*, IRENA, *Geopolitics of the Energy Transformation: The Hydrogen Factor*.
[92] IRENA, *Geopolitics of the Energy Transformation: The Hydrogen Factor*.
[93] IEA, *Global Hydrogen Review 2022*.

chain that require dedicated infrastructure or significant retrofits[94]. One of the biggest challenges to hydrogen is thus financial, economic and material coordination.

An influence on demand uncertainty, which also creates a barrier to the development of the hydrogen economy more generally, **is the high cost of blue or green hydrogen** in comparison to fossil fuels. Green hydrogen is bound to the price of renewable energy, and cost projections by all actors see green hydrogen prices as higher in the short-term. Green premiums will drive up costs for hydrogen derivatives, which will be felt more by producers than consumers, except for jet fuel where consumers would shoulder more of the costs. These premiums are driven by both the cost of energy and the costs of transforming tech infrastructure[95]. Blue hydrogen prices in the short term would be lower than green, but by definition higher than grey due to the added costs of CCS[96], and cost are regarded the major factor in phasing out grey hydrogen[97].

For both green and blue hydrogen, **carbon prices and other market based policies are seen as essential** for competing against grey hydrogen and other fossil fuels[98]. Carbon prices are seen as being technology neutral, allowing "the market" to determine the most effective paths of decarbonization. Different carbon prices would be needed for different ended uses; for green steel, aviation and shipping – the hard to decarbonize sectors that hydrogen for which hydrogen is most crucial – high carbon prices are needed, approximately $60 per ton for steel and $150 per ton for aviation and shipping fuel[99] . In addition to carbon prices, a variety of other policies or regulatory measures are recommended, such as mandatory quotas, tax credits, and carbon contracts for difference[100]. The present cheapness of fossil fuels is seen as a major obstacle to scaling up green hydrogen, and policy intervention in the market is seen as necessary to make it cost competitive and bring it scale.

Even if CCS achieves high capture rates and the blue and green hydrogen economy scale up successfully, an increased supply of low emissions fuel does

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[94] IRENA, *Green Hydrogen for Industry: A Guide to Policy Making*.
[95] Energy Transitions Commission.
[96] Ibid.
[97] Hydrogen Council, *Hydrogen for Net Zero*.
[98] Energy Transitions Commission, Hydrogen Council, *Hydrogen for Net Zero*.
[99] Energy Transitions Commission, 77.
[100] Energy Transitions Commission, Hydrogen Council, *Hydrogen Insights*, IEA, *Global Hydrogen Review 2022*, IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and the Way Forward*.

not guarantee decreased greenhouse gas emissions. As Jevons paradox states, gains in efficiency are generally met with increased energy usage, and ecosocialist thinkers have used this to argue that capitalism's growth requirement moves it towards making use of all available energy rather than switching energy source[101]. For blue hydrogen, its role in reducing emissions depends both on how much blue hydrogen is produced as well to what degree it is replacing more emissions intensive fuels. If energy demand continues to increase and blue hydrogen is scaled up, that would mean increased aggregate emissions from blue hydrogen production. The growth of energy demand limits the decarbonization potential of blue hydrogen as well as green. Global freight, for example, is expected to more than triple by 2050, an increase which is expected to impede decarbonization[102]. An aggregate increase in fuel required will decrease hydrogen's ability to actually decarbonize the sector. Hydrogen's ability to decarbonize thus very much depends on its role in the makeup of overall energy supply, as well as the magnitude of overall energy demand.

We should also consider the interaction between green and blue hydrogen production. While most of the documents argue that green and blue hydrogen are complementary, the analysis of different decarbonization pathways by the Hydrogen Council shows fossil fuel-based production is vulnerable to the development of renewable energy – if the world shifts more towards renewables the hydrogen produced from fossil energy will be less viable[103]. This essentially shows that a hydrogen economy based on the priorities of fossil fuel producers has a clear economic interest in actually limiting the development of renewable energy.

The combination of green and blue hydrogen also has ideological effects. The fact that there are different imagined pathways that privilege either blue or green hydrogen in the long run does not undermine the future-making project of the hydrogen economy; rather it allows for hydrogen to play different roles in different visions of the future. For those looking for decarbonization and fossil fuel phaseout, they can turn to the green-hydrogen focused visions of the future; for those attached to the continued use of fossil fuels, they can turn to the blue-

[101] Rikard Warlenius, "A Renewable Energy Transition: Capitalist Barriers, Socialist Enticements," in *The Politics of Ecosocialism: Transforming Welfare* (Abingdon, New York: Routledge, 2015).
[102] Jaramillo, and A. Hammer Strømman.
[103] Hydrogen Council, *Global Hydrogen Flows*.

hydrogen focused futures. The plurality of visions for hydrogen production pathways means that, in imaginations of the future, hydrogen can play the role that people want it to play.

4.2.2 A second life for fossil fuel infrastructure

Blue hydrogen is not the only way that fossil fuels would be integrated into the hydrogen economy. Fuel blending, either in natural gas pipelines or through industrial cofiring, is a way that fossil fuels and hydrogen, either green or blue, can co-exist. Fuel blending brings us to a second major way in which hydrogen intersects with fossil fuels – **through the continued use of fossil fuel infrastructure**. There is a major push within the hydrogen documents to authorize the repurposing and expansion of natural gas or hybrid pipelines. Existing pipelines are portrayed as being able to transport hydrogen in various forms [104]. Synthetic fuels, or e-fuels, are seen as the most feasible for pipelines[105]; produced through the transformation of hydrogen into fuels like kerosene, they themselves can be purely hydrogen based or blended with fossil-based sources. Existing natural gas lines could also be used to transport natural gas to sites of blue hydrogen production. For transmitting pure hydrogen, new pipelines would be needed, and shipping mainly reserved for derivatives like ammonia or green steel[106]. Importantly, integrating hydrogen into the existing gas grid through blending is not anticipated to reduce emissions significantly. The IEA sees blending as reducing only 2% of emission associated with the infrastructure - the goal of blending is actually price reduction through increasing hydrogen demand with the goal of scaling up production[107].

Beyond pipelines, liquid natural gas (LNG) terminals could be integrated into the hydrogen economy; while much of the existing infrastructure is incompatible with hydrogen or ammonia, new or retrofitted terminals could be built to accommodate hydrogen and ammonia as well as natural gas[108]. The backwards compatibility of new hydrogen infrastructure is a recurring feature, one that is also important for new hydrogen pipelines[109] as well as gas powered electricity

[104] BloombergNEF, Energy Transitions Commission, European Commission, IEA, *Global Hydrogen Review 2022*, IRENA, *Geopolitics of the Energy Transformation: The Hydrogen Factor*, Wijk et al.
[105] IEA, *Global Hydrogen Review 2022*.
[106] Hydrogen Council, *Global Hydrogen Flows*, IEA, *Global Hydrogen Review 2022*, IRENA, *Geopolitics of the Energy Transformation: The Hydrogen Factor*, Wijk et al.
[107] IEA, *The Future of Hydrogen*, 182.
[108] IEA, *Global Hydrogen Review 2022*.
[109] Ibid.

turbines[110]. Cofiring is another way in which hydrogen extends the life of fossil fuels and fossil fuel infrastructure. Cofiring – the simultaneous burning of hydrogen or ammonia with natural gas and coal – is presented as a short-term option for steel and concrete production as well as electricity turbines, in conjuncture with CCS[111]. The lifespan of fossil fuels and their infrastructure is extended by hydrogen through multiple technological pathways.

The academic literature on hydrogen fuels reveals several problems with using existing fossil fuel infrastructure. Using natural gas grids to transport hydrogen, for example, has multiple technical challenges; hydrogen can cause metal embrittlement by degrading steel and other metals, the long-term effects of which are not fully understood, and the difference in its compression rates and viscosity make it incompatible with many existing components of natural gas grids[112]. While this means that pure hydrogen cannot be used in existing grids, blending is technically feasible within certain limits, but these are generally very low percentages. Proposed hydrogen blending projects have not ventured above the 20% threshold, and the majority of them have remained below 5%[113]. Producing e-fuels and shipping them by pipeline is rather inefficient: e-fuels have a generally low conversion efficiency, between 10% and 35%, which "outstrips efficiency gains of using electricity from renewable rich countries"[114].

This vision of the hydrogen economy imagines the existing networks of fossil fuel - specifically natural gas - transportation and consumption as integral to the hydrogen economy. It argues not only for its continuation but its expansion, specifically its expansion through backwards compatible hydrogen infrastructure: dedicated hydrogen infrastructure that could be used for future fossil fuel consumption. We can partly understand this vision as a reflection of the fossil fuel industry's concern over the energy transition producing stranded assets, its inability to retrieve the full value invested into fixed capital. Fixed

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[110] Energy Transitions Commission.
[111] Energy Transitions Commission, IRENA, *Green Hydrogen for Industry: A Guide to Policy Making*.
[112] Devinder Mahajan et al., "Hydrogen Blending in Gas Pipeline Networks&Mdash;a Review," *Energies* 15, no. 10 (2022), https://www.mdpi.com/1996-1073/15/10/3582.
[113] Xia Wu et al., "From the Perspective of New Technology of Blending Hydrogen into Natural Gas Pipelines Transmission: Mechanism, Experimental Study, and Suggestions for Further Work of Hydrogen Embrittlement in High-Strength Pipeline Steels," *International Journal of Hydrogen Energy* 47, no. 12 (2022/02/08/ 2022), https://dx.doi.org/https://doi.org/10.1016/j.ijhydene.2021.12.108.
[114] Ueckerdt et al.

capital is capital that materializes as the instruments of the production process, and as David Harvey argues, fixed capital "cannot be defined independently of the use to which material objects are put"[115]. The value invested in fixed capital can only be retrieved once that capital is used to produce commodities, but as Harvey points out, machines and tools can have multiple uses, so fixed capital can be expanded not only by adding objects but by adding uses. Early decommissioning of fossil fuel infrastructure interrupts the cycle of capital accumulation, whereas repurposing it sustains or expands it. Fossil capital, by virtue of its structural position, has an interest in extending the life of its infrastructure as far as possible into the future. The effect of this can be conceptualized as fossil fuel lock in. The capitalist hydrogen economy is the development of an energy economy that might make us dependent on fossil fuels if hydrogen fails to scale, or more specifically, that allows the fossil fuel industry to keep selling and using its product as long as it remains cost competitive. But the value of particular infrastructure and the economic interests of specific capitalists is not the only dynamic promoting the continued use of fossil fuels. Natural gas pipelines, steel factories, and power plants all exist as nodes in a global economic landscape through which energy and resources flow. This bring us to the third way in which hydrogen interacts with fossil fuels: in their movement through the fossil fuel landscape.

4.2.3 Reproducing the fossil fuel landscape

The concept of the fossil fuel landscape brings into focus the various social, economic and ecological relations that surpass fossil fuels themselves but are entangled with their production, transportation and consumption. There are two themes relating the reproduction of the fossil fuel landscape; **sustaining relations of everyday fossil fuel consumption**, and **sustaining the global mobility of industry**. The risks that both these changes highlight are competition against direct electrification and sidestepping broader systemic transformations.

In contradiction to the theme of seeing hydrogen as being used for the hard to decarbonize sectors, some actors promote the potential use of hydrogen in sectors like electricity generation, home heating, and ground transport. Some consider the use of hydrogen for these applications as one option among others,

[115] David Harvey, *The Limits to Capital* (London: Verso, 1999), 205.

and even a less ideal option[116], whereas some see these applications as ideal. There is a particular push to justify the rapid development of ground transport and hydrogen refueling stations, partly as a way to drive down hydrogen costs[117]. As we have seen above, the use of hydrogen for blending with natural gas in existing grids is also seen as a desirable short-term option, one which is also justified by its potential to drive down long-term costs. This is again a reflection of the logical theme of **deploying technologies to reduce costs**. But we can also see a drive to **sustain relations of everyday fossil fuel consumption**, particular through the persistence of motor-vehicles. The transport industry is an active player in shaping and funding the hydrogen economy, and the largest portion of investments in end use applications, around 25%, comes from the ground transport industry[118]. Fuel cell development also dominates most of existing hydrogen application research and investment, fuel cells making up 41% of existing patents for hydrogen technology[119]. In spite of the hydrogen's professed role in decarbonizing the hard to decarbonize sectors, what we see instead is the near-term application of hydrogen to sectors like road transport in which direct electrification would be more energy efficient[120], justified by the economic rationality of price reduction. By competing against direct electrification, hydrogen in these industries produces the risk of fossil fuel lock in[121], by making their decarbonization dependent on the scaling up of a new industry, rather than on an industry that already exists.

Producing hydrogen for cars and home heating does not only compete against direct electrification – it also reproduces the geographies of everyday life produced by fossil fuels. Attachment to fossil fuels is partly about the role that these fuels play in social reproduction[122]. As Huber points out, ideas of freedom and the good life, particularly in the United States, have been built upon the personal mobility and the abundance of cheap energy that fossil fuels provide. The atomized social structure of one family households and individual car ownership are made possible by fossil fuels so that, as Carton argues, fossil fuel consumption is both "a material and ideological condition": consuming fossil

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[116] Energy Transitions Commission.
[117] Hydrogen Council, *Hydrogen for Net Zero*, European Commission, IEA, *The Future of Hydrogen*, Wijk et al.
[118] Hydrogen Council, *Hydrogen Insights*.
[119] IRENA, *Geopolitics of the Energy Transformation: The Hydrogen Factor*.
[120] Plötz, Ueckerdt et al.
[121] Ueckerdt et al.
[122] Huber, Carton.

fuels is a necessity for day-to-day existence under capitalism, as well as a way of acting out one's identity and values. Hydrogen, applied to these more everyday industries, particularly the automobile industry, is a way of sustaining daily relations of reproduction produced by fossil fuels. But if hydrogen fueled cars can move in line with the social "inertia" of the fossil fuel landscape, wouldn't that make them a more desirable path to decarbonization? Not quite – by making car transport appear more viable, hydrogen works against reorganizing systems of transport and shifting them from private to public, in which overall energy, space and resources can be conserved. Decarbonizing the transport industry requires reorganizing transport and urban space so as to reduce car dependence – simple switching fuel or engine technologies is not enough[123]. Further, as Malm and the Zetkin Collective argue, cars are harmful for more than their direct emissions; they exude an "ideology of anti-collectivity… the ideology most detrimental to any efforts to cut emissions"[124]. The hydrogen economy works to prevent the broader social and material reorganizations that would be necessary to reduce overall energy consumption and resource use; it reproduces the position of the individual capitalist consumer that has abundant energy and resources at their disposal, rather than creating new cultural standards of sustainable and collectively governed energy usage.

A similar dynamic of sidestepping systemic transformation can be seen at the broader economic level. One of the main new uses of hydrogen would be to decarbonize the shipping industry or extractivist industries like steel production; many of the new hydrogen hubs envisioned would be built around existing sites of fossil fuel refining, ammonia production, steel making, or ports[125]. Hydrogen would likely involve some redistribution of industry; countries with cheap renewables would take on a new role in the global economy, new sites of global steel production would likely be established[126]. But a change of positions within global trade dynamics is not necessarily a problem for capitalism: what is essential is that through hydrogen, **mobility itself is maintained**.

[123] Jaramillo et al.
[124] Andreas Malm, and Collective The Zetkin, *White Skin, Black Fuel: On the Danger of Fossil Fascism* (London, England: Verso Books, 2021, 2021), 386.
[125] Energy Transitions Commission.
[126] IRENA, *Geopolitics of the Energy Transformation: The Hydrogen Factor*.

The mobility of fossil fuels is a key part of what makes these industries possible. But shipping is unique among these industries, in that the role of the shipping industry is mobility itself. By decarbonizing the shipping industry - capital's technological ability to spread extraction, production, and consumption across the globe - capitalism sidesteps the spatial constraints of direct electrification. That is, if renewables, without hydrogen as medium, are unable to move energy and materials cheaply and freely through space, decarbonization would exert a pressure towards localization; supply chains would have to be shortened, and production would have to be increasingly domestic and regional. This would undermine capital accumulation in several ways. If, as Mau argues, transportation is a weapon in service of the exploitation of workers by increasing market competition[127], decarbonization would blunt this weapon. The ability of wealthier parts of the world to displace ecological consequences to distant, poor, and racialized populations would also be diminished. The reduction of transport and mobility is not only the loss of profit but the loss of economic power. We can see hydrogen as a way to (eventually) decarbonize the energetic foundation of capitalism's logistical and spatial power.

The hydrogen economy would mean the continued use of fossil fuels through carbon capture and storage technology, of fossil fuel infrastructure like pipelines and LNG terminals. It authorizes the development of backwards compatible infrastructure, allowing for the continued use of fossil fuels if they turn out to remain cheaper than renewable energy. It is being developed to reproduce the landscape of cars and combustion engines, as well as the landscape of a globally distributed economy that, through its mobility, can exploit nature and labour to produce cheap goods. What we see here is more than mitigation deterrence: it is the mute compulsion of the fossil fuel landscape, the economic, political and cultural logic of fossil capitalism reproducing itself through the deployment of a new energy technology. While the technology may be new, the social relations which it embodies are not. At the level of the global economy, hydrogen can be understood as working to sustain the economic relations that have structured global trade for the last few centuries: ecologically unequal exchange.

[127] Mau, 273.

4.3 Hydrogen in space: Ecologically unequal exchange in the hydrogen economy

Decarbonization is only one way of thinking about the ecological impact of the hydrogen economy, and a narrow one at that. Beyond carbon emissions, and even if it was able to decarbonize certain sectors, the hydrogen economy would have a significant ecological footprint. Hydrogen is produced through the conversion of energy and water; energy, either fossil or renewable, requires land. Fossil fuels have a much higher spatial energy density than solar or wind, the two favored inputs for green hydrogen production, meaning that the electrification of global energy systems will require significantly more land[128]. So, while green hydrogen has an emissions advantage over blue hydrogen or unabated fossil fuels, it does require significantly more space. This is amplified by the fact that hydrogen is energy carrier, so energy is lost in conversion – commercial electrolyser technologies have efficiencies between 59% and 82%[129]. Overall, developing a hydrogen economy will mean developing additional renewable resources. Increasing renewable energy production will require the increased use of land on the order of millions of square kilometers, and the material requirements for renewable energy would significantly increase rates of mining and exhaust known reserves of some metals by 2050, meaning intensified extraction and exploration would be needed[130].

The expansion of mining, renewable energy, and water usage are already sources of conflict[131]. For example, the development of wind energy in the north of Sweden has conflicted with the traditional use of the land by Sámi peoples[132],

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[128] Palmer-Wilson et al.

[129] Jun Chi, and Hongmei Yu, "Water Electrolysis Based on Renewable Energy for Hydrogen Production," *Chinese Journal of Catalysis* 39, no. 3 (2018/03/01/ 2018), https://dx.doi.org/https://doi.org/10.1016/S1872-2067(17)62949-8.

[130] R. J. Lowe, and P. Drummond, "Solar, Wind and Logistic Substitution in Global Energy Supply to 2050 – Barriers and Implications," *Renewable and Sustainable Energy Reviews* 153 (2022/01/01/ 2022), https://dx.doi.org/https://doi.org/10.1016/j.rser.2021.111720.

[131] Arnim Scheidel et al., "Environmental Conflicts and Defenders: A Global Overview," *Global Environmental Change* 63 (2020/07/01/ 2020), https://dx.doi.org/https://doi.org/10.1016/j.gloenvcha.2020.102104, Sofia Avila, "Environmental Justice and the Expanding Geography of Wind Power Conflicts," *Sustainability Science* 13, no. 3 (2018/05/01 2018), https://dx.doi.org/10.1007/s11625-018-0547-4.

[132] Vasna Ramasar et al., "When Energy Justice Is Contested: A Systematic Review of a Decade of Research on Sweden's Conflicted Energy Landscape," *Energy Research & Social Science* 94 (2022/12/01/ 2022), https://dx.doi.org/https://doi.org/10.1016/j.erss.2022.102862.

and the Nujio'qonik green hydrogen project in Newfoundland, Canada, which would be a windfarm dedicated partly to hydrogen production, has produced local resistance and conflict[133]. Nickel, palladium, and iridium are all required in increased quantities for hydrogen production[134]. Conflicts over nickel mining in Indonesia have resulted in forceful resistance from local activists[135], as well as a ban on raw nickel exports so that mined nickel would be refined and processed inside the country[136], a ban which the WTO has found to be in violation of its rules[137]. Energy is only one half of hydrogen input – the other is water. "The projected 409 million tonnes of green hydrogen needed by 2050 in IRENA's 1.5°C pathway would require around 7–9 billion cubic metres (m3) of water a year – less than 0.25% of current freshwater consumption"[138]. While water availability might not be a problem at the global level, a focus on local conditions changes the picture. North Africa, for example, is one of the most water-scarce regions of the world[139]. Where drinking water is already scarce, hydrogen production will further deplete water availability[140]. In so far as hydrogen would increase pressure in all of these sectors, it is also possible that hydrogen aggravates and multiplies conflicts and hardships.

4.3.1 The global distribution of the hydrogen economy

If the hydrogen economy has significant space and resource requirements, part of the value of hydrogen's mobility is to be able to selectively distribute

[133] CBC News, "Protesters in Mainland Block Road to Wind Power Test Site over Water Supply Fears," *CBC News*, 25 January 2023, 2023, accessed 2023/5/5, https://www.cbc.ca/news/canada/newfoundland-labrador/port-au-port-road-blockage-1.6725920, Patrick Butler, "Tensions High on Port Au Port Peninsula over Wind-Hydrogen Megaproject," *CBC News*, 2022, 2022, accessed 2023/5/5, https://www.cbc.ca/news/canada/newfoundland-labrador/port-au-port-world-energy-concerns-1.6688210.

[134] Energy Transition Commission.

[135] Bambang Hudayana, Suharko, and A. B. Widyanta, "Communal Violence as a Strategy for Negotiation: Community Responses to Nickel Mining Industry in Central Sulawesi, Indonesia," *The Extractive Industries and Society* 7, no. 4 (2020/11/01/ 2020), https://dx.doi.org/https://doi.org/10.1016/j.exis.2020.08.012.

[136] I. Gusti Ngurah Parikesit Widiatedja, "Indonesia's Export Ban on Nickel Ore: Does It Violate the World Trade Organization (Wto) Rules?," *Journal of World Trade* (2021), http://www.kluwerlawonline.com/api/Product/CitationPDFURL?file=Journals\TRAD\TRAD2021028.pdf.

[137] European Commission, *Wto Panel Rules against Indonesia's Export Limitations on Raw Materials* (Brussels: 2022).

[138] IRENA, *Geopolitics of the Energy Transformation: The Hydrogen Factor*, 97.

[139] Janpeter Schilling et al., "Climate Change Vulnerability, Water Resources and Social Implications in North Africa," *Regional Environmental Change* 20, no. 1 (2020/06/30 2020), https://dx.doi.org/10.1007/s10113-020-01597-7.

[140] Lindner.

these requirements around the globe. Indeed, there is a clear spatial distribution of the hydrogen economy and a logic behind who produces hydrogen and who imports it. Three categories of countries are identified by the documents: net exporters, or countries with high supply and low demand, generally encompassing countries in Africa, the Middle East and South America, with Australia sometimes included; self-sufficient countries, or countries where supply and demand match, encompassing North America, China, and once again sometimes Australia; and net importers, or countries with high demand and low supply, generally Europe and East Asia[141]. There are varying emphases on which countries would become key exporters and why. The IEA sees Chile, the Middle East and Africa, specifically Namibia and South Africa, as key suppliers for Europe, but sees Australia, Mauritian, Chile, Argentina and Brazil as the biggest future exporters[142]. IRENA sees North Africa as the biggest potential exporter, with a strategic position in being geographically close to Europe[143]. The Hydrogen Council also places special focus on North Africa, Namibia, and South Africa, along with the Middle East and Australia due to the low price of producing hydrogen[144]. Dii Desert Energy has dedicated an entire manifesto to arguing for hydrogen trade between North Africa and Europe, premised on the difference in cost and the ability to make use of natural gas networks[145]. The EU Hydrogen Strategy reflects Europe's interest in Africa, specifically North Africa, seeing it as a source of "abundant renewables" where hydrogen can be produced in "geographic proximity" to Europe and provided at a "cost competitive" rate. As such, the EU recommends that renewable energy generation be "strongly accelerated in these countries" and that EU should encourage this and support "sustainable development" by investing in hydrogen projects abroad [146].

Europe is of course not the only potential importer of hydrogen, but it is likely to be the biggest. The bulk of demand is projected to come from China, India, Japan, South Korea, Europe and North America. However, as we have seen, countries like China, India, the United States and Canada can meet more of their demand through domestic production, so that leaves Europe and East Asia

141 Hydrogen Council, *Global Hydrogen Flows*, IRENA, *Geopolitics of the Energy Transformation: The Hydrogen Factor*.
142 IEA, *The Future of Hydrogen*.
143 IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and the Way Forward*.
144 Hydrogen Council, *Global Hydrogen Flows*.
145 Wijk et al.
146 European Commission, 19.

(excluding China) as the main importers, specifically Germany, the Netherlands, and Japan[147]. Import of hydrogen is desirable for these countries due to a combination of limited domestic potential, restrictions on technology choices (e.g. nuclear, CCS) and relatively poor renewable resources, in spite of the cost of transport that hydrogen incurs[148]. Europe is currently the leader in hydrogen projects (50%) and investment (35%), and Europe, Japan and Korea are leading the way with development, but are followed closely by North America and China[149].

A clear spatial distribution emerges; hydrogen is produced in and flows outward from countries in the Middle East, South America and Africa, towards Europe and East Asia. This is a flow of **hydrogen from generally poorer countries towards generally wealthier countries**. If we use the income designations used by Dorninger et al. in their investigation of ecologically unequal exchange, most countries that are seen as primary exporters of hydrogen, such as Brazil, Argentina, Chile, Namibia, South Africa, Mauritania, and North African countries like Morocco, Algeria, Tunisia, Libya, Egypt, and Sudan, are either lower, lower middle, or upper-middle income countries (the exception being some countries in the Middle East, specifically countries made rich off their oil and gas reserves, which qualify as high income countries). Importing countries, specifically Germany, the Netherlands and Japan, along with the rest of western Europe, are high income countries. As Dorninger et al. show, there are already flows of embodied energy, land, materials and labour from the bottom three categories of countries towards the wealthiest countries. The hydrogen economy thus seems, unsurprisingly, to be developing in line with existing patterns of ecologically unequal exchange. Importantly, as Hornborg and others have stressed, ecologically unequal exchange is not a new phenomenon but rather a continuation of colonization: the main hydrogen producing regions envisioned by these documents are South America and Africa, continents that were colonized and plundered by Europe for hundreds of years.

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[147] IEA, *Global Hydrogen Review 2022*, IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and the Way Forward*.
[148] BloombergNEF, IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and the Way Forward*.
[149] Hydrogen Council, *Hydrogen for Net Zero*.

The reason for this global distribution is very simple: to **ship hydrogen from where it is cheap to where it is not**[150]. The cost of producing hydrogen is the main factor in determining the global distribution of production. The geographic position of countries, their abundance in natural resources, the cost of renewable energy or gas, and other "soft economic factors" all influence price, but generally the main influences are land eligibility, the price of renewable energy – which are related, and also involve meteorological conditions, i.e. how much sun and wind are blowing – and transport costs[151]. IRENA examines the viability of different trading relationships for hydrogen and hydrogen derivatives. As they see it, hydrogen derivatives will be shipped more than hydrogen itself, which would then entail moving certain industries to sites of cheap energy[152]. Hydrogen based jet fuel, for example, is considered highly shippable, but for concrete it makes more sense to bring the energy to the site of production. Green steel production would be located both at sites of existing production (which would be retrofitted) and at new sites that are more proximate to cheap energy[153]. The essential point is that the viability of a particular trade of either hydrogen or hydrogen derivatives is based on a particular difference in the price of hydrogen between the exporter and the importer.

4.3.2 The value of land and labour

Over time, this price differential is expected to decrease as the market and industry develop and as technological and capital costs decrease, and trade will likely be limited to specific circumstances, for instance countries like Japan with high spatial restrictions[154]. However, some differential would remain, "driven by the difference in resource quality and by the cost of capital differential due to the economic conditions of each country (i.e. country risk)"[155]. We can understand

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[150] Energy Transitions Commission, IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and the Way Forward*, Wijk et al.
[151] Energy Transitions Commission, Hydrogen Council, *Global Hydrogen Flows*, IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and the Way Forward*, Wijk et al.
[152] Hydrogen Council, *Global Hydrogen Flows*, IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and the Way Forward*.
[153] IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and the Way Forward*.
[154] Energy Transitions Commission.
[155] IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part Iii - Green Hydrogen Cost and Potential* (Abu Dhabi: 2022), 21, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Global_Hydrogen_Trade_Costs_2022.pdf?rev=00ea390b555046118cfe4c448b2a29dc.

"resource quality" as speaking both to the meteorological and geo-physical qualities of a location, as well as to the price associated with accessing them. The "cost of capital differential due to the economic conditions," a rather obfuscatory phrasing, speaks to a multitude of factors, and we must consider labour among them. Differentials in the cost of hydrogen production cannot be solely explained by references to geo-physical differences between locations; this difference also arises from a social difference in the valuation of land and labour. Indeed, it must be stressed that the valuation of labour is socially determined, a product of global trade relations as well as racialization and sexism[156].

The purpose in pointing this out is to refute the claim that the hydrogen market will necessarily move towards price equalization over time, or that the market generally acts as an equalizing mechanism. While there might be a drive towards price equalization through the proliferation of the industry and competition, economic arrangements built on a price differential will exert their own drive towards maintaining that difference. We can then see, in the underlying logic of the spatial distribution of the hydrogen economy, one of the key dimensions of ecologically unequal exchange: the asymmetric valuation of land, labour, energy and materials. Particular patterns of trade will involve the relocation of industries and the construction of new infrastructure: they will materialize as part of the emerging hydrogen landscape. The price differentials that make these economics relations possible will become embedded in the landscape, and part of the inertia of the hydrogen landscape will be to maintain this price differential, and invested actors will have an interest in maintaining that differential. The cheapness of land, energy and labour in producing countries then becomes a feature of the hydrogen landscape.

The value of land for hydrogen production is based not only on meteorological conditions but on the **perception of availability**. What makes lands "available" for green hydrogen production? A report by IRENA offers an answer. They establish exclusion and inclusion criteria for land – forests, protected areas, wetlands, and urban areas and settlements were excluded for solar and wind, with crop land only excluded for solar, and sloped terrain excluded at different rates for each. What remains? Shrublands, savannas and grassland, croplands for wind, barren land or land covered in snow and ice. The

[156] Gayatri Chakravorty Spivak, "Can the Subaltern Speak?," in *Can the Subaltern Speak? : Reflections on the History of an Idea*, ed. C. Morris Rosalind (New York: Columbia University Press, 2010).

result of this analysis is that "countries with large areas of unused space with little vegetation, namely shrublands and desert, show a large installable renewable generation potential"[157].

But a closer examination of the countries that IRENA considers to be sources of "unused land" reveals a more complex picture. As Muller et al. show, Morocco produces much of its renewable energy in politically contested territory, and the hydrogen project in Namibia would use a large portion of the countries land, including the Kunene region, the home of various Indigenous groups[158]. The "unused desert-like areas that can be used for renewable power"[159] in the United States and Australia are, in many cases, home to Indigenous peoples. In Canada, the Nujio'qonik hydrogen project is located on land used and lived on by the Mi'kmaq, and the proposal has been divisive within Mi'kmaq communities[160]. The land which these documents portray as unused, unoccupied, uninhabited, available, or empty is, in reality already being used by people. The emptiness or availability of this land is not an empirical fact but a political designation, one that is aimed at authorizing the use and exploitation of these lands.

The portrayal of these lands as empty can be understood as belonging to the doctrine of *terra nulius*, a key component of the Doctrine of Discovery, the legal framework through which European colonizing nations laid claim to indigenous land. *Terra nulius* is the legal claim to so-called "empty land" or land that was not used according to European standards even if it was used and inhabited by Indigenous peoples[161]. By what standards did Europeans consider the appropriate use of land? As Ellen Meiksins Wood argues, it was by the standard of economic productivity, or the production of surplus value[162]. Wood's examination of John Locke's theory of property, which she takes to be representative of the general European - and specifically English - colonial and capitalist attitude towards land, shows that it was the ability to make land

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[157] IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part Iii - Green Hydrogen Cost and Potential*, 18.
[158] Müller, Tunn, and Kalt.
[159] IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part Iii - Green Hydrogen Cost and Potential*, 18.
[160] CBC News, "Mi'kmaw Chiefs Look for Mediator Help to Solve Wind Energy Conflict," *CBC News*, 19 February 2023, 2023, accessed 2023/5/5, https://www.cbc.ca/news/canada/newfoundland-labrador/mi-kmaw-chiefs-mediator-wind-energy-conflict-1.6751861.
[161] Robert J. Miller, "The Doctrine of Discovery and the International Law of Colonialism," *The Indigenous Peoples' Journal of Law, Culture, & Resistance* 5 (2019), accessed 2023/04/25/, https://www.jstor.org/stable/48671863.
[162] Ellen Meiksins Wood, *The Origin of Capitalism: A Longer View* (London: Verso, 2002).

economically profitable which authorized ownership and appropriation. Land occupied by Indigenous people, in the Americas for example, that was not put to industrious use was considered "waste land" and thus the European appropriation of that land was ethically and politically justified[163].

We can see this kind of **logic of economic productivity** applied in the hydrogen documents. The IRENA document makes an important distinction in the availability of different types of crop land: "The land type dataset distinguishes between cropland and cropland/natural, while the former is completely excluded for the installation of PV, the latter, being a mosaic of 40-60% cultivated land and 60-40% natural trees, shrubs or herbaceous vegetation, is excluded by only a 60% fraction"[164]. By this distinction, made at a resolution of 1x1 km^2, land which is put to full industrial agricultural use is unavailable, but agricultural land that falls outside the intensive model of industrial capitalist agriculture, and which allows more land to remain wild, would be considered at least partly available.

This analysis of land shows how economic productivity is embedded in scientific analysis. Historically, the appropriation of "empty" land was not only authorized through the political-legal category of property but through scientific concepts of energy and evolution. In *The Birth of Energy*, Cara New Daggett shows how the contemporary thermodynamic concept of energy was shaped by industrial and colonial interests and Protestant ethics of work and waste. She examines Alfred Lotka's integration of energetic, evolutionary and biological concepts, which characterizes evolution as a "general scrimmage for available energy" that favors species that increase "the total energy flux," and his prediction that humanity would "learn to utilize some of the sunlight that now goes to waste" thus increasing "the rate of energy flux through the system of organic nature." Daggett sees Lotka's description as "emblematic of the thermodynamic approach: all energy exchanges on Earth that are not being exploited by human industry can be considered waste, including waterfalls and each ray of sunlight"[165]. Daggett further argues that such approaches to waste

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163 Barbara Arneil, "Colonialism: Locke's Theory of Property," in *John Locke and America: The Defence of English Colonialism* (Oxford University Press, 1996).
164 IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part Iii - Green Hydrogen Cost and Potential*, 17.
165 Cara New Daggett, *The Birth of Energy: Fossil Fuels, Thermodynamics, and the Politics of Work* (Duke University Press, 2019), 120.

have been part of the logic of appropriating indigenous lands and making them "productive."

Such an ethic of waste is also visible in the hydrogen literature. Reports by the Hydrogen Council discuss hydrogen's ability to access "stranded renewables," renewables that are too far from sites of production to currently be used[166]. The use of the term "stranded" is noteworthy. Not only does it bring to mind the image of a helpless resource which needs liberating from spatial separation from economic activity, but in a climate context it also invokes the concern over stranded assets: fossil fuel infrastructure rendered inoperable and unprofitable by a renewable energy transition. It implies that, by virtue of their current underutilization, these resources are already property rightfully belonging to the companies and countries seeking to exploit them. The term "stranded renewables" represents the perceived ethical and rational obligation to make productive use of these resources.

4.3.3 Social relations of hydrogen technology

So far, we have examined the envisioned spatial configurations of the hydrogen industry, including the global distribution of its environmental footprint, as well as the rationale and discourse deployed in authorizing this configuration. Now, we shift our focus to an examination of the spatial relationships embodied in hydrogen technology itself, first through an examination of electrolysers, and second through particular end use applications of hydrogen. Electrolysers are the essential technology for producing green hydrogen, splitting water into its base components of hydrogen and oxygen through electricity. **Becoming a leader in producing electrolyser technology is a top priority for the EU**[167]. "The European hydrogen strategy is geared explicitly towards maintaining the region's competitive strengths in electrolyser manufacturing"[168]. Electrolyser production is currently mostly in Europe, but other actors in the Middle East and Africa are emerging as potential competitors. There is a general concern of losing out on manufacturing like Germany did to China with solar production, even though Chinese electrolysers are already cheaper and they export more of them[169].

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[166] Hydrogen Council, *Global Hydrogen Flows*, 9, Hydrogen Council, *Hydrogen for Net Zero*, 14.
[167] European Commission.
[168] IRENA, *Geopolitics of the Energy Transformation: The Hydrogen Factor*, 62.
[169] Ibid.

What kind of social relations are embodied by electrolysers? We should first of all conceptualize an electrolyser as a technology of extraction. An electrolyser is a machine which converts electricity and water into hydrogen gas. Its productivity is absolutely contingent on the sustained flows of its two inputs. The work it performs is one of conversion, the conversion of water and energy into a fuel which then, especially in places like Africa and South America, will be shipped elsewhere. It is a technology of extraction because it embodies, depends on and reproduces extractivist social relations. The resources, embodied in hydrogen or its derivatives, flow outwards from the countries where electrolysers operate towards the richest parts of the world. With lower entropy, thus more capacity to perform work, the transfer of hydrogen is a transfer of embodied land, energy, labour, and materials. Europe's desire to become leading exporter of electrolyser can then be conceptualized as a desire to accumulate monetary value through the sale of electrolysers, and to then expend that money on accumulating hydrogen - which embodies resources, most importantly land, that Europe cannot access so cheaply within its own borders. The export of electrolysers and the import of hydrogen can be understood as self-reinforcing cycle of ecologically unequal exchange.

Social relations of extraction are also embodied in the various end use applications of hydrogen. Key long-term uses of hydrogen include extractive industries like mining, where the physical mobility of hydrogen is made valuable by the very nature of the industries themselves, that they consist in the extraction of resources which are distant from their sites of consumption. Hydrogen would be used to decarbonize long distance transport, a key condition of possibility for global trade. As Mau argues, shipping is a key aspect of capitalism's economic power: "mobility is power, and means of transportation and communication are weapons"[170]. Shipping allows for the competitive pressures of capital to be applied to global level, and allows for production to chase the lowest wages and the weakest environmental protections around the globe. Hydrogen would also contribute to sustain the global distribution of industrial agriculture, as it is an input in synthetic fertilizer production[171]. Synthetic fertilizer plays an essential role in sustaining the metabolic rift, Marx's term for the interruption of the socio-ecological metabolism produced by

[170] Mau, 273.
[171] IRENA, *Green Hydrogen for Industry: A Guide to Policy Making*, IRENA, *Geopolitics of the Energy Transformation: The Hydrogen Factor*.

capitalist production, particularly agricultural production. The metabolic rift, which Marx conceptualized through an examination of the impoverishment of the soil produced by industrial agriculture, highlights the fundamentally extractivist nature of capitalism. Ammonia produced with green hydrogen allows for the draining of nutrients and biodiversity from agricultural soils to proceed in a decarbonized fashion.

The social relations embodied in hydrogen technology are thus those of a spatially separated socio-ecological metabolism. In a capitalist hydrogen economy, built on the foundations of ecologically unequal exchange and structured to perpetuate this dynamic, these social relations are fundamentally extractivist. We can conceptualize the value of hydrogen to capitalism as **sustaining global relations of extraction** in the face of ecological necessity and societal pressure to decarbonize.

4.4 What kind of change is the hydrogen economy?

The hydrogen economy is the quintessential green capitalist vision of the future – fossil fuels scrubbed of their carbon, integrated and interchangeable with renewable energy through a new common medium, a medium so dynamic and versatile that it can preserve existing relations of production and tap into new “stranded” resources. Converted into a common medium, the specificity of energy sources is concealed, the abstraction of energetic output becoming the common language through which all energy can be substituted. The hydrogen economy is, at its core, the real subsumption of nature; the mediation of energy metabolism through substitutability, aimed at preserving the exploitative and extractive character of fossil fuels and extending that character to renewable energy. It is a physical and temporal displacement of environmental consequences: physical by transferring the burden of decarbonization onto other peoples, places, and ecological processes; temporal by delaying mitigation into the future, while giving the appearance of actively decarbonizing. Hydrogen perpetuates the alchemical myth of green techno-capitalism; that through innovation, we can sidestep material constraints and access endless abundance, that we can have the perpetual growth of energy output without paying the ecological costs, or in Bockris’ words without “a pollutional limit to economic growth” – that we can get something for nothing. A closer look at the material conditions of hydrogen production however reveals that it would entail abundance for some at the expense of others by sustaining the spatially mediated relations of production that allow for global dynamics of extraction to persist.

Calling hydrogen a technology of extraction might seem reductionist. But, just as Matt Huber argues of oil, hydrogen is not a thing in itself, but a set of social relations. Even if the hydrogen economy does not yet exist, its envisioned deployment maps onto the social geography of the fossil fuel landscape. To call it a technology of extraction is not to say that this is an inherent property of the technology, but rather that this is a property that the technology comes to embody through its deployment in a historically specific set of circumstances. If we are to think critically about how else hydrogen could be developed, we need to distinguish between social relations embodied by hydrogen fuels on two levels: on the level of abstract possibility and on the level of historical specificity. On the first level we are talking about what social relations are theoretically possible or encouraged by the physical characteristics of the technology, specifically its mobility through space and time. These social relations would be a spatial and temporal mediation of energy production and consumption; the ability of hydrogen to move renewable energy about the globe would seem to lean towards globalization and interconnectedness. Its ability to store energy for future use and balance grid intermittencies is more complicated to assess, but would seem to both facilitate energy independence through energy self-sufficiency as well as interconnectedness, as surplus in one area could be used to balance shortages in another.

On the second level we are talking about the specific social relations that would emerge or be perpetuated by the development of the hydrogen economy as envisioned by current political and economic powers. These social relations are a specifically spatially distributed flow of resources, land and energy. Land in poorer, developing countries, many of them in Africa and South America, as well as former colonies of Europe that already supply Europe with a flow of embodied land, labour, energy and material, will be used to supply rich parts of the world, specifically western Europe and East Asia, with energy. This is environmental load displacement and ecologically unequal exchange: Europe is unwilling and unable to use the land within its own borders to generate sufficient energy for its economic activities, so it acquires land abroad, land embodied in the hydrogen it imports. And it is hydrogen which makes this displacement possible. Extractivism is the historically specific social relation which the hydrogen economy is on track to embody. At this level we can think of the hydrogen economy as a hydrogen machine, a concretizing system of hydrogen production and distribution, which depends on and reinforces the specific material flows that make it productive.

In reality, these two levels of social relations are developed simultaneously in the hydrogen economy documents. The abstract possibilities of hydrogen are immediately applied to bolstering already existing social energy relations. Hydrogen's mobility, which theoretically could be applied in a myriad of different ways, is immediately circumscribed to the function of bringing energy from where it is abundant and cheap to where it is economically desired and profitable. Electrolysers are being built in places where land and energy are cheap, and pipelines are being built to move the hydrogen they produce to the most affluent parts of the world. The material and social character of the technology are being developed in unison. How then do those of us who are interested in both decarbonization and the end of extractivism intervene?

5. Considerations for an eco-socialist hydrogen economy

If capitalism's structural attachment to fossil fuel delays emissions reductions, deploys the technology through market logic, and reproduces colonial relations of extraction, then a different vision for a hydrogen economy is needed. Intervention is also urgently needed, as this analysis highlights how the materialization of the hydrogen economy would further sediment its economic power. Striking the balance between pragmatism and critique requires an interruption of the future being shaped by a capitalist hydrogen economy as well as the articulation and construction of alternative futures before those alternatives are foreclosed. Such an intellectual and political project can be thought of as ecological socialism.

Ecosocialism is key for intervening in and undercutting the economic power of the fossil fuel landscape. As we have seen, fossil capital has a structural interest in extending the life of its fixed capital. Hydrogen's role in mitigation deterrence lies in its ability to sustain fixed capital by developing a new use for it, while also sustaining fossil fuels. As Sabrina Fernandez argues, the urgency of climate change requires us to fight for decarbonization even while under capitalism. She sees the seizure and early decommissioning of fossil fuel infrastructure as part of this struggle[172]. This is both a project of decarbonization and building socialism, as it involves workers and the broader public taking control over significant parts of the energy economy. Resisting the mitigation deterrence function of hydrogen while developing its decarbonization function requires building the political power to take control of and forcefully decommission existing fossil fuel infrastructure.

Fossil fuel infrastructure is not the only way in which the logic of profit shapes the hydrogen industry. Throughout, we see concerns of profitability guiding the industry down inefficient paths, potentially delaying its deployment and hindering it's scaling. If profit and price shape the direction and speed of hydrogen deployment away from effective decarbonization, a new guiding economic logic is needed. I would argue that such a logic is ecosocialist economic planning. As these documents reflect, the development of functional hydrogen supply chains requires significant logistical and material coordination, meaning some level of higher-level planning is needed. An ecosocialist planning system, such as the one articulated by Troy Vettese and Drew Pendergrass in *Half Earth Socialism,* would reject the singular metric of price, and instead integrate various biophysical limits and consequences and attempt to balance them with equitably meeting the varying needs of the global population[173].

As they emphasize, a planned economy should not be a technocracy but a democracy. Planners would not make decisions about what consequences are acceptable and what needs are essential or not, but instead would generate multiple plans to show a range of possibilities. The adoption of economic plans would be decided democratically through rounds of feedback and participation. For hydrogen, we can imagine that the costs, benefits, and appropriate uses of the technology would be assessed differently by different people. What is ecologically and socially acceptable is not definitely given, and therefore must be negotiated. Viewed in this light, we can understand ecosocialist economic planning as a process of globally negotiating ecological and social trade-offs. A market economy uses money as a tool to conceal these trade-offs and uses technologies of trade and extraction to burden peripheral populations with the consequences of resource exploitation from which the core benefits. The goal of

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[172] Sabrina Fernandes, "Ecosocialism from the Margins," *NACLA Report on the Americas* 52, no. 2 (2020/04/02 2020), https://dx.doi.org/10.1080/10714839.2020.1768731.
[173] Troy Vettese, and Drew Pendergrass, *Half-Earth Socialism: A Plan to Save the Future from Extinction, Climate Change, and Pandemics* (London, New York: Verso, 2022).

ecosocialist economic planning would be to make visible the material flows of the economy and to make impossible the rationalization of extraction and exploitation through the logic of price.

What might the role of hydrogen be in an ecosocialist planned economy? This depends on the desirability of its social relations: what is the role of spatially and temporally separated energy production and consumption in and ecosocialist society? Which injustices, inequalities and violence could this separation sustain, and which could it rectify? The definitive answer to these questions cannot be theoretically or empirically given – rather they must be democratically negotiated, and that is the very point of democratic economic planning. One key problem that an ecosocialist hydrogen economy must confront is the subordination of specific and regional interests to any kind of "global" or "systemic" logic. Even in a world where private property has been abolished and the expansive quest for profit no longer structures global relations of productions and exchange, the implementation of another universal logic, which comes with its own social and ecological harms, is still possible. For example, if some of form of industrial socialism which still takes technological advancement and the expansion of productive forces as the main goal of economic activity, it is likely that a globally interconnected energy economy would still engage in ecologically unequal exchange and environmental load displacement.

Marx argued that freedom in human relationships with nature meant that humanity would "govern the human metabolism of nature in a rational way, bringing it under their own collective control instead of being dominated by it as a blind power, accomplishing it with the least expenditure of energy and in conditions most worthy and appropriate for their human nature"[174]. While freedom from the domination of the "blind power" of capital through the self-governance of interactions with nature should remain a key goal of ecosocialism, we should also be attentive to the way concepts of "collective," "rational," and "human nature," carry within them hegemonizing tendencies, reproducing colonial and Eurocentric assumptions about the "human" and prescribing universal norms. As postcolonial scholars like Gayatri Chakravorty Spivak and Dipesh Chakrabarty have argued, the concept of a "rational collective" of humanity that emerges from Marx is built on Enlightenment ideals of the

[174] Karl Marx, cited in Foster, 159.

human[175]. That is, it presupposes both the content of "rational" and "collective" in a way which privileges the white, male, European proletarian worker as the default subject of the "collective" of which it is an extension, and European epistemologies and values as the definitively "rational." The idea of a human collective which must "rationally govern" the earth thus risks reproducing logics that value a certain type of humanity over others, or that take the economic priorities of Europe as rational and universal. A true human "collective" must remain open to the plurality of rationalities and human natures which are manifest across our species.

For these reasons, an ecosocialist hydrogen economy, and in fact ecosocialism more broadly, cannot emerge through the imposition of a universal economic or political regime, but must emerge through international solidarity and economic democracy. If a spatio-temporally separated energy economy is to be developed in a way in which it does not subordinate local interests to the global and which does not displace consequences onto particular groups in the function of some higher logic, this economy needs to be developed on the basis of radical sovereignty and democracy. Theis means that the determination of higher-level economic priorities should emerge from and be negotiated between lower levels – economic democracy from the bottom up. While actualizing this economic reality might still be far away, the near-term intervention against the rapid expansion of capitalist energy landscape, whether hydrogen or fossil, requires collective action in the present as well as a collective vision of the future.

6. Conclusion

The capitalist hydrogen economy, as envisioned in documents produced by dominant economic and political powers, is an energy economy that builds upon and reproduces the ecological and social relations of the fossil fuel economy. In answering my first research question, I found that hydrogen production, transportation and use would involve continued fossil fuel consumption, the preservation and expansion of fossil fuel (compatible) infrastructure, and the

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[175] Spivak, in *Can the Subaltern Speak? : Reflections on the History of an Idea*, Dipesh Chakrabarty, "Chapter 2: The Two Histories of Capital," in *Provincializing Europe : Postcolonial Thought and Historical Difference*, *Princeton Studies in Culture/Power/History* (Princeton, N.J.: Princeton University Press, 2000).

reproduction of the fossil fuel landscape: the material and social relations of the fossil fuel economy. Together, these constitute mitigation deterrence on multiple levels, by working not only to extend fossil fuel usage but also to delay deeper systemic transformations required to reduce emissions. Beyond carbon emissions, the hydrogen economy has spatial and material requirements that come with social and ecological consequences. The hydrogen economy documents envision that these requirements and consequences would, through hydrogen's mobility, be foisted onto impoverished and racialized populations, meaning that the hydrogen economy would perpetuate relations of ecologically unequal exchange. Discourses of land availability, justified by a logic of economic productivity, are deployed to authorize this unequal exchange. Broadly, my analysis suggests that the eco-social relations embodied in hydrogen technology are those of extraction. I argue that ecosocialism is a potential pathway for resisting the development of an extractivist hydrogen economy, as well as for envisioning the development of a decarbonized and post-extractivist global energy economy into which hydrogen might be integrated. Hydrogen and the hydrogen economy remain an understudied topic, particularly from critical social sciences perspectives, and further examinations of the eco-social consequences of the technology will be needed as the hydrogen economy develops.

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