Imperial hydrogen -Trading the Land

Ecological unequal exchange between Namibia and Germany

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Abstract:

Climate change is escalating. In the search for alternatives to fossil fuels, many countries are pushing green hydrogen as an energy vector. The development of a hydrogen economy is planned, and social and ecological consequences are at risk of being neglected. Namibia has excellent conditions for renewables and plans to be a major exporter of green hydrogen. Germany is set to import green hydrogen while exporting technologies to produce the green hydrogen. To investigate the material consequences of the trade of hydrogen, especially embodied land, the thesis investigates at the first large-scale hydrogen project in Namibia, developed by Hyphen Energy. In a scenario where Namibia is exporting hydrogen to Germany while wind turbines and electrolyzer technologies are traded from Germany to Namibia, I am analyzing the ecological unequal exchange occurring from this trade. This is done by using a life cycle assessment-based approach to calculating ecologically unequal exchange. These insights which reveal the consequences of this trade are further discussed from a radical environmental justice perspective. The concept is used to discuss if it can lead to argumentation that limits ecologically unequal exchange.

The findings show that a future green hydrogen trade will probably include a significant unequal exchange of embodied land. Radical environmental justice applied to this case could change power structures which again could lead to less ecologically unequal exchange.

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List of acronyms

BMBF	Federal Ministry for Education and Research in Germany
BMWK	Federal Ministry for Economic Affairs and Climate Action in Germany
CBNRM	Community-Based Natural Resource Management
EUE	Ecologically Unequal Exchange
GMP	General purpose money
GWh	Gigawatt-hour
kWh	Kilowatt-hour
LCA	Life cycle assessment
MWh	Megawatt hour
USD	United States Dollar
PEMCE	polymer electrolyte membrane electrolysis cell

1. Introduction

Climate change is escalating, alternatives to fossil fuels are needed. Renewable energy could enable less emission-intensive energy production if they are not just added to the existing use of fossil fuels(York & Bell, 2019). However, not all applications in the current industry and energy system can be replaced through the direct use of renewable electricity. Green hydrogen can be produced out of water and renewable electricity, in this way it can store energy and if needed be burned to generate process heat and electricity again. These properties make green hydrogen an imminent part of a transformation towards zero emissions. Global demand for green hydrogen is projected to increase by 6% yearly reaching 150MT in 2050, which is more than 20% of the global energy sector (IEA, 2023).

Many countries want to benefit from this emerging hydrogen economy, decreasing emissions while profiting economically. Namibia, with its excellent wind and solar conditions, wants to improve energy independence and generate income with green hydrogen exports (Ministry of Mines and Energy Namibia, 2022).

In the industrial centers, more energy is consumed than can be produced by renewables, with Germany being an example. Germany and other countries therefore want to import hydrogen while exporting technologies for green hydrogen production (BMWK, 2023; Mukelabai et al., 2022; Noyan et al., 2023). In Germany, hydrogen should play an important role as a combustible energy carrier, with demand expected to reach 90 to 120 TWh by 2030 and 500 to 600 TWh by 2045, roughly equivalent to today's electricity consumption. 50 to 70 percent of the hydrogen will have to be imported, requiring new value chains and infrastructure (BMWI, 2020; BMWK, 2023) The two countries share a common history characterized by the violent colonial rule of Germany, including the genocides of the Nama and Herero tribes.

The perspective on the hydrogen economy in the public and scientific discourse is characterized by the question of feasibility. How can enough hydrogen be produced and delivered to the point of use? This technical approach is important to develop the technology that can reduce emissions. But as Kalt and Tunn (2022) highlight, the socio-ecological consequences are under-researched. A social and just transition is important to avoid potential conflicts and questions about social structures that are not addressed by more technical approaches.

The concept of Ecologically Unequal Exchange (EUE) looks at the trade between core and periphery in the capitalist world system. Ecologically unequal exchange occurs when there is a significant transfer of materials, energy, and labor, as embedded in internationally traded goods, from one country to another. This concept, as described by Alf Hornborg in 1998, highlights how such transfers typically flow from peripheries to core regions in the world system. These exchanges are not merely economic activities but also represent an imbalance in ecological impacts, resulting in resource depletion and environmental damage in the exporting countries while the importing countries reap the benefits without facing equivalent ecological consequences (e.g.Dorninger et al., 2021; Givens et al., 2019; Hornborg, 2021; Oulu, 2016; Roos, 2022).

This theory applied to renewables helps us to understand what the materiality behind the trade of energy is. More concrete, through its focus on energy in the form of land and work it sheds light on the social-ecological condition behind the extension of renewables. The focus of this thesis will be land necessary to produce green hydrogen. It gives a grounding for evaluating environmental justice and the development of ecological debt the global north owes to the global south (Hornborg & Martinez-Alier, 2016).

A critical analysis of a future hydrogen economy using the examples of Germany and Namibia will shed more light on these consequences and enrich the discussion about normative aspects in the structure of a potential hydrogen economy informed by EUE. I am trying to start filling a research gap around social and material consequences of the emerging hydrogen economy.

This is done by answering two research questions:

1. Does the development of a green hydrogen economy lead to further expending ecological unequal exchange?

2. Can radical environmental justice applied to the case of Germany and Namibia provide arguments to reduce EUE?

The first questions aim to analyze the land use in the trade of wind turbines and electrolyzers from Germany to Namibia while Germany is importing hydrogen or its derivatives from Namibia. Derivatives are chemical compounds in which other elements are bound with hydrogen. The fertilizer Ammoniac (NH_3) is one example: hydrogen is combined with nitrogen from the air which makes it easier to transport. This question aims at an analysis of the material basis of the future hydrogen exchange between the countries.

The second question brings explores the potential of the concept of *radical environmental justice* by Schlossberg (2008) to argue for a reduction of EUE. To answer this, the need for a reduction of EUE is discussed and the dimensions of radical environmental justice are applied. In total this thesis informs future research on the hydrogen trade between the global south and the global north, especially looking at justice implications.

This work is relevant to human ecology as it investigates a changing human-nature relationship. I am looking at the material basis (land) of the evolving hydrogen economy. Typical for human ecology, an interdisciplinary approach is chosen to enrich the discussion about hydrogen trade from the global south to the global north, while asking how changes for a more just conceptualization can be made.

The thesis is structured as follows. First, a basic understanding of hydrogen, as well as Germany's and Namibia's roles in future hydrogen production and trade will be established. Second, the theoretical concepts at hand will be introduced to better understand the development of energy production in the capitalist world system leading to the use of green hydrogen. Third, the method of life cycle assessment based on EUE will be introduced, and the results will be displayed. The results and the discussion inform the first research question. In the discussion part, the second research question will be answered.

2. Background

2.1. Hydrogen Economy

The climate crisis is primarily driven by the large-scale use of fossil fuels and capitalist relations of production (Malm, 2016). The consequence of this is that global temperature is dramatically increasing, potentially reaching 2,9 degrees Celsius above pre-industrial levels in 2100 (Olhoff et al., 2023). This urgent issue has led to a global consensus on the need for change manifested through the 2015 Paris Climate Agreement. This agreement should guide the member states of the United Nations towards carbon neutrality. To achieve this, hydrogen emerges as a promising alternative fuel. This section explores the concept of a hydrogen economy and its potential role in Germany and Namibia.

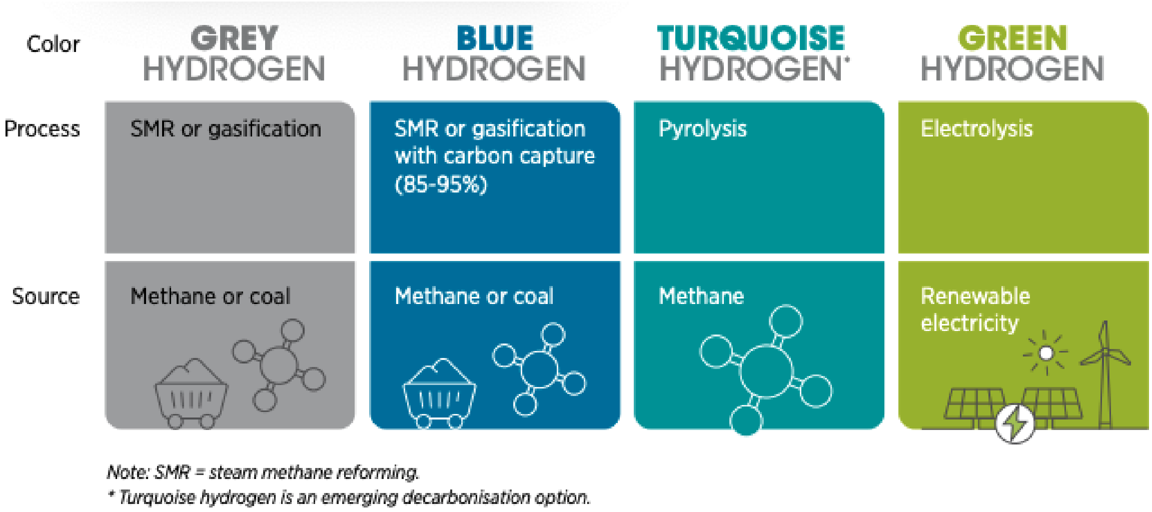
Historical context and initial developments

Hydrogen (H) is the most abundant element in the universe. It easily combines with other elements (e.g. water H2O or methane CH4). Hydrogen atoms combined as H_2 can be burned with oxygen. These properties were interesting for economic activities in already decades ago.

The beginning of the concept of a "hydrogen economy" can be traced back to the 1970s and was envisioned in the 1970s by pioneers like J. O'M. Bockris. He proposed hydrogen as a versatile and clean energy vector, promising clean air (J. O. Bockris, 1972). This vision gained prominence against the backdrop of the oil crisis, where hydrogen first was discussed as an alternative to fossil fuels. The concept was brought up again in the 1990s with advances in fuel cell technologies. Despite the initial hype, a fully realized hydrogen economy was not achieved. This was mainly due to technological and economic barriers at the time and the accessibility of fossil fuels (J. O. Bockris, 2013).

Hydrogen production and usage

Currently, hydrogen serves primarily in the chemical industry, particularly in ammonia production for fertilizers, methanol, and as a reducing agent in crude oil refining. These applications rely on 'gray hydrogen', derived from steam reforming of natural gas, coal, or oil, the most prevalent form of hydrogen production today. Grey hydrogen accounts for 96% of the total hydrogen production of around 70 million metric tons and accounts for 2% of global greenhouse gas emissions (IEA, 2019). Another type of hydrogen that should be mentioned in the color spectrum of hydrogen is blue hydrogen. This is obtained from fossil fuels, but some of the CO2 produced in the process is to be captured by carbon sequestration. An overview of the different hydrogen colors is provided in Figure 1. The current application is still marginal, but this hydrogen should promote the market entry of hydrogen as "low carbon" hydrogen (AlHumaidan et al., 2023).



Color	GREY HYDROGEN	BLUE HYDROGEN	TURQUOISE HYDROGEN*	GREEN HYDROGEN
Process	SMR or gasification	SMR or gasification with carbon capture (85-95%)	Pyrolysis	Electrolysis
Source	Methane or coal	Methane or coal	Methane	Renewable electricity

Note: SMR = steam methane reforming.
* Turquoise hydrogen is an emerging decarbonisation option.

Figure 1: Hydrogen spectrum (Meyer, 2022)

Green hydrogen

A hydrogen economy that aims to live up to the hope of decarbonization must be based on green hydrogen. Green hydrogen is based on renewable energies. Water is split into hydrogen and oxygen through an electrolyzer and electricity. Only around 1% of the global hydrogen production is “green” (IRENA, 2024). Predictions suggest a shift towards large-scale application in the coming decades (ibid).

Green hydrogen should not be considered a standalone technology. It can be converted to ammonia, a process that is being pursued in Namibia. Additionally, hydrogen-based fuels, or "e-fuels," can be produced by combining hydrogen with carbon (C). This process increases the energy density and, consequently, the range of applications. However, these processes are still energy-intensive and expensive (Ueckerdt et al., 2021).

Oliveira et al., (2021) have delt with this future. They project that it can decarbonize around 18% of energy-related sectors. From their perspective, the rollout of the green hydrogen economy should be done in three steps, first being used in chemical feedstock, second as a transition fuel for long-distance transportation and heating, and finally as storage for electricity as seasonal storage. In general, hydrogen is seen as an option for the so-called hard-to-abate sectors, industries where direct electrification is not possible (ibid). These properties make hydrogen particularly attractive, especially for industrialized countries like Germany. The historic unequal economic conditions enable core countries to afford more energy (Hickel et al., 2021), at the moment with the import of fossil fuels and probably in the future with alternatives. Energy-intensive industries like steel and chemical sectors see green hydrogen as an alternative to fossil fuels. From Namibia's perspective, green hydrogen can be seen as an opportunity to deliver energy to the world market and generate income (Staiß et al., 2022).

2.2. Germany's Hydrogen Future

Scheller et al., (2023) evaluated several scenarios of hydrogen use in Germany, concluding that emission reduction is a primary motivator for developing a hydrogen economy. Their research indicates a moderate positive correlation between the setting of ambitious climate goals and an increase in hydrogen usage and its derivatives by 2050. This motivation is also formulated in Germany's National Hydrogen Strategy. The strategy aims to combine emission reductions with economic development, seeking to secure the country's industrial sectors while promoting decarbonization through the use of hydrogen technology (BMBF, 2023). In other words, green growth through a hydrogen economy.

The strategy formulates Germany's ambition to achieve ″technological leadership in hydrogen technologies" to profit from a developing hydrogen economy they want to foster (BMBF, 2023, p. 4). Recognizing the limitations of domestic production, Germany is actively working on relations to import hydrogen in the future. Current forecasts suggest that renewables will require up to 2% of

Germany's land area (Kreutzfeldt, 2022). The production of hydrogen without imports would increase land use for renewables. The increased demand for land for renewable energy has already led to spatial conflicts (Steinhäußer et al., 2015), which currently hinder the pace and public acceptance of the energy transition (Schönauer & Glanz, 2023). Imports could therefore be a solution to avoid these conflicts. The volume of the imports is significant 50-70% of the total hydrogen use in Germany equaling more than 2,7 million tonnes in 2030 (BMBF, 2023).

An expert committee, from science, the economic sector, and civil society, advises policymakers on the progression of the hydrogen economy (BMWI, 2020). By 2025, Germany plans to lay the foundation for critical projects, like pipelines, and establish international partnerships to secure imports, as in the case with Namibia (BMBF, 2021). The partnerships include loans and knowledge as well as technological transfer(BMBF, 2021) By 2030, the goal is to integrate hydrogen into the industrial and also the transport sector. In the long term, meaning after 2040 a hydrogen economy should be established and linked with international supply chains (BMBF, 2023; BMWI, 2020). A proposed 9700 km network of hydrogen pipelines is central in this plan (tagesschau.de, 2023)

A positive vision of hydrogen is communicated by officials to the public as the example Economic and Climate Minister Robert Habeck is indicating. He called the hydrogen the "Next big thing" (Hofmann, 2023). Another example is the Ministry for Research and Education which labels hydrogen the "oil of the future" (BMWK, 2023).

The politically supported expansion of the hydrogen economy should achieve a global scale as the state-financed trading platform H2Global indicates (H2Global Foundation, 2024). The projected import volumes are only set to increase further in the future. This creates opportunities to meet and jointly develop this demand, as the case of Namibia as an export country shows.

2.3. Namibia's Hydrogen plans

As a hydrogen trading partner, Namibia offers Germany and the emerging hydrogen market good conditions to produce hydrogen: Namibia is one of the most sparsely populated countries in the world, with a population of about 2.5 million and a vast, mostly desert surface (Worldometer, 2023). It has excellent conditions for the production of wind and solar energy and its location on the Southwest coast of Africa (Figure 2) (H2Atlas-Africa, 2024). The access to the Atlantic Ocean enables desalination of water, which is needed for green hydrogen, as well as hydrogen trade via ships to the world markets. Additionally, Namibia is politically stable, which is another aspect to attract international investment (ibid.). Thus, Namibia is setting the stage for significant development, leveraging its ″world-class renewable energy sources" to produce green hydrogen, primarily for export purposes (Ministry of Mines and Energy Namibia, 2022, p. 9). The country's Green Hydrogen Strategy aims to drive job creation, GDP growth, and sustainable economic development, marking a strategic move towards harnessing renewable resources for energy production and economic activities (ibid). The government’s collaboration with international partners, notably Germany, plays a pivotal role in achieving these objectives, providing a blueprint for transformative socio-economic development through green hydrogen production. Investments as well as technological transfer are needed to develop a hydrogen economy in Namibia.

Figure 2: Location of Namibia

Regional Plans and Projects

The plans for the development of hydrogen in Namibia are concrete: In the Southern Region, located in the Tsau/Khaeb National Park, the Hyphen Hydrogen Energy project emerges as the first large-scale green hydrogen production side (Hyphen, 2024; Ministry of Mines and Energy Namibia, 2022). This case will be the focus of this thesis. The Central Region, encompassing Walvis Bay and Windhoek, aims to establish a synthetic fuel (e-fuels) hub. This area is set to foster early pilot projects and infrastructural developments, including the clean energy Namibia initiative and an HDF Energy project, with a long-term production target of 3 Mt annually by 2050 (Ministry of Mines and Energy Namibia, 2022). Last, in the northern parts of Namibia a third area will be developed with a vision to generate 5 Mtpa of hydrogen by 2050.

2.4. The Case – Green Hydrogen from Hyphen Energy in Namibia

Figure 3:Hyphen location (Rischer, 2023).

The joint venture Hyphen Hydrogen Energy, has been conferred with the status the of preferred bidder for a significant tract of land, spanning approximately 4,000 square kilometers, within the confines of the Tsau/Khaeb National Park (Figure 3). The park is a long-protected area with special flora and fauna and is considered a biodiversity hotspot (Grobler, 2023). The pictured project, with an approximate financial outlay of US$10 billion, should be finished in several phases by 2030. The culmination of this development is projected to yield an annual production of 350,000 metric tons of green hydrogen. This will be facilitated by a renewable energy generation infrastructure, anticipated to possess a capacity of between 5 to 6 gigawatts, complemented by an electrolyzer apparatus with a capacity of 3 gigawatts. To ship the energy the hydrogen will be transformed into ammoniac (Hyphen, 2024).

Hyphen Hydrogen is a joint venture of Nicholas Holdings Limited (51 %) and ENERTRAG South Africa (SA) (49%). ENERTRAG SA is a company of the German energy provider ENERTRAG and brings experience in the production of renewables and is starting to invest in green hydrogen. Nicholas Holdings is a strategic investor, bringing in mainly capital. The Namibian state will own 24% equity in this project (Matthys, 2024). This should ensure longlisting advantages for the Namibian state. The CEO of Hyphen is Marco Raffinetti, who praises the area as optimal for hydrogen with its options for wind, solar, and the nearby sea for export (Lohse, 2021). The execution of this initiative is forecasted to engender approximately 3,000 enduring job opportunities, alongside 15,000 job positions throughout a four-year construction phase. It is projected that more than 90% of these employment opportunities should be procured by the local Namibian populace (Hyphen, 2024).

The trade of energy from this project to Germany is already a resolved matter. A preliminary agreement has been concluded with the German energy producer RWE for 300,000 tons of green ammonia from 2027 (RWE, 2024). RWE is an energy producer that operates large lignite-fired power plants in western Germany, which are due to close by 2030.

2.5. Namibian History and its colonial relation to Germany

German colonization of Namibia, then known as German Southwest Africa, started in 1884, leading to a brutal colonial regime that inflicted suffering and violence on the indigenous population. Notably the Herero and Nama peoples, culminating in a genocide between 1904 and 1908 (Melber, 2020). The Herero and Nama populations decreased from 80,000 and 20,000 to 15,000 and 10,000, respectively. German settlers used their power to dispose Herero and Nama from their land (Wallace & Kinahan, 2011).

During the colonial period, German settlers exploited and dominated sectors like agriculture, mining, and fishing. These established structures still form the basis of Namibia’s current economy (Dale, 2001; Weigend, 1985) The German settler community in Namibia, particularly between 1923 and 1950, established a continued ownership of large land areas. Especially their influence in agriculture and mining enabled them capital accumulation which is continuing until today (Dale, 2001).

The German colonial rule in Namibia was followed by South African occupation (1920-1990). The discussions and negotiations around land reforms in Namibia reflect the historical injustices of German and South African colonialism. Both periods resulted in the consequence of extreme inequalities in land ownership, with lasting impacts on the landless majority. There are social movements demanding change in land ownership. However, they face resistance from political elites, who are often large landowners themselves (Tjirera, 2023).

There's a continuing struggle to address the skewed land distribution and power dynamics rooted in the colonial era (Melber, 2020). Community conservation and land use debates in Namibia involve diverse visions and policies, with tensions between agriculture, livestock, conservation, and tourism, reflecting the complex interplay of environmental, economic, and social factors. Green hydrogen brings another aspect to this struggle as will be elaborated on in this study.

The relationship between Namibia and Germany post-colonial period is marked by negotiations and debates over historical responsibility, recognition of past atrocities, and reparations. Germany recently acknowledged the genocide and is offering development aid as compensation. Compensations remain a contentious issue (Melber, 2020).

3. Theoretical framework

In this thesis, I adopt a critical realist perspective underpinned by ecological Marxist approaches to explore the intricate interplay between social relations and power structures in the nascent hydrogen trade between Germany and Namibia. This perspective foregrounds moral considerations and emphasizes the material basis of social interactions, particularly the uneven distribution of embodied land. This approach is instrumental in framing discussions about global environmental justice and the emerging hydrogen economy.

Understanding human's use of energy

Historically, a shift in human energy sources has marked significant shifts in human development. The historical utilization of energy therefore provides a vivid backdrop for understanding transitions in human history. Huber (2009) highlights a critical transition from reliance on animal and human muscular power to fossil fuels. Similarly, Andreas Malm (2013, 2016) discusses the shift from water to steam power, noting how it enabled more efficient exploitation of labor and resources, thus facilitating capital accumulation.

Technological progress, here in the sense that people were able to use more energy, not only influenced the technology that was used but also changed social structures. The replacement of muscle power by technologies, such as steam engines, changed the relationship between capital and labor. Capitalists were able to bring more means of production under their control, making muscle-based labor increasingly exchangeable (Huber, 2009).

A key development was the introduction of steam engines run on fossil fuels, which facilitated production that was both continuous and geographically independent (Malm, 2016). Consequently, factories were no longer dependent on water turbines powered by natural water flows, marking a transition to a more controlled and exploitative energy regime. Andreas Malm (2016) in his central work, *Fossil Capital*, highlights the importance of this shift, emphasizing that this transition to fossil fuels is meant to enhance control over production processes and labor, enabling further capital accumulation.

The second law of thermodynamics sheds light on the environmental consequences of this transition toward the use of fossil fuels. Georgescu-Roegen (1971) integrates economics and thermodynamics. He demonstrates that fossil fuel production processes increase entropy (disorder) and contribute to global climate change through increased carbon emissions. Fossil fuels are products of photosynthesis from millions of years ago, existing in relatively high order (many bonded carbon atoms). Burning and releasing this energy increases disorder by breaking carbon chains, consequently releasing more CO2 into the atmosphere. Malm expands this analysis by linking economic activities with rising CO2 levels in a capitalist economy. He refers to Altvater (2007) and Georgescu-Roegen (1971) to make use of the concepts of energy "stocks" and "flows". Flows is energy that is in motion. For example, sunlight can be made into electricity with solar panels if the sun is shining. In this conceptualization, stocks represent concentrated energy forms accessible and independent from flows, like fossil fuels.

The use of fossil energy stocks enabled continued growth in production and energy use. Andreas Malm (2016) articulates how this relationship between the rising capitalist economy and increased CO2 emissions contributes to climate change. In essence, the release of energy from fossil fuel stocks stored millions of years ago, leads to increased entropy, more CO2, and climate change.

The use of technology that produces renewable energy is trying to break this connection, utilizing the current flow of sunlight processed via solar panels or wind turbines into electricity (ibid.). Renewable technologies should harvest energy from the sun's, a current energy flow, enabling a disconnection of direct emissions from production. They are conceptualized as zero-emissions energy sources, but still are not as their production is dependent on fossil metabolism (Schreiber et al., 2019; Zhang et al., 2023). Green hydrogen, used to store energy, can then be seen as a stock of renewable energy. These stocks are in comparison to fossil stocks produced and placed by humans and are not naturally formed. Ideally, a supply chain reliant solely on such energy flows would mitigate direct emissions from production processes. However, this is only possible if all parts of the supply chain are disconnected from the use of fossil fuels stocks (Malm, 2016). If this is possible is questionable and cannot be assumed (Roos, 2023). The use of energies has inherent relations between societies and their natural environment. The following concept is one way to approach these relations.

Social metabolism

The concept of social metabolism refers to the ways in which societies organize their exchanges of energy and materials with the natural environment This notion is similar to biological metabolism. It focuses on how human activities, technological advancements, and economic systems both affect and are affected by the flows of resources and energy within and across ecosystems. It offers a framework for analyzing the transformations and throughput of materials and energy in socio-economic systems, emphasizing the interdependencies between society and the natural environment (González De Molina & Toledo, 2023)

John Bellamy Foster (1999) highlights the role of the metabolic relation in Karl Marx's development of his labor theory. Marx described metabolism (Stoffwechsel in German) as the process of exchange between humans and nature, asserting that both realms are mutually influential (Marx, 1992). From this perspective, a connection between humans and the natural world is apparent. One could argue that our social systems and the technologies we employ are extensions of our physical selves, participating in a metabolic relationship with nature. Andreas Malm (2016) and Matthew Huber (2009) further argue that this interconnection through tools technology and resources influences the social arrangements within capitalism, facilitating domination and economic exploitation. The structuring and allocation of technologies are further described in the next concept.

Formal and real subsumption

The concepts of formal and real subsumption of labor offer a critical lens through which to analyze the evolution and intensification of capitalist production processes. For the capitalist to accumulate capital from the surplus value generated by the worker the capitalist must somehow be part of the production process. If they achieve this without transforming the production process, the subsumption process is formal (Malm, 2016). Real subsumption represents a transformation, where the labor process itself is fundamentally redesigned to maximize the extraction of surplus value. This restructuring extends beyond the workplace, influencing broader societal structures and patterns, as noted by scholars such as Malm (2016) and Sicilia (2022).

Andreas Malm's analysis (2016) of the historical transition from water to steam power illustrates the real subsumption. He shows that this transformation is not just a technical evolution but a strategic capitalist maneuver. The adoption of steam power allowed capitalists to centralize production facilities and extend working hours. Malm argues that it was not efficiency driving this transformation, but control. This example underscores the broader implications of real subsumption, where technological and organizational advancements in production are primarily geared towards reinforcing capitalist control and optimizing the exploitation of labor (ibid)

The transition to hydrogen could potentially change the current socio-ecological metabolism, although a complete transformation or 'real subsumption' under capitalist conditions appears unlikely. Current trends indicate a rise in the share of renewable energy production, primarily supplementing existing energy systems rather than replacing them. York and Bell (2019) characterize this phenomenon more as an 'addition' of energy rather than a full 'transition'.

Hornborg et al. (2019) note that fossil fuels substitute for space and time by utilizing ancient sunlight stored underground. Harvesting current flows for energy production, such as through solar panels or wind turbines, needs significant space, materials, labor, and ongoing use of fossil fuels (e.g. the example of solar panels (Roos, 2022). This shift makes Hornborg argue that land is a contested resource once again, particularly as the availability of livable land diminishes due to the climate crisis.

Imperial metabolism

Bringing this energy transformation to a global level, Hornborg's (2021) concept of imperial metabolism offers a framework that aims to better understand how the exchange of energy and time is embedded within global power structures and material flows.

Imperialism is to extend the power of a region or nation over other regions or nations. This is a process that was again and again seen in history with different means (Upadhyay, 2018). Where it often was a force in the past, today more economic dependencies can be seen as a means to achieve this. Hornborg (2021, p.456) identifies "The appropriation of (human) time (and natural) space in the form of embodied time and embodied labor (…)" as quantifiable entities to measure the imperial metabolism. However, the disconnection of energy from space with the emergence of fossil metabolism made some land more valuable as different amounts of fossil fuels and therefore energy could be appropriated. The use of renewables reconnects the power over space with the ability to appropriate energy and accumulate capital.

This perspective reveals the complex network of relations that not only facilitates the flow of energy and materials but also perpetuates a hierarchical world system where the distribution of benefits and burdens is uneven. Thus, examining the transition to hydrogen through the lens of ecologically unequal exchange is essential for critically assessing whether this shift might replicate or challenge these entrenched disparities.

3.1. Ecologically unequal exchange (EUE)

The central concept to answer research question one is ecologically unequal exchange (EUE), which offers invaluable insights into the global dimensions of environmental justice, particularly from a distributive perspective. The concept helps to understand how environmental burdens are disproportionately distributed across regions (Dorninger et al., 2021; Oulu, 2016; Temper, 2017). EUE is a concept used in environmental economics and political ecology.

The objective of this study is to apply EUE to the developing green hydrogen trade between Germany and Namibia. First, I will elaborate on the development of history, followed by dimensions identified and connected by Alf Hornborg in scholarly works (1998, 2019b, 2022, 2023). The dimensions are general purpose money (GPM), technology, and environmental load displacement.

EUE is defined by Martin Oulu (2016, p.1) as "(…) a net flow of natural resources from peripheral developing to core industrialized countries through international trade, a situation which undermines the development of the periphery while enhancing that of the core." This definition already indicates the development of EUE: dependency theory and world system analysis (ibid.). The theorists Wallerstein and Frank (1967) used a world system perspective differentiating the world into core and periphery and showing imperialist structures of capitalist accumulation. Whereby core regions typically are centers of consumption.

Howard T. Odum's emergy concept (1988) added to the discourse by introducing a quantifiable measure to assess the energy and resources embedded in global trade. Emergy is the amount of energy that has been consumed in direct and indirect transformations to make a product or service (ibid.). It thus is deepening our understanding of the ecological impacts associated with trade. Having these direct and indirect ecological impacts of products or services in mind and adding this logic of trade between the "core" and "periphery" highlighted the often-invisible environmental costs transferred.

Odum and Arding (1991) were concerned that the ratio of energy to the dollar was unequal from the periphery to the core, adding another facet, which will be further elaborated with general-purpose money.

General purpose money (GPM)

The cultural factor enabling unequal exchange is money. Through money, trades seem reciprocal (Hornborg, 2022). A product or service in exchange for money a trade that we are doing daily – the consequences of this trade like climate change or ecosystem degradation or social harm are not directly seen in the price. Hornborg further elaborates on the concept of GPM, as

"(...) basically an idea about the generalized interchangeability of all things. In making products and services from all over the world commensurable in terms of a single metric, the nineteenth-century world economy vastly increased the opportunities for – and the scope of – unequal exchange" (Hornborg, 2012, p. 150).

This financial mechanism plays a crucial role in global market dynamics, enabling core regions to acquire vast amounts of resources, land, and labor from the periphery without directly acknowledging or compensating for the ecological and social costs involved.

The economic abstraction provided by GPM is instrumental in perpetuating resource and wealth consolidation in the core regions of the world. The systemic nature of GPM in international trade and finance effectively obscures the underlying ecological debts and labor inequalities, perpetuating a global economic system that thrives on asymmetric exchanges. Thus, the role of GPM in sustaining global capitalist structures is pivotal, as it not only simplifies but also normalizes transactions that lead to significant ecological and social disparities. Hornborg (2019, p. 128) points out that money, specifically GPM, along with technology, serves as “social arrangements” that allow certain countries, like Germany, to “dissipate more energy than others,” highlighting the disparities in energy consumption and environmental impact facilitated by these economic tools.

Technology – “machine fetishism”

Technological development plays a pivotal role in the dynamics of EUE, often accentuating the disparities between the core and the periphery. Hornborg’s analysis of "machine fetishism" critiques the dominant narrative that glorifies technological progress, stating the concealed socio-ecological costs that this progress imposes on the peripheral regions (Hornborg, 1992, 2001b). This critique underscores the fact that technological advancements in the core are frequently achieved at the expense of environmental and economic strain in the periphery, thus perpetuating a cycle of dependency and exploitation facilitated by global capitalist structures. Technological progress, in this case, the development of technologies for the production and use of hydrogen, is seen as independent from global capitalist relations of production and therefore a potential savior. Reduction of emissions, economic development of entire countries. Behind this fetishization, the socio-economic consequences and perquisites often remain hidden (Hornborg, 2022; Roos, 2021). This thesis tries to uncover them. The idealization of technology, as Hornborg (2022) critiques, masks the unequal exchanges facilitated by monetary transactions that appear reciprocal on the surface.

Environmental load displacement

The concept of environmental load displacement within the EUE framework provides a critical perspective on how industrialized core regions systematically shift their environmental and social burdens onto the less developed peripheral areas. Hornborg (2019) elucidates this process as a strategic maneuver, enabling the core to sustain its technological progress, economic growth, and high-consumption lifestyles at a significant cost to the periphery. This strategic offloading not only involves the physical relocation of pollution-intensive industries but also the transfer of ecological degradation and social consequences, such as health problems, loss of livelihoods, and deterioration of local environments. The qualitative shift in environmental impacts through load displacement further accentuates the injustice, as it often leads to exacerbated vulnerabilities in peripheral regions, undermining their ecological integrity and social cohesion. The insidious nature of this displacement means that the true environmental costs of core region lifestyles are obscured, allowing for the perpetuation of unsustainable consumption patterns and economic activities that are fundamentally predicated on ecological extraction and exploitation (ibid.)

Taken together, all these concepts look behind the process, which is often represented as reciprocal exchanges. Applying these concepts to green hydrogen enables us to identify potential unequal exchanges that are behind the "win-win" scenarios for example aculeated in the German and Namibian hydrogen strategies. The use and development of the technologies mentioned here have material consequences. In particular, the negative consequences need to be examined in detail. The analysis of the ecological unequal exchange presented here is intended to make a contribution to this.

3.2. Power Density

Power density is a critical concept used in various technological and engineering fields to measure the amount of power (time rate of energy transfer) per surface area (Smil, 2015). The concept is mainly used in engineering contexts. This work is primarily about the unequal exchange of space in relation to how much energy can be extracted from it in a given time. Vaslaw Smil (2015) argues for the watt derived through of earth's surface and sees the biggest advantage in the universal applicability. This creates a relationship between space and time that Hornborg (2019) believes is essential for comparing renewable energies to each other and to fossil fuels. The unit used here is power density, which is watts (W) per square meter (m^2). Watt (W) is a measure of energy per unit of time, W/m^2 considers energy in relation to both time and space. Hornborg (p.131) points out that this "(…) illuminates the transposability of space and energy (…)″ which is central to this thesis. To make renewables comparable to fossil fuels it would not be accurate to just measure the energy density in relation to the space they need. As Roos (2023) points out renewable energy technologies need global value chains and the appropriation of time and space to function. When is the boundary to start measuring power density is therefore important. This is a reason why I choose a life cycle approach in this thesis to measure the impact of the production as well as acknowledge that these technologies are not just renewable as they need energy and resources for production.

3.3. Environmental justice

When considering the consequences of the spatial expansion of capitalism, such as in the case of renewable energy, conflicts over land are inevitable. Not only does this lead to the displacement of territories, but pollution is also global and disproportionately affects marginalized communities; race and class often play determining roles (Holifield, 2001; Holifield et al., 2017; Schlosberg & Collins, 2014; Svarstad & Benjaminsen, 2020)

The Global Environmental Justice Atlas lists over 3,900 conflicts worldwide as of March 2024. These conflicts range from fossil fuels to biomass, land conflicts (forests, agriculture, fisheries, and livestock management), biodiversity conservation, water management, tourism recreation, infrastructure and the built environment, waste management, industrial and utilities, mineral ores and building materials extraction, to nuclear waste, renewables, and hydrogen (EJ Atlas, 2024). Observation and resistance to such injustices have led to the development of the concept of environmental justice since the 1970s in the United States, with its roots traced back to grassroots movements opposing the dumping of toxic waste, particularly affecting Black and economically marginalized people. As Robert Bullard, (1983, p. 1) notes in his study on toxic waste in Chicago in 1983, “(...) solid waste sites were not randomly scattered over the

Houston landscape but were likely to be found in predominantly black neighborhoods and near black schools.” This pattern, as Schlosberg (2007) observes, is prevalent in most discussions of environmental justice, focusing on the “maldistribution” of goods and the uneven distribution of environmental harms and benefits.

Over the years, Bullard and others expanded the concept geographically and, as seen in the EJA, to different causes of environmental harm and resources (e.g. Been, 1992; Holifield, 2001; Holifield et al., 2017)

Different foci in various contexts were and are present, with a common critique, being the Western origin of these concepts and their applicability in different contexts. While Western environmentalism has often been morally rooted and centered around the politics of consumption, southern environmentalism is more about survival (Guha & Gadgil, 1995; Temper, 2017) (Álvarez & Coolsaet, (2020) point out that Western environmental justice frameworks, if applied uncritically, can fail to recognize local knowledge systems and impose external definitions of environment and justice.

Therefore, this thesis adopts the clear, predefined radical environmental justice framework developed by David Schlosberg (2007). As my origin and this thesis are rooted in Germany and thus, part of Western epistemologies, transparency and reflexivity are intended to limit harm. Moreover, this thesis focuses on global unequal exchange, with material consequences in the use of space. In this context, it is not the aim to connect the understanding of (environmental) justice to a concrete movement or group. As stated in the research question, the aim is to look at the reduction of EUE, and whether radical environmental justice principles when applied can facilitate this.

David Schlosberg's (2007) environmental justice understanding, combines former thoughts on distributional justice and incorporates concerns of valuing non-human nature derived from ecological justice (Wienhues, 2020). He developed a radical environmental justice definition under four principles which are distribution, recognition, capabilities, and procedural justice (Schlosberg, 2003, 2007).

The first and most frequently used perspective in environmental justice theory is distributional justice. This perspective, as already seen in the origins of EJ, deals with the distribution of goods and environmental harms and benefits.

Schlosberg (2007) incorporates an extension of the distributional aspect, by looking at the process of how this allocation evolved. This is procedural justice, which focuses on how equitable the decision-making process is in this context here the focus is on how the process of developing a new hydrogen economy is structured, and who is heard.

Nancy Fraser, (e.g. 1995) among others added the aspect of recognitional justice which focuses on acknowledging the cultural, historical, and social identities of communities impacted in the process of attaining justice. An important aspect of this justice aspect is as pointed out by Schlosberg (2007, p. 3) “(...) the status of the less well-off in distributional schemes.” This aspect can strengthen the view on power dynamics as in trade relations, unequal exchange, and imperialist patterns.

The last aspect Schlosberg incorporates is a perspective on capabilities and developed from Nussbaum, (2002)and Sen,(2004). Capability justice interrogates the extent to which individuals and communities possess the freedom to pursue life trajectories that they value as meaningful and fulfilling, addressing structural inequalities and confronting systemic power imbalances that lead to environmental injustices. Herby one can look at how primary goods can be transformed in this capacity to live a fulfilling life (Schlosberg, 2007; Svarstad & Benjaminsen, 2020)

In this example, I refer to environmental justice instead of climate justice for two reasons. Firstly, this paper focuses more on land than emissions, the second would have better aligned with the concept of climate justice. Additionally, while this work examines international trade, it primarily focuses on local injustices, as rather typical in the context of environmental justice (Schlosberg & Collins, 2014).

While discussion of environmentally just procedures can be done on this basis, the link to the research question and (ecological) unequal exchange is given as well. As stated by different scholars (eg. Givens et al., 2019; Hornborg & Martinez-Alier, 2016) ecological unequal exchange is bringing the distributional justice aspect of environmental justice to geographically bigger perspectives. As mentioned the origins dealt with local conflicts and ecologically unequal exchange the material basis of trade between two or more entities.

4. Method

The central method of this thesis is life cycle assessment (LCA) based EUE and is primarily used to answer the first research question. The second research question is done by applying the concept of radical environmental justice to the results. Together, these should enable an enriched understanding of the materiality as well as justice considerations of green hydrogen trade.

4.1. A critical realist approach to the hydrogen economy

Ontology

The study presumes the existence of a relationship between the use of land and energy in the form of technologies and labor. This is subject to significant evolution over time, influenced by socio-political and economic processes such as hydrogen strategies. This investigation is underpinned by a critical realist approach, grounded in ontological realism. As postulated by Guba and Lincoln (1994), reality within this paradigm is considered ascertainable, yet it is shaped and constructed through an interplay of influential factors, including social, political, cultural, and ethnic dimensions. These factors give rise to structures that are perceived as "real." In this thesis, I endeavor to look closely at these structures from the perspective of radical environmental justice. Applying this to the research, I posit that the EUE calculated may indeed reflect the reality of the future, albeit one that is modulated by a myriad of variables.

Epistemology

Concerning the epistemological question: “What is knowledge?” I follow Guba and Lincoln (1994) in their understanding of critical realism which is that the subject of investigation and the investigator are connected. In this study, I assume, that my interaction with the data is subjective and value mediated. In the section about positionality, I will further elaborate on parts of what this could include. Critical realism is committed to epistemological relativism. Epistemological relativism, as formulated in the paradigm of critical realism, contends that while our knowledge is influenced by our social and cultural contexts, this does not imply that all interpretations are equally valid. Critical realism maintains a belief in an objective reality that exists independently of our perceptions, but it acknowledges that our understanding of this reality is always partial and mediated through various lenses (ibid).

4.2. LCA-based accounting of EUE

Ecological unequal exchange is a multifaceted concept that can be evaluated through a variety of methodologies, in this case, the LCA-based method. A prevalent quantitative approach is to focus on the ecological unequal exchange between world regions or nations. The distinction is based on divisions of labor described in the world system analysis (e.g. Dorninger et al., 2021; Dorninger & Hornborg, 2015; Giljum & Eisenmenger, 2004; Pérez-Rincón, 2006). Through an LCA-based approach, it is possible to access the ecological unequal exchange of specific goods in this emerging trade (Oulu, 2015; Roos, 2022). This method suits well as it allows to access the most relevant goods involved in the trade of the hydrogen economy. It can thereby be seen as a concrete exchange of goods between these two countries but could also be transferred to a more general picture of the core (Germany) and periphery (Namibia) and asymmetric flows of resources between them. The LCA-based approach was chosen to allow discussion of environmental load displacement and illuminate the exchange of land behind the technologies of a green hydrogen economy.

The lifecycle-based approach to the account of EUE has two basic steps. The first one is to calculate the embodied resources in the commodities traded. Second, to calculate the exchange of these commodities, on a comparable scale. These broad steps in turn have four sub-steps:

1. Scope definition: Establishes the subject of analysis (functional unit), the extent of study (system boundaries), and units for measuring resources, impacts, and economic value. This step is presented in the methods section.
2. Inventory analysis: Quantifies resource use and emissions per functional unit of commodities, relying on secondary data from existing LCA studies. The inventory can be found in the results.
3. Impact assessment: Compares resource intensities against commodity exchange values to identify unequal exchanges, using methodologies like

Ecological, Carbon, or Water Footprints. This part can be found in the results section.

4. Interpretation: Discusses findings, highlighting commodities or trade relations with significant ecological-economic imbalances, and suggests policy and trade practice improvements. This part can be found in the general discussion of this thesis

This LCA-based method provides a systematic way to assess the environmental impacts of trade, identifying asymmetric trade of embodied resources, thus guiding towards more just and sustainable trade policies and practices.

Scope definition

To estimate the EUE in the future hydrogen economy between Germany and Namibia, I chose to analyze three commodities. The first commodity is green hydrogen produced in Namibia, based on the estimates of the Hyphen project.[1] Figure 4 shows that the boundaries are set only around the land needed in the value chain. This is done due to two main reasons. First, the focus of this work is based on land. Second, the data given on this project is limited, only the area is clear as previously described. Further infrastructure e.g. for shipping or transport could only be guessed as no further data is available on this project.

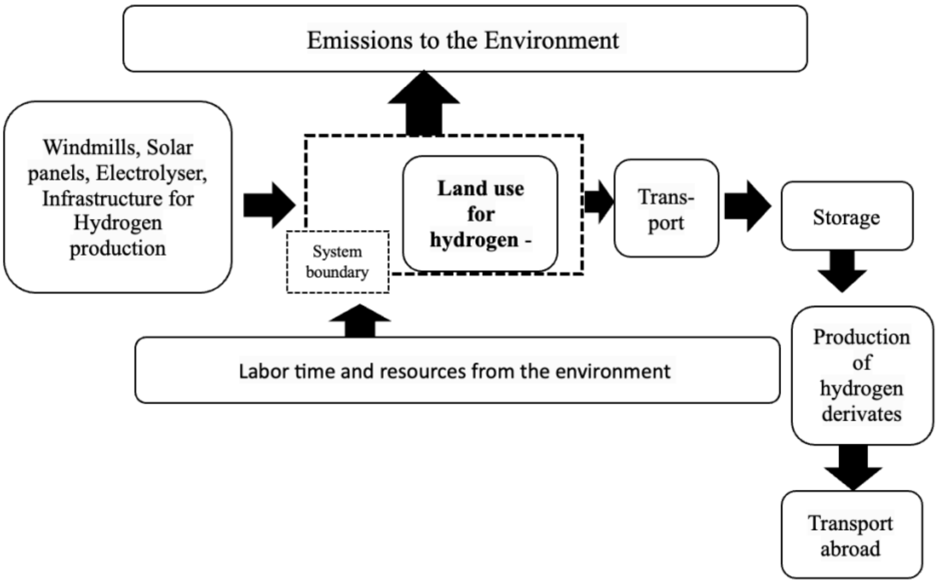


Figure 4: System boundaries hydrogen (own illustration)

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[1] 4,000km2 for 350.000 t hydrogen annually

In exchange, two products from Germany are analyzed. The first product, the electrolyzer used here is a polymer electrolyte membrane electrolysis which is fitting to large-scale hydrogen production made from renewables (Kolb et al., 2022). Figure 5 shows the boundaries of the main compartments of the electrolyzer which are multiple polymer electrolyte membrane electrolysis cells (PEMCE) connected to a so-called stack.

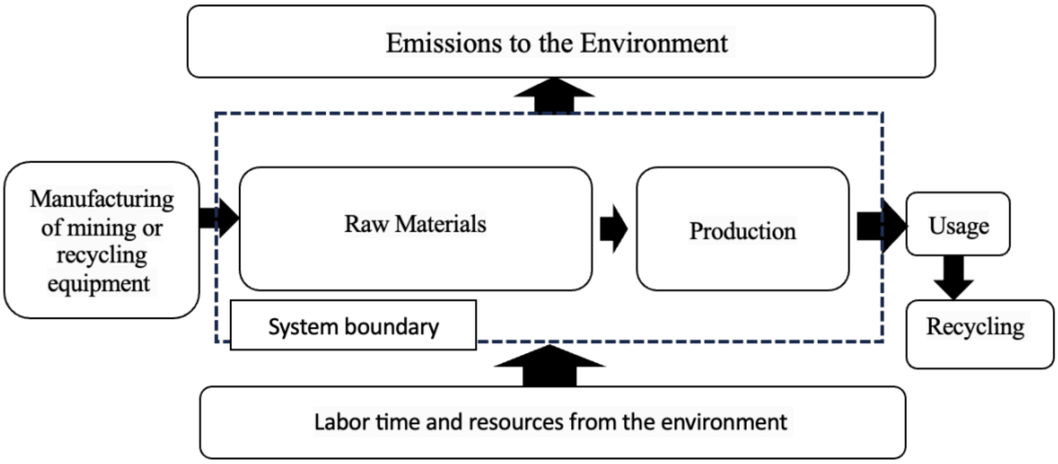

Figure 5 System boundaries PEMCE-Stack (own illustration)

The manufacturing of the mining equipment is excluded as their footprints are not comprehensible in the calculation of Zhao et al., (2020) where my calculation is based on. The second product is a wind turbine produced in Germany; the boundaries can be seen in Figure 6.

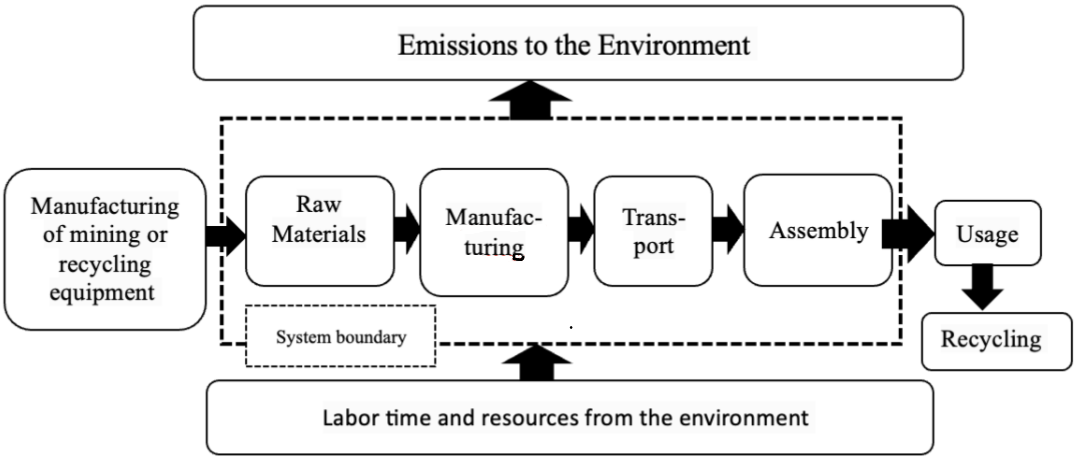

Figure 6: System boundaries Wind turbine (own illustration)

The data includes the energy and material input, waste, emissions in air, soil, and water as well as side products (Eisemann, 2021). Only the production is counted until it can produce energy. Transportation here is included in the emissions lifecycle.

The boundaries chosen can be seen as rather broad. Also, the efficiency of the production process could emerge due to technological development in the coming years. Smaller boundaries and an increase in efficiency would result in less emissions and less land use. Therefore, the EUE of embodied land would increase because the land needed in Namibia is fixed. Therefore, my results can be seen as rather conservative. The result of both LCA is based on CO2 emissions[2], displayed as carbon footprint. The unit that is central to this work is land.

To make the measurements easier to compare and relate to the central product of this thesis, another unit used is kilogram hydrogen.[3] In order to bring land area and energy produced through the different technologies together and compare them to fossil fuels, energy density (W/m^2) is another unit used. The embodied land is then compared to a unit of exchange values (USD).[4]

4.3. Limitations

The calculation of EUE has potential limitations due to data reliability. The thesis assumes there will be a future trade between Germany and Namibia in hydrogen and hydrogen-related commodities. More specifically, I assume (1) there will be a trade of the named products between Germany and Namibia, and (2) the (technological) developments in the next years have no significant influence on the LCA of the three different products.

For the wind turbine, data for the primer resources is taken from the GaBi life cycle assessment databases (Eisemann, 2021, p. 283). The data is not detailed, values in general are the average of different wind turbines produced in Germany. Subsequently, the data shows trends, actual figures can differ.

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[2] Wind mill emissions based on Eisemann, (2021); Emissions PMCE-stack based on Zhao et al. (2020).

[3] Whereby 50 kW/h per kg hydrogen(Zhao et al., 2020) and hydrogen energy content of 33 kWh.

[4] Whereby 1 kg hydrogen 4 USD (optimistic low price for around 2030) (Lenivova, 2022; Tracey, 2023)

The PEMCE electrolyze has by far the highest emissions in comparison to other electrolyzers according to Zhao et al., (2020) but is also most applicable for large-scale production with renewables (Bareiß et al., 2019). A different electrolyzer technology in the application can have an influence on the results. Furthermore, Zhao et al. (2020) utilized the Danish energy mix for producing the electrolyzer. This electricity mix is less CO_2 intensive in comparison to the German energy mix. However, Germany is expected to lower its CO2 intensity per kWh generated in the coming years (Hamels, 2021).

The production processes considered here can be more efficient, with lower material inputs and therefore also lower emissions along the line. According to Zhao et. al (2020) especially an improvement in the material intensity can be achieved in the future.

Another limitation is the way I convert CO_2 footprints to land use. The actual land use can be first independent of CO_2 emissions which I base my land use for wind turbines and electrolyzers on. An example here is mined resources like coal. Coal has in comparison to land use high emissions. The embodied land here must therefore be seen in relation to emissions. I assume it is legitimate as one goal of the green hydrogen economy in Germany and Namibia is emission mitigation (BMWK, 2023; Ministry of Mines and Energy Namibia, 2022). Due to the data situation, however, a direct land calculation was not possible.

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5. Results

5.1. Inventory analysis

The inventory of the hydrogen LCA is based on basic information from the website of the Hyphen project (Hyphen, 2024). The investors want to produce 350,000 tons of hydrogen annually and require 4, 000 km^2 for this (ibid.).

Table 1: Inventory Hydrogen from the Hyphen project based on Hyphen (2024)

Hydrogen at Hyphen	**CO_2 eq.**	**Km^2**
350,000 tones	1050 +/- 475 t CO_2[5]	4000km^2

Table 1 summarizes the outcomes in green hydrogen, emission, and land use which should result from the Hyphen project. CO_2 was not given in the data. Therefore, land use was converted into emissions using the factor developed by Mancini et al., (2016). The CO_2 equivalent data for hydrogen are in the range of other projections (Cetinkaya et al., 2012; De Kleijne et al., 2022).

Additional land may be required for hydrogen trade infrastructure, such as pipelines and harbors. The total project costs are projected to be approximately 10 billion USD and the total project should reach a renewable capacity of ~7GW and ~3GW electrolyzer (Hyphen, 2024).

Emissions to Land conversion

The LCA data from the wind turbines and the PEMCE-stack is based on emission, the carbon footprint[6]. The unit which is in the center of this work is land. To bring the products on a comparable unit, one has therefore transferred emissions to land and the other way round. A way to do this is to take the area needed to sequester the carbon emitted in one year. The carbon footprint component within the Ecological Footprint methodology represents the area of forest land required to absorb the carbon dioxide emissions produced by human activities that are not already absorbed by the oceans (Mancini et al., 2016). Mancini and colleagues calculated a value for the Forest Carbon Sequestration taking worldwide

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[5] 0.73 tones square meters of carbon sequestering per year based on Mancini et al., (2016)

[6] Wind turbine emissions based on Eisemann, (2021); Emissions PMCE-stack based on Zhao et al., (2020).

ecosystems and forest types into consideration. The result is 0.73 ± 0.37 tons of C per hectare per year. I take this calculation as a bridge between, as I will explain in the following.

Tsau /Khaeb National Park may be considered a deserted area, which could result in a lower carbon sequestration rate compared to an average forest. Consequently, the emissions for the land on which the hydrogen is produced may be lower due to the reduced opportunity for land sequestration. However, it is important to note that the land required to sequester the carbon from the wind turbine and PEMCE-stack may be larger. It is argued that taking the averaged value is more accurate, as differentiating the value of land based on its ability to sequester carbon would neglect cultural value and ecosystem services, such as biodiversity. Additionally, climate change is a cross-boundary problem, where historically, Global South countries like Namibia are less responsible for emitting but experience more drastic consequences compared to the Global North(Sultana, 2022). Devaluing land in Namibia due to its lower carbon sequestration capacity could be considered unjust. This thesis is an example of international trade and is at the forefront of the evaluation of unequal ecological green hydrogen trade. To simplify the calculations, I have used an averaged value by Mancini et al. (2016).

Wind turbine

The wind turbine inventory is based on Eisemann (2021) for the Umweltbundesamt, a German state agency. In this case, the total GWh produced is ca. 11,400-14,600 MWh over a 20-year lifetime. This data is for an onshore area with high wind (ibid.). The production of the wind turbine is broken down according to its different parts and displayed in the following Table 2.

Table 2: Inventory wind turbines based on Eisemann (2021)

Wind turbine	**CO_2 eq./kWh[7] in gram**	**Land use per m^2/kWh[8]**
Foundation	1.4	0.0192
Tower	4.5	0.0616
Nacelle	2.2	0.0301
Transportation	0.1	0.0014
Manufacturing process	0.4	0.0055
Rotor blades	0.8	0.0110
Total	**10g CO_2 eq./kWh**	**0.137 m^2/kWh**

What is striking in this inventory is the high emissions for building the tower. The used value of 10g CO2 eq./kWh makes the application easy and transparent
The data for the inventory analysis is taken from the GaBi life cycle assessment databases (Eisemann, 2021, p. 283). Comparable data from Eisemann (2021) shows that the used data is in the middle range as other studies find a range from 7.25 g/kWh (DFIG, DDPMSG) to 12.43 g/kWh (DDSG). A conversion from CO_2 equivalents to land is made based on Mancini et al. (2016).

Electrolyzer

The technology inventory for electrolyzer technology is based on a study by Zhao et al. (2020). The study focuses on stacks, units that can produce hydrogen. Stacks are composed of multiple cells and enable hydrogen production. Cells are the parts where electrical energy is used to split water into hydrogen and oxygen. The study considers different materials and assesses their impacts from mining onwards. No emissions are allocated to maintenance. Recycling would reduce

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[7] Based on(Eisemann, 2021)

[8] 0.73 tons C sequester per hectare based on Mancini et al., (2016)

30% of the emissions, but it is not included in the system boundaries and therefore not included in the following overview.

Table 3: Inventory PEMCE stack based on Zhao et al. (2020)

PEMCE stack	**CO_2 per functional unit (m PMCE stack)**[9]	**Land use per m^2/ FU** [10]
Oxygen electrode	1,101.73 kg CO2-eq	15,092 m^2
Hydrogen electrode	871.81 kg CO2-eq	11,947 m^2
Interconnects	298.39 kg CO2-eq	4,090.55 m^2
Total	**2,295, 28kg CO2-eq/FU**[11]	**31,130.02 m^2**

Table 3 shows the land and emissions resulting from the different parts of the PEMCE stack. The lifetime is considered about 50,000 hours of usage with a total output of 40 tons of hydrogen per functional unit (FU=m2) Zhao et al (2020). There is no accessible database to compare the inventory with the literature.

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[9] Data from Zhao et al., (2020)

[10] Land needed in one year to sequester the amount of carbon (Mancini et al., 2016); (FU= m2 stack).

[11] 1% more in total for additional parts

5.2. Results EUE

Coming to the calculation of the EUE the following Table 4 shows the results in the units chosen.

Table 4: Results LCA in comparable units

	m^2 per kg of hydrogen	CO2 per kg of hydrogen	w/m^2
Hydrogen (at the hyphen project)	**11.43m^2**	**3 kg CO^2**	**0.499 W/m^2**
Wind turbines	**1.865 m^2**	**0.5 kg CO^2**	**0.833 W/m^2**
PEMEC stack	**0.201006 m^2**	**0.0533 kg CO^2**	**--**

The results from the inventory lead to the results in Table 4.

Looking at hydrogen (second row), I calculated the annual kg of hydrogen produced (350.000 tones) through the total embodied land (4000km^2) resulting in m^2 per kg hydrogen by adapting the metrics. To calculate emissions, I used the conversion factor of Macini et al. (2016) and applied it to the total land of the Hyphen project (4000 km^2). To calculate the power density (w/m^2), the first calculation needed is the amount of energy needed to produce the 350,000 tons, which are in the case assumingly 50 kWh per kg of hydrogen in a year. The result is converted to watt (W) and then divided by the square meters needed to produce this amount (4,000 km^2).

To calculate the data for the wind turbines I assume 50 kWh are needed for one kg of hydrogen (Tao et al., 2022; Zghaibeh et al., 2022). This results in the emissions of one kg of hydrogen and again is converted using Macini et al. (2016) factor to get the results for embodied land. The power density is based on the data from Eisemann (2021). On this basis, it is assumed that 13,000 MWh are produced in one year and the surface needed for this is 1,781 square meters.

With the information that 40 tons of hydrogen can be produced per functional unit of the PEMCE stack the emissions per kg can be calculated (Zhao et al., 2020). For this product, no power density is calculated – as in the case of the electrolyzer no energy is produced on an area.

The results show that 11.43 m^2 is needed to produce one kg of hydrogen in the area of the Hyphen project. To produce one kg of hydrogen with a windmill produced in Germany, 1,865 m^2 is needed, and 0.202 m^2 with a PEMCE stack.

One can conclude from this that Namibia buys the capacity to produce one kg of hydrogen from German windmills and electrolyzers (1,865m^2 + 0.201m^2), and exports hydrogen (11,43m2) under the assumptions made. Germany imports a net amount of 9,364 m^2 of land from Namibia. In other words, there is an unequal exchange of land in the chosen scenario.

Impact assessment

To perform the third step of the LCA-based EUE, it is necessary to put the results into perspective. In the international context, the dollar is the most commonly used currency, making it possible to compare the impact of a trade value measured in dollars. This is displayed in the following Table 5.

Table 5: Results in relation to USD

	Hydrogen[12]	**Wind turbine**[13]	**PEMEC stack**[14]	**Ratio of wind turbines and PEMCE-stacks as could be at Hyphen** [15]
m^2 per 10.000 USD	28,575 m^2	19,900 m^2	9,136 m^2	18,070 m^2

With the prices considered in the footnotes, the square meters embodied land per 10,000 USD are calculated. If we now look at the approximate costs of the products and relate them to a comparable unit of environmental impact (here m2),

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[12] 1 kg hydrogen 4 USD (optimistic low price for around 2030) (Lenivova, 2022; Tracey, 2023)

[13] Price based on ESFC, (2024) (1 million USD per MW)

[14] Price based on Holst et al., (2021)

[15] If taken as in the example Germany is exporting 3250 mio USD in wind turbine and 660 mio in PEMEC stack which is ratio of 83% to 17%.

it becomes clear that the trade implies an export of embodied land from Namibia to Germany. It is significant that in a scenario where a mix of wind turbines and PEMCE stacks is exported to Germany, the embodied land imported from Namibia is around 58% (28,575m^2/18,070 m^2) larger.

In summary, the intended trade of hydrogen between Germany and Namibia increases the EUE between these two countries. The production of hydrogen requires a significant amount of land, approximately 11.42 square meters per kilogram of hydrogen. This is despite, or perhaps because of, the favorable international conditions for the production of renewable energy. Interestingly, hydrogen production requires more land than the production of the machines that can be used to produce hydrogen, such as wind turbines and electrolyzer. When comparing trade, the inequality remains even when expressed in currency. If each product were traded for $10,000, the land required for production in Namibia would be nearly 60 more in comparison to the land needed in Germany.

Trade that could happen for the Hyphen project:

If we are now considering the actual trade that could emerge in the coming years for the Hyphen project, we can calculate the embodied land and emission for the exact scenario.

In the Hyphen project, 3 GW of electrolyzer capacity is planned. These electrolyzers would amount to a cost of around 660 million.[16] This includes the PEMCE-stack requiring a total of 602,976,000 m^2 embodied land. Considering a lifecycle of 20 years this amounts to 30,148,800 m^2 of forest plantation to sequester the CO_2-eq. emitted in the production of the electrolyzer.

To produce enough energy for the electrolyzer to work, 7,5 GW in renewables are planned to be installed for the Hyphen project. Out of these 7.5 GW, I assume a total of 3.25 GW of wind power (see e.g., Rischer, 2023). Buying this wind power from German producers of wind turbines costs around 1 million per MW (ESFC, 2024). In total investments of around 3.25 billion USD to build wind turbines with the assumed capacity for the Hyphen project.

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[16] Based on (Holst et al., 2021)

The area of land for the total lifecycle of wind turbines based on Eisemann (2021) is 9,611,875,000 m^2. The life span of wind turbines is 20 years (ibid.). This leads to the result that 480,593,750 m^2 are needed to sequester all emissions for the wind turbines at the Hyphen project.

Table 6: Results EUE for the Hyphen project

Hyphen	**Trade volume**	**Embodied land**
Hydrogen	1,4 billion USD per year	4 000 km^2
Namibia	**1,4 billion USD per year**	**4 000 km^2**
Wind turbines	3,25 billion USD	480,593750km^2
Electrolyzer (PEMCE-stack)	660 mio USD	30,1489 km^2
Germany	Over 20 years 193,259 Mio USD yearly in total 6,825 billion USD	510,742550 km^2

Table 6 summarizes the trade in USD and the associated embodied land. The trade scenario chosen here implies that there is a need to invest 3.91 billion USD for electrolyzers and windmills for the planned production of hydrogen in the Hyphen project. If Germany in exchange imports all the hydrogen from this project, which is 350,000 tons per year, for 4 USD per kg this equals a trade volume of 1.4 billion USD yearly. Assuming the whole project runs over 20 years with these outputs and Germany buys the produced hydrogen we would have a total volume of 28 billion USD. However, the sequestering of the emissions is based on yearly land use, therefore just the embodied land of 4000km^2 for hydrogen production applies.

In total, Germany is only exporting 12,77% of the land it is importing from Namibia. The answer to the first research question is that EUE is occurring in the green hydrogen trade and in the case of the Hyphen project. Germany is exporting 510,74 km^2 yearly while importing 4 000km^2 embodied land. This is an unequal exchange of 3 489,26 km^2 of embodied land Germany is importing more than exporting to Namibia.

6. Discussion

A case of ecologically unequal exchange

This thesis unravels the dynamics of EUE in the future hydrogen economy, with a focused lens on Germany and Namibia's bilateral relations. The findings offer an extended perspective on the EUE, where the emerging hydrogen economy seems to widen the resource exchange divide between the Global North and the Global South, or the divide between the world core and world periphery, according to EUE theory. The response to the first research question is affirmative: the hydrogen economy, as conceived under the Hyphen, will likely result in ecological unequal exchange.

Discussion of the EUE results

Under the assumptions made, the Hyphen project can create a significant EUE, which means less land and emissions are allocated in Germany due to the trade of green hydrogen. 3,489 square kilometers less, or only 12.7 percent of the land area that is needed in Namibia, is embodied in Germany in the trade scenario presented here. In this way, Germany imports land, a finding that is supported by other EUE research. For example, it has been shown by Dorninger et al. (2021) that both land and time are routinely appropriated by core nations. This trend seems to continue with the emerging hydrogen economy.

The CO_2 emissions per kg of hydrogen are comparable with the numbers presented in the literature which assume around 0,8-3,2 kg CO2 eq. for the complete value chain (Kolb et al., 2022). In my approach, the emissions from the transport are not included. This factor would even increase the amount of emissions. My values are bound to the sequestration factor used and therefore are not the direct emissions measured in the production process of hydrogen. A combination of both approaches, measuring the emissions of the lifecycle and including the land used, could generate more accurate results.

Looking at land, the results show that the power density of wind turbines (0,833 w/m^2) and of hydrogen (0.499 W/m^2) are very low. In his extensive work on power density, Smil (2015) calculates the power density of wind farms of 2-3 W/m^2. This is the case as relatively large amounts of land are needed to sequester the carbon emitted in the production process of wind turbines. More efficiency in producing and sequestering the carbon per square meter would lead to a higher power density. Unless the efficiency improvements are associated with higher energy expenditures and CO_2 emissions. This power density is too low to sustain industrial societies without significant pressure on domestic food supplies, substantial loss of habitat, and perhaps an increase in land rents (Smil, 2015).

It is evident that the wind power density is higher, as for the hydrogen production around 40% of the energy potential is lost in the production process – the power density of hydrogen is 60% the power density of the wind turbines (Giddey et al., 2012). The degree of direct electrification in future societies will therefore have an influence on land use. As in Germany land prices and the conditions for renewables are not as good as in Namibia the opportunity costs in monetary terms seem in favor of producing in Namibia. Global price differences for land can thus be seen as a condition for EUE.

Green hydrogen: From stocks to flows

The thesis conceptually underscores what is perhaps an obvious point: whereas traditional fossil capitalism utilized 'stocks' in the form of fossil fuels, the hydrogen economy seeks a paradigm shift towards 'flows.' As Hornborg (2019, p. 120) articulates, “harnessing contemporary sunlight” and wind necessitates greater spatial allocation compared to extracting ancient photosynthetic products from beneath the earth's surface. However, what follows out of this? Do we see another significant change in the physical and technical structure to maximize the production of surplus value, a real subsumption?

Like oil and gas, hydrogen can function both as an energy carrier and a storage medium. Its utilization, controlled by the owners of the means of production, could replicate the advantages highlighted by Malm (2016) during the development of the steam engine. It is noticeable that the structures established by fossil capitalism are still relevant with the introduction of hydrogen, suggesting that production locations will continue to be determined by factors favorable to capitalists, including access to labor, natural resources, regulation, and political stability. These are all factors used in the African Hydrogen Atlas a website that explores the most promising location for hydrogen production on the African continent, championing Namibia (H2Atlas-Africa, 2024).

This seems at first to introduce a new structuring of the production process in Namibia and therefore signify a formal subsumption. For the construction of the Hyphen project, there will be 15,000 temporary and 3,000 permanent jobs. The town, of Lüderitz, itself only has 15,000 inhabitants (Aznations, 2024). The allocation of workers for large projects such as Hyphen might be new to Namibia but is not new in the capitalist system. The relation of capital towards the workers remains – the workers are paid and enable the investors to extract surplus value (Rischer, 2023).

Land - A contested resource

Hornborg, (2019) argues that land is becoming an increasingly contested resource due to energy technologies. Hydrogen at its extensive land use shown in this thesis is a continuation of this. After 2007/2008, large-scale land acquisitions took place in the Global South, and East Europe and is continuing according to Neef et al., (2023). Reasons are multifaceted, among them are Covid-19 and major geopolitical shifts. Others are and have been agro-industry, energy, mining, tourism, infrastructure, urban development, conservation, and carbon sequestration projects (ibid). The authors even find comparisons of this trajectory to a rush - comparable to the land rushes during European colonialism.

Echoing Hornborg (2018), the wind energy harnessing process, especially for hydrogen production, demands considerable land use. The PMCE Electrolyzer, central to this study, exhibits an efficiency rate of approximately 60%, signifying a loss of 40% of the captured energy (Zhao et al., 2020). Furthermore, the production of 1 kg of hydrogen requires about 9 kg of water (ibid). Since the electrolysis process requires fresh water, in an arid area like the Lüderitz area, desalination is required (Schutz, 2021). This requires even more land and energy, making Namibia's hydrogen even less efficient.

Direct energy utilization is markedly more efficient. For example, using energy directly in transportation could save over 40% of energy, correspondingly reducing land use (Giddey et al., 2012). Consequently, strategic planning concerning the application of hydrogen profoundly influences land use changes.

Green hydrogen is in this case competing with biodiversity and other services that are provided on this land.
For the transition away from fossil fuels this means that it must be carefully evaluated and planned how to use which land and in what way. How much energy is needed and where and how the least amount of negative social and environmental can be achieved.

Green hydrogen – Continuation of imperial metabolism

Hornborg's concept of imperial metabolism (2021) vividly describes how existing capital power structures channel energy and resources toward the Global North. It is now possible to say that the Hyphen project exemplifies such an imperial metabolism. The land acquisition involved aligns with Borras et al.'s (2012) definition of land grabbing: the large-scale acquisition of land, often shifting usage toward extraction. The term "renewable grabbing," as coined by Scheidel et al. (2023), captures this pattern, which is evident in the Hyphen project's substantial budget and land acquisition plans. As the characteristics of even less efficient energy use and the use of water in the production of green hydrogen, as exemplified by Namibia, even necessitate the use of more land, it can be argued that in the future, *hydrogen-grabbing* will occur in similar patterns to those previously outlined.

Given that existing power structures enable this trend, it is critical to trace the trajectory back to the core nations acquiring the land—in this case, Germany. German policies, especially those concerning hydrogen, significantly impact land use and, by extending EUE.

Following the German hydrogen strategies, German politics aim for a worldwide increase of (green) hydrogen production (BMWK, 2023). Facilitating the trading with the platform H2 global and aiming for high national demand. The focus is on industry (e.g. steal and chemical), transport, and building (ibid.). Looking at a meta-study on German future hydrogen use and demand according to sectors, it becomes clear that the demand will depend on political decisions (Wietschel et al., 2023). The study brings together price and demand and comes to the conclusion that in Germany hydrogen will first be used in industry (process heat and chemistry), then in some parts of long-distance transportation and the energy system, and least in the building sector (ibid.).

Looking back at the political level, Germany is investing billions in hydrogen and sees it as a new chance for economic growth (BMBF, 2023). First, the German government has decided to be open to private hydrogen heating systems, which are unlikely to take off because of their poor efficiency compared to other heating options (Doucet et al., 2023). The same applies to the transportation sector, where individual transportation with hydrogen or its derivatives is considered a luxury because of its inefficiency (Bannert et al., 2023). This can lead to the conclusion that the expansion of the EUE exchange is a political decision and an outlay of power structures to accumulate capital with land change consequences elsewhere - often in the Global South and peripheral regions like Namibia.

The fetishization of hydrogen

Projects akin to the Hyphen initiative have emerged in various locations. Favorable site conditions are expected to facilitate competitive hydrogen production costs and, as highlighted by Richer (2023), primarily serve to amplify investor capital. The material consequences and the appropriation of land are accepted by governments as the hydrogen strategies of Namibia and Germany reveal (BMWK, 2023; Ministry of Mines and Energy Namibia, 2022). As the results show, this is all attributed to the narrative of economic development and an apparent "win-win" situation.

Hornborg's concept of "machine fetishism" (2012) offers a critical lens through which to view the narratives driving the hydrogen economy. Economic growth is heralded alongside climate mitigation and emissions reduction. This association underscores the dual objectives emphasized in the hydrogen strategies. The prevailing narrative abounds with "opportunities" and "win-win" scenarios, which often conceal the material realities of technological advancement. Notably, the German hydrogen strategy fails to address the subtleties of indirect land acquisition. Specifically, advocacy from the German Liberal Party (FDP) for less efficient hydrogen-based heating and individual transportation systems (Schmidbauer, 2023), exemplifies a drive for economic benefit under the guise of technological advancement. This thesis reveals that an increase in hydrogen consumption is leading to land use changes abroad, as seen in Namibia, thereby intensifying EUE. Such advocacy for hydrogen's application in sectors where it is not necessary may represent 'machine fetishism'.

It should also be noted that Namibia and the Hyphen project are driven by demand. If policy shifts or technological advancements lead to a reduction in hydrogen prices or negate the need for it entirely, the project's profitability could collapse the production of hydrogen in Germany and other European nations seems to be cheaper in the coming decades (Merten & Scholz, 2023). Potentially making the profitability of the project questionable– ecosystem services would be damaged, and biodiversity lost.

Unfair EUE through GPM

The concealment of EUE behind a "win-win" façade can be attributed to the General Purpose Money (GPM) framework. This creates an appearance of equitable trade, as market prices ostensibly compensate for the material consequences. However, Rischer (2023) illustrates, using Hyphen as an example, that investors stand to profit substantially from the production aspect of hydrogen. In this scenario, profits are largely privatized, while risks are assumed under the presumption of planned functionality. The loss of biodiversity and ecosystem services remain unprecise in the hydrogen strategies, with local communities bearing the brunt of the impact, as opposed to financial rewards in the Global North. Consequently, through GPM, capital accumulation is facilitated, giving green hydrogen trade an illusory aspect of reciprocity.

Behind the trade and the acquisition of land is an asymmetrical valuation of land, labor, and the power density that can be harvested on this land. The investors behind Hyphen could have invested in Germany. However, the valuation for these resources is higher in Germany. Due to the hydrogen economy, the perception of availability therefore might change. New areas, as in this example get profitable for capital and extend the spatial frontier of the capitalist world system. Not considered are the socio-ecological consequences of this extension and the derived EUE.

6.1. Reduce EUE?

The examination of the burgeoning hydrogen economy, through the lens of the Hyphen project between Germany and Namibia, reveals ecological unequal exchange (EUE) and underscores the contemporary manifestations of global power imbalances. Green hydrogen is used by countries like Germany to load the burden of decarbonization in the form of land use to Namibia – which can be seen as environmental load displacement. In total, this study has shown that the trade of hydrogen has deeper underpinnings of land appropriation, economic dependency, and environmental consequences, aligned with historical patterns of resource extraction from the Global South to fuel the growth and sustainability goals of the Global North. If EUE change can be measured as a pattern connected to unjust trajectories the question is if EUE can be reduced and what would this mean.

First, if core regions reduce the import of embodied energy this would result in less environmental pressures in periphery. Core regions use disproportionally more resources, a reduction of the resources would also lead to more equal consumption patterns and more sustainable development (Dorninger et al., 2021; Rice, 2007).

Second, Ricci, (2023,p 1) comes to the conclusion that “Unequal exchange emerges as a structural manifestation of the uneven development of capitalism, which exacerbates the global environmental crisis and pre-existing power imbalances by reproducing global economic and ecological hierarchies”. A reduction could lead to different power structures, which are not fairer per se but could be developed more equally. All in all, it can be seen as a way to achieve more justice as peripheral regions often suffer more from climate consequences, waste disposal, and less power due to uneven monetary resources (Givens, 2018).

But is this possible? Implementing fair trade practices and equitable compensation for resource extraction and externalities is vital for mitigating the impacts of unequal ecological exchange (EUE) and the perception of reciprocity. This approach would involve revising international trade laws to ensure that countries exporting valuable natural resources receive fair compensation (Dorninger et al.,

2021). In the case presented, this could mean that the prices of the ecosystem services degraded by the land needed for the hydrogen economy would need to be adapted. This would need to happen internationally to make the prices comparable and not just lead to environmental load displacement. Higher prices would also lead to a more effective use of energy and perhaps to less demand for green hydrogen. The aforementioned internalization of EUE would in this way include the environmental load displacement and would make it more expensive for the core regions to load their waste in the periphery. If they do so the periphery would at least be compensated.
However, it is argued that a significant decrease in material throughput is needed in the core region. (Althouse et al., 2020) as especially current core regions emit more than the earth system can compensate for (Givens, 2018).

On this basis, I can now discuss the second research question of this thesis and evaluate if radical environmental justice could lead to less EUE.

Radical environmental justice

Germany and Namibia are aiming for profitable positions in the hydrogen economy. These positions reflect EUE: “Germany now has the chance to play a key role in international competition for the development and export of hydrogen technologies (…). (BMWI, 2020, p. 7). While Germany wants to export technologies and import hydrogen, Namibia aims for more welfare through the export of green hydrogen: “Green hydrogen will accelerate Namibia’s Prosperity Plan to deliver broad-based prosperity to its citizens An at-scale hydrogen industry could grow Namibia’s economy substantially” (Ministry of Mines and Energy Namibia, 2022, p. 34)

Climate protection is cited as a justification for developing a hydrogen economy in both of the country’s hydrogen strategies. These strategies reflect the long-term ambitions of the governments on how to develop a hydrogen sector. Both aim to disregard environmental conditions along the hydrogen supply.

Distributional justice

Beginning with distributional justice, Rischer (2023) showed that probably the investors will gain the largest margins of the economic benefits reached with this deal. However, the value of the ecosystems downgrade through the production sides and the consequences for the people living there are not considered. By including the state as a shareholder of the Hyphen project one could argue that the Namibians are among those benefiting economically from this project. This is uncertain as Namibia is one of the most unequal countries in the world, as a Gini coefficient of 59.1 in 2015 shows (World Bank, 2024). A just distribution of potential economic benefits within Namibia is therefore not given. This argument is strengthened by the historical argumentation that through the colonialist past, there is an “elite” that is powerful and has large land areas (Tjirera, 2023). Aiming for more distributional justice through trade schemes which include externalities could lead to more equitable outcomes. As such trade schemes could reduce EUE (Dorninger et al., 2021), applying distributional justice can strengthen the argumentation to include such trade schemes.

Looking at Germany, the one distributional issue raised is the commitment to reduce emissions due to the responsibility to comply with the Paris Agreement (BMWK, 2023). As discussed above, the embodiment of land through energy use in Germany can arguably be seen as an environmental load displacement. Throughout the German strategy, only "win-win" scenarios are described (ibid.). Who wins and to what extent is not clear. Dunster (2023), who summarized key success criteria for sustainable trade & production, sees the potential for Germany to play a positive role in global decarbonization through hydrogen. She demands that Germany itself should be more concrete in how benefits and losses across the supply chain are distributed. Enabling value creation in the producing countries is seen as a major aspect of distributing the benefits. A more local value creation would lead to less trade across national borders and could thus decrease EUE between nations. Nevertheless, it can be argued that national core and periphery regions will still have patterns of EUE.

Procedural justice

Another aspect of radical environmental justice that could enable a transparent approach to the rollout of the hydrogen economy is procedural justice. According to the strategy papers, transparency plays an important role in the establishment of a hydrogen economy. Yet, it is not addressed how such transparency will be assured (BMWK, 2023; Ministry of Mines and Energy Namibia, 2022). Where does the hydrogen come from, who is involved, profiting, etc. In both national hydrogen strategies, it is not made explicit on how the transparency should be assured. A lack of these concrete mechanisms is already criticized, as the process of why Hyphen was chosen by the government is unclear (Grobler, 2023).

Namibia is referring to community-based natural resource management (CBNRM) as a procedure that should be applied in the rollout of the hydrogen project (Ministry of Mines and Energy Namibia, 2022, p. 45). The idea is to involve the inhabitants surrounding a resource, which in this case is land, and give them more responsibilities for costs and benefits (Heffernan, 2022). The results of this nature conservation were a doubling in the black rhino and elephant population in Namibia and can be seen as a success as it increases nature capital. Meat and ecotourism are possible benefits for the population (ibid.). As this might have been successful, the situation with the hydrogen sights is different. In this case, the resource is controlled by external capital. Seemingly they do have not the direct power to influence the place of the hydrogen sites or even to own parts of the sides to generate direct benefits of the economic success of the projects. The benefits as aculeated by the Namibian government should be jobs and infrastructure. However, for some, this could also lead to negative consequences, as the sides cannot inhabited by flora and fauna which is attractive for tourists and ecosystem services.

To create procedural justice, binding and verifiable rules must be established. This applies to both social and economic guidelines. As Christiansen, (2022) notes, participation must not be a case of "checking a box". This means that regular and open participation and evaluation of the process is necessary. These guidelines could be promoted bilaterally or through a commitment to certification by both countries. The risk of not doing this explicitly is that the people who are least heard will not be seen in the processes surrounding a hydrogen economy. If people have an influence on the trade in the procedure, they could be enabled to reduce EUE. It is not per se the case as the interests could be the developing of a green hydrogen economy similar to the case of Hyphen. However, there could be more power for the affected to decide if and to what extent EUE is developing.

Recognitional justice

When it comes to recognition, the “traditional communities” and the “roundtables” are a concrete, if not precisely differentiated, way of recognizing groups (Ministry of Mines and Energy Namibia, 2022, p. 46). Especially in a country like Namibia, where different groups of people and different indigenous communities live together, interaction and recognition are of particular importance (Sippel, 2001). I could not find any evidence of the special significance of the Hyphen area for such a group. However, as it is not made clearer who is affected by the project one cannot fully evaluate to what extent recognitional justice is applied. Just the recognition alone does not change any power structures of material as well as monetary flows and thus does not necessarily lead to less EUE.

Recognizing the past obviously has a special meaning in a bilateral relationship between Namibia and Germany. The reappraisal of this past is still criticized by the Hero and Nama, whose ancestors were murdered by Germans. There were payments from Germany to Namibia amounting to EUR 1.1 billion based on a bilateral agreement between the two governments. There was no direct negotiation between the ethnic groups and Germany, which is criticized by the Nama and Hero (Ngutjinazo, 2021).

Recognition on a general level could also include the recognition of the EUE and the different levels of concern and responsibility for climate change. The cancellation of “debts” for the Global South is a possible demand to begin countering the historical imperial metabolism (Ambrose, 2005). These debts can be accounted for in EUE (Hornborg & Martinez-Alier, 2016), and thus recognition of the historical past can lead to less EUE.

Capabilities

In the case of capabilities, the question is if water from desalination as well as electricity enables the local population to have a better life and make use of their resources. Access to energy for everyone not only in the direct surroundings could be important to improve capabilities. The question of who is the worst off in this case cannot be answered with the data available. However, an analysis of the effects of the project could have a special focus on this perspective.

Recognizing capabilities, especially if it improves the ability to develop a self-determined life by using primary resources would strengthen the point that people should decide on how to use the land. A singular usage as it is for hydrogen production is unlikely to enable more capabilities than access to energy and perhaps access to water through desalination. In exchange, the resources from the land are lost. If this would increase the capabilities remain unclear. Also, it is hard to say if a strengthening of the capability approach would lead to arguments to decrease EUE. This would only be the case if it would strengthen the decision power of affected people, who would decide on less or no green hydrogen production.

To summarize, I see how decisions are made about land in the various categories as crucial. Radical environmental justice can guide these decisions and can be used to argue for less EUE. As explained, there is a tendency for land to become increasingly contested - and thus also for usable land to become more valuable (Hornborg, 2019a). Access to land, decisions about land and, above all, the question of ownership is central (Sovacool, 2021). Land and project-specific and independent evaluation could prevent mistakes. Direct benefits for the population are important for acceptance, which could also be demanded by importing nations such as Germany. Weighing up the use of land for renewables against ecosystem services such as biodiversity will play an ever-greater role as land use increases. The inclusion of externalities can theoretically lead to different trade patterns and reduce EUE. To answer research question two, it is likely that the application of radical environmental justice will shed light on these patterns of EUE and enable arguments for changing them and reducing EUE.

6.2. Outlook

Green hydrogen has the ability to decrease emissions in many so-called hard-to-abate sectors (AbouSeada & Hatem, 2022). The approach shows that on the one hand, embodied land is transferred through green hydrogen trade and increases EUE.

My analysis is the first indication of the aforementioned structures and considerations explored. To the best of my knowledge, it is the first work of applying EUE to hydrogen. A deeper analysis with more precise data as well as the evolving regulations and policy field could set my hypothesis on a more robust ground. Especially the land use of the wind turbine and the electrolyzer, which is here based on the average sequestration factor of forests, could be improved (e.g. measuring of land use of the products).

Assuming that these significant tendencies of EUE will evolve if Hyphen and similar projects are set, a general justice question evolves, independent of whether environmental justice concerns are met or not. It seems to be a continuation of imperial metabolism – the appropriation of land and the accumulation of capital in Germany – and the Global North.

The dimensions of the EUE will depend on the mass and location of the use of hydrogen and its derivatives. If hydrogen demand from Germany and the Global North is as predicted, it appears that Namibia could also benefit from its share in the project. However, as the investors do not come from Namibia, the profit, again, would mainly be found in the Global North (Rischer, 2023). To reduce this difference and allow the local population to participate, as much of the resulting added value as possible must remain locally. This can theoretically be seen in South Africa, for example, where iron ore is to be processed with the help of green hydrogen (Trollip et al., 2022). However, there is a risk here that the population will be exploited, and the actual profit will be accumulated primarily by the capital providers.

Concepts such as energy democracy or socialist approaches call for the population to be directly involved and have the right to make decisions on renewable energy.

The profit could thus be distributed more equally, which in turn could increase the acceptance of the projects (Fairchild & Weinrub, 2017).

A counterargument that often arises at this point is feasibility. In this case, impracticability is often the lack of capital and knowledge. In order to accommodate the historical and current EUE, debt cancellation or payments from the Global North would be one way of financing this. This could be a recognition of historical exploitation in several aspects. In addition to the democratization already mentioned and thus at least enabling a fairer distribution of benefits, this would also be a recognition of responsibility regarding climate mitigation. Germany and the so-called Global North have historically emitted more emissions and continue to do so. Financing such projects could thus lead to a reduction in emissions if the energy is not just added to the current energy use.

If one looks at the planetary boundaries and acknowledges the multiple pressures humanity is overstepping, the argument for green growth, which is highlighted in both hydrogen strategies, must be questioned (Stoknes & Rockström, 2018). Concepts like the donut economy (Raworth, 2017), degrowth (e.g. Demaria et al., 2014; Dengler & Seebacher, 2019; Hickel, 2020; Kallis et al., 2012), and eco-socialism (e.g. Löwy, 2005; Pepper, 2002) therefore aim for a democratic deliberate decrease of material throughput and I would argue also the need to reduce EUE. If policies based on these concepts are adopted, the hydrogen trade will not be to the extent projected now, possibly making projects like Hyphen uneconomical, as closer production of green hydrogen is cheaper due to fewer transportation costs (Wulf et al., 2018). Stranded assets and destroyed landscapes could be the consequence. Applying radical environmental justice principles in the development of such projects could, as concluded, enrich arguments for less EUE and perhaps also for the alternative concept just mentioned. A deep-rooted analysis of the consequences and possible scenarios is lacking.

7. Conclusion

This thesis argues that the development of a hydrogen economy, while potentially beneficial for reducing global carbon emissions, risks perpetuating historical inequities between core and periphery nations, as exemplified by the trade relationships between Germany and Namibia.

The results show that in the applied trade scenario, firstly, an environmentally unequal exchange occurs in the form of appropriated land exported from Namibia to Germany. Secondly, radical environmental justice applied to the case enriches the perspectives on externalities, decision-making, and power structures and thus leads to argumentation to decrease EUE. These findings emphasize that the emerging hydrogen economy is a continuation of historical trade imbalances and that there is a great need for more precise policy measures to ensure sustainability and environmental justice.

In order to achieve a more environmentally just introduction to the hydrogen economy, I recommend that the principles of radical environmental justice be considered in the development of a hydrogen economy. An integration of concrete measures to ensure the assessment of social and environmental impacts could be necessary. Affected communities could be at the center of this process. These processes should be as inclusive as possible. Empowering affected communities to make decisions could improve the outcomes of this process and perhaps decrease EUE. Transparency and accountability mechanisms that ensure impacts are reviewed and addressed are important to ensure procedural justice in a future hydrogen economy.

Further research is needed to thoroughly investigate the socio-environmental impacts of the hydrogen economy. Future studies should consider longitudinal impacts and incorporate a broader historical perspective that considers past inequalities, such as those stemming from colonialism.

This study has several limitations, including its reliance on projected data for future hydrogen production and trade scenarios. The dynamic nature of technological and economic developments in the hydrogen sector could significantly alter the results. Therefore, the results should be interpreted as indicative rather than definitive.

This work contributes to a more nuanced understanding of the potential impacts of the hydrogen economy and provides a basis for developing more equitable energy trade practices at a global level.

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