A master's thesis:

Exploring Open-Source Hardware as a Global Phenomenon

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Abstract

With the current global challenges of climate change, ecosystem collapse, and the energy transition, exploring different tools which can bring about systemic change is important. There is a growing movement towards open-source hardware (OSH), but its full potential for growth and even the extent to which it is desirable has yet to be agreed upon in academia. In this research, a literature review and interviews were used to explore the OSH movement, attempting to shed light on the extent to which it can be considered global, and how such a movement might be influenced by external factors. From the research the following was discovered: academic research on OSH tends to implicitly focus on the Global North (GN); differences in terminology when discussing OSH are likely to lead to misunderstandings and miscommunications between the GN and Global South (GS), and hinder the development of OSH globally; some shared perspectives on OSH amongst academics, entrepreneurs and individuals in the renewable energy field were identified; and a tentative framework to developing a thriving OSH ecosystem was developed, by exploring the influence of four key factors: *culture*, *awareness and knowledge about OSH*, *Funding*, and *Collaboration*. Furthermore, the explorative nature of the research opened numerous avenues for further research, including OSH and systemic change, GN/GS differences in OSH applications, and OSH for the energy transition.

Keywords: Open-Source, Open-Source Hardware, Global North, Global South, System Change

Preface

Since as long as I can remember, I have been feeling a sense of growing urgency with regards to our world. News are always dire, I'm very aware, but few moments in history can claim to be as influential to the fate of humankind as today is. And it is entirely our fault. Challenges that are global and incredibly complex, are popping up with no clear solutions to them. Climate change, the sixth mass extinction, ecological collapse. Basically, the end of the world as we know it.

Some are calling it a civilisation collapse. Which also means we are in the midst of a civilisation rebirth. New ways of thinking, working, and living are emerging all over the world with one thing in common: they acknowledge the need for change. My generation is calling for a 'system change, not climate change', and slowly (way too slowly) but surely, we are seeing it take place.

Considering how pivotal we are to the fate of most species on earth right now, including ourselves, it seems evident that this change should be understood and acknowledged by all of us "everyday individuals." Yet, this is not the case. Only rarely do we as individuals get the time to reflect and acknowledge the changes that are taking place, and only rarely do we get a glimpse of how fast these changes are taking place. Our world is way too overwhelming for that.

And so, I decided to make my master thesis about one of those things that has the potential to change the system – open-source hardware (OSH). Considering I have been working on an OSH start-up for the past two years, it is unsurprising that this is the topic I chose to focus on.

What I did not expect from all this research, was leaving this thesis more confused than when I started it. I wanted it to be an answer to my questions (will OSH help us solve the energy transition, inequality, knowledge sharing, etc? can OSH really work in our world today? Are we crazy thinking that we should stick to OSH with our start-up when the dominant paradigm is clearly not supporting it?). I wanted to end this thesis satisfied and content, not overwhelmed.

But ending this thesis, I realise that being overwhelmed from OSH and how immense its potential is, might not be such a bad thing. On top of that, I end this thesis with enthusiasm. Enthusiasm for OSH and its movement; enthusiasm for pushing past the boundaries of capitalism and the world as we know it; enthusiasm for the coming years which are going to drastically change the way our society functions. For this, I want to thank some of you.

My supervisors and those I interviewed: Udo, you have no idea how supportive and great you were even when I thought I was getting nowhere – you really gave me the freedom to do and explore what I wanted, and this thesis would surely not have been as it is otherwise. Fatima, your perspective and enthusiasm for my work was so, so valuable, there is no way it would be as it is today if it wasn't for you. All the people I interviewed

and chatted about my thesis to, I'm so grateful! Thank you for the insights, the perspectives, suggestions, and support.

My familyyyy : Maman, Papa, merci pour tout ce que vous m'avais offert, pendant ma thèse, mais surtout les 23 années précédente qui on fait de moi la personne qui a pu écrire ce dossier-si. Jahna, Romane, Nathanaël, you guys are the bestest. You know how much I love you eheh. Timour, thank you for the studying, the swimming, the support, the laughs, and the horizons you brought me – you made finishing my thesis even more fun than it already was.

The whole Biosphere Solar team, Puck, Judit, Sujith, Maitheli, Liam, and I'll stop here I'm sorry, but the list goes on! In particular though, Siemen and Tim(othy): I think it goes without saying that I'm so grateful we're changing the world together 😉 There's no-one I'd rather have by my side working on the next step in solar energy.

And finally, my (love, life, work) partner who I've just thanked, I know, but need to thank again: Si, I don't want to make this too cheesy, but you're everything I could hope for, and so much more. There is literally no way my thesis would be as it stands today if it wasn't for you – thanks to your continuous insights, the work we've done together leading up to my thesis, and of course, the incredible feedback you gave when I needed it most (thank you so much for that proof-read coupon!). I don't think anyone will ever read this as thoroughly as you read it.

Here's to closing off this thesis so that I can (finally!) focus entirely on taking OSH to the next level.

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List of Abbreviations

Abbreviation	
A&K	Awareness & Knowledge
CAPEX	Capital Expenditure
CE	Circular Economy
COP	Conference of Parties
GN	Global North
GS	Global South
IE	Industrial Ecology
OS	Open-source
OSS	Open-source software
OSH	Open-source hardware
OSSH	Open-source software and hardware
NDA	Non-Disclosure Agreement
P2P	Peer-to-peer
PV	Photovoltaic
RE	Renewable Energy
RQ	Research Question
SDGs	Sustainable Development Goals
TDs	Transition Discourses
USP	Unique Selling Point
WoS	Web of Science
WEIRD	Western, Educated, Industrialized, Rich and Democratic

Chapter 1. Introduction

The world has been experiencing the consequences of exiting the Holocene for a few decades now, but only the past few years have allowed humanity to truly experience the impacts of the Anthropocene. Today, climate change, catastrophic weather events, the sixth mass extinction, and increasing wealth disparity are just a few of the global scale challenges which humanity is tasked with overcoming (Adger et al., 2006; Pievani, 2014; UNEP, 2019; Wiedmann et al., 2020). Despite having never lived in an era with such low mortality rates, high gender equality, and reduced absolute poverty, humanity is now faced with challenges on a planetary scale which undermine the long-term benefits of these improvements.

Through the Sustainable Development Goals (SDGs), the Conference of Parties (COP), and other agreements, some of the world leaders come together to attempt solving these challenges (Häyhä et al., 2016; Jung et al., 2020). In 2016, the Paris Agreement was a significant event which brought together 194 parties to legally bind them to meeting the target of maximum 1.5 degrees Celsius global warming. Despite discussions and agreements, legally binding or not, the world is currently not on track for meeting such targets (Healy & Barry, 2017; Rogelj et al., 2016; Tong et al., 2019). Global warming is one of the major challenges which humanity is attempting to overcome and failing to do so fast enough to avoid global catastrophe.

1.1. Systemic Change and Sustainability

To meet the 1.5 degree Celsius targets of the Paris Agreement, the SDG goals and other targets, it is therefore clear that changes need to be implemented faster than they are currently being implemented (Rogelj et al., 2016; Tong et al., 2019). Academics and activists alike argue that systemic change is essential to solving the pressing problems of climate change, poverty, scarcity of resources, ecological collapse, etc. (Boisseau et al., 2018; Escobar, 2018; Extinction Rebellion, n.d.; Fridays For Future, n.d.; Healy & Barry, 2017; Pearce, 2015).

Such a systemic change can be found first-hand in the energy transition taking place. The Renewable Energy (RE) sector is growing exponentially, and evidence suggests that from the past decades of a nearly entirely fossil-based system, we are now moving towards a RE-based system (IEA, 2021). There is a growing body of literature on how to tackle this change, including thorough research on the steps required for establishing a 100% RE-dependent world (Bogdanov et al., 2019; Breyer et al., 2022; Hansen et al., 2019; Ram, 2019). Yet, there are aspects of a 100% renewable energy world which suggests politicians, academia, and industry should be exploring it from a systemic point of view – for example when looking at the materials required to enable such a change, it becomes apparent that systemic changes for the energy transition are yet to be holistic (Owen et al., 2022). Studying the energy transition is therefore compelling not only because it is a crucial aspect of our society that needs to change if we are to move towards a sustainable future (Rifkin, 2015), but also because it is a demonstration of a current systemic change that is still encountering drawbacks and resistance.

The term 'sustainable' is often widely used and a myriad of definitions are continuously cropping up, leading to misunderstandings. In this context, sustainability is defined as it is most commonly cited: "development that meets the needs of current generations without compromising the ability of future generations to meet their needs and aspirations" (Brundtland et al., 1987). Following this definition, sustainability is seen as encompassing three main pillars: economic, social, and environmental sustainability. To experience a systemic change towards sustainability requires tackling all three of these pillars (Bell et al., 2020; Healy & Barry, 2017). Current discussion on a Circular Economy (CE) reflects the movement towards the three-pronged approach to sustainability. The CE provides an alternative to the take-make-waste disposal system currently in place, and although a broad range of definitions have been coined, its definition can be boiled down to an economy in which materials are circulated within society as long as possible, for the highest value possible (Kirchherr et al., 2017).

1.2. Transition Discourses (TDs), Buen Vivir and the Commons

Research on systemic changes has been explored from various perspectives, including 'civilisation collapses'. Bauwens (2022) is one of many academics who argues that the systemic change required to move towards more sustainable systems is a reflection of the 'civilisation collapse' our society is experiencing. The study of these 'civilisation collapses' and systemic changes has been coined Transition Discourses (TDs), and is well-explored in dozens of different fields, including ecology, food, energy, social movement research, and digital technologies (Escobar, 2018). The exploration of various TDs has not only been carried out extensively in different fields of study, but also across different geographies which includes both the Global South (GS) and Global North (GN) perspectives[1] (Escobar, 2018).

Of the discourses held in the GN for systemic change, the rise of the Commons is apparent (Bauwens, 2022; Benkler, 2006; Gerhardt, 2020; Ostrom et al., 1999; Rifkin, 2015). The 'Commons' is a reflection of concepts long established in the GS such as 'Buen Vivir', 'Sumak Kawsay' and 'transitions to post-extractivism' (Altmann, 2020; Escobar, 2018). These ideas denote the sharing of resources by all in a society, independent of one's social status, to enable a 'good life' (Altmann, 2020; Ostrom, 2002). They entail a different way of structuring our society from what it is today (Escobar, 2018). In the GS, the terms 'Buen Vivir' or 'Sumak Kawsay', which have been rooted in the indigenous culture of Latin America and particularly in Ecuador, are well-established (Escobar, 2018; Fatima Delgado, personal communication, March 2023); these concepts promote the living in harmony with nature, and were coined long before the 'commons' arose as a concept in the GN (Altmann, 2020).

Bauwens (2022), after researching the rise and fall of civilisations, has argued that "when things go well, the commons decline and weaken; when things go bad the

[1] In academia and politics, the terms GS and GN have emerged to replace more valuing ones such as developing and developed country, or first world and third world (Hollington et al., 2015; Trefzer et al., n.d.).

commons grow and become stronger". According to Bauwens, it is therefore not surprising that the commons and similar concepts are being paid increasing attention considering the looming crises of climate change and other global existential threats.

1.3. Open-Source Hardware

Surrounding the topic of the commons/Buen Vivir, and because of social trends, new terminologies have emerged in the GN. This includes peer-to-peer (P2P), open-source software (OSS) and open-source hardware (OSH). OSH is "hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design" (OSHWA, n.d.). Such a definition suggests the potential for global collaboration, and indeed, a global movement. But is the rise of OSH really a global movement? Is there a discrepancy to be seen between the GN and GS, and how OSH is developing in these areas? Unlike OSS, which is well-established and was first seen to emerge in the mid-1990s (Lee et al., 2009), OSH is a relatively novel concept, and therefore these questions have yet to be explored.

OSH largely developed from the OSS movement, as individuals working in makerspace and Fablab[2] spheres were inspired by the collaborative nature of OSS (Gupta et al., 2016; Lee et al., 2009). Similarly to OSS, OSH reflects a movement towards decentralised production, with the aim of achieving greater economic, environmental and social sustainability (Moritz et al., 2018). As highlighted in a previous MSc thesis, although research to date has yet to quantify the impact of OSH on environmental sustainability, the idea that OSH designs tend towards environmental sustainability more than closed source designs has repeatedly been suggested (Brinksma, 2021; Kohtala, 2015; Kostakis et al., 2015; Kostakis & Bauwens, 2014).

In addition to potential environmental sustainability, the emergence of OSH as a topic of research in academic literature has led to the identification of various benefits. These benefits include increased safety in national security (Pearce, 2022), increased innovation, reduced costs of production, and reduced risks of lock-ins (Arancio et al., 2022), reduced costs of R&D and IP protection (Buitenhuis & Pearce, 2012; Giotitsas et al., 2015; Moritz et al., 2017), amongst others.

1.4. Relevance to Industrial Ecology and Research Gap

Industrial Ecology (IE) is one amongst various disciplines which have emerged over the past decades as a result of the acute awareness that our society needs to change in order to overcome the challenges of the Anthropocene. It studies ways of transitioning to more sustainable industrial systems by bridging the gap between nature and society (Ayres & Ayres, 1996). IE employs systems thinking, studies material and energy flows in our society and its environment, and thereby attempts to provide solutions to the sustainability challenges of our times (Jelinski et al., 1992).

[2] Makerspaces and Fablabs are places where individuals can gather and work on projects, using both low-tech and high-tech methods. These have become increasingly common around the world notably on university campuses (Girdzijauskaitė et al., 2018; Hellenes, 2016)

The newly emerging TDs reflect some of the solutions that have been investigated by the field of industrial ecology (IE). According to some scholars, TDs are a manifestation of the limitations and inadequacies of the existing dominant economic system, i.e., capitalism – they represent a paradigm shift towards more sustainable economic models (Escobar, 2018; McKay, 1997; Raworth, 2017; Rifkin, 2015; Schumpeter, 1942; William & Avaria, 2020). Fredric Jameson amongst others, has said that for many, "it is easier to imagine an end to the world [rather] than an end to capitalism". And yet, capitalism is only an 'evolutionary process', as Schumpeter (1942) has highlighted, and it is bound to constant change (Klein, 2015; Mason, 2013; McKay, 1997). Assuming that the capitalist system will evolve and be replaced, we therefore need to ask ourselves questions such as: What will replace capitalism? When will it be replaced? And how will it be replaced? Exploring such questions is highly relevant to IE researchers, as an understanding of our future economic, cultural, and social system is crucial to develop solutions to our current societal challenges (Jelinski et al., 1992).

Of the many TDs explored in academia, research uniting the commons, capitalism and the use of OSH to tackle current world challenges and notably the energy transition is beginning to emerge (Buitenhuis & Pearce, 2012; Giotitsas et al., 2015; William & Avaria, 2020). Various books have been published on these topics and how they interlink (Benkler, 2006; Klein, 2015; Kostakis & Bauwens, 2014; Rifkin, 2015). But there is still much left unexplored.

1.5. Research Questions

This master thesis therefore explores the role of open-source hardware in a systemic transition, with a particular interest in the differences in its application in the GN and the GS. This exploration aims to explore the overarching question of: "**How is OSH as a global movement being perceived and explored?**"

During this research, the extent to which OSH can be considered a *global* transition was first explored. Literature research was done on the current work of OSH in the academic field for both the GN and the GS, guided by the following research question (RQ):

- RQ1a: What is the current state of knowledge on OSH in academic literature
- RQ1b: To what extent is the OSH research in academic literature about both the Global North and Global South?

Little research to date has explored how individuals from different lines of work view OSH as a potential tool for systemic change. Therefore, the author aimed to identify some of the opportunities and challenges which an OSH global transition might encounter by exploring the opinions of various individuals in academia, the energy transition and entrepreneurship. The research therefore aimed to explore the following question:

- RQ2: What are some of the main themes which individuals in academia, entrepreneurship, and the renewable energy sector express when discussing OSH?

Finally, knowledge obtained from RQ1 and RQ2 were combined to develop a basic framework which further explored the main research question and a third research question:

- RQ3: What are the main factors influencing the development of a global OSH ecosystem, and how do these interact with one-another?

Chapter 2. Methodology

2.1. Overall Methodology

Due to the novelty of OSH in academic work, this thesis research was very explorative. The research followed the Grounded Theory approach, which entails carrying out research, developing hypotheses, and repeating this cycle with the goal of exploring a specific topic (Charmaz, 2006). This approach enabled the research to adapt its approach to findings which emerged over time. The research involved iterations of literature research and semi-structured interviews to answer the research questions (Figure 1).

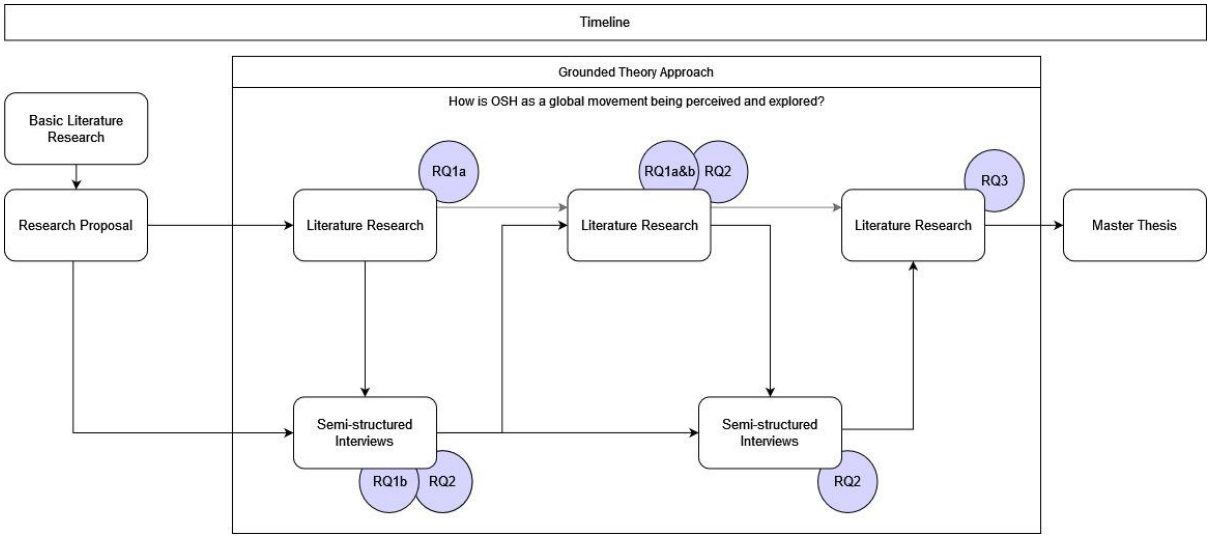

Figure 1 Methodology of the research (arrows indicate flow of information; blue circles showcase where the research questions were answered).

Using the Grounded Theory approach in this research meant exploring the topics of OSH and how these related to the GN and GS. The knowledge gathered from both interviews and literature was then used to develop hypotheses about the state of OSH in the GS and GN.

In Figure 2, the concepts explored in this thesis are visualised in a theoretical framework. The research explores the Maker and OSS movement which formed the foundations of the OSH movement and explores how this movement ties into Transition Discourses (TDs) and system change. In the TDs explored, concepts from the GS ('Buen Vivir', 'Sumak Kawsay' (Escobar, 2018)) and GN (the Commons (Ostrom, 2002)) are touched upon.

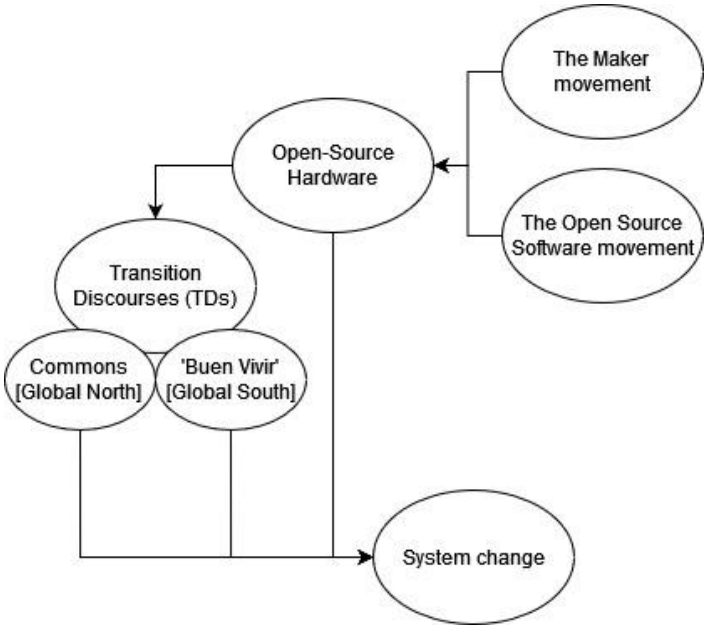

Figure 2 Theoretical framework behind the methodology

2.2. Desk Research Methodology

For RQ1a, an academic literature research was done and analysed using a trends analysis on the academic literature database Web of Science (WoS). The search query used was: "*open-source hardware*" OR "*open source hardware*". Using the *Analyse Results* tool of WoS, the number of publication research results per year of the keyword was obtained. Only data for the years 2000 to 2022 was used due to the novelty of OSH in academic research leading to very few papers published before 2000, and to ensure only complete years were included (therefore excluding 2023). The results were compiled in a spreadsheet and analysed (Appendix 1). The step-by-step procedure can be seen in Figure 3.

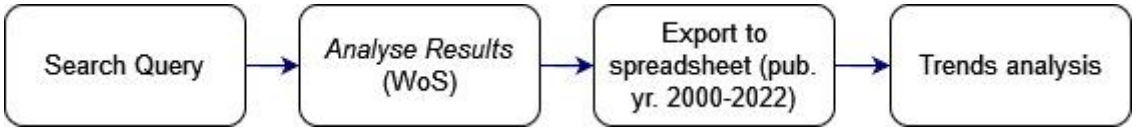

Figure 3 Research methodology of RQ1a, trends analysis

The literature research for RQ1b was carried out using the methodology exemplified in Figure 4. Keywords (Table 1) were identified and used as input for WoS to collect research articles, using the constraining boundaries of published date (2010-2022), and language (English). Note that search queries which did not yield any results were omitted in Figure 4.

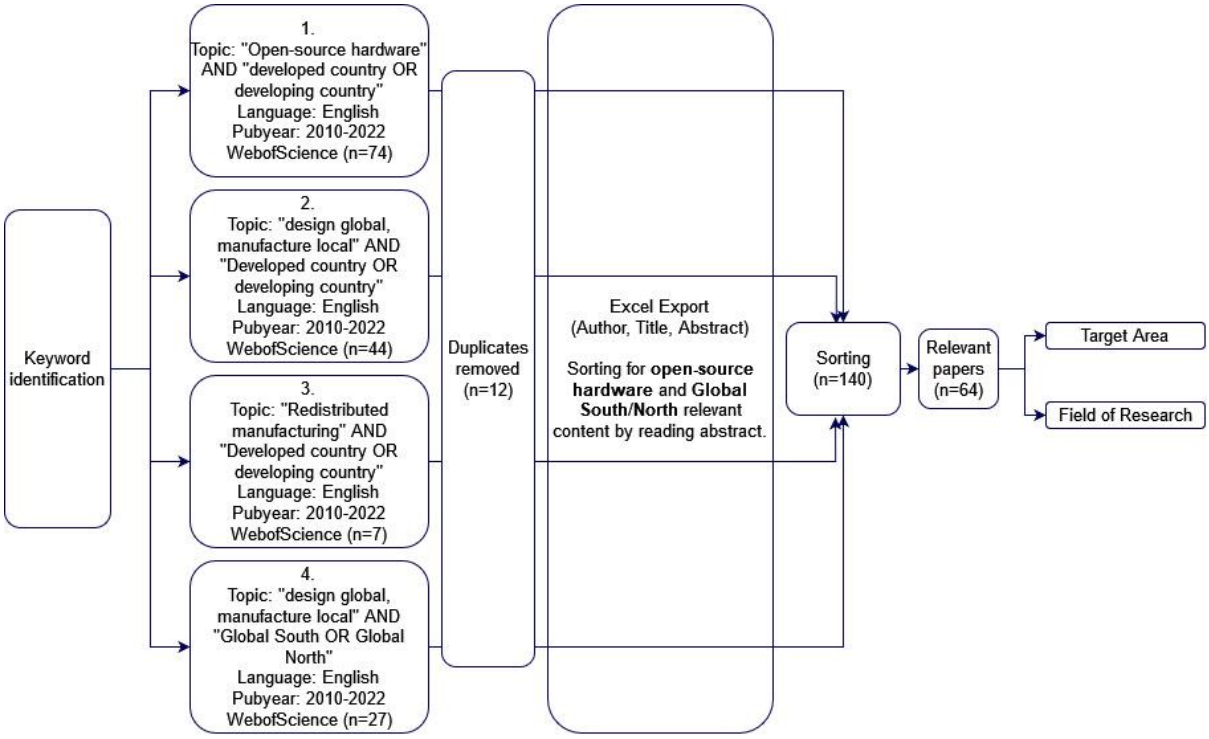

Figure 4 Research methodology for RQ1b.

Table 1 Keywords used for RQ1b

Query	Keywords
1	"Open Source Hardware" AND "developed country OR developing country"
2	"design global, manufacture local" AND "developed country OR developing country"
3	"Redistributed manufacturing" AND "developed country OR developing country"
4	"Design global, manufacture local" AND "Global South OR Global North"
5	"Open source hardware" AND "Global South"
6	"Open source hardware" AND "Global North"
7	"Redistributed manufacturing" AND "Global South"
8	"Redistributed manufacturing" AND "Global North"

Author, title, and abstract from each paper was extracted from WoS and the articles were combined in an excel sheet. Duplicates were then removed. A screening was carried out on the 141 resulting papers: each abstract was read and papers discussing OSH were kept, whilst others were removed (n=76). This included papers discussing OSS, redistributed manufacturing without the OS aspect to it, and papers which discussed developing countries or developed countries without reference to OSH.

A screening was carried out on the remaining papers (n=64) by once more reading through the abstracts of the articles and giving them a label in two categories: target area,

and topic. Decision of the target area was carried out by noting when papers explicitly mentioned the research being carried out for the GN, the GS or having both target areas in mind (note that alternative terminology to GN and GS was employed – see Table 1); papers which did not mention target area were labelled as 'not specified'. Topics were decided in conjunction to reading the papers, and labels were allocated accordingly. See Figure 5 for a visualisation of the screening procedure.

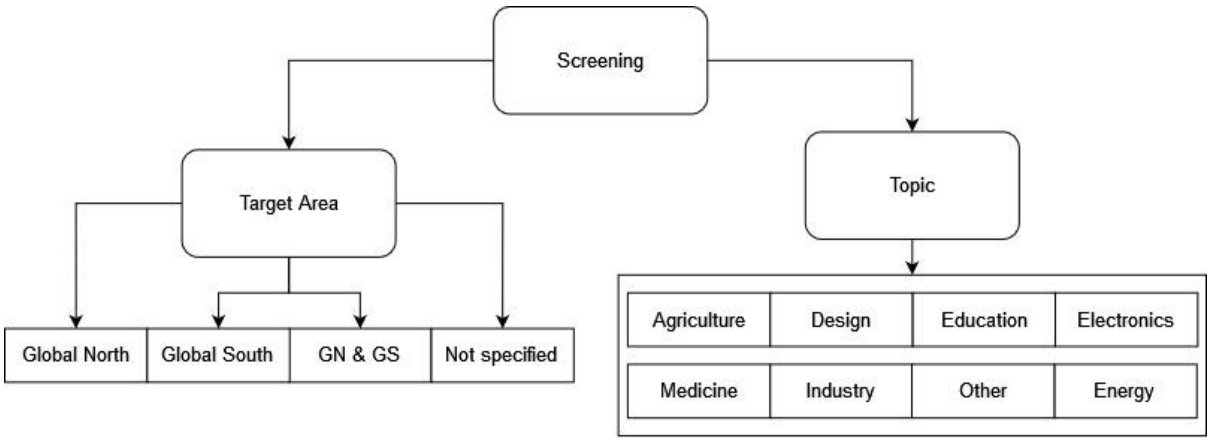

Figure 5 Screening procedure for the allocation of target area and field of research

2.3. Interview Methodology

The interviews carried out were done over a period of five months and were done in a semi-structured interview manner (see Bhattacherjee, 2012). Table 2 gives an overview of the interviewees and expertise (n=9). The interviewees were found through the author's network, research papers individuals had authored/co-authored, and through snowball sampling. Consideration was placed in interviewing people with diverse gender identities, however this proved difficult to balance due to the limited number of women and gender divergent people that could be found working in this field.

Additionally, emphasis was made on attempting to find individuals based in different countries across the world and representatives of the GN and the GS. However, this once more proved to be difficult, both due to lack of responses, and the few possible interview candidates which were found (highlighting a potential lack of representation from the GS when exploring systems change or TDs). Prior to each interview, a basic understanding of the interviewees and roles in their respective jobs were researched via LinkedIn and Google Scholar to confirm their relevancy to the research.

Table 2 Interviewee list and description

Interviewee	Abbreviated name	Location	Gender	Expertise description
OSH Entrepreneur 1	Int.OSHE1	US	M	An entrepreneur living and originating from the US, who has been working in the field of OSH for three decades. He has developed his own OSH company

				that is considered highly successful due to its financial stability, project developments, and social work.
OSH Entrepreneur 2	Int.OSHE2	Brazil	M	An entrepreneur living and originating from Brazil. He has been working in the field of OSH for two decades. He is passionately involved in many active projects including OSH product developments and OSH-related teaching.
OSH entrepreneur and Renewable Energy Engineer	Int.OSHE3	Germany	M	A renewable energy engineer that has been working in the field of wind energy for nearly a decade, and joined an OSH project turned cooperative, developing wind turbines in Germany. He is currently one of two heads for the cooperative and is working on it part-time.
OSH entrepreneur 4	Int.OSHE4	US	M	An OSH enthusiast who experienced a change in career path in the past few years and became an entrepreneur after being exposed to a large OSH company in the US. Since then, he has been working on various OSH projects and on doing research to help guide an OSH transition.
Renewable Energy Researcher	Int.RER	US	M	A French researcher working at the National Renewable Energy Lab in the US. He has published papers on solar recycling, LCA and circular economy.
Peer-to-peer academic	Int.P2PA	Netherlands	M	An academic from the Netherlands who has been working on P2P and blockchain technology for a decade at the Technical Universiteit Delft. He has published various papers, including one on P2P, blockchain and the energy transition.

Open Source Software and Hardware researcher	Int.OSSHR	Belgium	F	A researcher and strategic director at one of the leading institutions in Europe for open source. She has been working on the topic of open source for 4 years and co-authored an important paper by and for the European Commission on the topic of OSSH.
Renewable energy expert	Int.REE	Netherlands	M	A project manager at a semi-government organisation based in the Netherlands. He previously extensively worked in the field of solar cell technology, and his company is working on accelerating innovation by enabling funding and collaboration between companies and research institutes. The department he leads focuses on the energy transition and renewable electricity.
OSH energy investor	Int.OSHI	US	F	A head of operations at a large investing company based in the GN and investing in the GS. The company funds projects working on renewable energy access mainly across Africa.

The interviewees were categorised into the following target groups: academics, entrepreneurs, and individuals in the Renewable Energy field. Individuals could be part of multiple target groups. Academics were considered individuals currently working in academia; entrepreneurs consisted of self-proclaimed entrepreneurs, who were then given a background check to identify entrepreneurial activity (e.g., starting a company, or joining a company at an early-stage to contribute significantly to its development); individuals in the RE field were individuals currently working in the RE field.

These target groups were a result of needing to narrow down the scope of the research. Individuals working in the RE field were included due to the relevance of the energy transition to our society today. They were interviewed to further explore how OSH could benefit the energy transition, if at all. Entrepreneurs were included due to their relevance in instigating and supporting transitions in our society (Schumpeter, 2000). They were interviewed to explore further how they view an OSH transition, beyond a business model/motive discussion. As OSH has largely been studied by

academics from a business perspective but little else, it was deemed valuable to include academics in the research. They were interviewed with the purpose of identifying further what their opinions on OSH were, beyond its potential in business.

For the interviews, all questions were posed open-ended, and related questions were posed in the middle of the conversation when interesting points arose. The interviews lasted between 20 – 120 minutes via video conference or in-person meetings, and all interviews were audibly recorded with the permission of the participants. The questions changed slightly for the first three interviews, after which a more set structure was created. The resulting questions can be found in Table 3. Not all questions were asked to each interviewee – the relevant themes and questions for each person were determined pre-interview based on the interviewees' specialisation.

Table 3 Interview questions

Questions	Theme
Tell me about yourself and what you do.	Background information
What are your thoughts on and experiences with OSH and/or P2P?	OSH, P2P
What were some things you would have liked to know when starting to work in the OS sphere, or would still like to know?	OSH
How do you see OSH and/or P2P influencing sustainability, if at all?	OSH, P2P, Sustainability
What do you think the role of OSH and/or P2P is in the energy transition?	OSH, P2P, Energy transition
Do you see any differences in the way that OSH and/or P2P is being applied in the GN and GS? If so, what differences?	GN & GS
Do you have any suggestions or recommendations to people working on OSH and/or P2P projects?	Recommendations

Before each interview, a consent form was sent (Appendix 2), and after each interview, the transcripts were carefully reviewed and pseudo-anonymised. This entailed the removal of any personal information which could lead to identification of the interviewee. Following this pseudo-anonymisation, a technical transcript was created in which only the relevant data to the research themes was included (Appendix 3).

The technical transcripts were then coded according to the following themes: Background, Barrier, Business models, Circularity, Closed Source, Culture, Finance, OS, OSH, OSS, Other, P2P, Circularity, Closed Source, Culture, Energy, Further Research, Global N/S, Open-source, Open-source Software, Open-Source Hardware, Peer-to-Peer, Suggestions, and System Change (Appendix 4). The themes were created according to the information present in the interviews. Following each coding of the transcripts, if it appeared that a new theme needed to be included because the quotes/concepts

discussed did not fit in any of the initial themes, then a new theme code was created. The themes were used to structure the analysis and discussion of the results.

Chapter 3. Academic Literature Research

In this chapter, the state of the academic literature regarding OSH is explored with a quantitative approach (RQ1a: What is the current state of knowledge on OSH in academic literature, and RQ1b to what extent is the OSH research in academic literature about both the Global North and Global South?).

However, to first provide a better understanding of OSH and where it lies in the broader OS context, Figure 6 provides an overview of the various terms and concepts used in this field and how they relate to one another. These were concepts recurringly found in the literature review and are sometimes used interchangeably.

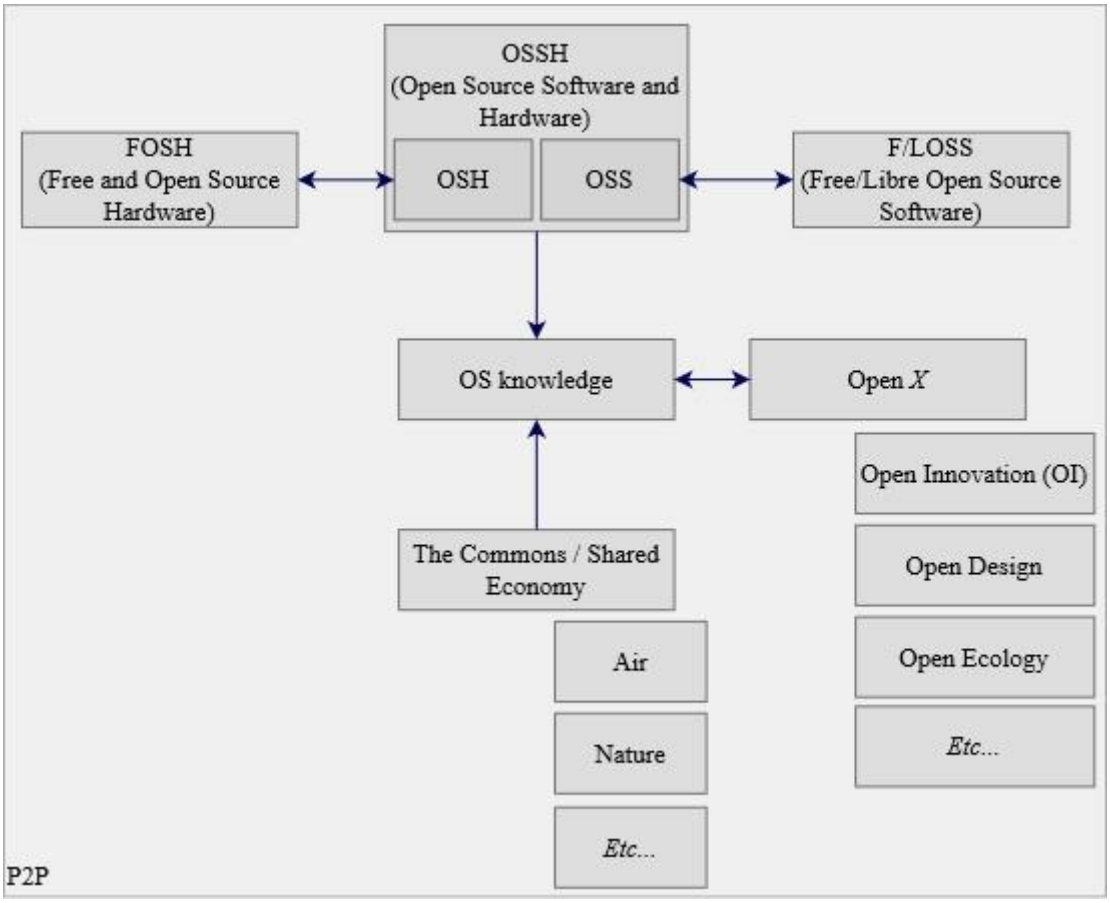

Figure 6 Terminology employed in a P2P paradigm (author's work).

3.1. OSH Publications in Academic Literature

From the literature research done for RQ1a, it became apparent that the past two decades have seen an impressive growth in the attention being paid to OSH: publications statistics found in a trend analysis on WoS using the keyword "open-source hardware" OR "open source hardware" (Figure 7) show a hundred-fold increase over the past 20 years (Web of Science, 2023). An upward non-linear growth in publications is observed from 2010 onwards, with 90% of all publications mentioning OSH being published after 2010. Since 2019, the trend seems to have stabilised at approximately 700-800 publications per year (see Figure 7).

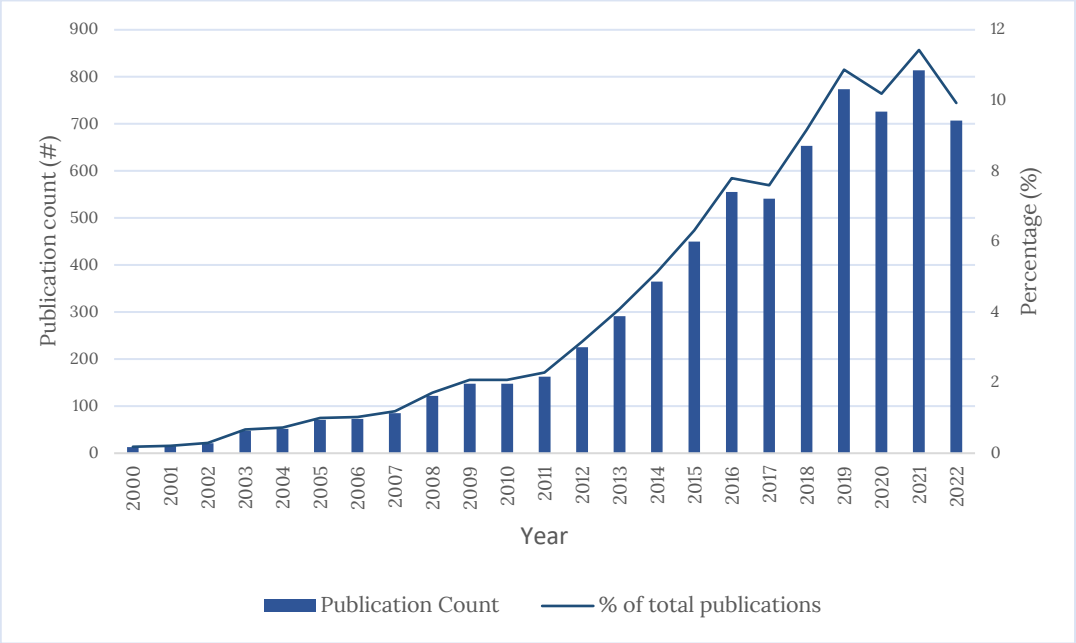

Figure 7 Open-Source Hardware publication trends analysis (total publication count (bars); percentage of total publications (curve)) - RQ1a research results

3.2. OSH Academic Literature for the GN and GS

As explained in section 2.2, exploring RQ1b meant using keywords such as "Global North/South" or "developing/developed country" in combination with "Open-Source Hardware". Comparing this to results found for RQ1a which only searched for "Open-Source Hardware" showed a large difference in publication numbers: OSH & GN/GS searches yielded a total of 140 published papers, whilst the search for OSH yielded a total of 6,412 papers.

An analysis of the papers returned from the searches including GN/GS keywords showed that the majority of the publications included in the results were related to the GS; only one of the papers explicitly used the keyword Global North. This trend is visualised in Figure 8, which depicts the target area mentioned for each paper that was returned from the query search of RQ2.

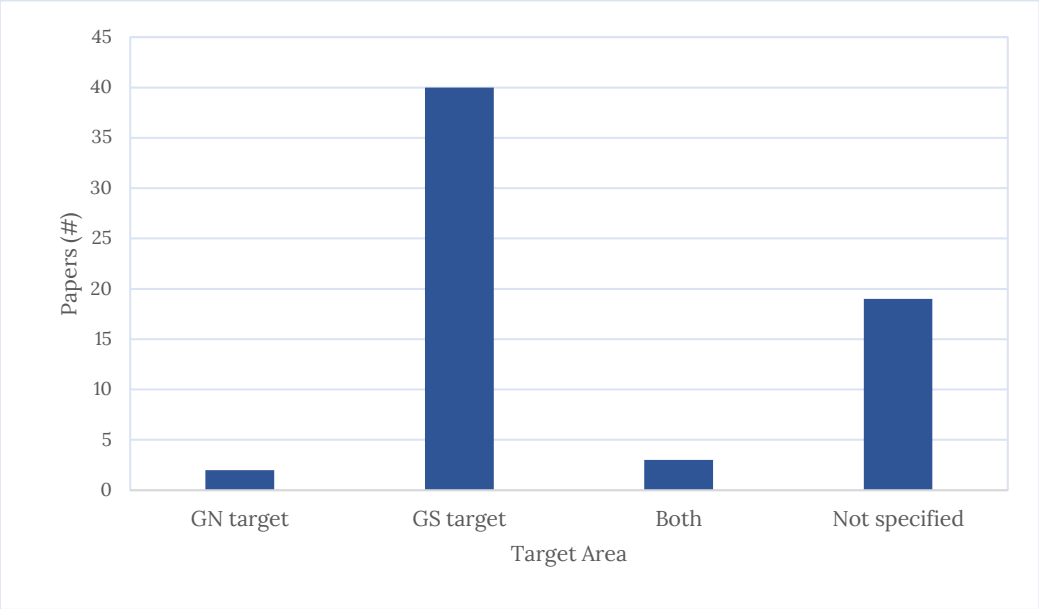

Figure 8 OSH & GN/GS publication trends target area analysis - RQ1b research results

Chapter 4. Interviews

After a thorough desk research, it became apparent that due to the relatively novel concept of OSH in society, there is much left unexplored about OSH and how it is being applied and perceived. By far the most explored subject was found to be how OSH is used in business, particularly by entrepreneurs (Antoniou et al., 2022; Bonvoisin, 2016, 2017; Bonvoisin et al., 2021a; Hellenes, 2016; Li et al., 2017, 2021; Li & Seering, 2019a, 2019b; Nascimento & Pólvora, 2016). In these publications, the main area of research was found to be how to create successful businesses from OSH products, and what motivations hardware entrepreneurs have in utilising OS.

In this master thesis, it therefore became a main point of focus to understand how different groups perceive OSH (RQ2), not only from a business point of view but also from a 'societal implications' point of view. In the following chapter, a summary is given of interviews carried out with entrepreneurs, academics, and individuals in the field of renewable energy. The findings from these interviews are compiled to propose further hypotheses and can be used as a basis from which to further explore OSH and its development in our society.

4.1. Interview Groups

4.1.1. OSH Entrepreneurs

Four OSH entrepreneurs were interviewed for the research. All of them were male, two were based in the US, one in Brazil and one in Germany. The background of each of these individuals varied, with one knowingly saying he lives on "the fringes of system and cultural changes" (Int.OSHE2), and the three others having had a higher education in Science, Technology, Engineering and Mathematics (STEM) and living in more conventional western lifestyles.

Despite their different origins and upbringing, all entrepreneurs had in common **a drive for creating a better world**. One described it as making "products that we really need in the world" (Int.OSHE3); whilst another said that when he had been working in a US-based company as an engineer, he "saw a lot of unmatched needs and [...] unused material that could be shared" mentioning that "it felt very stupid. Like this system is highly inefficient" (Int.OSHE1). This resulted in a drive for contributing to a more efficient system, and for working in a way which does not hinder innovation, but rather promotes it.

Two of the entrepreneurs explicitly mentioned that they believe "capitalism is definitely broken" (Int.OSHE4), and that we are living "a very very complex civilisation collapse" (Int.OSHE2). The belief that the system we live in today is dysfunctional was also mirrored by Int.OSHE3, who stated that things should be OS so that "humanity learns something of it. Otherwise, we keep doing the same mistakes again". Overall, the four interviews carried out reflected a desire for an economic and social system beyond the one predominant today. They reflected a desire to establish a more "[OS] and transparent paradigm" (OSH1).

To establish such a paradigm, and for any system change to occur, all emphasised the **role of culture**. A general trend throughout the interviews was that main barriers to adoption of a novel economic or social system are cultural since "the worst enemy that we have in this transition is culture" (Int.OSHE1). This naturally raises the question of: which culture? And as Int.OSHE1 asked: "What are the characteristics of a culture that makes it compatible with [OS]?"

Int.OSHE2 from Brazil stated that there is "a very collaborative and sharing culture" in Brazil, and that people already "create all sorts of machinery in a very open hardware dynamic, but no one calls it open hardware". Int.OSHE1 who has worked in the Middle East and Africa, said that what "is incompatible with peer-to-peer is the tribal mentality and culture". He suggested that the reason for this is that in a "peer-to-peer economy, [roles are] distributed across the network. We talk about the wisdom of network, not the wisdom of the elderly in the village". Regarding the US, Int.OSHE1 said that people who came to his OS company greatly struggled "because they have been moulded within institutions where they have to watch out for competition among employees". In his experience, it took "two or three years" for somebody working in his company to "really get comfortable".

The entrepreneurs did not suggest they have the solution to the cultural requirements that an OS society would need in to thrive. However, various **characteristics to an OS-based system** came up that they suggested would be required for it to prosper. This included *openness*, *decentralisation*, *dealing with complexity in our society*, *collaboration*, and *consumers becoming prosumers*[3] among others. One of the entrepreneurs when asked about the topic of circularity, suggested that although he does not think OS and circularity are linked, he believes that "people in the circular economy usually share the values of openness, transparency, collaboration, so they become easily friends and can work together" (Int.OSHE1).

Additionally, the roles of governments, universities, individuals, communities, and funding bodies as having an important role in a transition were all discussed. Each stakeholder group was said to have a role to play in enabling a transition towards the more OS-oriented society which the entrepreneurs are working on.

The interviews served to highlight the zealous belief that some OSH entrepreneurs have in the paradigm shift towards a more open and collaborative system. It does not seem solely a 'business case' for them, but rather a new way of living and working. As Int.OSHE1 puts it: "I jumped on open-source and I said, this is the future, this is the future if we want to solve world problems".

[3] Prosumers – a term used to describe a customer who wants to contribute to the design and production of the products they use (originating from the words "producer" and "consumer"). *Definition retrieved from the Cambridge Dictionary*

4.1.2. Academics

Of the three academics interviewed, one was based in the Netherlands, one in Belgium, and one in the US. There was one female and two males, all having carried out higher education (post-doctorate or Master of Science). Two of these individuals have previous experience in the government and industry and are currently active in the academic sphere. All three interviewees had experienced the concepts of OS differently: Int.P2PA was actively working in a research group advocating P2P; Int.RER was working in a national research group which advocated for OS research, but still conformed to the use of Non-Disclosure Agreements (NDAs) and patents; and Int.OSSHR had carried out research for the European Commission on OSSH, and been working on further developing OSSH at a policy-level for four years.

All interviewees believed that **OS could be beneficial**. Some benefits they highlighted included:

- Int.RER said that "for us researchers, it would be great to have more [OS] data", which would result in **better research.**
- All three interviewees saw the idealistic aspect of applying OSH to make systems **function better and more efficiently**. They provided a point of view often neglected in the academic discussions on OSH: the idea that OSH, just like OSS is a way of "working for the common good" (Int.P2PA), and that this is a valid reason for developing OSH systems. This was reflected in a quote by Int.P2PA saying: "our lab has a profound focus on the common good. We have this idealistic vision of having things that can be used by anyone, that are free to use".
- Another benefit mentioned was **lower barriers to entry**, and **prevention of lock-ins** (Int.P2PA)

In addition to discussing the benefits of OSH, the interviewees acknowledged that the implementation of OSH still had a long way to go before it could be applied widely. Some barriers that were identified included:

- Int.OSSHR highlighted that the research commissioned by the European Commission in 2022 "was basically the first time that policymakers wanted to know more about open-source hardware". Prior to their research OSH was only thought to be 3D printing by the European Commission indicating a clear **lack of awareness and knowledge in OSH** at a policy level. Meanwhile, Int.P2PA said that a key barrier is that "from an industry perspective [OSH] is not taken seriously at all", and that this lack of awareness and knowledge makes it difficult to push forward OSH in industrial systems.
- Int.RER suggest that **collaboration was lacking** and since "you need more collaboration between companies, which is not necessarily what is happening" OSH would not progress unless change in this realm took place. According to him, developing a system which was collaborative would require "access to information" and "trust", which in his view is not present enough in our society today.

- Concerns about a fully decentralised system which OS often advocates for were mentioned. Int.P2PA expressed doubts about OS functioning as intended, and he suggested that we "would probably need to [have] a sort of hybrid system".
- Other concerns evoked by Int.P2PA also revolved around the potential increase in the challenge of interoperability across systems and products, which he believed would increase if OSH become prevalent.

4.1.3. Individuals in the Renewable Energy Field

Of the individuals interviewed, five were involved in the renewable energy field. Some had more recent experience and their everyday job was in the renewable energy field (Int.OSHI, Int.OSHE3, Int.REE). Others had been involved in the renewable energy sector at one point in the past five years but had now switched to a different field of research (Int.P2PA, Int.RER). Four out of five of them were men, two were based in the Netherlands, two in the US, and one in Germany. No individuals based in the GS were interviewed from this target group, however, the company of Int.OSHI funds innovations working mainly in the GS, in areas with low energy access.

Of the individuals interviewed, none expressed direct opposition to OS and its fundamental values, yet all acknowledged challenges that would hinder its influence in RE. Additionally some expressed scepticism about applying OSH to the (renewable) energy value chain. In Table 4, quotes from some of the interviewees were gathered to highlight the support for and against OSH in the RE industry.

Table 4 Renewable Energy experts' point-of-view on OSH

Quotes supporting OSH in RE	Quotes doubting OSH in RE
"The transition is really depending a lot on the open source, and I think the beauty of open source is collaboration and the community." (Int.OSHI) "Some core innovations being open innovations can really help in expediting [the energy transition]." (Int.OSHI)	"Depending on who's bringing the value or the investing in, you might have to have a close source product. We are very clear about this: we don't say that there is, it's an either-or approach." (Int.OSHI)
"I don't see any fundamental restraints to [open source becoming big]." (Int.REE)	"I think [success] depends on what part of the value chain you're in." (Int.REE)
"It was a success in software engineering, right? If they succeeded, then my first reaction would be like, why wouldn't it work for hardware and like PV." (Int.RER)	

On the one hand, there were specific barriers identified in applying OSH to the RE field. These barriers included finance, and lack of understanding and awareness of what OSH is by anyone not working in OSH:

- Finance consisted of two challenges. First the difficulty in **finding funding for OSH** (Int.OSHE3). The experience of Int.OSHE3 with attempting to develop an OS business with small-scale wind turbines in Germany was a challenging one as they "got a little money here and there", but larger investments from the government did not go through. Over time, this meant people in their company had to stop working on the project and focus on other jobs to receive an income.
- The second challenge in finance for OSH, was the **capital-intensive nature of hardware** which drastically differs from software and leads to different scaling economics (Int.REE). According to Int.REE, "venture capital and open-source business models are poor combination" and so OSH businesses would need to depend on "crowdfunding or philanthropy".
- The barriers of a **lack of understanding and awareness** of what OSH is was highlighted by both the entrepreneur (Int.OSHE3) and the investor (Int.OSHI). According to Int.OSHI, the "biggest challenge is lack of awareness and lack of understanding of what is open innovation". In their company, they experienced this by recurringly encountering the issue of "people only understand[ing] open source as software" (Int.OSHI), and according to them, "most companies and stakeholders or actors in the energy space really don't understand open source" (Int.OSHI). Such a statement emphasises the importance of raising awareness if a society to adapt to new concepts. For Int.OSHE3, he experienced this lack of understanding through funding applications, as "the guy who checked our proposal was a former patent lawyer, so he didn't get the concept at all". This illustrates the intertwined challenging aspect of financing OSH projects when a lack of awareness/understanding is dominant in society, and by extension, industry.

On the other hand, the interviewees highlighted some opportunities that would arise as a result of OSH being implemented in the renewable energy field. These opportunities are as follows:

- When asked about circularity, the interviewees mentioned that due to their focus on placing user experience over profit motives, OSH projects often end up producing products which are "designed in a repairable way" (Int.OSHE3) which then leads to **higher circularity**. As Int.OSHI emphasised, OSH projects focus on designing solutions that prevent the need for "post-fix" approaches. By addressing potential issues during the design process, such as through designing for modularity to facilitate recycling, OSH designs aim to increase product lifetime and eliminate the need for finding solutions after a problem has already occurred.
- Int.RER also mentioned the potential which an OS approach has for pushing forward sustainability by encouraging transparency: knowledge of how to deal

with products at their End-of-Life (EoL) is essential to sustainability. When discussing the potential of a material passport[4] Int.RER was found highly enthusiastic, as he suggested that it would enable better recycling strategies to be developed and implemented.

- An additional benefit to employing OSH strategies to the energy space, was suggested to be the prevention of "reinventing the wheel" (Int.OSHI), which referred to the **increased efficiency and effectiveness of innovating,** when innovations are OS. One of the major challenges which Int.OSHI and her company identified when first starting business in the GS (more specifically Tanzania), was that "all of them are doing the same background technology stuff" (Int.OSHI), consequently "spending their limited resources, financial as well as human, in developing these innovations". This, she suggests, could have been avoided if the innovations had been available open source, and the companies would have been able to focus on their unique selling point (USP) instead.
- An additional benefit which Int.RER and Int.OSHI both agree would come about having more OSH strategies in the field of renewable energy, would be the **research quality improvements**. Not only by having more brains working on the same projects (Int.OSHI), but also because of the limitations imposed by closed data when doing research (Int.RER).

Overall, some of the interviewees were quite convinced that OSH would push the renewable energy sector forward and be highly beneficial, whilst others were more sceptical but still acknowledged the potential it could have if its various barriers were overcome.

[4] A material passport is a dataset containing all the information one might need to understand a product. This might include the materials a product contains, technical facts about the product, or information about its upstream supply chain. Research on the potential of material passports in a Circular Economy has shown great potential in increasing circularity of a product (Hoosain et al., 2021)

Chapter 5. Synthesising the Findings

Chapter 3 and 4 have served to explore RQ1 and RQ2 through an academic literature review and analysis, and semi-structured interviews with individuals in the field of entrepreneurship, academia, and the renewable energy sector. In this chapter, the knowledge obtained is brought together to discuss the main findings.

5.1. Growing Academic Literature on OSH

To answer RQ1a (*What is the current state of knowledge on OSH in academic literature?*) the literature research showcases the growing body of literature discussing OSH (Figure 7). Figure 7 adds on to previous literature which has suggested that there is a growing social trend for OSH, but had yet to quantify this (Bonvoisin et al., 2021b; Kostakis & Bauwens, 2014; Li & Seering, 2019b; Pearce, 2018).

According to Hellenes (2016) who studied the growth of Makerspaces, Hackerspaces and Fab labs, this growing trend in OSH since 2010 can be explained by the development of OSH strategies by makers following the financial crises in 2009. Whilst no direct research had been done on the trends of OSH in academic literature, various papers have highlighted the increased release and production of OSH products (Antoniou et al., 2022; Bonvoisin et al., 2018; Pearce, 2015, 2017, 2022). This was mirrored in the discussions held with the Entrepreneurs and Academics (Section 4.1.1 and 4.1.2 respectively), who expressed a growing movement towards OSH.

5.2. Findings of the Global North/South Research

Answering RQ1b (*To what extent is the OSH research in academic literature about both the Global North and Global South?*) yielded two main findings. One, that the majority of research on OSH is being carried out with a GN perspective, and two, that the disparity in GN/GS OSH research may be due to terminology differences.

5.2.1. WEIRD Research

A clear discrepancy can be observed when comparing the results of Figure 7 which depicts the growing trend in OSH publications, and Figure 8 which compiles the research queries of OSH combined with a focus on location (GS/GN). The difference between these figures suggests a significant bias in OSH academic research for the GN. The large differences in returned queries and the analysis of the returned queries showed that there is an implicit assumption for a GN target audience when doing research on OSH. This is not an uncommon practice in research, and one that has even been allocated a term: Western, Educated, Industrialized, Rich and Democratic (WEIRD) research (Henrich et al., 2010).

Research that is carried out using a WEIRD target group is by far most prevalent across academic literature, and has been acknowledged as a trend in psychology, biology and behavioural literature amongst many other fields (Dan, 2010; Henrich et al., 2010; Masuda et al., 2020). To identify this trend in OSH academic literature is therefore not unusual, yet, it has yet to be acknowledged as a limitation in literature. On the contrary, previous

research has identified this discrepancy, but circumvented it by suggesting that OSH is a global movement (Hassan et al., 2021).

As this research suggests, although OSH might be a global movement, it has yet to yield balanced input from both the GN and the GS at an academic level.

5.2.2. Terminology Constraints

Through the interviews, it seemed that individuals may not even be aware of a GN/GS divide regarding OSH. Considering acknowledging a limitation is crucial to overcoming it, such a finding suggests that OSH might be far from being explored on an academic level using both the GN and the GS as target areas. However, this discrepancy may be largely rooted in a difference in terminology: in academic literature from the GN, OSH is clearly a term growing in use, but research comparing terminologies of Transition Discourses in the GS and GN has highlighted the divergence in words used as each location adapts concepts to their local culture (Altmann, 2020; Escobar, 2018). In other words, OSH in the GS may have an equivalent term which the GN in its research is not utilising, and vice versa.

This was also a reflection that emerged from one of the interviews, where OSH2 suggested that OSH is a concept that has been 'westernised'. According to the interviewee and some academic literature in many countries of the GS, OSH is seen in everyday objects and ways of work, but is not termed OSH (Altmann, 2020). Acknowledging that OSH is a GN-based concept could greatly shift the discourse on OSH and its role in both the GN and the GS: not only would it be particularly important in overcoming differences in terminologies which can prevent misunderstandings and facilitate effective communication; it would also foster collaboration between the GN-GS and allow the GN to learn a great deal on how/whether to apply OSH. The challenge of aligning on common terminology suggests that further attention on GS/GN applications of OSH needs to be given to ensure OSH academic literature represents the global perspective it currently only implicitly explores.

A parallel to this discrepancy in OSH terminology can be found in work on the 'commons', which is a GN-based term inspired by the GS-based term "buen vivir" (Altmann, 2020). Much of Ostrom's work (a prevalent figure in developing the concept of the commons) is based on the GS, where the principles of the commons are explored and understood based on real-life applications (Ostrom & Gardner, 1993; Poteete et al., 2010). Overall, it may therefore be sound to argue that applying OSH in the GN would greatly benefit from further research on how equivalent concepts and ways of work/life are being used in the GS.

5.3. Common Themes to a Global OSH Ecosystem[5]

Through the research carried out to answer RQ1 and RQ2, various factors influencing the development of a global OSH ecosystem were identified. In this section, the findings

[5] Note that the 'global' aspect of the ecosystem does not suggest that what is to be established is an ecosystem which uses solely the terminology 'OSH'. As established in section 5.2 OSH as a

are brought together to answer RQ3 (What are the main factors influencing the development of a global OSH ecosystem, and how do these interact with one-another).

In the interviews with academics, entrepreneurs, and individuals in the renewable energy sector, it was found that OSH is considered both a tool to develop and promote solutions, as well as an inherently different way of doing work, which includes increased collaboration and transparency. In other words, OSH is considered a part of what Escobar (2018) terms a Transition Discourse, and is in line with the 'Buen Vivir' and 'Commons' mindset found in the GS and GN respectively. Similar to the discourse around Buen Vivir and the Commons, OSH promotes the key aspects of 'collaboration' as opposed to 'competition' (Int.OSHE1, Int.OSHE2, Int.OSHE3, Int.P2PA).

Of the factors influencing the development and thriving of an OSH ecosystem, four central drivers emerged. Although the factors influencing OSH were found to be non-exhaustive, the four factors shown in Figure 9 were the ones found to appear most often and were most apt at incorporating other factors both for the GN, and the GS. In our case the four factors included: Awareness and Knowledge about OSH, Finance, Collaboration, and Culture.

This method of identifying factors influencing a certain ecosystem or innovation is similar to that explored by Ortt and Kamp (2022). In their research, a framework that allows for the development of potential strategies to influence a system is explored, including an exploration of the influencing conditions, and building blocks of the system. The identified barriers to an OSH ecosystem were found to reflect somewhat the Technological Innovation System (TIS) framework of Ortt and Kamp (2022). Awareness and Knowledge about OSH, Finance, Collaboration and Culture can be linked to the influencing conditions which Ortt and Kamp (2022) highlight: Knowledge and awareness of technology, Natural human and financial resources, Competition, and Socio-cultural aspects. Although the framework by Ortt and Kamp (2022) is created to explore specific innovative technologies from the perspective of companies rather than systemic changes from a wider perspective, it is insightful to acknowledge the similarities between the TIS framework and the framework portrayed below.

From the research findings, it was possible to identify a tentative suggestion of the societal groups which most influence these factors. The societal groups identified were **governing bodies** (Blind et al., 2021)– municipalities, national governments, international collaborations, etc; **academics** – individuals carrying out research for private or public institutions; **entrepreneurs** – individuals who start and/or manage an enterprise, usually with high-risk of failure and who tend to be innovators; **investors** – individuals or groups who possess capital and invest in enterprises or projects; **universities** (Signorini, 2019)– a body which carries out education at higher-level; **SMEs** (Blind et al., 2021)– small and medium size enterprises which produce the relevant OSH products; and **OS**

GN-concept could be termed otherwise in the GS. This would by no means suggest less influential and fundamental aspect to the development of such an ecosystem. From here-on however, the terms 'OSH ecosystem' are used for the sake of clarity and consistency.

communities (Hassan et al., 2021) – usually hackers and makers who come together to work on (individual) projects.

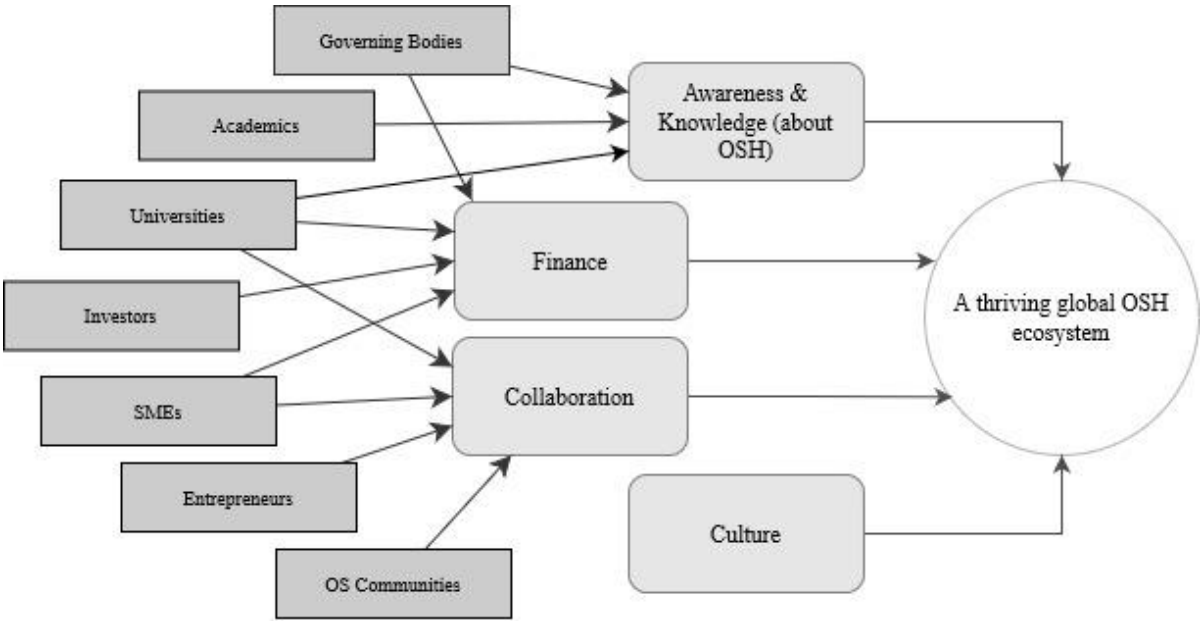

Figure 9 Factors influencing the development of an OSH ecosystem (author's work)

'Awareness and Knowledge (about OSH)' (from here-on referred to as A&K of OSH), here is used to denote the extent to which people are aware of what OSH is, and the technical understanding they have of it. As such, this includes understanding what licenses there are for OSH and the different tools already available for OSH development (for example in 3D printing which is an area of OSH extensively researched) (Gupta et al., 2016).

Following the five stage adoption process used in the diffusion of Innovation theory, A&K of OSH is the first step to adoption (Kaminski, 2011). As such, it can be identified as the largest bottleneck to the development of an OSH thriving ecosystem. Through the interviews and the literature research, it was found to be a hindrance to both organisations and individuals for different reasons. For organisations, lack of knowledge about OSH could result in higher R&D costs, and reduced innovation (Li et al., 2017; Int.OSHI). For individuals:

- Entrepreneurs who could benefit from applying OS by reducing R&D costs and obtaining community support amongst other benefits (Li et al., 2017)
- Individuals in remote communities who could benefit from producing their own OS products locally. This includes (parts of) distributed infrastructures such as solar panel installation racks, mini-wind turbines, or rainwater harvesting systems (Argenton Freire et al., 2022; Bassett & Fleischmann, 2012; Franz et al., 2022)
- Academics in the field of medicine, ecology, energy, electronics, and many others (Chavez & Kovarik, 2017; Gupta et al., 2016; Moritz et al., 2017) who could benefit from increased knowledge sharing

- ❖ Policy makers who can utilise OSH to improve security, innovation, and sustainability (Pearce, 2022; OSH Aca.)

When investigating the social groups which most influenced A&K of OSH, it was found that governing bodies, academics, and universities had the most influence. For governing bodies, this originates from their power over the setting of standards and in normalising activities (Blind et al., 2021; Emmy Tsang, OpenForum Europe, personal commmunication, February 2023; Andrew Katz, OpenForum Europe, personal commmunication, February 2023); by advocating for OSH and raising awareness through policymaking, governing bodies have the potential to influence a systemic change (Blind et al., 2021).

For academics and universities, their influence lies in their role in shaping the skillsets and knowledge of future working generations. Providing education on OSH legislations, design, challenges, opportunities, and much more can greatly influence the development of an OSH ecosystem (Arancio et al., 2022; Signorini, 2019).

The hurdle of low A&K of OSH was initially experienced by the OS software movement, and was identified as one of the main challenges it had to overcome before it began to thrive (Feller & Fitzgerald, 2002). As such, it seems evident that a major emphasis on raising awareness about OSH and its potential needs to take place if a global OSH ecosystem is to develop further.

'Finance' in this framework represents available funding for OS projects/businesses, costs of developing a business, and business models for OS projects/businesses. Funding was repeatedly seen in both the desk research and through the interviews as a key enabler to a thriving OSH ecosystem. In the renewable energy field in particular, limited availability of capital for OSH projects was identified as a major barrier (Int.REE).

The funding challenge that OSH projects face is also experienced by most capital-intensive industry. However, it is particularly acute for OSH projects as most investors tend to have little trust in the competitiveness of companies that share their IP, which goes against the predominant paradigm of strong IP protection leading to high profit returns (Int.REE; Int.OSSHR; Dawson, 2022). Such reasoning explains the success of OSH in 3D printing, which requires low capital expenditure (CAPEX) and is easily replicated in a decentralised manner.

Societal groups which were found to influence the finance factor most were SMEs, Universities, Investors, and Governing bodies. SMEs (especially in the hardware sphere) allocate a significant amount of their capital to R&D, which often results in individual silos of innovation per company (Int.OSHI). This lack of collaboration could be avoided through OSH, and lead to more efficient development of innovation. Inspired by the OSS movement, this could take the form of multiple SMEs funding OSH R&D projects, which all of them benefit from.

Large funds are also available from Universities for project developments, Investors for business creation, and Governing bodies through tenders, subsidies, or other financial mechanisms. A recent report by the EU commission highlights the importance of funding

from government and investor-related bodies for OSH projects (Blind et al., 2021), whilst Signorini (2019) thoroughly explores the role Universities play in encouraging OSH development.

'Collaboration', as mentioned throughout this research, is one of the key pillars of OSH. To thrive, it is essential that collaboration become a norm, and especially so between businesses. Patents were initially developed with the intention of protecting the commercial interests of innovators and encouraging them to continue innovating and turning their ideas into projects; yet patents today have been found to restrict economic development and hinder innovation, due to the lack of collaboration most patents instigate (Li & Seering, 2019b; Mazzoleni & Nelson, 1998; Osborn et al., 2015). If the financing barrier was overcome, Entrepreneurs and SMEs would be key to increasing collaboration in business. Additionally, Universities and OS communities influence collaboration between individuals due to their role in bringing together diverse individuals with various skills.

Paradoxically, OSH not only increases collaboration, but was also identified as a way of increasing competition within an industry (Int.P2PA; Andrew Katz, OpenForum Europe, personal communication, February 2023). By removing the use of copyright, the barriers to entry into a market are lowered, and as previous research has discussed, monopolies are less likely to arise (Pearce, 2018, 2022). Whether this is something to encourage and support is another question entirely, however there are societal benefits to preventing the rise of monopolies, which suggests further research similar to what Pearce (2022) has done, could greatly benefit our society.

Finally, **Culture** was recurringly found to be one of the key factors enabling the development of an OSH ecosystem. Culture for this research, was the cumulation of intangible aspects of social life which make up the way a society behaves. It is a topic well-researched in Transition Discourses (TDs), and one which plays a large part in enabling systemic changes (Escobar, 2018). The differences in the GN and GS and how OSH is applied in these areas appear most starkly when discussing Culture. Through this research, it became apparent that the differences in TDs of the GN and GS which Escobar (2018) amongst many others highlights, is reflected in the OSH movement. According to some of the interviewees, the use of OSH may be more challenging in GN societies which possess a culture that contrasts starkly with the values of OSH communities.

The factor of collaboration was identified as a trait which is strongly influenced by culture and may drastically impact the development of OSH. It was also found that the zealous aspect of people advocating for OSH may be based in and influenced by culture, and is key to its development (Feller & Fitzgerald, 2002).

As can be seen in Figure 9, **culture as a factor** was not found to be influenced by any one social group. This is because by definition culture is what arises from all the different perspectives of each group. Therefore, all individuals and all societal groups can be assumed to influence culture.

5.3.1. Dependencies of the Factors Influencing an OSH Ecosystem

Each of the factors described in the framework above are key contributors to the creation of a thriving global OSH ecosystem. Through the framework, we can better understand the bottlenecks and points of improvements hindering the promotion of the global OSH ecosystem. In this section, a further analysis is proposed which describes tentatively the interactions between each of the factors, and how these relate to one another (Figure 10).

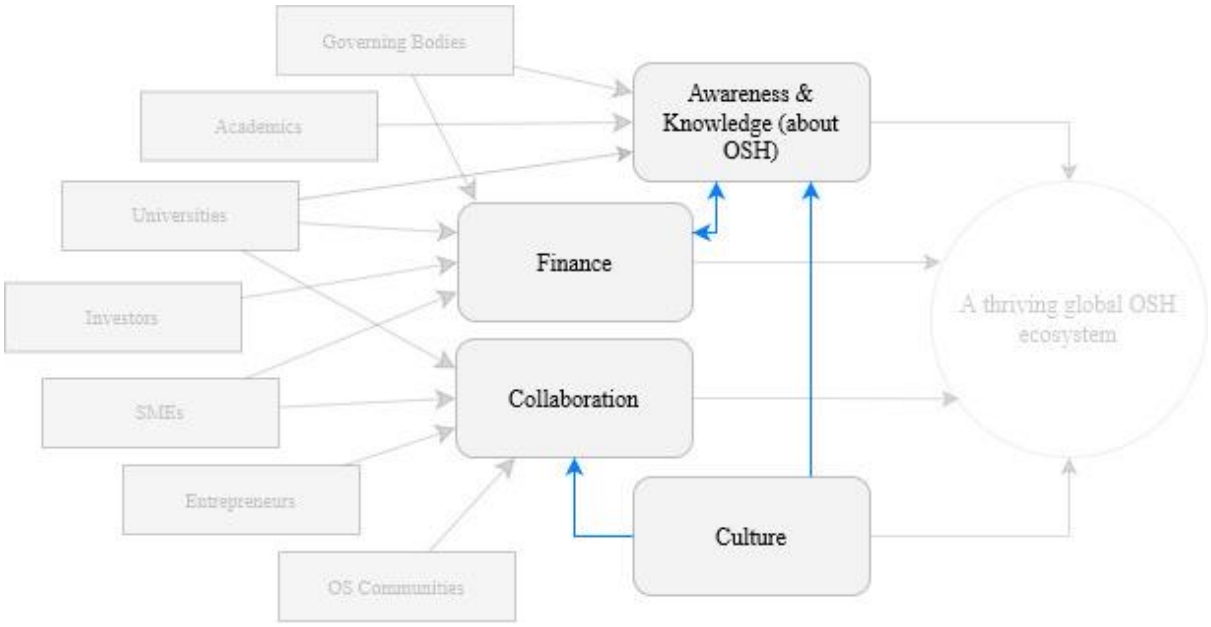

Figure 10 Interdependencies of the factors influencing an OSH ecosystem (author's work)

A&K of OSH was found to closely influence Finance, and vice versa. This is because finance can enable A&K of OSH through education and other strategies, and because of the many aspects of finance which are dependent on OSH being understood by relevant parties. In this research, the relevant parties were identified as:

- governments which can provide funding via subsidies, tenders and other financial mechanisms (Blind et al., 2021; Int.OSHE3; Int.OSHI)
- Funders of various kinds, such as philanthropists and venture capitalists (Li et al., 2022; OSH Aca., Int.REE)
- And finally companies, ranging from SMEs to multinationals, which can invest their R&D capital into OSH, but may not find it in their interest to do so if they are not aware of the benefits which OSH can bring both to them and society (Hassan et al., 2021; Int.OSHI)

The interviews carried out and the desk research repeatedly highlighted the influence which culture can have on A&K of OSH and collaboration. This influence is reflected in various Transition Discourses, which highlights the key role of culture in social structures (Escobar, 2018). As previously mentioned, future work would therefore do well to explore how the GN and GS might differ in their interpretation of OSH, and whether different

cultures can lead to a clearer understanding of how A&K of OSH and collaboration can be encouraged.

Chapter 6. Limitations of the Methodology

Before moving to conclusions and suggestions for further research, we must look at the limitations of the methodology. As with all research, some evident limitations include lack of time and subjective lenses which the author could not help but possess when carrying out the research.

Additionally, the literature research had some clear limitations. When the literature research was designed, the research aimed to emphasise OSH and how it is being developed in the GN and GS. As this (the limitations of how OSH is being applied in the GS) had yet to be explored, the author did not realise until post-literature research that the research queries would yield such biased results. In other words, by placing focus on the OSH side of research, less importance and time was allocated to the GS which is underrepresented in the research and would therefore require much more attention. This presents a limitation in the research, but also an opportunity for future studies.

Additionally, although the literature research attempted to overcome the limitation of terminology when discussing GN/GS, a stronger emphasis could have been placed on including a broader range of terminology. For example, the terms GN and GS were coined in the late 20th century, and as such are slowly gaining representation in academia but may still be underused (Hollington et al., 2015; Pagel et al., 2014). To compensate, the terms "developing country" and "developed country" were used: these were coined in mid-20th century and have been more broadly used than GN/GS. However, other terminology such as "third world" and "first world" could have been employed (Wolf-Phillips, 2007). Further research should therefore dive further into these terminologies and how they are being employed by academia.

Regarding the interviews, there was an inherent GN-bias in the interviewed carried out, as the author is based in the GN, and has a personal network predominantly based in the GN. This meant that reaching out to individuals based in the GS was time-consuming, often yielded no responses, and individuals with a GS-perspective were simply more difficult to find. This was reflected in the interviews carried out, which did not include a balanced representation of individuals originating in the GS and GN. Additionally, a limitation found is the male-dominated interviewee sample. Further research would do well to overcome this by obtaining a more balanced sample of genders, which could provide more diverse responses.

Regrettably, this lack of balance of opinions, notably from GS-/GN-based individuals, means that this master thesis research, like much of the other research carried out today, is done with a biased WEIRD and GN lens. As such, the research does not provide nearly as full a picture of the 'global' aspect of the OSH movement and is certain to lack depth when addressing the challenge of different terminologies which the GN and GS apply when discussing OSH-related topics.

The interviews also had a crucial limitation to providing a more holistic vision of how OSH is influencing systems: interviewees were mostly OSH proponents. Identifying and

finding OSH opponents was found to be challenging but should most certainly be included in further research exploring the role of OSH in our society.

A final limitation to the methodology which should be highlighted, is the lack of statistical analysis. A statistical analysis could have further quantified the significance of the differences in the GN- and GS- based literature research. To generalise the findings and to draw more concrete conclusions from the research done here, such a limitation must be overcome.

Chapter 7. Conclusion

This thesis was guided by the overarching question of how OSH as a global movement is being perceived and explored. While the research provided some answers, due to its explorative nature it also generated many more questions. By exploring the OSH movement, the author aimed to gain a better understanding of how the global North and global South might use OSH as a tool for systemic change; especially so during critical times that require innovative tools to enable a sustainable system to arise.

The first research question (RQ1a&b) sought to examine the current state of knowledge on OSH in academic literature and the extent to which it is studied in (and by) both the Global North (GN) and the Global South (GS). Through the research, it was possible to see a clear and consistent growing trend in OSH academic research, which has stabilised over the past two years. However, in this trend, a clear implicit bias for the GN in the research was identified. This was seen in the tenfold number of papers which are published (implicitly) discussing OSH in the GN, rather than the GS.

By calling it a 'global movement', we therefore risk obscuring the relevance and actuality of the differences between the GN and GS approach to OSH. Considering OSH is found to be a GN-based term, further research would benefit from exploring how OSH-equivalent terms are being researched in both academic and non-academic settings for the GS.

In the second research question (RQ2), some of the main points of discussion which academics, entrepreneurs and individuals in the renewable energy sector discuss were explored. Combining RQ2 with the research of RQ1 enabled the answering of RQ3, which identified the main factors influencing the development of a global OSH ecosystem. How these factors interact with each other was better understood through the research and allowed the development of a tentative framework (see section 5.3). This framework can be used to evaluate the development of OSH and identify where some of the bottlenecks in its development may be.

Overall, although the relative novelty of applying open source to hardware provides much room for further exploration, the groundwork is being laid out. Considering the critical point at which humanity stands today with regards to the challenges of climate change, scarcity of resources and growing wealth disparity to name a few, exploring tools to systemic change such as OSH can yield valuable insights. For this, the basics of OSH and how it could act as one of the many solutions to some of our most pressing problems is essential, and further research building upon this thesis would do well to explore it.

7.1. Personal Reflections

The most challenging part of this thesis was in knowing and deciding where to stop. After two years of personal experience in developing an OSH start-up, I thought there would be little in the literature that I would encounter that I would get lost in, since I thought I had likely experienced it all first-hand. For the most part, this was true, but I most certainly did not account for the excitement which reading through papers and

speaking to individuals about OSH would bring me, making me want to dive ever deeper into the complexity of the topic and how/whether we should be applying it more widely.

There is limited research on OSH and its use as a tool for systemic change, and so I was quickly forced into moving away from papers and into the 'real world' world. The interviews were invaluable in my research, and although no opponents to OSH were interviewed, my personal experience kept me grounded in the reality of the limitations of OSH. Without it, I am almost certain that the contagious enthusiasm expressed by the interviewees regarding OSH as an essential tool to future systems (both economic and social) would have led me to writing an opinionated piece on OSH rather than a MSc thesis. As it stands, I hope I have provided a somewhat valuable and insightful thesis which can be used to further explore both the future opportunities of OSH, as well as its downfalls.

Paradoxically, because of the limited research in OSH, identifying what to research was a challenge. The immensity of the research gap meant that I was constantly re-evaluating the questions I was attempting to answer, and where they fit into the larger picture. Not only that, but turning the frustration at finding little to no non-male and/or GS-individuals which work on OSH projects into valuable findings was challenging. Only upon writing about necessary further research did I manage to consider my work as having been worthwhile. It is therefore with great hope and enthusiasm that I encourage you to read section 8.2, which might just galvanise you into taking up the baton and starting on a journey towards OSH and all its potential.

Chapter 8. Drawbacks and Further Research

8.1. Drawbacks of the Research

Throughout the research, there was an emphasis on taking a global approach to the OS transition, which meant trying to understand and position both the GN and the GS. However, it quickly became apparent that very little research has been carried out on the differences in an OSH approach when considering cultural and geographic factors. This means that most of the literature and research available on the OSH movement, is employing a GN lens. Previous research has argued that OSH being a global movement means that such an approach to research is generalisable (Hassan et al., 2021). Yet, this thesis uncovered differences in how the OSH movement is seen and used by the GN and GS, as OSH is greatly influenced by culture. This discrepancy in the literature is therefore clearly a cause for concern which may lead to further deepening of the inequality in GN/GS academic research regarding OSH and may even lead to erroneous assumptions about how OSH is being used globally.

In the current context of social and environmental justice, aligning OSH research for the GN and GS, is essential. In the following section, further research highlights how this could be done, as this was a part of this master thesis which did not go in enough depth and comparison. Additionally, the topic of neo-colonialism, although growing in awareness and having been mentioned briefly in one of the interviews, was not explored in this thesis. This was beyond the scope of the research but is clearly lack when discussing topics of inequality between the GN and GS.

A final drawback to mention, is the novelty of OSH research in academia, particularly in exploring the social implications of OSH and cultural influences. Such a drawback meant that an explorative approach was necessary to uncover as far as possible findings which could answer the research questions but could not go further than tentative suggestions and conclusions. However, as the following section will showcase, through this approach a considerable amount further research could be identified.

8.2. Further Research

As mentioned, the explorative nature of this master thesis uncovered many areas in OSH which would benefit from further academic work. In this section, potential avenues are discussed.

8.2.1. GN/GS Differences

The most important finding from the literature research, is that there is a huge research gap to overcome when discussing OSH and the GN/GS. This research gap is reflected in the number of papers published explicitly discussing the GS and becomes evident when attempting to explore how culture can influence OSH and the lack of research in this domain. It became apparent that OSH is a concept drastically more popular in GN-oriented literature, whilst there seems to be a lack of understanding regarding alternative terminologies to 'OSH' which are employed in the GS. Although research on the 'commons' for the GN has been done and how this is rooted in concepts

such as 'buen vivir' in the GS, equivalent research for OSH has yet to be done. By doing such research, academia could begin to identify the reason for a low amount of OSH GS-oriented research and could begin to fill the research gap.

Additionally, exploring how the GS utilises OSH (or its equivalent) could provide a better understanding of how OSH is a 'global movement'. This global understanding should be explored taking cultural aspects into consideration. This would enable further research which can provide a clearer understanding of how different cultures and locations might benefit from utilising OSH as a tool for a systemic change. Such research could take the form of exploring how different cultures understand and apply some of the pillars of OSH, namely: transparency, collaboration, and reciprocity. According to one of the interviewees, applying OSH to the GN is likely to result in more resistance than if applied to cultures which already showcase values of openness, and collaboration. Such a statement could be researched using case studies of OSH projects from both the GN and GS. Learning from societies which already apply to some extent the pillars of OSH could provide invaluable insights to how OSH might grow and benefit or hinder society.

Through a quick analysis of the authors included in the literature research, it became apparent that the majority of papers mentioning the GS were authored by individuals based in the GN or were discussing OSH projects developed by individuals from the GN for the GS. Further comparative and quantitative research should be carried out to determine whether this is a trend, or an erroneous finding by the author. This research could provide a better understanding of the extent to which OSH is being developed by the GN for the GS, and by the GS for the GS. Considering the influence of neo-colonialism in knowledge sharing and its impact on both the GN and GS, such research would be highly relevant. Additionally, no research to date (as far as the author was able to find) addresses the topic of neo-colonialism and OSH. There is therefore much room for research in this field and understanding GN-GS relations in OSH might be essential to potentially preventing the extension of a neo-colonial trend to OSH.

8.2.2. OSH and Systemic Change

This research didn't explore in much depth the benefits which OSH can bring about in meeting human needs. However, as was witnessed during the pandemic when OSH ventilators and other medical devices were developed (Chong et al., 2021; Haque et al., 2021), there is large potential for OSH to be used as a tool to enable rapid humanitarian aid. Further research would therefore do well to identify areas in which OSH would best benefit our society, for example in aiding in humanitarian crises, or in addressing the social and planetary boundaries (Raworth, 2017).

Additionally, exploring how capitalism, the free-market, and ownership influence OSH and are influenced by OSH, was not done in this research but would provide an interesting topic of further research. Especially so if considering the GN and GS which have drastically different approaches to these concepts (Escobar, 2018). Jeremy Rifkin in his book "the Zero Marginal Cost Society" explores the topics of capitalism, free-market, OS, and others, but it has yet to be researched from a more 'scientific' perspective. Indeed, exploring Rifkin's theory of capitalism and the commons having a parent-child

relationship (respectively) could be valuable, and may lead to insights on the social and cultural trends taking place today.

The discussions with entrepreneurs suggested that a drive for working in the sphere of OSH was a desire to work for a better world and to overcome the 'failures' of capitalism. According, to them, OSH was the future of business, as it has been with OSS. The motivation of entrepreneurs to contribute to OSH on moral grounds has been studied in literature (Li et al., 2017, 2021). However, studying the role of a somewhat pious or spiritual approach to OSH has yet to be explored.

8.2.3. Gender in OSH

Although the scope of this research did not extend to identifying gender (in)equalities in the field of OSH, the challenge of identifying non-male OSH entrepreneurs and participants to the interviews suggests an area for further research. Through a rapid web of science search using the keywords 'gender' and 'Open-source hardware', the lack of relevant results returned suggests that gender (in)equality in the field of OSH is an area that has yet to be explored.

Considering entrepreneurship tends to be a male-dominated field (GaweŁ & KrstiĆ, 2021; Rietveld & Patel, 2022), doing research on whether OSH entrepreneurship is male-dominated and comparing it to closed source entrepreneurship could be an interesting area of research. Additionally, through such research an understanding of whether gender is a factor which influences the open aspect of start-ups could be understood. As a side project beyond the scope of this research and with the purpose of exploring OSH and gender in start-ups, a survey was created (Appendix 5 – analysis provided upon request). A further exploration of the results of this survey and a higher response rate could provide insights into whether gender influences IP protection.

8.2.4. OSH in Academia

The interviews highlighted a difference between the motivations of individuals in academia vs entrepreneurship or RE sector individuals when discussing OSH. For individuals in academia, OSH was seen as a very practical decision – collaboration and sharing means better research and better science. As Open Access is growing in the academic sphere, further research would be valuable to explore to what extent such a movement towards OSH is representative of academia at large, and whether this movement can be leveraged to develop an OSH ecosystem in academia. An example of such a growing movement is found at the Technical University of Delft, where OSH is being pushed forward by the Delft Open Hardware group (TU Delft, n.d., 2022; de Vos, Personal Communications, March 2023).

Additionally, what was noticeably absent from the interviews with the academics was the lack of a business perspective or 'finance oriented' discussions. This was surprising, as most academic research today on OSH is around business models and the motivations of developing OSH businesses. This suggests that further research by academics would do well to explore how OS is understood from a cultural or as a social movement point of view, rather than solely from a business point of view.

8.2.5. Dealing with Complexity

A topic briefly mentioned in some of the interviews with the entrepreneurs but not further elaborated upon in this thesis, was the potential which OS and P2P have for dealing with complexity, and therefore wicked problems. Wicked problems have been described as having clear properties, including being understood as problems which are ambiguous, complex and whose solutions are multiple (Rittel & Webber, 1973). The hyper-connectedness of our world, and growing global society has resulted in a growing body of wicked problems, including sustainability, and climate change (Pryshlakivsky & Searcy, 2013).

By advocating for decentralisation OSH provides an alternative to standardized solutions, which may be a valuable tool for seeking solutions to wicked problems. However, there has been little to no research done on the use of OSH for addressing wicked problems. As such, future research would benefit from researching these topics and how they interlink.

8.2.6. OSH for an Energy Transition

Although the thesis initially aimed to focus on how the OSH movement can contribute to the energy transition, new insights arose which altered the focus – instead, the discrepancy in how OSH is being understood in the GN and the GS, and what factors hinder the development of a global OSH ecosystem were given focus. However, this meant that OSH and how it can contribute to the energy transition is still yet to be researched on various fronts. Through the literature research, it became clear that there are various academics already exploring how OSH could promote the energy transition (Buitenhuis & Pearce, 2012; Giotitsas et al., 2015); however, there is still much to explore in this field. Some areas of potential research which emerged in the research include: where OSH can be used most effectively in a RE supply chain to accelerate the transition; how OSH RE projects can overcome the barrier of funding which tends to be particularly high due to high CAPEX requirements; and to what extent is OSH a tool for inclusivity in the RE transition.

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Appendices

Appendix 1 Trends Analysis (RQ1)

External Appendix

Appendix 2 Consent Form

External Appendix

Appendix 3 Technical Transcripts

External Appendix

Appendix 4 Coded Transcripts

External Appendix

Appendix 5 Survey

External Appendix