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Decarbonising plastics

On the technologies and framings of carbon capture and utilisation

ELLEN PALM
TECHNOLOGY AND SOCIETY | FACULTY OF ENGINEERING | LUND UNIVERSITY

Decarbonising plastics
– On the technologies and framings of carbon capture and utilisation

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On the technologies and framings of carbon capture and utilisation

Ellen Palm

DOCTORAL DISSERTATION
for the degree of Doctor of Philosophy (PhD) at the Faculty of Engineering at Lund University, to be publicly defended on 5 April at 09.00 in lecture hall V:A in V-building, John Ericssons väg 1, Lund.

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Title and subtitle:
Decarbonising plastics – On the technologies and framings of carbon capture and utilisation

Abstract:
Plastics consist of fossil fuels, from both a feedstock and energy perspective and thus need to decarbonise. This thesis maps and explores the framings and technologies that surround plastics decarbonisation and the potential mitigation pathway of carbon capture and utilisation. Here, three of the main findings are presented.

By unpacking how EU policymakers understand issues concerning plastics, this thesis exposes how they are mainly conceptualised as a waste issue. This narrow framing of the issues concerning plastics neglects their complexities and systemic nature. The explicit downplaying of climate impact is especially noteworthy. If policymakers do not recognise the connection between plastics and climate change, it is not likely that they will introduce policy measures to address it.

In a first-of-a-kind study, this thesis shows that, from a technological perspective, European plastics production could decarbonise via the pathway of carbon capture and utilisation. However, producing plastics from water and carbon dioxide is extremely energy-intensive and hence very costly. Even if this perspective neglects all the social, political and institutional considerations, it serves as a thought experiment that plastics production could decarbonise.

How expectations of carbon capture and utilisation, and the larger imaginary of circular carbon, are articulated can shape and limit how and whether they are enacted. This thesis maps and analyses such framings in two cases: firstly, within the scientific carbon capture and utilisation community, and secondly within the plastics and petrochemical industry. The material shows that the scale of production (growth) is not discussed, and strategies to decarbonise via low-tech pathways are often neglected.

If supporting the technological development surrounding plastics decarbonisation, all these aspects must be recognised. Failure to do so risks resulting in delayed decarbonisation efforts. In conclusion, this thesis advocates for a pluralistic approach to plastics decarbonisation and emphasises the importance of considering both high- and low-tech mitigation pathways, since one perspective or technology is insufficient to address the complexities of plastics decarbonisation.

Key words: plastics, carbon capture and utilisation, carbon circularity, industrial decarbonisation, climate mitigation, interdisciplinarity

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The object ‘Recycle’ from the exhibition Materiality & Aggregation illustrates the Troxler effect. It is described in the following way. ‘Stare at the point for 30 seconds. Stare too blindly at details and you will lose sight of the holistic view required for a transition towards a more circular plastics system.’ The exhibition was created in collaboration with researchers from the Mistra Steps programme, with Willner developing and designing five objects based on our publication ‘Pathways to sustainable plastics – A discussion brief’.

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Till Sissela och Torkel

Prologue

The issues and complexities of plastics caught my attention long before I started the PhD position. Before my work life was centred around plastics decarbonisation, sailing was my main occupation. Living on small boats and crossing large, vast expanses of water is somewhat like a simulation of human life on Earth. Issues of democratic decision-making and food and water availability are at the centre of everything, but the waste management procedures also become more evident than in a land-based life. Everything we bring on board must be dealt with. What can be thrown into the ocean, and what must be separated, cleaned, dried, and stored in a sanitary way in the limited space and tropical heat on board until we next reach port, perhaps weeks away? Every little piece of paper, metal, glass, and, of course, plastics requires a decision and procedure.

Initially, I must admit that I did not see the point of us having to go through all the hassle. What difference does a few people's litter make? My grandfather used to say that the oceans are so immense that we can never contaminate them. Perhaps I had that same feeling while living isolated with the shifts in wind and daylight as the main source of influence. However, after reaching one of the most remote atolls in the Pacific Ocean and seeing the sand on the windward side mixed with a large proportion of plastics, my mind started to wander. If plastics had managed to reach all the way here and pollute this pristine area, the issue with plastics must be both massive and global. The immediate thought was that if plastics pollute and poison nature even in these isolated locations, something needs to be drastically changed.

What I couldn't get my head around was that the boat I lived on mostly consisted of plastics. The hull kept me dry and safe from both the raging storms and burning sun and made it possible to move through the water much more smoothly than the historical wooden vessels I had previously sailed. However, it was not just the hull, but also the sails, ropes, electric system, clothing and, of course, the food packaging that consisted of plastics. Without food packaging our supplies would have run out within a week or so, but largely thanks to the beneficial properties of plastics, we could sail on for a month at sea without suffering from hunger. It turned out that plastics have both valuable and troublesome aspects. This complexity and the overwhelming presence of plastics fascinated me and made me want to know more about it. Wishing to better understand plastics, I applied to become an environmental engineer to learn more about the chemical composition, material properties and environmental impact of plastics. Little did I know then that this journey would take me into sciences way beyond my imagination and that, instead of solving issues and digging deep into the chemistry behind polymers, I would become interested in posing questions and argue for the need for multiple perspectives on plastics decarbonisation.

Table of Contents

Abstract

Plastics consist of fossil fuels, from both a feedstock and energy perspective and thus need to decarbonise. This thesis maps and explores the framings and technologies that surround plastics decarbonisation and the potential mitigation pathway of carbon capture and utilisation. Here, three of the main findings are presented.

> The climate impact of plastics is downplayed as a policy issue in EU plastics governance.

By unpacking how EU policymakers understand issues concerning plastics, this thesis exposes how they are mainly conceptualised as a waste issue. This narrow framing of the issues concerning plastics neglects their complexities and systemic nature. The explicit downplaying of climate impact is especially noteworthy. If policymakers do not recognise the connection between plastics and climate change, it is not likely that they will introduce policy measures to address it.

> From a technological perspective, EU plastics production could decarbonise via carbon capture and utilisation. However, this requires large amounts of renewable electricity.

In a first-of-a-kind study, this thesis shows that, from a technological perspective, European plastics production could decarbonise via the pathway of carbon capture and utilisation. However, producing plastics from water and carbon dioxide is extremely energy-intensive and hence very costly. Even if this perspective neglects all the social, political and institutional considerations, it serves as a thought experiment that plastics production could decarbonise.

> If supporting carbon capture and utilisation technologies, the expectations of climate mitigation should be thoroughly examined to avoid delayed or failed decarbonisation.

How expectations of carbon capture and utilisation, and the larger imaginary of circular carbon, are articulated can shape and limit how and whether they are enacted. This thesis maps and analyses such framings in two cases: firstly, within the scientific carbon capture and utilisation community, and secondly within the plastics and petrochemical industry. The material shows that the scale of production (growth) is not discussed, and strategies to decarbonise via low-tech pathways are often neglected.

If supporting the technological development surrounding plastics decarbonisation, all these aspects must be recognised. Failure to do so risks resulting in delayed decarbonisation efforts. In conclusion, this thesis advocates for a pluralistic approach to plastics decarbonisation and emphasises the importance of considering both high- and low-tech mitigation pathways, since one perspective or technology is insufficient to address the complexities of plastics decarbonisation.

Populärvetenskaplig sammanfattning

Plast är något av en dold klimatbov. Det är nämligen så att plasttillverkningen beror av fossil olja, gas eller kol i dubbel bemärkelse. Dels används fossil råvara som energi i de processer som tillverkar plast och detta bidrar till stora utsläpp av växthusgaser. Dessutom gäller att kolatomerna i de fossila energislagen används som den huvudsakliga råvaran i plast. Plast alltså både består av och tillverkas med fossil råvara. Detta bidrar sammantaget till att plasttillverkningen står för en betydande del av den globala olje- och gasanvändningen. Om vi som samhälle vill mildra effekterna av de pågående klimatförändringarna, måste vi alltså också minska klimatpåverkan från tillverkningen av plast.

Denna avhandling utforskar spänningar mellan att nå klimatmålen och en fortsatt närvaro av plast i våra samhällen. Utgångspunkten i avhandlingen är fossilfria råvaror för plast. Mer specifikt fokuserar jag i huvudsak på en teknik som utforskar att använda kolet i koldioxid som råvara för plasttillverkning. I avhandlingen undersöks både de tekniska förutsättningarna för att implementera detta på stor skala, samt hur olika aktörer formulerar problemen, lösningarna eller framtiderna kopplade till dessa tekniker. Det är viktigt att analysera hur ett problem formuleras, samt vilka förväntningar eller visioner som målas upp kring framtiden, då det påverkar vilka lösningsförslag eller tekniker som utvecklas.

Min forskning visar att plastens klimatpåverkan är en förbisedd aspekt inom den europeiska styrningen av plast. Plast formuleras i huvudsak som ett nedskräpnings- och återvinningsproblem och de åtgärder som introduceras syftar till att styra detta. I förlängningen innebär det att det inte introduceras styrmedel för att minska plastens klimatpåverkan, något som minskar våra chanser till en industriell omställning.

Ur ett tekniskt perspektiv visar avhandlingen att den europeiska plastproduktionen skulle kunna bli fossilfri genom att använda koldioxid som råvara för plasttillverkning. Men det finns dock stora utmaningar med detta. Det är en mycket energikrävande och därmed mycket kostsam tillverkningsmetod. Teknikerna finns dessutom bara i mindre skala, och har inte provats i den här typen av tillämpningar ännu. Detta innebär ett potentiellt glapp mellan vad teknikerna lovar och vad de kan åstadkomma.

När tekniker inte kan konkurrera med nuvarande kostnader, prestanda eller produktfunktioner, konkurrerar de i stället med hjälp av förväntningarna på framtida prestanda. Förväntningar blir då ett sätt att attrahera kapital, bygga nätverk och skapa legitimitet för teknikerna. Denna avhandling kartlägger och analyserar detta på två sätt. Dels studeras förväntningar inom det vetenskapliga fältet som utvecklar tekniker för att använda koldioxid som råvara, dels studeras visioner inom den plast- och petrokemiska industrin kring att tillverka fossilfri plast. Sammantaget visar jag att det finns motstridiga förväntningar vad gäller teknikens möjlighet att minska utsläppen av växthusgaser, samt att lågteknologiska åtgärder som minskad förbrukning och återanvändning försummas i dessa högteknologiska visioner.

För att undvika en fördröjd utfasning av fossila bränslen inom plasttillverkningen, bör de visioner och motstridiga förväntningar som omger teknikerna inkluderas i hur vi styr och finansierar utvecklingen. Det blir också viktigt att ta fler aktörers perspektiv än bara industrins i beaktande i en sådan process. Slutligen betonar avhandlingen vikten av att överväga både hög- och lågteknologiska åtgärder för att uppnå en fossilfri plasttillverkning. Ett enda perspektiv eller tekniskt tillvägagångssätt kommer inte vara tillräcklig för att minska plasttillverkningens klimatpåverkan.

List of papers

Paper I

Ellen Palm, Lars J. Nilsson & Max Åhman (2016) Electricity-based plastics and their potential demand for electricity and carbon dioxide, Journal of Cleaner Production, 129, 548-555. https://doi.org/10.1016/j.jclepro.2016.03.158

Paper II

Ellen Palm & Alexandra Nikoleris (2021) Conflicting expectations on carbon dioxide utilisation, Technology Analysis & Strategic Management, 33:2, 217-228. https://doi.org/10.1080/09537325.2020.1810225

Paper III

Ellen Palm, Jacob Hasselbalch, Karl Holmberg & Tobias Dan Nielsen (2022) Narrating plastics governance: policy narratives in the European plastics strategy, Environmental Politics, 31:3, 365-385. http://doi.org/10.1080/09644016.2021.1915020

Paper IV

Ellen Palm, Joachim Peter Tilsted, Valentin Vogl & Alexandra Nikoleris (2024) Imagining circular carbon: A mitigation (deterrence) strategy for the petrochemical industry, Environmental Science & Policy, 151, 103640. https://doi.org/10.1016/j.envsci.2023.103640

Author contribution

Paper I

The first draft was developed, analysed and written by me. All the authors contributed to the conceptualisation and editing of the final draft.

Paper II

This paper was developed and written collaboratively. I formulated the initial idea for the project, which was later developed together. Alexandra Nikoleris suggested the theoretical starting point, which was used to develop the analytical framework together.

Paper III

All the authors contributed to all stages of the development, drafting and revision of the paper. Karl Holmberg and I did most of the initial analysis and first draft, while the later analysis and text were co-developed and co-written by all the authors.

Paper IV

This paper was designed, analysed and written collaboratively, with Joachim Peter Tilsted and myself as the lead authors. I had the role of project lead and coordinator and conducted the participant observations. Joachim formulated the initial idea for the project and played a leading role in terms of theoretical refinement.

Other relevant publications

During my PhD studies, I also contributed to several other publications.

Peer-reviewed publications

Bauer, F., Nielsen, T. D., Nilsson, L. J., Palm, E., Ericsson, K., Fråne, A., & Cullen, J. (2022) Plastics and climate change – Breaking carbon lock-ins through three mitigation pathways, *One Earth*, 5(4), 361-376. http://doi.org/10.1016/j.oneear.2022.03.007

Tilsted, J. P., Palm, E., Bjørn, A., & Lund, J. F. (2023) Corporate climate futures in the making: Why we need research on the politics of Science-Based Targets, *Energy Research & Social Science*, 103, 103229. http://doi.org/10.1016/j.erss.2023.103229

Kloo, Y., Nilsson, L. J., & Palm, E. (2024) Reaching net-zero in the chemical industry – A study of roadmaps for industrial decarbonisation, *Renewable and Sustainable Energy Transition*, 100075. https://doi.org/10.1016/j.rset.2023.100075

Other publications

Palm, E., & Svensson Myrin, E. (2018) Mapping the plastics system and its sustainability challenges. Lund University. Department of Environmental and Energy Systems Studies.

Nielsen, T., Palm, E., Madsen, S., Nilsson, L. J., & Lindblad, E. (2018) Pathways to sustainable plastics – A discussion brief.

Bauer, F., Holmberg, K., Nilsson, L. J., Palm, E., & Stripple, J. (2020) Strategising Plastic Governance: Policy Brief.

Scientists' Coalition for an Effective Plastics Treaty (2023) Policy Brief: Climate change impacts of plastics. http://doi.org/10.5281/zenodo.7972056

Acknowledgement

Starting this PhD process, I did not think I would understand much if I opened a thesis. Since then, it would be an understatement to say that my reading and writing difficulties have been challenged. However, these years have by no means been spent only inside my head. There are so many people and communities over the years who have contributed: from my first stumbling steps as a research assistant to completing this thesis.

First, I would like to thank my supervisors, Lars J. Nilsson and Alexandra Nikoleris. I feel lucky to have had two such open-minded, genuinely curious and encouraging supervisors. I want to thank you for two things in particular: for always having and sharing your different opinions and not striving towards consensus, and for the unheard-of flexibility and trust in me that you have maintained throughout these years. With your support, I have been able to find my way through this thing called academia and engage with people, themes and places that are as interesting and rewarding as I hardly dared dream that adult life could be.

I have also been part of a PhD community at the department of Environmental and Energy System Studies (IMES) to be proud of. Thanks to Jens Portinson Hylander, Johanna Olofsson, Malin Aldenius, Oscar Svensson, Malin Pettersson and Valentin Vogl, for turning the PhD meetings into an open space for sharing without offering solutions and for taking me through the pandemic with our digital writing sessions. Thanks to those who have previously contributed to shaping the community, Alexandra (again), André Månberger, Clemens Schneider, Yuri Joelsson and Natalie Bergame, and those who will take IMES PhD life to new and exciting places: Jonas Algers, Eugéne Petelin, Hannes Sonnsjö, Zhenxi Li, Lovisa Harfeldt-Berg, Natasha Fiig, Felix Ivo Grosse-Kreul, Christina Gratorp and Oscar Gustafsson. Lastly, and kind of because I don't know where to place you in the categories above, Joachim Peter Tilsted – thanks for writing abstracts as procrastination and making our 'dream team' a reality.

A huge thank you is also due to those who have provided stability and predictability in the working day. The administrators and cleaners, especially Astrid, Sus, Stina (at Chalmers), and Sussie. Besides all the various forms you have facilitated my work, I want to thank you for coming early to the office and for our cherished morning conversations.

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particular thanks to Stine Madsen, Karl Holmberg, Tobias Nielsen, Jacob Hasselbalch, Teis Hansen, Fredric Bauer, Johannes Stripple, Lars (again), Karin Ericsson and Katya Chertkovskaya. I look forward to reading whatever you publish next, and to continuing our collaborations in one way or another. Karin – thanks also for initially being my co-supervisor. In the final writing process, I would like to thank Max Åhman, Em Christley, Jack Wright, and (again) Katya, Johanna and Joachim for your time and effort in reading and providing valuable questions and input on various parts of the draft.

Since the autumn of 2022, I have been on an exchange in the Science, Technology and Society (STS) department at Chalmers and would like to thank Martin Hultman and the management for this opportunity. Thanks are also due to everyone at the office for welcoming me into this wonderful workplace, with your inspiring seminars and post-seminar culture. Special thanks to Angelica Wågström and Parissa Mokhtabad Amrei, for endless amounts of units and valuable chats in between. Further, I have our ESA-STS feedback sessions with Erik Klint, Frida Hermansson and later Barbara Hedeler to thank for all the questions and suggestions that you have brought to this text.

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But what has and will always be most important is my own little family. Joel, sharing and creating a life with your enthusiasm and love has contributed to this process in so many ways. Thank you for supporting me and prioritising my needs in this somewhat invasive work situation. Torkel and Sissela, the playfulness and curiosity you bring into our lives are the highlight of my day. Despite the fact that your English vocabulary consists of 'no', 'baby watch' and 'overnights'. Or that you can't read. This book is yours.

Ellen Palm
February 2024
Gothenburg, Sweden

1 Introduction

When the European Commission presented a roadmap on a circular economy for plastics, the dependence on fossil feedstock was stated as one of the main issues (European Commission, 2017). However, in the final version, the role and importance of a decarbonised plastics system or feedstock were barely mentioned (European Commission, 2018). Instead, the two other main issues dominated: low recycling rates and littering. This removal of focus on decarbonising plastics in governance is remarkable given the urgency of climate change and EU climate mitigation ambitions in other sectors, including industrial ones (European Commission, 2023a). Instead of addressing the scale of production or climate impact, the global roll-out of plastics governance has focused on consumer single-use items such as restrictions on plastic bags (Nielsen et al., 2019).

In plastics production, fossil fuels are used in two ways. They are used for energy and thus result in direct carbon dioxide emissions, and they are used as feedstock and incorporated into the material. Estimates show that the plastics life cycle accounted for around 4.5% of all global greenhouse gas emissions in 2015 (Zheng and Suh, 2019). Almost all of the emissions (approx. 96%) are derived from the production stage, whereas other parts of the value chain such as incineration and recycling account for only a minor fraction (Cabernard et al., 2022). Further, plastics are composed of fossil carbon atoms and this share is typically not emitted as carbon dioxide (if the material is not burned or incinerated). The discrepancy between emissions and the share of oil and gas used in the production is a unique characteristic of plastics. The share of global oil and gas consumption that goes into plastics is larger than the share of global emissions. Estimates show that 14% of global oil demand and 9% of global gas demand go into the petrochemical industry, with plastics representing the largest product fraction (IEA, 2020). This discrepancy calls for more research and governance attention to be paid to plastics decarbonisation.

The use and consequent production of plastics are projected to grow, contributing to an even more significant climate impact. Historically, plastics production quadrupled from 1950 until 2020 (Borrelle et al., 2020) and production is projected to double by 2060 (OECD, 2022). The increased use of plastics in packaging is a primary driver, accounting for about 40 % of all plastics, and other growth sectors include the construction and automotive sectors (Plastics Europe, 2022). Despite the connection between plastics production and climate change, (ocean) pollution and waste (management) remain at the forefront of most plastics-related discussions (Chertkovskaya et al., 2020; Nielsen et al., 2020).

The interconnectedness between plastics and climate has long been lacking in governance, scientific and societal debates. However, there is an emerging sense of urgency and crisis acknowledgement regarding decarbonisation in the plastics and petrochemical industry. Over the past few years, decarbonisation roadmaps have been published by industry actors (Cefic, 2019; Systemiq, 2022), environmental non-governmental organisations (CIEL, 2019; IEA, 2018) and within the scientific literature (Meng et al., 2023; Meys et al., 2021). These emerging decarbonisation visions and roadmaps are still in the making and reveal large discrepancies regarding technologies, networks and ambition levels (Kloo et al., 2024). However, the petrochemical industry claims to be well underway already, acting as transition enablers and thereby downplaying the need for governance intervention (Tilsted et al., 2022). The industries' ambitions to transform via circular economy or decarbonisation strategies are also critiqued as future-proofing the industry with little change (Mah, 2021) and empty promises (Buck, 2022). Even though the connection between plastics and climate change is becoming visible, this remains a marginal perspective on the plastics crisis.

The PhD project is situated in this context, where addressing plastics from a climate perspective is an underdeveloped area. Based on this gap, the focal point in the thesis is decarbonised feedstock for plastics. It builds on the tension between striving to reach the climate goals and the continued, but changed, presence of plastics in our societies. Here, tensions are underlying conflicts that have not yet been activated, but where there is a dissonance between the parallel ideas. The thesis explores such tensions and conflicts surrounding the technologies and framings of one plastics decarbonisation option, namely carbon capture and utilisation.

1.1 Decarbonisation pathways for plastics

Plastics decarbonisation is about enabling plastics production with a substantially lowered climate impact. Following Vogl (2023), decarbonising plastics means a radical reduction and eventual elimination of greenhouse gases from the production of plastics. While both the input energy and feedstock needs to be based on decarbonised sources, this thesis focuses on feedstock-related issues. Decarbonised feedstock involves using carbon-based materials such as plastic waste and various forms of grown (e.g. algae) or cultivated (e.g. sugar cane) biomass, as well as carbon dioxide from both point sources and the atmosphere. An important note on decarbonising plastics is that it does not mean eliminating carbon atoms, as decarbonisation can do in other sectors (e.g. the power sector). Instead, carbon atoms unquestionably remain the key building block for polymers but should be of non-virgin-fossil origin. Stating that decarbonised plastics feedstock includes 'non-virgin-fossil' carbon signals two points. First, virgin fossil carbon feedstock such as oil, coal or fossil gas is excluded. Second, recycling and carbon capture and utilisation are included as decarbonised feedstock – irrespective of whether the recycled plastics and carbon dioxide are of fossil or non-fossil origin. Since recycling or reuse does not entail extraction of virgin fossil fuels, it is here and elsewhere (Meys et al., 2021), considered a resource-efficient way to radically reduce the greenhouse gas emissions from plastics production. Meaning it is a decarbonisation effort.

Before moving to the core of the thesis, I want to address a common reaction when I highlight the need to explore plastics decarbonisation. In my experience, when talking about the imperative of addressing the climate (and other environment-related) issues of plastics in societal debates, the benefits of plastics are often highlighted as a shield against such issues. This comment can take many different forms and shapes, and to avoid pointing at a specific actor or organisation, I will present an example statement to illustrate the position. It can be summarised as including something along the lines of:

> Plastics are a great group of materials. They contribute positively to the climate, environment and society by reducing food waste, enabling lightweight vehicles and providing us with modern health care. It should be highlighted how much plastics reduce the climate impact of other value chains. (Therefore, we should look instead at decarbonising other parts of the economy.)

While it is indisputable that plastics have some impressive material qualities and versatile applications, this does not mean that the climate issues connected to their value chain should not be given serious consideration. The products highlighted as the societal and environmental motivation for the benefits of the omnipresence of plastics, such as medical applications, food safety, lightweight transport and renewable electricity transfer, account for a proportion of our current use of plastics. Packaging might reduce food waste, but it is not the only thing it does. Plastic packaging is also used for branding, appearance, convenience and many other things. Additionally, not all food packaging reduces food waste, and there is indeed a use of plastics that serve no sustainability-related purpose. This includes, but is not limited to what the ongoing UN plastic treaty negotiations refer to as 'problematic and avoidable plastic products, including short-lived and single-use plastic products and intentionally added microplastics' (UNEP, 2023, p. 15). I recognise both the benefits and constraints of plastics as a material, as well as the unquestionable need to explore and scrutinise suggested decarbonisation pathways. Thus, the need for climate issues to be addressed and for plastics to maintain a presence in our societies are equally clear. However, that relationship requires fundamental changes in how we use and produce plastics, and there are various options as to how to decarbonise plastics.

Plastics can decarbonise in a variety of ways. In Bauer et al. (2022) we divide the plastics feedstock decarbonisation into three main pathways that address different parts of the value chain. These three pathways include reduced use, bio-based and alternative feedstocks (e.g. carbon dioxide) and recycling, see Figure 1. First, reduced production of plastics should be considered. This is crucial since all other decarbonisation pathways include limitations that mean that decarbonised plastics cannot be produced in the same volumes as today. Hence, without decreased demand and production, decarbonising plastics would fail to materialise (Meng et al., 2023). Further measures include increased reuse and substitution efforts, such as second-hand markets, refillable packaging and substitution with other materials (Bauer et al., 2022). These are all strategies that would reduce the demand to produce virgin plastics in line with the increasing number of calls for a global limit on plastics production (Bergmann et al., 2022). However, the projected production growth in the plastics industry does not speak in favour of this happening voluntarily any time soon (Bauer and Fontenit, 2021).

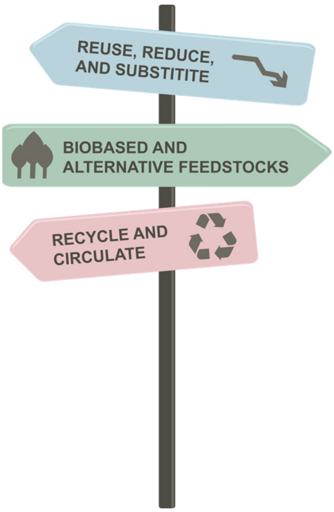

Figure 1: Three potential decarbonisation pathways for plastics.

Besides reduced production and consumption, plastics can decarbonise via increased recycling and the introduction of non-virgin-fossil plastics feedstock. Recycling entails feedstock replacement via both mechanical and chemical routes (Ragaert et al., 2017). This pathway has technical, structural and feasibility limitations, and inevitably requires some 'new' carbon atoms to enter the system. One renewable source involves using biomass. However, increasing the current use of biomass also has substantial limitations. In addition to the technical issues of what plastics to produce and how to recycle them, this involves issues related to biodiversity loss, biomass scarcity, land use change and water use (Brizga et al., 2020). One last option is to decarbonise plastics by using carbon dioxide as a carbon feedstock (Palm et al., 2016). This is often referred to as carbon capture and utilisation and will be developed in detail and motivated in the section below.

1.2 Carbon capture and utilisation as decarbonisation

Carbon capture and utilisation (CCU) is an emerging set of technologies that seeks to use carbon dioxide in other materials or applications. The technologies have many similarities with carbon capture and sequestration (CCS), where carbon dioxide emissions are stored in, for example, geological formations. The overall aim is to mitigate climate change by storing or using carbon dioxide, rather than emitting it into the atmosphere. However, the boundaries between what is storage and what is utilisation are not yet agreed upon by its developers. In the following section, the technologies and associated applications will be introduced in relation to this tension. Subsequently, the motivation as to why carbon capture and utilisation is of interest to plastics decarbonisation is developed. Before the aim and limitations of the thesis are presented, the various ways of referring to carbon capture and utilisation used in the text will be explained and motivated.

Carbon-containing applications, products or materials can utilise collected and processed carbon dioxide in different ways. Using carbon dioxide is thought of as a decarbonisation pathway that enables a shift away from 'simply' storing carbon dioxide in underground formations as a means of carbon capture and sequestration (Styring et al., 2011). Examples in use range from direct utilisation in beverage carbonation and enhanced oil recovery (the practice of injecting a gas into depleting oil reserves to extract more fossil fuels) to indirect use via conversion to mineral carbonates, fuels or chemicals (Naims, 2016). Currently, the biggest market volume for carbon dioxide utilisation is the production of urea, an organic compound widely used as a fertiliser within agriculture. Overall, the proponents of carbon dioxide utilisation argue that carbon dioxide can become a useful feedstock, a low-carbon option for several forms of applications. Compared with the negative public perception of carbon capture and sequestration, carbon capture and utilisation is a more unknown technology (Jones et al., 2017). However, research is exploring the role of public perception and aiming at informing societal debates on the potential benefits of carbon capture and utilisation (Bruhn et al., 2016; Olfe-Kräutlein et al., 2022). Besides questions of legitimacy and potential societal acceptance, there are technical issues and uncertainties with carbon capture and utilisation that call it into question as a general mitigation strategy (de Kleijne et al., 2022). By providing a non-virgin-fossil carbon feedstock, carbon capture and utilisation can offer the petrochemical industry a mitigation strategy (Kätelhön et al., 2019; Meys et al., 2021).

Despite the decarbonisation ambitions, carbon capture and utilisation does not only include non-fossil carbon sources. Instead, carbon capture and utilisation typically include a broad set of fossil, recycled or bio-based carbon sources. Carbon dioxide is mostly thought of as being captured from industrial point sources such as waste incinerators, combined heat and power-, and manufacturing plants. Direct air capture is also sometimes included, despite its higher energy requirement and cost. Carbon capture and utilisation does not only consider bio-based carbon dioxide, hence choosing the origin of the carbon dioxide is neither always possible nor at the core of classification. For example, in both direct air capture and waste incinerators, there is inevitably a mixed flow of both fossil and bio-based carbon dioxide. Not considering the dichotomy between fossil and bio-based carbon important when striving towards decarbonisation is very different compared to most other sectors. In renewable energy efforts or their life cycle assessments, the origin of the carbon dioxide is of great importance for reporting and monitoring the mitigation potential of the decarbonisation strategy. This is not the case for carbon capture and utilisation, and a common denominator is that virgin-fossil carbon should not be included, but where that boundary is drawn is a subject of debate within the field. Regardless of the origin of the carbon, decarbonisation claims remain central to carbon capture and utilisation technologies.

The motivation to focus on carbon capture and utilisation builds on the increased attention it is gaining as a mitigation strategy for plastics and beyond. Carbon capture and utilisation and other technologies that limit emissions from entering the atmosphere are now central components in climate modelling (Malm and Carton, 2021). From a policy perspective, the high trust in its ability to mitigate climate change is illustrated by the importance assigned to it in the EU Innovation Fund. The EU Innovation Fund is based on the revenues from the world's largest carbon-pricing system, the EU Emissions Trading System (EU ETS), and is one of the largest programmes for climate mitigation technologies. In its calls for proposals, the EU Innovation Fund highlights carbon capture and utilisation as one of five core technologies for decarbonisation (European Commission, 2023b, 2023c). Considering the increased funding opportunities and the technological legitimacy gained, there is a need to unpack and map the expectations and subsequent promises. This calls for greater scrutiny of both the technologies and framings surrounding them. Some studies have explored the politics of negative emissions (Beck and Mahony, 2018), imaginaries of circular carbon in the fossil fuel industry (Buck, 2022) and technological limitations (de Kleijne et al., 2022; McLaren, 2020) as well as potentials (Bachmann et al., 2023; Kätelhön et al., 2019; Meys et al., 2021). However, the technologies and associated promises of carbon capture and utilisation have not been studied from a plastics decarbonisation perspective. Given the pronounced climate impact of plastics, coupled with the growing role of carbon capture and utilisation as a key mitigation strategy, a thorough exploration of this subject is important and greatly needed.

Depending on the intended use of carbon capture and utilisation, it is named differently throughout the thesis and publications. In Paper I, the end product is called *electricity*-based plastics – to emphasise the energy demand; in Paper II, the term carbon *dioxide utilisation* is used to frame out the capture part and instead emphasise the expectations of proposed applications and use; in Paper III, it is mentioned as a means to enable *carbon dioxide*-based feedstock for plastics, to highlight the carbon source, and in Paper IV, the technologies are called carbon capture and utilisation. This mixed use reflects how the concept has evolved during these years and how the research has taken an interest in different parts of the technologies. In the summary of papers, the concept will be named as in the original paper. However, all other parts of the thesis refer to what has become the dominant term, namely carbon capture and utilisation. All use of abbreviations (e.g. 'CCU') will be limited for style and reading accessibility reasons. What might be an obvious abbreviation for those within a field, might take some time to grasp for those outside it. Since I want to communicate with actors and scientists within various fields, I use only widely known abbreviations (e.g. EU). Thus, to facilitate the reading experience, both with and without audio assistance, abbreviations are kept to an absolute minimum and the technological concept is predominantly called carbon capture and utilisation.

1.3 Aim

Plastics are both based on and produced using fossil fuels. Thus, the production of plastics stands in conflict with the fossil fuel phase-out needed to mitigate climate change. Nevertheless, this remains a significantly understudied issue. In this thesis, I strive to engage in and contribute to a better-informed academic and non-academic conversation on decarbonising plastics. More specifically, **I explore and unpack tensions between climate mitigation and the continued use and production of plastics**. Empirically, I explore technologies and framings associated with the proposed mitigation strategy of carbon capture and utilisation. To do this, more than one disciplinary perspective is needed. This thesis moves between social scientific and engineering perspectives, qualitative and quantitative data, and explores the technological solutions, expectations, policy narratives and imaginaries of different actors across the plastics system. Collaboration with scholars from other disciplines is at the core of how this thesis has developed. In this eclectic combination of perspectives, data, actors and methods, the empirical focus on decarbonised carbon feedstock for plastics has been the constant factor, the guiding light. This is all motivated by an urge to highlight that plastics are fossil fuels, and the argument that multiple perspectives are needed to aim at mitigating the plastics crisis and the associated threat of ongoing climate change.

The thesis builds on four published papers that map and discuss the ins and outs of decarbonising plastics. The order of publications is chronological and delves into technologies and framings associated with the decarbonisation pathway of carbon capture and utilisation. Paper I explores this **technological decarbonisation pathway** and estimates the energy and carbon requirements for electricity- and carbon dioxide-based EU plastics production. Paper II maps and discusses the **conflicting expectations** of what counts as climate mitigation within the carbon capture and utilisation research community. Paper III explores EU **plastics governance** to better understand how plastics are framed as a political issue, as something that requires or does not require governance. Lastly, Paper IV explores the petrochemical industry's **circular carbon imaginary** and argues that it risks promoting mitigation deterrence rather than mitigation. Drawing on these publications, the discussion narrows down on the tensions in the empirical findings and the ways carbon capture and utilisation and circularity is framed by different actors, and then broadens out to a discussion on cultivating multiple plastics decarbonisations, arguing that diverse perspectives, technologies, and policies are important when striving towards decarbonising plastics.

Delimitations and outline

When writing a PhD thesis, it is as important to decide the central theme as it is to exclude other interesting aspects. Motivated by the urgency of climate change, this thesis focuses on decarbonisation as the main environmental issue with plastics. While most of the analyses in the papers consider one decarbonisation pathway and potentially decarbonised plastic feedstock, several of them also analyse other environmental and political aspects of plastics. This includes aspects such as circular economy, bio-based feedstock, and the imperative of reduced use and pollution. That said, the focus of this thesis remains on the fossil fuel dependency of plastics and alternative feedstocks via carbon capture and utilisation. Importantly, decarbonisation does not equal sustainability. This thesis is delimited to be about decarbonisation while acknowledging the importance of the multiple sustainability issues associated with the plastics system (e.g. Farrelly et al., 2021; Geyer et al., 2017; Liboiron, 2016; Muncke et al., 2020; Persson et al., 2022; Thompson, 2017). While it is not self-evident that decarbonisation cannot push the plastics system in a more sustainable direction, the important point is that it does not necessarily do so.

Plastics consist of polymers and additives. In this thesis, feedstock refers to polymers, which means that additives are not included. Additives can make up a large part of plastics, be fossil-based (Zheng and Suh, 2019) and emit greenhouse gases if incinerated (Huber et al., 2009). This delimitation is motivated by the focus on the energy- and emission-intensive production of plastics, rather than plastics compounding – where additives and polymers are blended to create the intended properties of the material. Further, the main decarbonisation pathway explored is carbon capture and utilisation, but as introduced earlier, there are several other feedstock options and decarbonisation pathways. These are not explored in depth in the thesis, but aspects of them are included in the analysis in several of the papers (I, III and IV).

This thesis is outlined as follows. Chapter 2 presents the analytical concepts used in the papers, including expectations, imaginaries and policy narratives. Chapter 3 contains the methodological considerations and outlines the research approach and methods. Followed by Chapter 4 which presents a paper summary. In Chapter 5, the key findings are discussed by first narrowing down to ideas of carbon circularity and then broadening out to advocate multiple plastics decarbonisations. Finally, Chapter 6 concludes the thesis, and put forward the argument that there is a need to change how plastics are produced, consumed, and managed that require substantive technological, economic and governance change.

2 Analytical concepts

Plastics decarbonisation and carbon capture and utilisation are explored via three analytical concepts: expectations, imaginaries and policy narratives. This section outlines the core elements of the concepts and how they have been used. On a general level, expectations, imaginaries and policy narratives are all analytical concepts that unpack how certain (parts of) discourses shape and contribute to the legitimisation of practices, policies or technological developments. They serve to assign meaning by reducing the complexity of a system, technological development or policy process. Expectations, imaginaries and policy narratives all represent different ways of framing how problems, solutions or futures are formulated, but there are some important differences between the concepts. 'Framings' is used as an umbrella term to capture the diversity of discursive representations included in the analysis. These framings explore different levels of analysis (broader societal or specific contexts), start from different disciplinary backgrounds (cultural political economy or sociology of expectations) and cover different scopes (politics or technological trajectories). The choice of analytical concept in each study is guided by the empirical tension of interest, rather than a strive to advance the understanding of it. Besides presenting the core of the concepts and how they have been used in this thesis, the differences and similarities are also developed and discussed below.

2.1 Expectations

Expectations can shape the development of emerging technologies. More specifically, expectations play a role in attracting resources, gaining legitimacy and building networks around emerging technologies (Borup et al., 2006; van Lente, 2012). Expectations can become promises that turn into requirements as to how a technology should perform, and hence shape the technological properties. Discursive realities can thereby become or shape technological realities (van Lente and Rip, 1998). It should be noted that even if expectations can shape technological development, such a relationship is by no means a fast, linear or given process. Equally, future developments of an emerging technology can be restricted by the limits of the expectations articulated by the proponents of said technologies. To include a variety of technological performances and associated futures, expectations are typically set high or wide to fit with a broad set of actors' perceptions of what is desirable. In the early stage of technological development, the technologies cannot compete on current cost, performance or product features. Instead, the expectations of future performance and capabilities typically become the competing factors for capital and other resources (van Lente and Bakker, 2010). Thus, the role of expectations of emerging technologies, and what they express as desirable and possible, can in different ways shape and limit the development. Based on these insights from the sociology of expectations literature, expectations are here understood as:

> real-time representations of future technological situations and capabilities. (Borup et al., 2006, p. 286)

Paper II analyses the conflicting expectations of emerging technologies associated with carbon capture and utilisation. The most basic expectation often relates to what issue a technology could solve or address if it were developed, representing a wishful enactment of such a desired future (Borup et al., 2006). To unpack such overarching expectations, questions are asked about the requirements, proposed applications, and future energy systems and carbon sources that are envisioned to be included in the technological development (van Lente, 2012). The empirical material consisted of published articles in scientific journals, and we studied representations in the form of both text and images. Mapping and uncovering the expectations made visible the conflicts between the advocated carbon dioxide utilisation futures. In the early stages of technology development, sharing expectations with a wide range of stakeholders is important to increase the chances of success when building networks, attracting resources and creating legitimacy. However, such early expectations are those most likely to differ the most from the future reality of the technology (Borup et al., 2006). Therefore, scrutinising such technological expectations is especially important if they claim to have mitigation potential. Our findings thus feed into a discussion on what to consider when deciding whether or not to support such development.

2.2 Imaginaries

Imaginaries refers to broad ideas about a system or solution. They can be used to trace how such framings promote certain futures. Imaginaries are not always future-oriented by definition, but here they are considered to contain a future-oriented aspect by referring to images of futures and emphasising new opportunities or capabilities. For example, they may include a broad set of ideas related to decarbonised futures. In this thesis, imaginaries are evoked in relation to the cultural political economy literature. This builds on a cultural turn within social science, where cultural aspects (how something is understood, framed or discussed) are integrated in the study of political economy dynamics. The analysis of semiotic systems is considered to serve to both interpret and explain such events and processes (Jessop, 2012). Here imaginaries are understood as:

> semiotic systems that frame individual subjects' lived experience of an inordinately complex world and/or inform collective calculation about that world. They comprise a specific configuration of genres, discourses and styles and thereby constitute the semiotic moment of a network of social practices in a given social field, institutional order, or a wider social formation. (Jessop, 2010, p. 344)

This dense definition requires some clarification. Semiotic systems include language, images, gestures and other symbolic forms of communication. In the definition, imaginaries consist of semiotic systems that reduce the complexity by making sense of an inherently complex world. Semiosis is necessary because the world cannot be grasped in all its complexities. Thus, actors must choose to focus on certain aspects of the world to be able to describe, interpret or act within it (Jessop, 2012). Complexity reduction and meaning-making can take a variety of representations, shapes and forms. These variations comprise different ways of acting and interacting (genres), ways of being or expressing identity (style) as well as social practices (discourses). Taken together, imaginaries highlight what an actor consider to be significant, and thereby emphasise certain solutions and futures while marginalising others. Whether intentional or not, such foregrounding and silencing can help legitimise and stabilise dominant economic structures, institutional orders or power relations (Jessop, 2010). Typically, technologies that suits the dominant economic and political structures are favoured in such dynamics (Markusson et al., 2022). Importantly, one imaginary does not hinder the existence of others, formulated by other actors, in other fields or on other scales. In conclusion, imaginaries reduce complexity and refer to the shared beliefs, values or symbols that shape the understanding of a certain reality.

Paper IV unpacks the petrochemical industries' mitigation strategies, named the circular carbon imaginary. Here, the interest lies in how the imaginary shapes the plastics system and encourages technocratic responses to the plastics and climate crisis. We explore the promotion of carbon management and circularity, and how it risk to downplay the need for other decarbonisation efforts via mitigation deterrence. Mitigation deterrence refers to the 'prospect of reduced or delayed mitigation resulting from the introduction or consideration of another climate intervention' (Markusson et al., 2018, p. 1), and imaginaries are one way through which this can occur. By exploring how the various forms of futures, solutions, proposed policies and promises are expressed in various forms of representations, we identify the key aspects and variations of the circular carbon imaginary. Taken as a whole, the analytical concept of imaginaries is used to bring together the wider discourse and discuss how the framings associated with it risk delaying actions to mitigate climate change.

Comparing expectations and imaginaries

Expectations and imaginaries are both analytical concepts that play a role in attracting resources and providing legitimacy for a certain future or technology. In both cases, such future-making can shape the development, and thus be generative. In contrast to expectations, imaginaries include a broader story that aims to reduce the complexity of an entire system or future. Imaginaries build on ideas that are desirable, such as freedom, democracy, or decarbonisation, but do not necessarily advocate for the probability of such futures or systems taking place. Expectations, on the other hand, include representations of specific parts of a system and ideas about how probable or plausible a development is. It can be exemplified by statements like: 'the conversion of carbon dioxide will be X% higher in five years'. Imaginaries and expectations thus focus on different discursive aspects and scales of futures or systems, exemplified by advocating for the importance of decarbonisation versus the probability of a certain technological development.

Expectations and imaginaries can also overlap. An imaginary can be constituted by several expectations, and expectations can relate to broader imaginaries. An imaginary of a decarbonised society may be needed for the expectations of a certain mitigation technology to gain force. Nevertheless, it is the scale – system or more detailed level – and the importance of whether it is a plausible future or not that are the important differences between the analytical concepts. Such differences in scale and plausibility enable the unpacking of different results. Here, the concept of imaginaries enables the display of broader ideas and stories about a future plastics system built on smart carbon management, as envisioned by actors in and around the petrochemical industry. In contrast, the concept of expectations is used to analyse the proposed performance and relevance of technologies associated with carbon capture and utilisation within the research community. In both cases, such analysis is motivated by the urgency to mitigate climate change (or decarbonise plastics) and scrutinise the role assigned to technological development in achieving that.

2.3 Policy narratives

Narratives are a form of stories that simplify the complexities of the world and can be used to influence policy issues. In social science, they are often of non-fictional and more formal character (Moezzi et al., 2017). Narratives are typically understood as discursive building blocks that reduce the complexity of the social world, assign meaning and define policy problems. However, narratives can simultaneously draw upon larger discourses, such as the circular economy to highlight its central themes. Discourses thus include a broader set of ideas or concepts than narratives but also shape (public and private) practises and thereby define a system or reality (Hajer, 1995).

In Paper III, policy narratives are used to uncover, illuminate and systematise how EU policymakers make sense of plastics governance. The content of a variety of policy narratives are categorised and subsequently analysed to discuss their role within EU plastics governance. Policy narratives give meaning to policymaking by selecting and prioritising certain issues, characters and contexts. In this meaning-making and complexity reduction, policy narratives influence how a problem is perceived based on both ideology and evidence. By shaping the public understanding of an issue, they also influence the policy decision. Thus, policy narratives shape or define how policies and their perceived solution are developed and implemented (Hajer, 1995). As such, policy narratives can be used strategically to promote a certain interest or agenda (Gupta et al., 2014). In Paper III, the policy narratives are considered to contain generalisable components and are organised in predetermined discursive categories according to the narrative policy framework (NPF) (Jones and McBeth, 2010). For a description of those categories and the systematic framework, see the Methods section.

Comparing policy narratives and expectations

Expectations and policy narratives both capture smaller building blocks of a larger discourse or imaginary. Here, discourses and imaginaries both represent the collective ideas about a larger system or reality. The analytical concepts of expectations and policy narratives have some overlapping features and important discrepancies. They both make sense of a specific part of the world by reducing complexity. However, they are not neutral. They serve to influence how actors perceive problems and the way policies or technologies are developed and implemented. An important difference between the two concepts is the scope that they cover. Policy narratives typically focus on current situations and (environmental) politics, while expectations pay attention to proposed or suggested future technological performances. Furthermore, since the thesis draws on the policy narrative framework, the policy narratives are conceptualised to entail fixed categories developed for a public policy context. The structure of the expectations on the other hand can be classified or categorised freely based on the empirical material. As such, this makes narratives a fruitful conceptualisation for policymaking and expectations of technology developments.

3 Methodological considerations

This section presents the research approach and methods used. Motivated by pluralism and reflexivity, the research approach is shaped by interdisciplinary collaborations. More specifically, to explore and unpack tensions in plastics decarbonisation, my natural sciences and engineering background is complemented with social scientific perspectives and methods. The wide range of methods and approaches includes techno-economic assessment, discourse analysis, narrative policy framework and participant observation. My motivation for exploring these different ways of knowing, conceptualising and doing research is that such an approach can improve the quality of both the research and the potential societal outcome.

3.1 Research approach

The research approach is explored through three main perspectives: pluralism, reflexivity and interdisciplinarity. First, pluralism is presented and underpins an argument for mixing multiple methods and study objects. Second, reflexivity and the idea of challenging one's assumption are presented. Last, the section includes a reflection on working in interdisciplinary teams and the idea of striving towards a multiplicity of understandings. In summary, the interdisciplinary research is inspired by ideas of pluralism and reflexivity.

Pluralism

As researchers and humans, we can only know so much. Pluralism is about acknowledging this and advocating that there are multiple ways of knowing and doing, and that aiming to reduce these to one theory or method is not desirable (Chang, 2012). Mitchell (2009) argues for undertaking pluralism based on the complexity of nature. She takes the empirical complexity within biology as a starting point and proposes an integrative pluralism that allows and encourages multiple (biological) theories to co-exist in a non-competitive and compatible manner. While Mitchell highlights the inter-scientific value of pluralism based on the complexity of the world, Stirling (2010) moves this into the realm of governance and policy. He claims that our knowledge about the world is uncertain and that this calls for presenting plural and conditional scientific results. This is emphasised concerning expert advice on policy debates or policymaking. Hence, the motivations for pluralism are about both the complexities inherent in nature and the equally inherent uncertainties in our knowledge of it.

A benefit of pluralism is not putting all your eggs in one basket. If a research community or scientific field uses only one theory or method to advance its work, this comes across as a risky endeavour since it might miss important characteristics or mechanisms (Chang, 2012). Pluralism thus concerns methodological aspects where complex issues can be addressed by employing a variety of analytical concepts and methods to triangulate and increase the reliability of the results. However, to contribute to a more nuanced understanding of the research topic, it is important to reflect on how the combined research perspectives complement one another. Furthermore, pluralism is not limited to scientific knowledge but can also enrich the direction and scope of governance, norms and technological development. As such, pluralism appears as a well-motivated endeavour to improve both the science and science–policy interaction.

In this thesis, pluralism can be seen in three different forms. Pluralism, as opposed to monism, has been chosen on ontological, methodological and science–policy interaction grounds. First, the thesis takes an interest in a diversity of study objects. This acknowledges the importance of different objects and how they exist in the world. In exploring plastics decarbonisation, both technological efficiencies as well as expectations, policy narratives and imaginaries can be important study objects. Second, multiple methods and concepts from a variety of scientific traditions and disciplines are used. This methodological diversity is further developed, exemplified and discussed in the sections Methods, Analytical concepts and Discussion. Third, concerning the results and proposed policy advice, I advocate for different forms of action and multiple decarbonisation pathways to be developed based on such diverse areas of knowledge. While encouraging going beyond the dominant paradigm, I simultaneously acknowledge the importance and relevance of within-paradigm development, provided such directions do not hinder other forms of development. This implies that technological pathways should only be supported and financed provided they do not obstruct other forms of mitigation.

Inevitably, there is a trade-off when aiming at such a broad research endeavour. Each of the elements above could have been the subject of a PhD thesis, and that would surely have been interesting. It is not a question of quality but rather a question of the chosen resolution. It has been a deliberate choice to prioritise the breadth by exploring plastics decarbonisation and carbon capture and utilisation from all these multiple angles. At the same time, it is acknowledged that it is not as in-depth as if only one perspective, method or study object had been studied. In making such a decision, it is equally important to acknowledge that opting for great depth would have been at the cost of some of the breadth presented in this thesis. Hence, the value added here is not the depth but the multiple angles and perspectives on plastics decarbonisation that are explored and scrutinised. A multiplicity of approaches is thus at the core of this thesis.

Reflexivity

Reflexivity is about challenging assumptions and breaking out of the dominant paradigm. It includes both the research subject and the researcher themself. Much like the pluralism described above, it is a position that acknowledges the uncertainties of the world. More importantly, it stresses that there is no such thing as self-evident or value-free assumptions, research questions or system descriptions (Alvesson and Sandberg, 2011; Leach et al., 2010). Starting from the research subject of decarbonising plastics, this involves being reflexive about which ideas are included and which are excluded. For example, there is a risk of too strong a focus on a production perspective creating a blind spot for other mitigation strategies or broader issues of why and how to use plastics. In industrial decarbonisation, or when aiming at sustainability, the starting point is unquestionably normative since it corresponds to a desired societal goal or outcome. Reflexivity then involves realising the normative assumptions inherent in the research, as well as challenging them. While the empirical focus on plastics is inspired by the experience of what became a total of two years at sea, taking a climate perspective on plastics is likely to be most influenced by the fact that I was born and live in Sweden. The visual and societal consequences of littering or malfunctioning waste management are not as significant there as they were during most parts of my circumnavigation. Hence, in terms of positionality, focusing on plastics as a climate issue – as opposed to the dominating issues of waste and pollution – is most probably shaped by my everyday Swedish relationship to plastics.

Being a reflexive researcher involves challenging the interests, values and positionalities inherent in the perspective applied (Leach et al., 2010). As I was trained to see the world through an engineering lens, I focused on problem-solving and quantifications. Engaging with environmental issues, this implied that they could and should be measured, calculated and evaluated accordingly. To exemplify this, Paper I presents estimates of an electricity-based plastics production system, where numbers and quantifications are used to ensure quality and trustworthiness. This is much like Porter's (1996) argument on mechanical objectivity and the blind trust in numbers that creates inevitability and desirability for a specific mitigation pathway. The quantifications of unknown futures make them come across as less risky, and more certain and easier for policymakers to enact (Stirling, 2010). However, having entered the research field of carbon capture and utilisation, I gained an interest in complexities beyond chemical structures, electricity demands and efficiencies. It turned out that the previous somewhat blind trust in numbers, and the underlying ideas and paradigms of quantifications, were not the only way of learning about or evaluating alternatives for plastics decarbonisation. However, following my argument on methodological pluralism above, I still believe that quantifications and variations in calculations are a relevant and interesting way to research plastics decarbonisation. For example, I recently co-authored a paper that compares quantifications in decarbonisation roadmaps for the petrochemical industry (Kloo et al., 2024). As this thesis exposes, I have also explored other ways of understanding, evaluating and discussing plastics decarbonisation. The problem-solving has been complemented with social scientific perspectives and methods. How this strive towards reflexivity has influenced the research is further developed in the Interdisciplinarity and Methods sections below.

Interdisciplinarity

Driven by curiosity and a strive towards reflexivity, I engaged with other disciplines, methods and research questions. These interdisciplinary collaborations challenged my previous assumptions of the proposed issues of and solutions for industrial decarbonisation. Research on industrial decarbonisation often consists of the modelling of technical systems (Karlsson et al., 2020) or evaluation of policies aimed at accelerating decarbonisation (Vogl et al., 2021). While the most common industries studied are steel (Åhman et al., 2023) and cement (Hills et al., 2016), the scope of industrial decarbonisation has in recent years paid more attention to the plastics and petrochemical sector (Janipour et al., 2022; Rootzén et al., 2023; Schneider, 2023). While narrative analysis is not new in this domain (Tilsted et al., 2022), the interdisciplinary research applied here aims to contribute to a broader palette of methods and approaches when analysing industrial decarbonisation. The research is intended to remain in dialogue with the technology and policy perspective but complement it by also exploring the discursive aspects of decarbonisation. In this undertaking, I engage with the political science, cultural political economy and sociology of expectation perspectives. This shift in focus from first carrying out techno-economic assessments to striving to engage in plastics decarbonisation from other ways of seeing the world resulted in interdisciplinary collaborations. However, it remains important to be reflexive about how such interdisciplinarity is carried out (Svensson et al., 2020).

Having fruitful interdisciplinary collaborations in an encouraging and challenging environment is about mutual care and trust. Interdisciplinary work, motivated by pluralism and reflexivity, is not about everyone agreeing or converging on the same view. It is about nurturing an interest in your peers' perspectives, being committed to contributing and trying to understand others' viewpoints (Bijsterveld and Swinnen, 2023). This involves both challenging and learning from one another. In such an exercise, one must let go of control and trust the co-authors and yourself. No one will understand everything or agree with all the decisions made in the process; that is simply not the desired outcome in such experimental learning processes. In practice, I have often had empirical expertise and interest in the collaborations, and my co-authors have often contributed the theoretical entry point, framework or method. Having an engineering and chemical background enables a new form of understanding when exploring the expectations, imaginaries or policy narratives. For example, my understanding of chemical bonds and molecular structures has facilitated the engagement at technical conferences and publications. It was in my own interest to stay within the field of plastics or decarbonisation but to widen my perspective beyond quantifications. During this thesis work, I have strived to learn from other fields of knowledge and ways of interpreting. As indicated by the above examples of caring about and trusting in my co-authors and daring to let go of control, I have explored things way beyond my previous disciplinary boundaries. This enabled a shift from an initial idea of a thesis on multiple technological pathways to what has now become a thesis that explores multiple perspectives for engaging with plastics decarbonisation.

3.2 Methods

Before something can be discussed or critically assessed, there is a need to map the field. Since plastics decarbonisation has been and remains an understudied area, the explorations in this thesis of one of its proposed mitigation strategies focus on unpacking and structuring the various framings and technologies surrounding it. First, techno-economic assessment and its use of quantitative data are described. After that, four methods using qualitative data are introduced, namely discourse analysis, narrative policy framework, participant observations and interviews. A commonality among these diverse methods is that they are used to map the implications of either the carbon capture and utilisation technologies or their associated framings. The data that feeds into the analysis is constituted by quantifications of proposed efficiencies, but predominantly, the data consists of framings and the various methods aids to explore their shape and meaning (Moezzi et al., 2017). In this combination, framings and quantitative assessments are considered to complement and diversify the understandings of plastics decarbonisation. The analysis of both framings and technologies seeks to add complexity and nuances to quantifications of their potential future performances. Furthermore, the mixed use of methods reflects and is a consequence of the pluralism and interdisciplinary approach previously described.

Techno-economic assessment

The techno-economic assessment in Paper I analyses the conditions concerning a process model for producing drop-in plastics from carbon dioxide and renewable electricity (Grunwald, 2009). An assessment model is developed based on data available in the scientific literature on the separate technologies of the proposed production system. These components are combined, and the implications of a future carbon dioxide-based plastics production system are explored. The study aims to estimate the energy and carbon dioxide demand of such an electrified process route. No other factors, emissions or environmental impacts are covered. Further system boundaries are that the model design preconditions the input and output. The input is carbon dioxide, water and renewable electricity, and the outputs are the most common plastics feedstock: ethylene and propylene. Two other key conditions for the model are assumed constant production and improved efficiencies of the technologies covered. Since EU plastics production has been relatively stable over the past 10 years (Plastics Europe, 2022), a constant production level is assumed until 2050. However, when applying the technological performances, projections in the literature of future efficiencies and yield of the process are used. The model and its results thus include several normative assumptions about the future, such as plastics production levels, technological development and availability of renewable electricity. Taking the results of the technological assessment as a starting point, a simple cost model based on the energy demand of the production route is established.

Techno-economic assessments can be used for various purposes, including promoting the technologies or aiming to improve how they are perceived (Grunwald, 2009). In Paper I, the purpose is to calculate the consequences of implementing the technologies and highlight what is neglected in these types of assessments. As such, it aims to inform and engage in a conversation on plastics decarbonisation by presenting a numeric result. Sometimes a number is what it takes to get a discussion started and potentially broaden the perspectives of what decarbonised plastics production could constitute. This enables a techno-economic comparison of this decarbonised plastics production with conventional routes.

Discourse analysis

In this thesis, discourse analysis is a method used to map the framings of future (technological) development. The method is used in both Paper II and Paper IV in similar ways and with similar aims. It enables an analysis of systems of meaning-making by focusing on how actors frame and relate to a specific topic. There are several traditions of discourse analysis, but a common starting point is to share a rejection of the realist notion that language is simply a neutral means of describing the world and a conviction that discourses take part in constructing social realities (Gill, 2000). The material analysed is understood to construct a specific version of the actor's reality and does not seek to understand a neutral or value-free system. The discourse is assumed to have a purpose, for example promoting a desired solution to an issue, such as a specific technological development or future plastics system. Discourse analysis is used to uncover the strategies employed to achieve those purposes. Another important component is what is not mentioned or represented when advocating for a certain solution to make it come across as neutral, desirable and sometimes inevitable (Gill, 2000).

Discourse analysis is employed in Paper II and Paper IV of this thesis. In both papers, the analysis is conducted through an iterative process of carefully reading the included material. It consisted mostly of scientific publications, images and policy documents collected via targeted searches and snowball sampling. However, interview transcripts and observations are also included. Taken together, this means that the analysis builds not only on written or spoken statements but also their graphical representation. An in-depth analysis of why and how carbon capture and utilisation or circular carbon economy are argued to be relevant or desirable is explored based on a question scheme. In both papers, the questions are inspired by the sociology of expectations literature, asking questions on expectations, promises, requirements, imagined solutions or futures, and potential conflicts therein (Borup et al., 2006; van Lente, 2012).

There are also important differences between how the discourse analysis is carried out in the two papers. For example, the scope and scale of the discourse vary. Paper II focuses on expectations and thus studies a specific set of representations in a common context and limited area – a technological development. In Paper IV, it is the imaginaries that are in focus, meaning that the broader societal context is the interest area. The discursive aspects of the circular carbon imaginary are used to explore how it risks promoting mitigation deterrence and how other decarbonisation strategies are left out. Nevertheless, both papers analyse discourses surrounding plastics decarbonisation or carbon capture and utilisation.

Narrative policy framework

Narrative policy framework is a structured schematic approach that enables the analysis of policy narratives. Paper III uses the framework to uncover the content of and systematically map and compare the policy narratives within EU plastics governance. On a general level, the idea of narrative analysis is more specific than that of discourse analysis. Narrative analysis takes an interest in the 'effects of the use of language in political debate' (Hermwille, 2016, p. 5). Unpacking policy narratives contributes to an understanding of what policymakers consider to be relevant and interesting policy issues and proposed solutions. As such, they are strategic constructions that seek to foreground their understanding in public policy debates (Gupta et al., 2014). A more specific contrast in this analysis to the discourse analysis described above is that the framework introduces generalisable narrative components. It departs from an understanding of narratives as stories in the most basic sense, with a beginning, middle and end, that contains a form of storyline and characters who drive the story. The policy narrative framework thus conceptualises the form of policy narratives to consist of (i) a setting or context, (ii) a plot, (iii) characters who are fixers of the problem (heroes), causes of the problem (villains) or those harmed by the problem (victims), and (iv) a moral or (policy) solution to the story (Jones and McBeth, 2010). Characters do not necessarily consist of individual humans but can also include broader concepts like liberty or the environment.

The framework is used in an interpretivist narrative approach by acknowledging the importance of stories in defining problems and their associated policy options (Jones and Radaelli, 2016). This is operationalised by working inductively with the data. The analysis is based on public documents and 16 semi-structured snowball-sampled interviews with actors associated with EU plastics governance; see the section on Interviews below. From the material, we identified the content of the narratives and classified them using the predetermined categories from the narrative policy framework. The framework has been criticised for both pushing 'statistical approaches to evaluate narrative elements' (Lejano, 2015, p. 368) and 'uncritical adoption of natural science methodology' (Miller, 2015, p. 356). Despite or because of this ongoing debate, the method continues to gain traction in both empirical applications (Gottlieb et al., 2018) and theoretical development (Schlaufer et al., 2022; Shanahan, 2023). In line with the research approach of this thesis, the narrative policy framework embraces pluralistic scholarship (Jones and Radaelli, 2016).

Participant observation

Participant observation is a method characterised by researcher engagement in the environment of the studied context or discourses. The researcher observes the group's behaviour and listens to the internal conversations. However, it is not only about observing. Typically the researcher also conducts interviews and collects written sources about the context to enhance the understanding of the culture (Bryman, 2018). In Paper IV, participant observation is one of many ways in which the representations of the circular carbon imaginary are collected and explored. It is not a long-term observation typical for such methods but builds on a similar foundation. In Paper IV, the idea behind participant observation is to complement the representations of the imaginary in published documents, strategies and policies with the arguments used in an internal and somewhat more informal setting. It seeks to better understand how professionals from the plastics industry describe the future of plastics among their peers in a so-called natural environment.

The participant observation can be classified as taking part in an open or public environment and via an open role. The chosen environment was the world's largest trade fair for plastics and rubber, the K2022 Fair in Düsseldorf, Germany. When participating in the biannual trade fair in October 2022, I did so in an open role, meaning that I told those I engaged with that I was a researcher interested in ideas of circular carbon and that I was at the fair to collect data. The environment can also be classified as open and public, at least for those with the monetary capacity to pay the entrance fee and high accommodation prices[1]. Nevertheless, in contrast to a closed environment, where a researcher must gain permission to participate, the trade fair is a public and open space. During the fair, observations were collected in the form of extensive notes, sound recordings and photos, but also through engaging in conversations with some key actors to gain deepened information on how they envision the future for plastics.

Interviews

To explore the policy narratives surrounding EU plastics governance, my co-authors conducted semi-structured interviews with key stakeholders. Even if the interviews were not conducted by me, I wish to here reflect on the method since I have used and analysed the data. The interviews were performed using an interview guide consisting

[1] The entrance fee was approximately € 150, and the only accommodation in Düsseldorf available within budget was a shared apartment with a nudist. In the end, I booked a hotel room in another city and commuted to the fair.

of open-ended questions designed to encourage the stakeholders to speak freely about their views on governance approaches to address the problems plastics are causing. While following the interview guide, they posed open questions and maintained a flexible position that allowed the interviewees to speak freely about the subject. They listened attentively, letting the person finish what they were saying, but also remained critical and interpretive by returning to subjects that were not clear or that were of specific interest to the research with follow-up or clarification questions (Kvale, 1996). In total, 16 semi-structured interviews were conducted with stakeholders engaging in EU plastics governance. This included four EU officials or policymakers, four business-oriented actors and eight environmental think tanks or NGOs. The actors were identified via desk research and snowball sampling and had all played a role in influencing or shaping the EU plastics strategy. All the interviews were transcribed and subsequently listened to and read several times by all the authors. Statements and illuminating quotes were highlighted, allowing the policy narratives to emerge from the material. In this iterative process, four mutually exclusive policy narratives took shape.

4 Summary of papers

This chapter summarises the papers, taking into consideration what is most relevant to the thesis aim. It is not a list of extended abstracts but rather a synthesis of how the different papers connect to one another and the aim, based on what I find to be the most interesting findings, tensions and conclusions. The papers all include several other interesting contributions that are not discussed here or elsewhere in the thesis. This is not a mistake or coincidence but should be considered a consequence of the interdisciplinary work this thesis builds on. Table 1 presents the paper's empirical scope, key concepts, methods and theoretical entry points to showcase the multiplicity of perspectives applied, thus further demonstrating the interdisciplinary nature and empirical focus of the thesis.

Table 1: Summary of the empirical scope, key concepts, methods, actors and theoretical entry points of the papers included in this thesis. CCU = carbon capture and utilisation.

	Paper I	**Paper II**	**Paper III**	**Paper IV**
Empirical scope	Electricity demand for CCU-based plastics production	Expectations within the CCU research community	Policy narratives of plastics within EU governance	Circular carbon imaginary as a mitigations strategy
Key concept	n/a	Expectations	Policy narratives	Imaginaries Mitigation deterrence
Method	Techno-economic assessment	Discourse analysis	Narrative policy framework Interviews	Discourse analysis Participant observations
Actor/ Data	Scientific literature	Scientific CCU community	EU policymakers	Petrochemical industry
Theoretical entry point	Literature review and analysis	Sociology of expectations	Political science	Cultural political economy

4.1 Assessments of electricity- and carbon dioxide-based plastics

Paper I is a first-of-a-kind study that assesses the electricity and carbon dioxide demand for decarbonising plastics by means of carbon capture and utilisation. The plastics decarbonisation pathway explored is based on renewable electricity, water and carbon dioxide. The production route consists of a combination of hydrogen (produced via water electrolysis) and carbon dioxide that reacts to the most common plastics feedstock, namely ethylene and propylene. What might sound like a crazy idea – producing plastics from air and water – is motivated by two things. First, the imperative of decreased climate impact on the plastics production system via switching from fossil to decarbonised feedstock and energy. Second, the limitations and scarcity of other non-virgin-fossil feedstocks, such as biomass or recycled plastics, motivate the need to explore other pathways. As well as going deep into the technical details of this low-carbon route, the results inform a discussion on multiple decarbonisation pathways and the limits of technological solutions.

In Paper I, the detailed assessments for ethylene and propylene production are scaled up to include all plastics feedstock in the EU by 2050. The results, building on technological developments and improvements, indicate that approximately 1600 terawatt hours (TWh) of electricity would be required to cover current plastics production levels. To put the numbers in perspective, this represents over half of EU net electricity generation in 2022 (approx. 2600 TWh) (European Council, 2023), implying that more than an additional 50% increase in electricity generation would be needed to produce this form of decarbonised plastics alone. For this development to be a low-carbon effort, the electricity would need to be renewable. The scale of the increase in renewable electricity demand is illustrated in Figure 2.

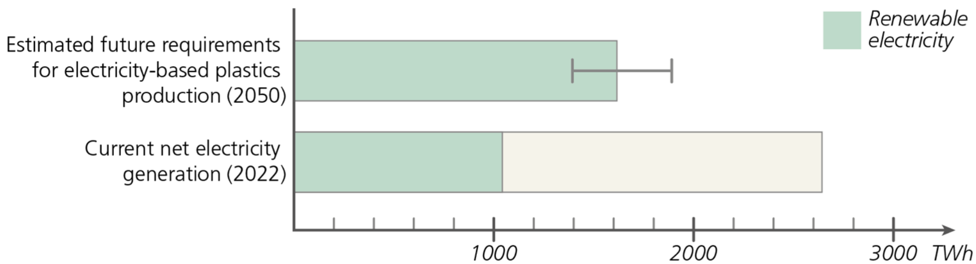

Figure 2: The estimated range of renewable electricity requirements for electricity- and carbon dioxide-based plastics production in the EU by 2050, compared with current (2022) EU net electricity generation. Green indicates the share of renewable electricity. TWh = Terawatt hours.

Electricity generation is expected to increase. Scenarios for 2050 in the EU range between 3800 and 6400 TWh, depending on the level of electrification of the industry and transport sector (Tsiropoulos et al., 2020). In either case, the estimated renewable electricity demand for an electricity-based plastics system must be considered very large.

The estimates for carbon dioxide demand and production cost of electricity-based plastics production add to the complexity of this decarbonisation route. The carbon dioxide requirement is calculated to be 180 megaton, and the available carbon dioxide from biogenic point sources and waste incineration (including both fossil and biogenic carbon dioxide) is estimated to be about twice that (395 megaton). This indicates that half of the point source carbon dioxide within the EU would be needed to cover its plastics production (Ericsson, 2017). Since carbon dioxide is not one of the cornerstones of our societies, this might not pose the same type of challenges as the electricity demand. The production cost of this process is mainly driven by the energy demand and is estimated to be two to three times higher than that of today. However, if the cost model were to include the capture, cleaning and transportation of carbon dioxide, it would be even higher.

These results exemplify the issues of imagining that there will be a one-size-fits-all technical solution to decarbonising plastics. The large amount of renewable electricity demand and the significantly higher cost inform the discussion of where and how to use plastics. Participating in conferences within the emerging field of carbon capture and utilisation, I was intrigued by the conversations on promises and expectations. What should a technological option deliver to count as carbon capture and utilisation? What is the risk of confusing carbon capture and utilisation as a 'sibling' of carbon capture and sequestration? And would that be an issue of legitimacy and credibility for the climate-friendly technology they considered themselves to be developing? Questions like these and others guided the interest in exploring expectations and promises expressed within the scientific community and led to the study in Paper II.

4.2 Conflicting expectations on carbon dioxide utilisation

The increased interest in technologies associated with carbon dioxide utilisation is accompanied by conflicting expectations. Paper II finds that the overarching expectation in the scientific literature on carbon dioxide utilisation lies in its ability to mitigate climate change. In the cases where climate mitigation is not highlighted as the main benefit of the technologies, other motivations, such as resource efficiency or feedstock security, are emphasised. The climate benefit of carbon dioxide utilisation is problematised since few studies show that using carbon dioxide as a carbon feedstock has that potential. As demonstrated in Paper I, replacing all fossil energy and feedstock for the plastics system in the EU would require implementation of renewable electricity on an enormous scale. As well as the energy issue, there are technology- and innovation-related uncertainties associated with developing or implementing such large technological systems (de Kleijne et al., 2022), not to mention the politics of such a roll-out (Malm and Carton, 2021). Furthermore, the scale of the carbon dioxide required for the EU plastics system (approx. 180 megaton according to Paper I) is not in the same order of magnitude as the annual carbon dioxide currently emitted in the EU (approx. 2800 megaton in 2022) (IEA, 2023). Hence, even if all plastics could be produced from carbon dioxide, the mitigation potential from carbon dioxide utilisation should not be overestimated. Consequently, developing these technologies should not be seen as an enabler of continued greenhouse gas emissions or plastics production growth.

From the overarching but contested problem definition of climate mitigation, three subthemes of conflicting expectations on carbon dioxide utilisation emerge. The key conflicts exposed in Paper II concern what carbon and energy sources are to be included, what end-products are most relevant and how the technology relates to carbon capture and storage. First, conflicting requirements on the sources of energy, hydrogen and carbon dioxide are presented with different answers to the question of whether those inputs should be renewable, fossil or perhaps both. Sometimes the source of the essential inputs is not even mentioned but simply thought of as framed out of the technological system. This indicates that inputs such as electricity, carbon dioxide and hydrogen will be available on this scale at the time and that their climate impact is not a crucial part of the benefits of carbon dioxide utilisation. The tensions and potential consequences associated with using fossil or non-fossil input are sometimes recognised within the field.

Second, conflicts are evoked about the framing of carbon dioxide utilisation, posing questions on the relationship to carbon capture and sequestration (CCS). While some advocate the advantages of potential synergies between the technologies, others stress the benefits of striving towards closed loops and the reuse of carbon dioxide. In contrast to the conflicting energy and feedstock requirements described in the section above, this conflict is readily acknowledged and discussed within the field. For example, at scientific conferences, it is debated in both workshops and informal conversations. Clear positioning on the question is common in opening talks, typically taking a stance against the less popular carbon capture and sequestration. Furthermore, it is discussed in scientific publications exploring the limits, relationships, and perceptions of carbon capture and utilisation versus sequestration (Bruhn et al., 2016). The limits of what should count as carbon capture and utilisation and its relationship to carbon capture and sequestrations remain contested.

Third, there are opposing ideas on what applications are suitable for the technology. The imagined end-product depends on what is considered most important: market size, long-term mitigation potential or economic viability. If market size and the potential to produce large amounts of the product is important, then fuels are suggested to be the best application. However, since fuels are typically burned and thus emit the carbon dioxide in a relatively short time span, others advocate for the long-term mitigation potential being more important. In those cases, plastics or other materials that have a significantly longer lifetime are considered to be the most suitable applications to develop. Others stress the economic viability of the product as the most important aspect and highlight the existing uses of carbon dioxide in urea or enhanced oil recovery as the most suitable. The relationship between the current fossil energy system and carbon capture and sequestration comes up again in the discussion of advocated application. In some cases, there is lack of agreement as to what is storage and what is utilisation. A recurring discussion regarding suitable applications is whether enhanced oil recovery with carbon dioxide (instead of methane) should be considered storage, utilisation or an oil extraction method with a potentially lower climate impact.

Depending on which expectations become dominant and enacted, implementing carbon dioxide utilisation could result in very different future carbon dioxide emissions and, thus, plastics systems. Paper II concludes that it is important to closely consider the expectations when considering how – and whether – to support an emerging technology. Given the urgency of climate change, and the risk involved in delaying climate mitigation, Paper II argues that it is even more important to use evaluation criteria for the expectations of technologies that claim to contribute to climate mitigation or industrial decarbonisation.

4.3 Narrating EU plastics governance

Plastics policies are shaped by which parts of the plastics system are considered a problem. This means that if something is highlighted as a political issue, it is more likely to be governed (Hajer, 1995; Schlaufer et al., 2022). Building on the narrative policy framework (Jones and McBeth, 2010; Jones and Radaelli, 2016), Paper III finds that EU policymakers mainly understand plastics as a waste issue, with a solution framework oriented towards waste management, and predominantly mechanical recycling. A circular economy is proposed as the answer to the dominating narratives of resource inefficiency and pollution but is understood differently by different actors.

The malleability of the concept works as a bridge between transformative ideas of reduced use and recyclability, and technocentric circularity based on eco-design and recycling.

Plastic policymakers within the EU give remarkably little attention towards the fossil-fuel dependence of plastics production. Paper III unpacks three main arguments for the lack of interest in decarbonising plastics in EU governance. First, there is uncertainty surrounding the environmental benefits of changing the plastics feedstock from fossil fuels to biomass. This is linked to the fear of repeating the mistakes made with the EU renewable energy directive (2009/28). The policy aimed to introduce biofuel to lower the climate impact of the transport sector. However, the methodological guidance presented by the European Commission unintentionally resulted in the promotion of biofuels with a negative carbon dioxide balance. To address this error, the renewable energy directive (2015/1513) was updated with a clarification of the sustainability criteria for biofuel, putting special emphasis on indirect land use change (ILUC). In our interview material, this experience is repeatedly claimed to influence policymakers to avoid advocating for bio-based products again. Since the plastics strategy was developed at approximately the same time, the influence of that recent mistake was considerably large.

Second, the risk of adding complexity to the recycling system by producing new types of polymers. If a new polymer is introduced, it is not very likely that it will be detected or recycled. And it would only be 'recycled' in the statistics, not into a new product. Recyclability and recycling do not aim towards the same goal. Recyclability aims to improve the material and product properties to recycle it into new materials that can enter the plastics system once more (Faraca and Astrup, 2019), for example by improving the design of the polymers and additives so that they fit with current recycling infrastructure or market demands and safety standards (Hatti-Kaul et al., 2020). In contrast, recycling aims to make sure that products are collected from the consumer or market and taken to a recycling facility, without a focus on the ability to introduce them back into the system (Ragaert et al., 2017). The latter and dominant view is motivated by how the policy targets are constructed, such that all the material that enters a sorting facility counts as recycled in the waste management statistics. Sorting facilities can typically detect a handful polymer types, and a large proportion of the plastics that enter a recycling facility are rejected and not recycled into a new product or material (Geyer et al., 2017). Thus, the recyclability of new materials is also highlighted as an issue that hinders policymakers from pushing for the development of new decarbonised plastic polymers.

Third, the dominant resource inefficiency narrative and its proposed solution of circular economy are increasingly also becoming the measure to address decarbonisation. The underlying idea is that increased recycling would result in an increased amount of recycled feedstock, which would decrease the demand for virgin fossil feedstock. This builds on the idea of a substitution effect, where recycled feedstock replaces the use of virgin fossil feedstock. In such a framing, the need for phase-out policies is largely ignored. The latest revision of the EU packaging directive includes a proposal for requirements for recycled content in plastic packaging (COM/2022/677). However, the imperative of recyclability and requirements for safe and more sustainable recycling (Groh et al., 2019), is still in its infancy within EU plastics governance and decarbonisation efforts are toned down in relation to other measures.

4.4 Imagining circular carbon: A mitigation (deterrence) strategy

In this last paper of the thesis, framings associated with circular carbon are explored, taking actors connected with the petrochemical industry as a starting point. Promoting a circular carbon economy is one of the industry's leading decarbonisation strategies, so from a societal and scientific perspective, it is important to scrutinise it. Further, Paper IV informs a discussion on the decarbonisation strategies that are not considered and thus risk being neglected. Interestingly, the previously mostly scientific debate on carbon capture and utilisation, which were analysed in Papers I and II, have now entered the sphere of policymakers and industry actors. Hence, the research focus here moves towards how industry actors envision decarbonised plastics production through circular carbon. The main argument of the paper is inspired by the literature on mitigation deterrence, as introduced earlier (Markusson et al., 2018), but moved from carbon removal technologies (Carton et al., 2021), and instead applied to the empirical realm of plastics.

Based on discourse analysis and participant observation, a variety of representations of the broader imaginary of carbon circularity are unpacked. The circular carbon imaginary is based on a diversified and circular flow of carbon to enable the continued production and growth of plastics. It builds on the collection, capture and utilisation of highly diversified forms of carbon-based sources such as plastics waste, carbon dioxide, biomass and sometimes fossil fuels. Known concepts within (industrial) decarbonisation such as 'circular economy' and 'renewable energy' are reframed to fit the petrochemical industry in terms of 'circular carbon' and 'renewable carbon'. The imaginary entails similar elements to the expectations unpacked in Paper II but sketches an even broader vision, building on larger flows and more diversified carbon sources.

These carbon sources are all thought to provide the necessary carbon feedstock for the growing production of plastics and other carbon-based chemicals in the petrochemical industry. However, the success of such decarbonisation relies heavily on promises of technological improvements and innovations.

Paper IV explores how the circular carbon imaginary risks delaying other decarbonisation efforts, and thereby promoting mitigation deterrence. By overlooking the need to reduce the production (growth) of plastics to mitigate both its climate impact and other environmental and sustainability related issues, it frames out the imperative of reduced production or consumption as decarbonisation strategies. Such low-risk and low-tech mitigation pathways could include practices, infrastructures, business models and governance related to reduction or reuse. The imaginary also neglects crucial uncertainties and risks associated with the proposed developments, including – but not limited to – energy demand, innovation failures and economic feasibility. Expectations of emerging technologies tend to be set high, and if they were to be realised, they would not perform at the same level (Borup et al., 2006). This is not recognised. Instead carbon management – a strategy that fit with current market structures and power relations – is proposed to provide a decarbonisation strategy where nothing needs to be lost, and the petrochemical industry can replace its current use of fossil fuels with what was previously considered waste. Namely, emitted carbon dioxide, plastics pollution and biproducts from harvested biomass. Taken together, the circular carbon imaginary as a mitigation strategy fails to acknowledge the possibility of not delivering on its promise and risks promoting mitigation deterrence.

Even though Paper IV points out several shortcomings of the circular carbon imaginary, this does not mean that I consider it to be inherently bad. Instead, I advocate for the importance of developing these high-tech strategies if the petrochemical industry aims to decarbonise. The point is that, like all decarbonisation pathways, the technologies associated to the circular carbon imaginary entail limitations, trade-offs and risks that hinder them to replace the current fossil-based plastics production. Therefore, other mitigation strategies must be considered simultaneously to decarbonise the plastics system and not risk delayed climate action.

5 Discussion

Taking the findings and methodological considerations as the starting point, the main contributions of the thesis are discussed in two different ways. It first narrows down into the various forms of carbon circularity explored in the papers. This part of the discussion highlights the tensions that arise from carbon capture and utilisation and the broader framing of carbon circularity as a mitigation strategy for plastics. These tensions carry some form of incompatibility that is likely to become problematic if such framings or technologies are brought closer to a realisation. Departing from the thesis aim to explore and unpack tensions in decarbonising plastics, the discussion connects the findings from policy narratives in EU plastics governance, techno-economic assessments and expectations of carbon capture and utilisation, and the circular carbon imaginary. Then the discussion broadens out and advocates the necessity to investigate multiple and diverse plastics decarbonisations. It builds on the need to include more than one perspective or interest in such efforts. The section highlights the relevance of applying plural analytical concepts within this form of interdisciplinary research, as well as provides some suggestions on the paths ahead for future plastics governance. It stresses that the dominant approaches and technologies are not sufficient to address the complexities of plastics decarbonisation. This contributes to the overall argument and conclusion that actors engaged in plastics governance, petrochemical production and technology development should cultivate multiple perspectives and pathways for plastics decarbonisation.

5.1 Decarbonising plastics via carbon circularity

Carbon capture and utilisation has emerged as a mitigation strategy for plastics. This idea, which builds on tapping into the natural carbon cycle and producing plastics from carbon dioxide and water, is gaining ground and growing within the scientific community (Papers I-II), plastics governance (Paper III) and industry actors (Paper IV). However, the understanding that is portrayed is highly technological. To discuss the variations in the empirical findings and conceptual diversity of the papers included in the thesis, I depart from the idea of carbon circularity. Representations of carbon circularity are present in the techno-economic assessment, expectations, policy narratives and imaginaries explored in the thesis. These ideas often contain a strong normative goal of realising the various forms of circularity in a not-too-distant future. In the subsequent sections, I will discuss carbon circularity and what might be obscured in such notions within EU plastics governance, the scientific literature of carbon capture and utilisation, and actors around the petrochemical industry.

Representations of circularity are dominant within EU plastics governance. The scale of circularity focuses on plastics as a material and emphasises increased collection of plastics waste for mechanical recycling to enable a circular economy for plastics. The concept of circular economy has been shown to articulate vague and uncontroversial expectations within EU governance (Lazarevic and Valve, 2017). Adding to that, Paper III show that such win-win narratives bridges gaps between the various policy narratives, irrespectivley if they depart from the issues of fossil feedstock dependency, resource inefficiency, pollution or toxicity. Overall, circularity is understood as change-enabling and predominantly motivated by the benefits of resource efficiency and feedstock security (i.e. not being dependent on imported fossil feedstock). Most policy actors make use of the narratives through strategic construction to advocate their specific understanding of the circular economy as mechanical recycling, and such end-of-pipe recycling solutions are thought to achieve a circular economy, decarbonisation and less pollution at the same time.

The policy narratives overlook the inability of certain technical options to address the multiple environmental and social crises associated with plastics. Thus, there is a tension between advocating for circular economy as the policy solution for all plastics related issues and downplaying the climate impact of the plastics system in such understanding. The lack of interest in decarbonisation efforts within EU plastics governance is particularly noteworthy. Instead of advocating more transformative directions, the policy issues are found to be formulated so that technologies that fit with current market and governance structures are favoured. It therefore becomes important to look beyond the dominating policy narrative of circularity as the answer for all issues derived from the plastics system. Issues connected to the toxicity, climate and biodiversity impact of plastics all need more policy attention. Taken together, the incremental solutions suggested by the dominating policy narratives carry little transformative potential towards decarbonisation.

Within the scientific community developing carbon capture and utilisation, the representations of carbon circularity are formulated predominantly by chemists. Circularity moves here from plastics as a material to a molecular level focusing on carbon atoms. Chemical engineers and chemists working to develop the technology strive towards making the almost inert molecular bonds in carbon dioxide react to an energy-intensive molecule such as methane or methanol. Through further reactions, these molecules can be transformed into the basic polymers needed for plastic production, and Paper I shows that such processes require large amounts of renewable electricity. This implies a future trade-off, and potential tension, between producing decarbonised plastics and the availability of renewable electricity. Envisioning a single technological solution for plastics decarbonisation further highlights the issues inherent to such narrow perspective. As such, chemical or mechanical recycling alone are not likely to replace fossil-based plastics, neither are bio- or carbon dioxide-based feedstock. Instead, if any of these decarbonisation options are developed, they are more likely to be just one part of multiple and context-specific decarbonisation pathways. A myriad of technologies, scales, actors and institutional settings could shape the decarbonisation efforts. For example, policies to introduce reuse measures and high-tech chemical recycling facilities could both contribute to decarbonisation in their specific ways. From a north-western European perspective, perhaps fossil-based plastics could be replaced by chemical recycling around the petrochemical infrastructure in Germany and by bio-based plastics in the cluster with proximity to and an established relationship with forest owners in western Sweden. While recognising that this supply-side technology-specific discussion excludes other sustainability issues, it should be highlighted that they cannot be solved by only changing feedstock. Nevertheless, this paper informs and opens up a discussion on multiple perspectives and decarbonisation pathways for the plastics system.

The results from Paper I inform a thought experiment for how a future plastics system could change. Besides numerically exploring a technological decarbonisation pathway for plastics, it poses questions regarding for which applications and by which actors plastics should be used. The underlying idea of the study is that if the EU is to decarbonise, it becomes self-evident that plastics production should too. Paper I shows that such decarbonisation is possible from a technological perspective, but if one third of EU electricity generation were required for plastics production alone, what would that mean for the structure of the plastics system? Perhaps it would become easier to decide what was an unnecessary use. Even if the material cost often represents only a proportion of the final product or application cost (Rootzén, 2015), it is not unlikely that a three-fold increase in cost of the material would accelerate conversations on where and how to use plastics. Deciding what is an unnecessary use of plastics is by no means an easy or uniform task. In the EU, the discussion has taken as its starting point the 10 single-use items most commonly found on beaches, but in other geographical contexts the consumption and pollution patterns are likely to be different. It might also accelerate other mitigation pathways with lower costs, and higher technological readiness, such as reduced demand, reuse of items and significantly improved recyclability. Examples could include stricter design requirements and recycling systems developed because of the increased energy demand and production cost of the material. Such discussion could inform the ongoing conversation on a global production cap on plastics (Bergmann et al., 2022; Pacific Environment, 2023).

The overarching idea of carbon circularity is that it will enable decarbonisation. This includes both the scientific community of carbon capture and utilisation and actors in and around the petrochemical industry. Within the scientific community, carbon circularity entails conflicting expectations of the emerging technologies of carbon capture and utilisation. These conflicting expectations are apparent on different levels and concern both what to name and include in the concept, as well as the underlying issues and expectations of which problems carbon capture and utilisation can 'solve' and how it 'should' be used. Since some representations include a continued use of fossil energy and feedstock, this creates a tension between promising to mitigate climate change while using fossil fuels. Within the petrochemical industry and among actors supporting its development, carbon circularity is similar but portrays a broader imaginary with even greater focus on the carbon atom. Carbon is portrayed as the atom of life that enables our current lifestyle and that, through smart management of its various forms, will become the core of the industrial mitigation strategy. The imaginary entails ideas of diversified, endless circles of carbon that enable unchanged or even increased use and production of petrochemicals while achieving societal goals of net zero and climate neutrality. Thus, this imaginary presents a tension of a technical solution to a decarbonised plastics system while not acknowledging other mitigation strategies. Further, the need to reduce the production of plastics to achieve decarbonisation, or address the wider plastics crisis, is not recognised.

Carbon circularity represents a plastics decarbonisation where carbon dioxide emissions are reused rather than released. Thus, carbon dioxide becomes a resource rather than a waste product or 'simply' a troublesome greenhouse gas. This further illustrates the malleability of the circularity concept and the ideas associated with it. All the papers included in this thesis relate to different forms and scales of circularity, such as fossil-free circular economy, circular economy and circular carbon (economy). However, the agreement on carbon circularity and circular economy hides irreconcilable tensions about the concept. This goes for the intended applications as well. The conflicts between the envisioned implementation of carbon capture and utilisation point to fundamentally different futures. Some expectations builds on an increased or at least continued use and extraction of fossil fuels for plastics production, whereas others imagine a plastics system based solely on renewable energy and feedstock. Despite these differences in system properties and end goal, these actors all advocate (their version of) a circular carbon imaginary. It is important to expose these conflicting expectations of investment practices or assessment criteria. Otherwise, there is a risk of delayed or failed decarbonisation – what has become known as mitigation deterrence. Similarly, there are issues associated with understanding the circular economy or circularity as purely collecting waste for mechanical recycling. This narrow framing risks obscuring other circular economy practices and policies, such as reduced use, reuse and design principles of recyclability.

These findings show the issues associated with downplayed decarbonisation efforts in policymaking, the technological potential and limitations of carbon capture and utilisation, and the risk of relying on a single technological pathway. Despite the critique presented above, I do not disregard the mitigation strategies or technologies associated with carbon circularity. Mechanical recycling, carbon capture and utilisation, and the wider circular carbon imaginary might well play important roles in decarbonising the plastics system. However, when engaging with carbon circularity, it is important to give serious consideration to the limitations of each decarbonisation strategy and simultaneously develop others. As this work continues, it is important that the climate impact of plastics receives the attention from the governance and technology perspectives required to address its decarbonisation.

5.2 Cultivating multiple plastics decarbonisations

Avoiding decarbonisation failure requires attention to be given to multiple pathways and perspectives simultaneously. As expressed above, high-tech solutions such as carbon capture and utilisation and the broader set of technologies associated with the circular carbon imaginary can have an important role to play in decarbonising plastics. However, such decarbonisation efforts should not hinder other forms of plastic decarbonisation. It is equally important to consider other low-tech, near-term and low-risk mitigation strategies at the same time. These include enabling innovation, governance, infrastructure, and business models for reduced use and production, as well as reuse. Examples include the no-waste events, stores and alternative ways to produce plastics explored in Chertkovskaya et al. (2023). Cultivating multiple decarbonisation pathways and perspectives for plastics can improve both scientific and societal outcomes. This includes developing infrastructure and principles for of both zero waste and carbon capture and utilisation technologies.

The future direction of a technological pathway is not predetermined. There is no linear progression or predetermined future with no alternatives, which is beneficial for all humans and non-humans. This idea of a linear progression enabled by one-dimensional technological development might be convenient, but is problematic (Stirling, 2008).

When supporting the technological development in industrial decarbonisation, the multiplicity of innovations and potential paths ahead are typically downplayed by asking questions about how much or how fast. Acknowledging the multiplicity of perspectives and pathways could instead be enabled by asking questions about what directions, why and according to whom (Leach et al., 2010)? By preparing and predicting in different directions and from different scales and perspectives, we can hedge our bets for reaching the normative goals we have set for our societies, such as decarbonisation. Multiple mitigation strategies can create a redundancy against the unexpected and, by extension, lead to a lower risk of failed or delayed decarbonisation. This argument is exemplified in Chang (2012) by how we would distribute people in a forest looking for a missing person. Would it be reasonable to send all the resources in one direction or spread them out in multiple directions? Despite such reasoning, mitigation strategies for plastics often tend to rely on the development of a single technological pathway, such as carbon capture and utilisation or chemical recycling.

Cultivating multiple mitigation pathways and ways of exploring them could open up discussions that enable us to see beyond today's power relations, conditions and knowledge systems. This can be done by inviting a broader set of actors representing other interests and different understandings of science in the research and policy–science interactions. In current plastics decarbonisation, the dominant position is that of the industry itself. Of course, the industry should be at the table, but other economic and non-economic interests should also be involved. For example, actors with relevant experience and knowledge of other parts of the plastics system. Based on the actors that are engaged in the UN plastics treaty process, this could include organisations representing fence-line communities, waste pickers, fisheries, tourism, youth, and indigenous people (UNEP, 2022). Not to mention a greater diversity of the variations in scientific knowledge systems that would facilitate a broader perspective of plastics decarbonisation. These actors all bring relevant lived experiences and expertise, which could contribute to multiple perspectives on plastic decarbonisation.

A pluralist reorientation is not about 'anything goes'; it is about allowing more than one perspective. If the normative ambition is to create more sustainable, or at least decarbonised, plastics production, it is useful to take our values seriously in such discussions. If we expose and discuss the underlying values, we can agree to disagree but still understand the other viewpoint and hence contribute to plural understandings of decarbonisation. For example, if one actor values the precondition that the incumbents of today shall remain the incumbents of tomorrow, then a decarbonisation pathway that favours current market and power dynamics, such as the circular carbon imaginary, might appear to be a desirable direction or perspective. In contrast, if another actor instead values the precondition that mitigating climate change is more important than the continued dominance of a specific company, then the principles of a zero-waste hierarchy or other pathways, perspectives or policies might appear more desirable. If these actors participate in the same policy process, exposing their values and consequent preferred futures, this might pave the way for a discussion on values, pathways or perspectives that they can agree to disagree or potentially act on. This might sound like an unambitious approach to pluralism, but it could be a starting point to cultivate multiple plastic decarbonisations.

If we can not even imagine alternative systems or problem framings, it is not likely that we will govern, develop technologies or act in those directions. There is a lot of power and economic interest in shaping the future in a way that favours the incumbent actors. However, that direction is not necessarily compatible with decarbonisation. My research here, and elsewhere (Tilsted et al., 2023), contributes to making this visible and can inform future research that further explores this relationship and the mechanisms behind it. In order not to leave the development of decarbonisation solely to commercial interests, it is important to facilitate a discussion that includes representatives from other parts of society. Therefore, I argue that a pluralistic understanding is necessary to grasp the complexities of the challenges involved in plastics decarbonisation.

In this thesis, multiple analytical concepts from different scientific traditions and disciplines are used to analyse various forms of framings surrounding plastics decarbonisation. Conducting research based on different analytical concepts comes with both drawbacks and benefits. One can ask what forms of conflict or tension exist between the concepts, and if and how that creates methodological inconsistencies. In line with pluralism and interdisciplinarity, a variety of analytical concepts are used to unpack the discourses from different angles, perspectives and scales. Since I do not merge or compare the concepts, whether they are considered to be incompatible becomes less relevant. Instead, I acknowledge and argue for the importance of the differences between the analytical concepts. So, my answer to the methodological inconsistencies would be: Yes, the different lenses are different lenses and thereby offer different ways of looking at things. However, what they have in common is that the discursive aspects all serve to influence or shape the development of plastics decarbonisation. And if presented together, the results can represent something previously not visible.

By unpacking various shapes and forms of framings, this thesis explores a wider variety of perspectives and thus contributes to a broader understanding of plastics decarbonisation and carbon capture and utilisation. The concepts and their results can be seen as pieces of a puzzle that in some places might fit together, but in other cases show variations. Inspired by the famous parable of the blind men and the elephant, where the multiple interpretations of how an elephant feels lead to several conclusions of what an elephant is. Imagine that the papers included in the thesis are four people positioned in relation to the elephant and are asked to describe what they experience. The one on top might describe how the sun and wind feel; the one in front facing the elephant might describe its long trunk. The one underneath the belly could describe the tight space and muddy smell, and the one at the back the disproportionately small tail and big feet. Despite the differences in what is described, all these observations, potential analyses and conclusions are relevant to understanding what an elephant is and how it lives. The benefit of the diverse analytical concepts I have used is similar to this analogy. Plastics decarbonisation is understood differently depending on what actors are studied, their time perspective and their monetary interest in maintaining the status quo of the plastics industry. Thus, using multiple analytical concepts enables an analysis of both technologies and framings associated with the proposed mitigation strategies of carbon capture and utilisation and mechanical recycling. Together, this presents a kaleidoscope of perspectives on plastics decarbonisation.

The range of policy interventions within plastics governance needs to be broadened to cultivate multiple plastics decarbonisations. As there is a need to regulate more actively towards plastics decarbonisation, one starting point could be influenced by the EU climate governance. EU climate governance builds on three main pillars: the renewable energy directive (2023/2413), the energy efficiency directive (2023/1791) and the cap on the total amount of carbon dioxide emissions (EU ETS) (European Commission, 2023c). However, when introducing efforts to decarbonise plastics feedstock, EU policies almost exclusively emphasise the renewable aspect, for example by pushing to increase the share of recycled content, advocating mass balance approaches, establishing sustainability criteria for biomass as well as pushing for a technocentric circular carbon economy (Calisto Friant et al., 2020; European Commission, 2023d). Hence, I suggest that there is a policy gap pertaining to plastics decarbonisation and that more policy attention should be directed towards other parts of the production system. Highlighting this gap, I suggest plastics decarbonisation should also more explicitly address issues of efficiency improvements (i.e. reduced plastic use) and a cap on plastics production to hedge our bets of achieving a plastics decarbonisation. What this would mean for the industry, how such policy measures should be formulated and who should be included in such discussions need more attention. My point is that these issues are currently not considered, and that broadening policy measures in this way, and including various perspectives and pathways, could support a clearer governance towards plastics decarbonisation.

6 Conclusion

Decarbonisation is a necessity to mitigate the plastics systems climate impact. However, the paths towards decarbonisation are contested and remain an underexplored area that requires more research and governance attention. This thesis contributes by exploring the tensions between climate mitigation efforts and the continued use and production of plastics. It does so by assessing carbon capture and utilisation as a technological decarbonisation pathway and by unpacking the conflicting expectations within its research community. Further, it explores and scrutinises EU plastics governance and the petrochemical industries' circular carbon imaginary of decarbonised plastics production. Taken together, the thesis concludes that (i) EU governance downplays the imperative of plastics decarbonisation and the risks associated with industry's fossil feedstock dependency. Further, EU plastics governance is dominated by narrow ideas of circularity that rely almost entirely on the collection of packaging waste for mechanical recycling. (ii) From a technological perspective, plastics could decarbonise by using carbon dioxide as a feedstock through carbon capture and utilisation. However, this process requires large amounts of renewable electricity and relies on largely unproven technologies. (iii) In addition, the imaginaries and conflicting expectations surrounding the climate mitigation potential of carbon circularity point towards different futures. While most representations advocate for decarbonised systems, some include fossil energy and feedstock in such futures, and most do not acknowledge the need for reduced plastics production. If supporting the technological development surrounding plastics decarbonisation, all these aspects must be recognised. Failure to do so risks resulting in delayed decarbonisation efforts. This enhanced understanding of the technologies, governance, imaginaries and expectations associated with carbon circularity is important to navigate the intricate tensions between the climate goals and plastics production.

An important aspect of this research is how certain futures or technologies are highlighted while others are downplayed. This is shown by how framings such as expectations, policy narratives and imaginaries assign meaning or legitimise a technology or system. Further, this thesis highlights the additional importance of acting on plastics as a climate issue within public policy, industry and research. Despite the downplayed importance of plastics' fossil fuel dependency within current EU plastics governance, there are emerging efforts on industrial decarbonisation of plastics. However, those efforts focus mainly on carbon circularity through recycling and carbon capture and utilisation. Going forward, there is a need for a systemic change in how plastics are produced, consumed and managed, and this in turn requires substantive technological, economic and governance change. In such efforts, it is of the utmost importance to think seriously about how policy measures should be formulated and who should be included in these discussions. The thesis argues for the need to cultivate multiple decarbonisations for plastics, which emphasises the importance of considering various high-tech and low-tech options simultaneously. Technocentric strategies can be explored, but only as long as they do not obstruct other mitigation strategies, since one perspective or technology is insufficient to address the complexities of plastics decarbonisation.

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Decarbonising plastics

Plastics are both based on and produced by using fossil fuels. The production and use of plastics thus conflict with the fossil fuel phase-out needed to mitigate climate change. Nevertheless, plastics decarbonisation remains a relatively understudied issue. This thesis explores and discusses plastics decarbonisation through the technologies and framings that surround the mitigation option of carbon capture and utilisation and carbon circularity. It concludes that multiple plastics decarbonisations are needed and that narrowing down to one perspective or technology risks the decarbonisation efforts failing or being delayed.

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