UNIVERSITY OF TWENTE.

TEXTILMASCHINEN Thies

Evaluating Thies´s Carbon Footprint and Devising Effective CO2 Reduction Strategies

Abstract

This thesis seeks to estimate the carbon footprint of Thies GmbH & Co. KG and to determine best areas to reduce emission. The primary sources include emissions from manufacturing processes, indirect emissions from purchased electricity, and emissions from stainless steel usage. Based on the findings, the following strategies should be undertaken: Use of renewable energy, adoption of energy-efficient technologies, use of energy management systems, and circular economy principles. These measures, when implemented together, lead to higher sustainability and economic benefits.

Keywords: Emission Reduction; Carbon Footprint; SDG; Sustainability; Textile Industry

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Research Information

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Preface

Dear reader,

In front of you is the bachelor thesis "Evaluating Thies´s Carbon Footprint and Devising Effective CO_2 Reduction Strategies." This research, conducted at Thies GmbH & Co. Kg in Coesfeld, marks the culmination of my Bachelor´s degree in Industrial engineering and Management at the University of Twente.

I would like to thank everyone at Thies for their support throughout the project. Special thanks are given to H. Evers for his guidance and insights, which were instrumental in navigating the complexities of this assignment.

I am also grateful to my academic supervisors at the University of Twente. I owe a special debt of gratitude to dr. H. Chen and dr. D.M. Yazan for their continuous support, extensive feedback, and encouragement during the process.

I hope you find this thesis both informative and engaging.

Lennart Engels

Management Summary

The textile industry is known to be one of the major polluters of the environment in terms of CO_2 emissions, water pollution, resources depletion, and waste output. The purpose of this thesis is to analyse the carbon footprint of Thies as a machinery manufacturer and to determine possibilities of reducing their emissions. This evaluation is crucial to ensure that Thies´s operations are in line with the SDGs while at the same time remain viable and competitive in the market.

Problem Identification

The paper looks at the extent to which the textile industry contributes to the emissions of CO_2, taking into consideration the different phases of production. Thies GmbH & Co. KG is a German company that specializes in the manufacturing of textile machinery for wet finishing. Hence, Thies is not a small polluter within the textile supply chain. However, they can have a good downstream effect. Still, there is a discrepancy between the company´s CO_2 emissions and the required SDGs although their strong commitment to sustainability.

Research Focus

The central research questions addressed is:

"What emissions reduction strategies can Thies implement to align its CO_2 emissions with the Sustainable Development Goals while maintaining operational efficiency and market competitiveness?"

To answer this, the study focuses on identifying the primary sources of CO_2 emissions within Thies´s processes and exploring effective mitigation strategies.

Methodology

The study uses a hybrid life cycle assessment model for tracking Thies´s Scope 1 and Scope 2 emissions and an environmentally extended input-output analysis for Scope 3 emissions. The data collection includes quantitative methods for precise measurement of emissions and qualitative approaches for understanding operational practices. Additionally, and Excel workbook was created to run distinct emissions scenarios once global and once specific for Thies.

Key Findings and Recommendations

1. Primary sources of emissions:
   - Direct GHG from manufacturing processes.
   - Indirect GHG from purchased electricity.
   - Emissions related to the use of stainless steel.
2. Recommended emission reduction strategies:
   - RE sources: Switching to company owned solar, wind, and hydroelectric electricity.
   - EET: Utilizing superior technologies to improve energy saving.
   - Energy management systems: Implementing control systems and improve energy efficiency.
   - CE practices: Adopting the principles of the three R´s in the management of waste materials and by-products.

Value Impact

Implementing these strategies can substantially enhance Thies´s sustainability. RE and EET can minimize the direct and indirect emissions. Additionally, the energy management systems can help to minimize the overall energy use. Besides that, CE can further decrease waste production and promote resource efficiency. Furthermore, the design of Thies´s machinery to cope with CE and to be energy efficient can decrease the footprint of their customers and so the industry footprint drastically.

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1 Introduction

1.1 Sustainability in the Textile Industry

In the rapidly evolving global landscape, sustainability has become a critical focus across industries, driven by the urgent need to address environmental degradation and foster a more sustainable future. Sustainability is basically designed for future generations, such that the current generation enables them to meet their needs while the current generation is meeting their own. This holistic approach encompasses economic, environmental, and social dimensions, ensuring balanced growth that can be sustained over the long term. For industries like the textile sector, which is among the largest polluters globally, the push towards sustainability is not just a response to regulatory pressures but a necessary adaptation to growing consumer demand for environmentally responsible products. The textile industry´s extensive environmental footprint is evident in its substantial water consumption, high energy use, and chemical pollution, all of which contribute significantly to its negative impact. This industry´s operations span from raw material extraction to fabric production and disposal, each stage leaving an environmental mark, primarily through carbon emissions, which are major contributors to global warming and climate change.

Analysing sustainability within the textile industry is crucial because it identifies key areas where improvement can be made to reduce the environmental impact. Such an analysis not only helps in understanding the current state of the art but also in pinpointing sustainable practises that can be implemented. For instance, by shifting to renewable energy (RE) sources, optimising resource use, and innovating around circular economy (CE), the industry can significantly lower its carbon footprint. Moreover, sustainability analysis supports the industry´s compliance with international standards and aids in achieving Sustainable Development Goals (SDGs), particularly those related to responsible production and consumption. It also provides a competitive edge in the market, as consumers increasingly favour brands that demonstrate environmental stewardship. Therefore, for companies like Thies, delving deep into sustainability analysis is essential. Such an analysis not only directs the company toward operational efficiencies and innovations that reduce environmental impact but also helps in shaping a brand image that is synonymous with sustainability and responsible business practises.

The textile industry's ecological impact is alarmingly high since it is one of the top polluters globally. The concern about the environment outgoing from the textile industry is especially paramount because its carbon emissions exceed even those of international flights and maritime shipping. These emissions, particularly scope one emissions, stem from direct operations in the industry. Due to those escalating environmental concerns, there is a rising and critical need for more sustainable practises (Akhtar et al., 2017; Filho et al., 2022).

The textile industry's carbon footprint spans from the complex and wide-ranging supply chain. Energy consumption, both electrical and thermal, plays a significant role in driving these emissions. For instance, the manufacturing phase demands high energy, often sourced from fossil fuels. Transportation, whether it is moving raw materials or finished products, adds to this impact, especially if fossil fuel-based vehicles are used. Making greener choices in these areas, like opting for RE sources or eco-friendlier transportation modes, can reduce the industry's environmental harm (Bevilacqua et al., 2011; Palamutçu, 2015). Nowadays, it is particularly vital to understand and manage the carbon footprint in the textile industry. This includes both the direct greenhouse gas (GHG) emissions during production and the indirect emissions associated with the entire life cycle of textile products including the production machinery manufactured by Thies. Tekin et al. (2024) highlight the importance of evaluating these emissions at various stages of the textile industry. For example, the carbon footprint of raw polyester textile production was found to be 119.59 kg-CO_2/100 kg, emphasising the need for a comprehensive approach to emission analysis. Additionally, adopting energy efficient practises and machinery in textile manufacturing can significantly reduce the carbon footprint. Thies, as a textile machinery manufacturer can tackle here (Yan et al., 2016).

1.2 Company Overview

Thies GmbH & Co. KG was founded in 1892 by Bernhard Thies. The Company has established itself as an innovative leader in the field of textile machinery and complementary equipment for over 125 years. Originating in Coesfeld, Germany, the company has been family-run throughout its history, signifying a commitment to tradition and quality. Thies is specialized in producing advanced process technology for the wet textile finishing sector. Their long-standing presence in industry is marked by significant achievements, including the granting of their first patent in 1894 and early international sales successes in 1926. As a manufacturer of textile machinery for the wet finishing market, there is only limited potential to reduce emissions of the overall fashion industry´s footprint. The main sources of emissions within the textile industry originate from material production, product use, but also wet finishing. The wet finishing sector adds up to 15% to the overall footprint of fashion industry. Hence, the supply of machinery that uses less chemicals, less water, less energy, and produces less waste can still have a significant impact, cutting down the fashion industry´s footprint. Consequently, Thies does not have the capability to reduce the overall fashion industry´s emissions through cutting down their own emissions, but they enable their customers to cut down their emissions which can make a difference in overall sustainability.

1.3 Thies´ Commitment to Sustainability

Since the textile industry is pivoting towards a more sustainable future, emphasise is set on ecological innovations. This shift is spearheaded by collaborations between business entities and policymakers, aiming to create environmentally friendly products and practises. Thies is a key example of this trend. A company known for its dedication to environmental stewardship and the production of energy efficient products. Their approach mirrors the current movement in the textile industry, displaying how leaders in the field can be catalyst for positive environmental change.

The textile industry's shift towards cleaner production and innovative technology aligns perfectly with the SDGs. Thies embodies this evolution. With over 125 years of experience, Thies still addresses the modern challenges of the dyeing industry to stay innovative for instance through their “Signature Series”. They concentrate on sustainable product solutions, exemplifying the industry's move towards environmentally friendly practises that also bolster economic performance.

In the textile industry, innovative practises, particularly the recycling of cotton textiles, plays a crucial role in diminishing CO_2 emissions. Such initiatives not only trim down the industry´s carbon footprint but also engender savings in terms of supply chain and energy expenditures. Specifically, the repurposing of cotton textiles in clothing production emerges as an astute tactic that furthers environmental conservation (Bashir & Clarke-Sather, 2019).

In leading textile-manufacturing countries, such as China, a substantial chance exists to curtail CO_2 emissions. Future estimations suggest that by the year 2025, this reduction may ascend to millions of tonnes, marking a key element in the sector´s quest for eco-friendly and responsible practises (Lin & Moubarak, 2014). Companies like Thies are pioneers in this domain, showcasing a profound dedication to ecological care and energy conservation. Their endeavours mirror a broader movement within the textile industry aimed at reducing CO_2 emissions, a step pivotal for its transition to a more sustainable and ecologically mindful future.

1.4 Problem Identification and Strategic Importance

Contextual Overview

A great aspect of the contemporary textile industry is environmental sustainability with a particular emphasis on reducing carbon emissions. This, as a key player in the textile machinery industry, faces the imperative of aligning its operations with ever-evolving environmental standards.

Variable: CO_2 Emissions

The focus is on the overall impact of CO_2 emissions generated by Thies. This includes a comprehensive evaluation of emissions from all operational facets at the headquarter in Coesfeld.

Norm: SDGs

The industry norm is represented by international and sector-specific SDGs. These standards are not just regulatory benchmarks but also reflect the evolving expectations of stakeholders, including customers, policymakers, and society at large.

Reality: Existing CO_2 Emissions at Thies

The current reality is Thies´s existing CO_2 emissions profile. Preliminary data suggest that while Thies is committed to sustainable practises, there is a gap between current emissions and the desired emissions to meet the SDGs.

Problem Owner: Thies

As the problem owner, Thies is responsible for addressing this gap. The company´s commitment to innovation and environmental stewardship positions it well to undertake this challenge.

Action Problem Statement

"Aligning Thies´s CO_2 emissions with SDGs by identifying and implementing effective reduction strategies across the company´s entire operation."

The textile industry plays a vital role in global CO_2 emissions, and companies like Thies are increasingly focusing on aligning their operations with the SDGs (Filho et al., 2022). This alignment is not just about being environmentally conscious; it is a strategic business move. By adhering to environmental regulations and meeting the growing market demand for sustainable practises, Thies enhances its competitive edge. Addressing these CO_2 emissions yields numerous advantages, including enhanced operational efficiency and diminished risks in the future. Additionally, innovative approaches like the utilisation of biomass as a substitute energy source can augment both environmental efficiency and financial gains (Shiwanthi et al., 2018). Such strategies also favourably impact a company´s reputation and elevate staff morale. Such an ambition of one of the components in the supply chain can have horizontal as well as vertical effects. This means effects on competitors (horizontally) and consequently effects not only on the own supply chain (vertically) but also further. Hence, Thies can play a more significant role in broader movement towards greater sustainability.

1.5 Research Focus and Objectives

In today's world where environmental issues are becoming more pressing and companies are striving to meet sustainability goals, Thies is encountering obstacles in aligning its operations with the SDGs. The main issue lies in the company's carbon footprint, which can be improved by implementing effective manufacturing methods, upgrading technology, and adopting comprehensive energy and waste management strategies. To address this challenge a holistic approach is needed that not only reduces emissions but also incorporates practises into all aspects of Thies´s business model. Some of the hurdles that need to be overcome include material and energy production processes, a lack of energy saving initiatives, sustainable transportation methods, stricter supplier requirements, improved waste management practises, increased employee involvement, and overall lifecycle management. Dealing with these challenges will require a strategy that focuses on advancements, process enhancements, energy conservation efforts, sustainable supply chain procedures, waste handling practises, and encouraging employees to actively participate in sustainability programmes.

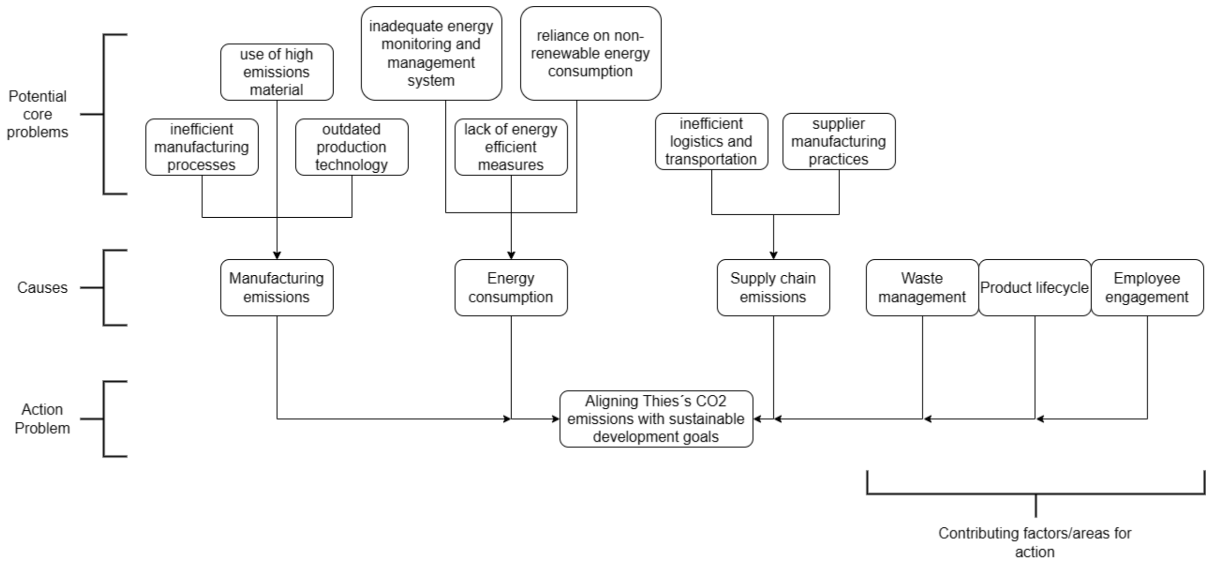


Figure 1: Problem Cluster

To align Thies´s emissions with the SDGs, a structured approach is essential. Initially, a detailed assessment of the company's existing CO_2 emissions from all operational facets is crucial. This involves quantifying emissions and understanding their sources within the company's operations. Subsequently, these assessed emissions need to be opposed against the targets set by the SDGs, particularly those focusing on responsible consumption and reducing the carbon footprint. This benchmarking phase is critical to understanding how Thies´s current emission levels stack up against global sustainability standards. After this comparison, Thies can move forward by pinpointing specific areas where emissions can be reduced. Strategies for reduction should be meticulously analysed for their effectiveness and feasibility. These might include adopting recent technologies, optimising existing processes, or even rethinking certain aspects of the supply chain. The end goal is to bridge the gap between the current emission levels and the SDG targets, thereby contributing to global efforts against climate change.

Based on what was outlined previously, the knowledge problem is composed as follows:

“What emissions reduction strategies can Thies implement to align its CO_2 emissions with the Sustainable Development Goals while maintaining operational efficiency and market competitiveness?”

To comprehensively address the knowledge problem of integrating sustainable practises into Thies´s operations, the following set of research questions should be considered. These questions are designed to dissect the problem into smaller, more manageable pieces.

Knowledge questions:

1. *What are the primary sources of CO_2 emissions in the manufacturing processes of Thies?*
2. *How do different phases of Thies´s operations contribute to its overall carbon footprint?*
3. *What are the current best practices and technological innovations in the textile machinery manufacturing industry for reducing CO_2 emissions?*

Action questions:

4. *What strategies can Thies implement to enhance energy efficiency and incorporate renewable energy sources within its operations?*
5. *How can Thies improve its supply chain management and circularity to reduce indirect CO_2 emissions?*
6. *What barriers might Thies face in fully implementing the SDGs within its operational and strategic framework, and how can these barriers be overcome?*

For a thesis aimed at aligning Thies´s CO_2 emissions with the SDGs, a detailed CO_2 emission report serves as a pivotal first deliverable. This comprehensive report will scrutinise Thies´s current emissions across all facets of operation. It would delve into production, logistics, and other areas to unearth the primary sources of emissions. The analysis should leverage existing models and tools such as those mentioned in the Corporate Climate Responsibility Monitor 2022, the Scope 3 GHG Emissions Programme, and the CRREM Project. By identifying these emission hotspots, Thies can prioritise areas for improvement, aligning their operational practises with broader environmental goals.

Developing a strategic sustainability action plan as a second deliverable for Thies would be a significant step towards reaching the goals. This plan should delineate concrete, achievable steps for the company. It would incorporate a spectrum of strategies, like the adoption of negative emission technologies such as afforestation (Campbell et al., 2022). More innovative approaches, as noted in recent academic studies and frameworks, can also be explored. For instance, insights from the alignment of the European Green Deal and the SDGs and the contribution of supply chain collaboration to sustainable development could be instrumental. The plan should aim not just at prompting CO_2 reductions but also at enduring sustainability objectives. This would involve critically assessing various emission reduction techniques for their practicality and potential impacts, providing a thorough and insightful academic contribution to the thesis.

Furthermore, a recommendation should focus on integrating sustainability into its core business strategy, drawing from insights from the CO_2 emissions report and the sustainability action plan. Firstly, Thies could prioritise reducing carbon emissions, not just through direct operations but also across its supply chain. Leveraging tools and software for decarbonisation could be effective here. Secondly, developing a comprehensive emission calculation tool would help systemize efforts towards climate targets. Thirdly, the strategy should go beyond carbon emission reduction. It could include diverse sustainability aspects such as resource efficiency, biodiversity, and social responsibility, ensuring an integrated approach. Lastly, regular reporting on sustainability initiatives and progress, coupled with a commitment to carbon elimination and credible offsets, should form part of the strategy, aligning with the practises of other leading companies. In conclusion, these deliverables offer a balanced blend of theoretical exploration and practical application serving the strategic needs of Thies in its pursuit of sustainability.

2 Literature Review – Context Analysis

The textile industry is at the centre of global environmental problems and is being criticized for exactly this. All the industries that are critically related to carbon emissions are under reconsideration because of the increased concern about climate change. Thus, this literature review will focus on sustainability in the textile industry with special attention to the knowledge and solutions to the carbon emissions that are emitted from the manufacturing processes in the textile industry.

This review is built in such a manner that the overview should provide the reader with an idea of the current situation of sustainability in the textile industry. It starts with the fact that the importance of the discussion on the sustainability challenges of this sector is put in context, thus, showing the very vital role that the textile industry is playing in the global economy and its corresponding environmental responsibilities. This report then proceeds to detailly analyse the main sources of carbon emissions in textile manufacturing. The process of evaluating Scope 1, 2, and 3 emissions and the sources of carbon release, both directly and indirectly, is the method of study.

The following parts of the literature review deal with the methods and best practises of the industry in depth on how to reduce carbon emissions. The study will examine the recent academic research and case studies of successful sustainability initiatives in textile production that will be useful in learning the effective techniques of CO_2 reduction and how to incorporate these techniques into business models that can be both profitable and environmentally friendly. Besides that, the technological breakthroughs and the regulatory frameworks that are influencing the increasing sustainable practises of the industry are also mentioned in the review. This, on the other hand, critically assesses the role of emerging technologies in the reduction of the carbon footprint and the effect of international sustainability standards and regulations on textile manufacturers. Hence, the review that will become the basis for the design and evaluation of the effectiveness of CO_2 reduction strategies at Thies which will be in line with the global industry´s goals in sustainable development.

2.1 Sustainability and Carbon Footprint in Textile Manufacturing

The textile industry, which is one of the main factors in economic growth worldwide, is also one of the major causes of the environmental pollution, especially through carbon emissions (Stramarkou et al., 2024). The industry is now acknowledging its environmental impact and, accordingly, it is increasingly turning to various sustainable practises. These practises are either the use of eco-friendly materials, energy efficiency, or CE. The textile industry's way to sustainability is a complicated but necessary trip. Through the use of sustainable materials, CE models, and energy-efficient practises, the industry can greatly reduce its environmental impact. Here, manufacturers of textile machinery like Thies, can have a great impact on the circularity, energy efficiency, and materials used by a textile producer. This is done trough providing more sustainable textile machineries.

Innovative material usage and sustainable production methods:

The main change in the textile industry is the move to use sustainable materials and the introduction of eco-friendly production methods. As an instance, Dissanayake and Samarasinghe (2024) investigated the possibility of pineapple leaf fibres as a sustainable option in the textile industry. This shift to sustainable raw materials is not only environmentally friendly but also creates new opportunities for the innovation of the textile industry.

Circular economy and waste reduction:

The idea of a CE is becoming more and more popular in the textile industry. It provides a picture of how sustainable growth can be achieved and at the same time, cut down waste to a minimum. Petänen et al. (2024) studied the circular product-as-a-service business model in the Finnish textile industry, and they pointed out its great potential in reducing the environmental impact significantly.

Energy efficiency and carbon footprint reduction:

The industry is facing the challenge of its contribution to GHG emissions, and thus energy efficiency and carbon footprint reduction are the main topics that are being discussed. Stramarkou et al. (2024) show that industries are the biggest source of GHG emissions which is why, among other things, there is a need for sustainable energy practises.

Regulatory frameworks and sustainability standards:

The textile industry is also being influenced by the regulatory frameworks and the international standards that are set for sustainability practises. These rules are driving manufacturers to more eco-friendly operations, thus the companies will be in compliance with the global environmental standards.

Challenges and opportunities:

Although the textile industry has made a lot of progress in the field of sustainable practises, it is still struggling to incorporate them into the whole industry. The shift entails huge investments, the invention of new technologies, and a change in the way consumers behave. Nevertheless, the trend of sustainability is increasing the chances of cost reduction, invention, and differentiation in the complex textile market.

The large carbon footprint of the textile industry is the result of several factors, such as energy consumption, raw material production, and manufacturing processes. The industry´s impact extends from the first stage of raw material production to the end-of-life management of products. The production phase is a significant factor in the industry's carbon footprint. The processes that are energy-intensive like spinning, dyeing, and finishing are the main factors in this case. This is where Thies´s machineries operate. For instance, Zaman et al. (2023) point out that the spinning process is very important and has a huge carbon footprint. This recognition emphasises the need for more environmentally friendly processes in these manufacturing phases. Besides, the application of chemicals in the textile manufacturing process is one of the main causes of the industry´s carbon footprint and negative environmental impact, especially in the dyeing and finishing processes. Li et al. (2024) conducted research on the sustainability of chemicals in consumer products, which also include textiles, thus, they highlighted this problem. The study, which uses the carbon footprint as a measure, finds out some chemical additives that make the textiles environmentally burdensome and harder to recycle. Due to the environmental issues that the textile industry faces, the industry is now more and more adopting the sustainable production methods. The above-mentioned practises are not only intended to cut the carbon footprint but also to be in accordance with the general worldwide movement towards sustainability. Chipambwa (2024) stresses the importance of the demand of consumers in the promotion of the industry to pursue more sustainable practises; thus, the consumer´s awareness is a main factor in the process of change. In addition, the worldwide movement towards green manufacturing in the textile industry is becoming more and more popular, as proven by bibliometric analysis. This trend, which is emphasised by Sarker and Bartók (2024), shows that there is a rising concern about the carbon footprint that is caused by the old textile manufacturing processes. The change is mainly because of the requirement to solve the serious environmental and health problems. Finally, the textile industry´s path to reducing its carbon footprint is a complex one that requires a multi-faceted approach throughout the supply chain. From the implementation of energy-efficient processes and sustainable materials to the acceptance of manufacturing practises the industry is increasingly aligning its operations with the SDGs.

The issue of carbon emissions in the textile sector is a major challenge that needs to be tackled, and it is essential to find and apply the best practises that will help to decrease CO_2 emissions. This exploration not only goes with the global need to protect the environment but is also a way to meet consumer demand for more sustainable products. The textile industry can gain a lot from these practises when being applied systematically. These are the areas of the industry that are being improved by the optimization of energy consumption, the substitution of sustainable dyeing and chemical management practises, the introduction of recycling and CE concepts, and the use of sustainable materials.

Reduction Strategy	Explanation
Energy Efficiency and Renewable Energy	Energy efficient technologies and the process design optimization can, in a big way, cut down the energy consumption and the CO_2 emissions of textile production. Besides, the green energy use such as solar or wind power is another way to reduce the carbon footprint.
Chemical Management and Sustainable Dyeing Practises	Sustainable dyeing practises, such as using eco-friendly dyes and mordants, can substantially reduce the carbon footprint. Research by Schmidt-Przewoźna and Rój (2023) discusses the reduced water consumption dyeing methods based on supercritical technologies. Hence, offering an alternative to conventional dyeing methods. These methods not only decrease water usage but also reduce energy consumption and CO_2 emissions.
Circular Economy	This also entails the recycling of materials such as carbon fibre-reinforced composites, which demonstrates that mechanical properties can be kept while at the same time reducing CO_2 emissions. The idea of CE in textiles leads to the reuse and recycling of materials, which in turn, cuts off the waste and the need for new materials, thus, the CO_2 emissions are reduced.
Sustainable Material Use	This includes the use of natural fibres, recycled materials, and biodegradable fabrics. The integration of sustainable materials reduces the overall environmental impact of textile products throughout their lifecycle.

Table 1

2.2 Case Study of Sustainability in the Textile Industry

The journey towards sustainability in the textile industry is multi-dimensional, involving a blend of social, environmental, and economic considerations. This presents numerous opportunities for implementing sustainable practises. Examining case studies from various parts of the world provides valuable insight into how different entities within this industry are navigating the path towards sustainability. Therefore, this section delves into three distinct case studies, each highlighting different aspects of sustainability within the industry.

Social and Environmental Sustainability in Ecuadorian Textile MSMEs (Micro, Small, Medium Enterprises) is a study of social and environmental challenges and opportunities of the Ecuadorian textile MSMEs. The textile industry in Ecuador, and especially the MSMEs, is a good example of the integration of social and environmental sustainability (Sigcha et al. , 2024). Through the use of the Social Organisational Life Cycle Assessment (SO-LCA), this study provides the reader with knowledge on how these enterprises go about their business, from the sourcing of raw materials to the final product distribution. The MSMEs are, indeed, working on the improvement of labour practises and community engagement, as well as their initiatives to cut down on water and energy consumption. These findings prove that small-scale operations can be a main factor in the sustainability agenda and that sustainability practises are not the only ones for large corporations.

Pre-consumer waste recycling in Bangladesh´s textile industry is a process of transforming the unused or unwanted materials from the production of textiles into new products. Waste management is one of the most essential aspects of sustainability in the textile industry, which is very well illustrated by the textile and garment manufacturing industries in Bangladesh (Azad et al. , 2024). This case study gives an example of new ways of recycling that are used to deal with pre-consumer waste, like textile scraps and defective garments. The investigation gives a detailed account of recycling in these industries, talking about the difficulties and chances of the expansion of these practises. In addition, it stresses the importance of the infrastructure, policy, and market demand for recycled materials, thus drawing the whole picture of waste management in one of the biggest textile-producing countries in the world.

Sustainable Manufacturing in global fashion businesses is a process that makes fashion businesses environmentally friendly and good for the future while still maintaining profitability. The whole global fashion industry, which has a very large territory and influence, provides a wide field for the research of sustainable manufacturing practises (Roy et al. , 2024). This case study investigates the ways in which the main fashion businesses are using sustainable materials, applying eco-friendly manufacturing processes, and making sure the labour is ethical. The text stresses the use of materials like organic cotton and recycled polyester, and the adoption of water-saving dyeing techniques and energy-efficient machinery. These practises serve as a model for the big textile manufacturers to restructure their operations in a way that they can align with environmentally sustainable goals, and at the same time, still make a profit.

The literature tree is the main tool that has been used to effectively synthesise and illustrate the wide range of literature that has been reviewed. This picture helps to sort the research into thematic categories and thus shows the dynamic interactions and development of the field of sustainable textiles. The literature tree is not only a way of navigation for the readers to see the development of the key themes and concepts, but also a methodological device that makes the interrelations among the various studies clear. The tree is structured around six major thematic categories that emerged from the literature: sustainable production techniques, CE and recycling practises, assessment of sustainability in textiles, innovative materials and applications, waste management and treatment, and consumer engagement and alternative consumption models. Every category consists of a bunch of studies. Links between studies are pointed out by linking phrases that state the kind of their relations – whether it is by direct extension, thematic overlap, or the methodological complementarity. The structure of this arrangement not only shows the development of ideas but also demonstrates the complex nature of research in sustainable textile practises. The literature tree, thus, is a complete map that can be used to navigate through the research that is the source of the wider discussion.

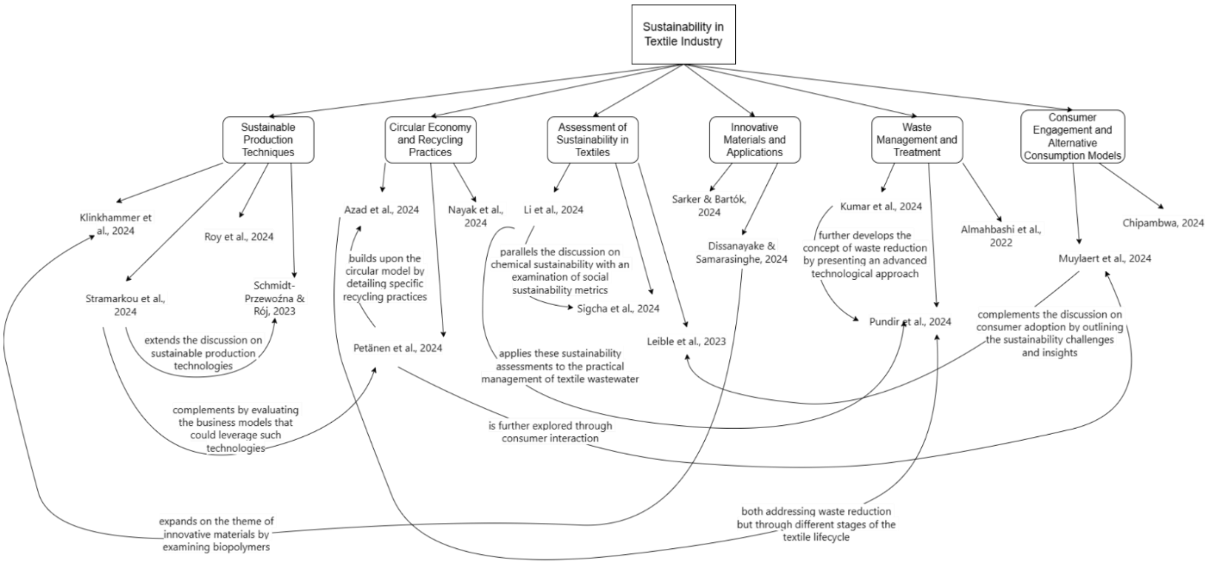


Figure 2: Literature Tree – Context Analysis

2.3 Technological Innovations in Sustainable Textile Manufacturing

Technological innovations are the main cause of the revolutionary changes that are also taking place in the textile industry. These developments are changing the way we make textiles and operate businesses that are in accordance with environmental and social responsibility goals. In the new era, where technology is the key to sustainability, the industry is moving to digital textile printing and eco-friendly dyeing technologies. Digital textile printing, which is shown by companies such as Kornit Digital, is a major development (Kumar, 2024). This technology solves the environmental problems that are related to traditional printing, like the excessive use of water and chemical waste. Through the on-demand production of digital printing, overproduction and waste are eliminated and sustainable practises are combined with technological efficiency. The field of dyeing has been transformed by the introduction of eco-friendly technologies which is a breakthrough. These techniques require less water and energy and use non-toxic dyes, which is very important in reducing the enormous water footprint of the industry. One example of such an innovation is the innovative signature series of Thies. Innovations like the ones mentioned are not only good for the environment but also set the pathway for safer and more sustainable dyeing processes (Nayak et al., 2024).

Besides, the development of sustainable raw materials, which is facilitated by technology, is changing the industry's way of thinking about materials. The invention and application of biopolymers, organic materials, and recycled fabrics are turning textile production into a more sustainable and less resource-dependent industry. In addition, the appearance of smart and functional textiles is evidence of the industry's dedication to innovation. These textiles, having advanced properties like temperature regulation and self-cleaning, show the combination of sustainability and enhanced functionality, thus, they are attractive to the new generation of environmentally conscious consumers.

2.4 Regulatory Framework and Sustainability Standards in Textile Industry

The quest for sustainability in textile production is centred on the relationship between regulatory frameworks and sustainability standards, which is a very important factor. These frameworks and standards not only guide but also force industry participants to follow more sustainable practises, which in turn, contributes to the achievement of broader SDGs. It is essential to grasp the relationship between the regulatory frameworks, the sustainability standards, and the SDGs. The textile industry is in tune with the SDGs, especially those that are centred on responsible consumption and production (SDG 12), clean water and sanitation (SDG 6), climate change (SDG 13), and industry, innovation, and infrastructure (SDG 9). Thus, companies like Thies can adopt these standards to improve their sustainable practises.

The incorporation of the SDGs into the operations is not only a response to global sustainability problems but also a strategic business decision. Companies are nowadays facing the need to obey various environmental regulations and sustainability standards, which are the keys to keep the market competitive and to meet customers´ expectations. The fact that the textile industry is urged to implement sustainable practises, is supported by the emphasis on environmentally friendly and sustainable solutions in the areas of wastewater treatment and circular clothing. Besides, the switch to more sustainable production processes, which is the main goal of the research by Klinkhammer et al. (2024), also the use of more efficient technologies is highly fundamental for textile machinery manufacturers. This sustainable production is mainly about using energy, water, and material efficient technologies that minimise chemical and material waste. These technological innovations not only help in the attainment of the SDGs but also fit in with the regulatory requirements of a more sustainable textile industry.

For Thies, the focus on SDGs implies the reconsideration and possibly modification of its machinery and processes in order to assist the textile industry in its transition to sustainability. This also means improving energy efficiency, cutting down on waste, and encouraging the use of environmentally friendly materials. Thies will be one of the leaders to introduce such changes which will not only meet the regulatory standards but also make Thies more sustainable contributing to environmental and social goals. The integration of SDG 6, which deals with clean water and sanitation, is of utmost importance, especially given the fact that the textile industry is a major consumer of water and producer of wastewater. Almahbashi et al. (2022) outline innovative methods in wastewater treatment, e.g., the use of bio-based materials for the decolorization of batik wastewater. This study emphasises the need for sustainable wastewater management solutions, which is vital for companies like Thies to take into account when they are designing and providing equipment to their customers. As far as the field of responsible consumption and production (SDG 12), Thies's job is not limited to the production of efficient machinery. A number of studies stressed the importance of the creation of GHG emission inventories and the use of environmental, social, and governance (ESG) practises. For Thies, this means to develop machines that will help in the production of sustainable manufacturing processes, hence cutting down waste and also lowering the environmental impact of textile production. Additionally, SDG 13 (Climate Action) is about the determination to reduce GHG emissions and to improve energy efficiency. The main path to this goal can be devised by energy-efficient machines that are designed for sustainability cutting the industry´s carbon footprint. This concurrence does not only comply with sustainability standards but may also make the adopting company the pioneer of eco-friendly textile machinery manufacturing. Lastly, SDG 9 (Industry, innovation, and infrastructure) should be the focus of the textile industry in its quest for sustainable practises. SDG 9 emphasises the need for infrastructure to be resilient, industrialization to be inclusive and sustainable, and the promotion of innovation which is highly important when navigating the textile industry´s evolving landscape.

2.5 Barriers for Integration

Each type of change is always faced with obstacles to be overcome. Especially, the sustainable practices face drastic challenges before they can be implemented successfully. Although, the aim of using environmentally friendly practices is evident, a number of obstacles can hinder their efficient application These barriers are not only multifaceted, but also the transition from one stage to another within the supply chain is complex and thus, the nature of barriers and their interconnection has to be taken into account. The following part of the paper discusses these obstacles and provides solutions on how to overcome them.

Financial Constraints

Financial limitations are one of the major reasons for the failure of innovative practice integration, especially for small- and mid-cap enterprises. This challenge is to be overcome by the development of new financing solutions, for instance, green loans, government subsidies, or the investment in cost-saving technologies that will pay back over time. Besides, a long-term cost-benefit analysis can be used to show the advantages of these investments. In general, more efficient practises will lead to savings in the long run which advocates initial investments.

Technological Challenges

Technological boundaries may also be the reason for the slow adoption of sustainable practises. The move to innovative, more sustainable technologies may be a skilled process that is currently in short supply in the industry (Muylaert et al. , 2024). The problem of the high cost of research and the isolation of research can be overcome by additional investing in R&D, as well as collaborating with technology providers, policy makers, and academic institutions.

Regulatory and Policy Hurdles

The intricate regulations are a problem that needs to be solved as well. Inconsistent policies and regulations can be the cause of the uncertainty that makes investing in sustainable practises less favourable (Pundir et al. , 2024). Government policies, which are clear, consistent, and supportive, are the key to persuading companies to invest in sustainable technologies and practises. Furthermore, it involves not only understanding and complying with existing regulations but also participating in policy development processes.

Cultural and Behavioural Factors

Cultural and behavioural factors are another obstacle that can hinder the process of development. Transforming the traditional ways of doing things and altering mindsets demands a lot of work (Kumar et al. , 2024). Leadership and employee engagement in sustainable activities are key to the success of sustainability and to overcome these challenges. Through programmes such as sustainable training, workshops, and internal campaigns, a culture of sustainability is developed, which in turn, encourages creative thinking and quicker practise adoption.

Market Demand and Consumer Awareness

Market demand and consumer awareness are the two factors that determine the acceptance and therefore supply of sustainable practises. If consumers are not aware of sustainable products, companies will not be willing to change their business model (Leible et al., 2023). Hence, consumer education and the creation of a sustainable product market are important steps in overcoming this barrier. Thies can be a part of the market education process, which, subsequently, can push the whole industry to embrace sustainable methods.

Collaborative Efforts for Industry-Wide Change

Lastly, the integrated work of different parties is key to solving most of these issues. Stakeholders should look for affiliations with the industry players, governmental bodies, NGOs, and consumer groups. Through such collaborations, idea sharing is enabled, best practises can be promoted, and more supportive ecosystems for sustainable practises can be created.

3 Research Methodology

3.1 Theoretical Perspective

The Innovation Diffusion Theory (IDT), which was created by Everett Rogers, is greatly applicable to understanding the adaptation of modern technologies. This theory delves into how innovative ideas and technologies gain traction and spread within a society. Through the application of IDT, innovative technological solutions in the textile machinery industry can be analysed and understood. This approach takes into account the key features of innovation including decision-processes, communication channels, social systems as well as the role of leaders. As the textile industry is currently transforming due to increased ecological concerns and technological advancements, IDT serves as an insightful lens for a better understanding of this phenomenon. It facilitates the understanding of environmental technological availability and acceptance by communities or organisations for sustainable and efficient management. This lens is most applicable for exploring the implementation of innovative and effective technologies in the textile industry which is currently undergoing radical changes due to environmental issues and technological progress (Duarte et al., 2018).

3.2 Research Design

In this segment, we explore the research design, an essential strategy formulated to tackle the identified knowledge gap and research inquiries. Having established the research questions, the emphasis transitions to the systematic collection and analysis of data to yield profound insights. This process involves the selection of the most fitting research methodologies that resonate with the subject matter. It entails making choices among qualitative, quantitative, or mixed-method approaches, taking into account the nature of the data required, the breadth of the study, and the availability of resources. The design is customised to ensure an in-depth investigation of Thies's industry, striving for results that are not only academically sound but also significant, contributing to real-world sustainability efforts. Basically, the most appropriate approach for the research questions and objectives would be a mixed-methods approach. This approach combines both qualitative and quantitative methods, offering a comprehensive understanding of the topic. Here, qualitative research in the textile industry delves deeply into subjective experiences, perceptions, and drivers, which offers rich insights into the facets of sustainability efforts. This approach sheds light on intricate challenges and practises in the sector. Conversely, quantitative research employs statistical tools to numerically assess and extrapolate findings from a selected group to a larger population. This method proves invaluable in quantifying carbon emissions, evaluating the success of eco-friendly measures, and forming wider conclusions about the industry's overall environmental impact.

The mixed-methods approach is vital in evaluating both the quantitative and qualitative aspects of sustainability as well as the objective and subjective features like carbon emissions, energy consumption, stakeholder attitudes, and corporate culture. For instance, qualitative research is good at pinning down Thies experience in sustainability integration, whereas quantitative research gives empirical evidence of the effectiveness of sustainable practises (Shahi et al. , 2020). Firstly, the research strategy will be based on a detailed case study and secondly, it will include a detailed process analysis. On the other hand, the case study will focus on the activities Thies does in operating their business, especially the part where they use sustainable technology. Through this disclosure, a true picture of the company's hurdles, plans, and success in sustainability adoption will be laid bare. In addition to that, the process analysis will be done, where the efficiency of the production process, sustainability, and technological progress of Thies will be examined. It will be a critical look at operational aspects like production, use of technology and supply chain management. Overall, this approach will give the reader an overall understanding of Thies's sustainability-related efforts in the textile industry.

The data collection method is strategically chosen to ensure comprehensive and relevant information gathering. Here, a blend of qualitative and quantitative methods will be employed.

1. Qualitative data will be collected by applying systematic techniques such as in-depth research for academic papers, conducting company reports, or talking to employees. These methods are fundamental in developing an understanding of the company's GHG emissions and water consumption in the production of textile machinery. Moreover, they help to understand the complex processes taking place within teams and also identify the perceived bottlenecks and opportunities that are experienced by those who are directly involved in the operational processes.
2. Quantitative data collection, next to the qualitative one, is about gathering concrete data, especially in the fields of production efficiency, energy consumption, and sustainability indicators of Thies´s operations. This methodology is a vital factor in the assessment of the impact of the firm's implementation of sustainable processes and the adoption of modern technologies.

This combination of data collection techniques will give a comprehensive overview of Thies´s operations, which can then be analysed in detail with regard to their sustainable practises within the textile industry.

In the investigation of sustainability within the textile sector, a variety of data analysis methods appropriate for the mixed-methods approach have been utilised. To begin with, the FMEA (Failure Mode and Effect Analysis) can be used for risk assessment and especially the identification of sustainability risk in the supply chain. This method helps to understanding the consequences on Thies in terms of operational decisions and the business model at large, and consequently, the identification of possible problematic areas (Giannakis & Παπαδόπουλος, 2016). After that, a tool for quantitative data analysis, turns out to be an instrument in understanding the attitude of Thies towards sustainability by providing details about CO_2 emissions. Besides that, qualitative content analysis is used to emphasise particular difficulties and opportunities. Finally, thematic analysis plays a critical role in uncovering salient themes connected to sustainability, especially those about traditional methods and cultural elements in the textile industry. Collectively, these techniques will provide both an empirical and subjective comprehension of sustainability practises and problems at Thies. They will also align cohesively with the research objectives, thus giving a holistic and balanced view of the sustainability practises and challenges at hand.

In examining the role of Thies in the sustainable textile industry, the research design confronts various challenges as identified in scholarly literature, which are pivotal for enhancing the integrity and reliability of the research findings.

1. Giannakis and Papadopoulos (2016) illustrate the complex and interlinking nature of risk management in supply chain sustainability. This complexity, however, can act as a barrier for the research, especially when it comes to isolating certain components within the organisation of Thies. Therefore, care should be taken while drawing any conclusions about whether Thies' business practises reflect the trend in a larger industry.
2. According to Von Der Heidt (2011) blending various research methodologies is a significant issue that exists, as outlined by sustainability management studies. As a result, mixed-methods strategies may include some challenges when attempting to draw concise conclusions because of the complexities of stakeholder viewpoints, and regulatory frameworks.
3. Santiago-Brown et al. (2014) caution that researchers should not have unacknowledged assumptions that could influence the outcomes of mixed-methods research, especially in the

field of sustainability. The research approach should be careful to expose and deal with any biases, particularly the interpretation of qualitative data, so that the outcome is not skewed.

3.3 Potential Social Impact

This study trails scientific norms, but also delves into a thorough investigation of its social impact, notably regarding Thies's influence in the textile sector. Embracing the philosophy of science, it underscores the dual goals of knowledge acquisition and its attendant responsibilities. Here, the intent is to explore ethical concerns in the textile industry's business practises. The focus is set on sustainability and corporate accountability. The necessity for business ethics research to critically examine its own ethical consequences and methods its underscored. The objective of this study is to enrich the discourse on how businesses can harmonise profit-making with social accountability, especially in industries marked by notable environmental impacts. It is expected that the findings will shed light on the broader societal effects of business activities, while stressing the significance of ethical decision-making and the adoption of sustainable practises.

3.4 Conflicting Responsibilities

Within the scope of this project, the professional duties are to manage the project holistically with particular emphasis on aligning actions to the predefined targets, especially sustainability in the textile sector. Part of this job is the ability to effectively perform tasks that are in conflict with each other, a situation that is common in complex projects. The importance is given to the prioritisation of the tasks by their significance and immediacy so that the critical aspects of the project are given enough attention and resources. The principal role of communication here is to bring together different views of team members and to achieve unity of understanding. On the other hand, it is essential to establish a climate that stimulates open dialogue as well as teamwork.

4 Methodology

This section is pivotal for illustrating the process and precision behind the carbon footprint assessment. It aims to meticulously outline the methodology utilised to calculate a company´s ecological footprint, delving into its systematic approach to capture and analyse data associated with GHG emissions.

4.1 Principles of the Greenhouse Gas Protocol

The GHG Protocol is an internationally recognised standard that provides a consistent measurement, management, and reporting of GHG emissions. The GHG Protocol (*Homepage | GHG Protocol*, 2024), which is the accounting framework for almost all the GHG standard programmes across the globe, was created by the collaboration of the World Resource Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). This protocol is a universal benchmark that is used by institutions from various sectors to measure and reduce their emissions. It provides an integrated and balanced structure that stipulates global standardised measurement and management of corporate GHG inventories from all the private and public sector operations, value chains, and mitigation activities. The standardisation of GHG inventories is key for the purposes of transparency, comparability, and consistency especially between different organisations and industries.

The GHG Protocol is built on several core principles that ensure the integrity and effectiveness of its framework (Gillenwater, 2022):

1. Relevance: The Protocol emphasises the importance of ensuring that GHG inventories accurately reflect the emissions of the reporting entity. Furthermore, it serves the decision-making needs of users and stakeholders.
2. Completeness: Inventories should encompass all relevant GHG emissions and removals, following the scope of the GHG Protocol.
3. Consistency: The Protocol advocates for consistent methodologies that allow for meaningful comparisons of emissions over time of one company.
4. Transparency: Information should be compiled, analysed, and documented in a clear transparent, and accessible manner.
5. Accuracy: Inventories should strive for accuracy to ensure that emissions are not underestimated or overestimated.

Next to the core principles, the GHG Protocol categorises emissions into three distinct scopes (Hertwich & Wood, 2018):

1. Scope 1 (Direct Emissions): These emissions are direct GHG emissions from sources that are owned or controlled by the reporting entity, such as emissions from combustion in owned or controlled boilers, furnaces, vehicles, etc.
2. Scope 2 (Indirect Emissions from Electricity): These are indirect GHG emissions from the usage through purchased energy sources consumed by the reporting entity.
3. Scope 3 (Other Indirect Emissions): This scope covers other indirect emissions that are a consequence of the operations of the reporting entity but occur from sources not owned or controlled by it. This includes emissions associated with the production of purchased materials, outsourced activities, waste disposal, etc.

4.2 Mathematical Foundations

The calculation of GHG emissions is underpinned by a fundamental equation, which forms the basis for assessing an organization´s environmental impact. This equation is represented as:

$$GHG\ Emissions = Activity\ Data * Emission\ Factor$$

Equation 1

1. Activity data is a quantitative data about the activity that is the cause of GHG emissions. Thus, it could be fuel used by the company's vehicles, the distance covered by corporate vehicles, the energy consumed by manufacturing processes, or the total area of heated or cooled office space.
2. The emissions factor is an index that represents the average emissions of GHG from a specific activity. The term of the activity is the total GHG emissions per unit of activity, which considers the emissions intensity and type of activity. The emission factors can differ drastically depending on the fuel used, the technology efficiency, or the electricity grid mix, among other factors (Kennedy et al. , 2010).

Emission factors are usually obtained from experimental data and research. The essential references on the emission factors for the different GHGs is given by the Intergovernmental Panel on Climate Change (IPCC), but also national environmental agencies usually publish region-specific emission factors. They are the outcomes of the evaluation of the amount of GHG emissions from a certain source for a certain period and the division of it by the activity that is connected to these emissions. For instance, the emission factor for a specific fuel is calculated by tracking the total GHG emissions from the burning of that fuel and then dividing it by the total amount of fuel burned. The IPCC might report that burning one gallon of diesel fuel typically emits 10.21 kilogrammes of CO_2. Thus, the emission factor for diesel fuel would be 10.21kg CO_2/gallon. This factor allows companies to calculate their Scope1 emissions from diesel fuel usage by multiplying the amount of diesel fuel used (activity data) by the emission factor (Kennedy et al., 2010).

<u>CO2 Equivalents</u>

GHG emissions are usually given as carbon dioxide equivalents (CO_2e). This section of the metric enables the comparison of emissions from differing GHGs according to their Global Warming Potential (GWP). The GWP is the index of how much a certain mass of GHG adds to global warming over a specified period, generally 100 years, when compared to the mass of carbon dioxide. This parameter reduces the complexity of reporting and analysing by transforming the emissions of various gases into one common unit. It is calculated as follows:

$$CO_2 e = Mass\ of\ GHG * GWP\ of\ GHG$$

Equation 2

where, the mass of GHG is the total mass emitted, and its corresponding GWP.

For example, if an organisation emits 1 tonne of methane and the GWP of methane is 25 times that of CO_2, then the CO_2e would be:

$$CO_2 e = 1tonne * 25 = 25\ tonnes\ of\ CO2e$$

Equation 3

This means that 1 tonne of methane is equivalent to 25 tonnes of CO_2 in terms of its GWP (Kennedy et al., 2010).

<u>Global Warming Potential</u>

The GWP is a factor that quantifies the heat trapped by a GHG in the atmosphere as a multiple of the heat trapped by carbon dioxide. The GWP is used to compare different gases based on the global warming impact. It is defined as the amount of energy that 1 tonne of gas will absorb in a period of time compared to the emissions that q tonnes of CO_2 will absorb at the same time. The IPCC provides values for GWP for different time horizons, commonly over 20, 100, and 500 years. The GWP is calculated based on a number of factors, including the gas´s ability to absorb heat and the length of time it stays in the atmosphere. For example, over a 100-year period, methane has a GWP of 25, meaning it traps 25 times more heat in the atmosphere than CO_2. Understanding and correctly applying the concepts of CO_2e and GWP is essential for accurate GHG emissions reporting. It allows organisations to compare and aggregate emissions from different GHGs, track and report their total GHG emissions impact, and develop strategies for emissions reduction targeting the gases with the highest GWPs (Shine et al., 2005).

GWP and CO_2e for non-Gases

Figuring out the GWP and CO_2e for a material such as stainless-steel requires holistic knowledge about its life-cycle emissions. Hence, emissions resulting from material production, use, and disposal are used to be calculated counter wise to gases. The calculation steps to follow for stainless steel are:

1. Determine all sources where GHG emissions are produced during the lifecycle of stainless steel. This might comprise emissions from energy used in manufacturing processes, transportation emissions, and emissions due to waste management.
2. After identifying all GHG sources, the emission factors are used to calculate the GHG emissions of each source. This should be done for each type of GHG emitted (e.g., CO_2, CH_4, N_2O). Here, the emission factors are usually offered by national or international environmental agencies or industry-specific studies.
3. Next, the emissions are to be transformed into CO_2e by calculating the GWP of each gas. The GWP values are mostly taken from the IPCC.
4. Lastly, the total lifecycle CO_2e of stainless steel can be calculated by adding up all figures from identified sources (Jing et al., 2019).

Suppose the production of 1 tonne of stainless-steel results in:

- 1,5 tonnes of CO_2 emissions from energy consumption.
- 0,1 tonnes of CH_4 emissions (with a GWP of 25 over 100 years).
- 0,01 tonnes of N_2O emissions (with a GWP of 298 over 100 years).

Calculate the CO_2e as follows:

- CO_2 emissions: 1.5 tonne of CO_2e (since CO_2´s GWP is 1)
- CH_4 emissions: $0.1\ tonnes * 25 = 2.5\ tonnes\ of\ CO_2e$
- N_2O emissions: $0.01\ tonnes * 298 = 2.98\ tonnes\ of\ CO_2e$

Total CO_2e for the production of 1 tonne of stainless steel is:

$$1.5 + 2.5 + 2.98 = 6.98\ tonnes\ of\ CO_2e$$

Equation 4

It can be said that correct comprehension of the units of measurement and conversion factors is imperative for the precise calculation and reporting of GHG emissions. Through a holistic understanding, the uniformity and comparability in GHG accounting of distinct organisations and sectors are secured (Jing et al., 2019).

4.3 Hybrid Life Cycle Assessment Model for Scope 1 and 2 Emissions

In the field of environmental sustainability, the hybrid life cycle assessment (LCA) model is a key tool, especially in the case of Scope 1 and 2 emissions. This model, which is based on the general framework of LCA, includes different aspects of environmental impact throughout a product's lifecycle, thus, giving an extensive analysis of emissions. At the core of the hybrid LCA is the consolidation of two distinct approaches: the process-based LCA that analyses specific and detailed process data and the economic input-output LCA, that uses wider economic data for impact estimation. This combination is not only innovative but also crucial to the meaning of environmental impacts, especially in the case of Scope 1 and 2 emissions.

For Scope 1 emissions the process-based aspect of the hybrid LCA is the key player. In this place, the collection of data in a very detailed manner at each stage of the process is extremely important. Therefore, the direct emissions can be assessed correctly. The economic input-output part of the hybrid LCA is more appropriate for Scope 2 emissions. This approach takes into account the environmental aspects of energy production and consumption and connects them with the overall evaluation of a company's emissions profile more specifically. In essence, the hybrid LCA model is a lens that allows the environmental impact of products and services to be seen as a whole. It deals with the difficulties that are built into Scope 1 and 2 emissions calculations; thus, it is a good tool for organisations to identify potential actions that they can implement to reduce their environmental footprint. Moreover, the hybrid LCA model aligns well with global standards like ISO 14040:2006, which provides the basic principles and frameworks of LCA. The alignment of the views of the experts in the field of industrialization and manufacturing pays off for the mode of the project and confirms its credibility and wide applicability in other industrial contexts (Ramaswami et al. , 2008).

<u>Mathematical Framework of Hybrid LCA Model</u>

Process-Based LCA Component:

$$\sum(Activity\ Data * Emission\ Factor)$$

Equation 5

Economic Input-Output LCA Component:

$$Emissions_{economic} = Economic\ Output * Leontief\ Inverse * Emissions\ Intensity$$

Equation 6

Where,

- Economic Output: The monetary value of the company´s production.
- Leontief Inverse: Matrix representing interdependencies between different economic sectors.
- Emission Intensity: Emissions per unit of economic output in each sector (Ramaswami et al., 2008).

Let´s consider a manufacturing company looking to calculate its GHG emissions for both Scope 1 and 2 using the Hybrid LCA model:

Scope 1: Process-Based LCA

Assume the company uses 10000 litres of diesel (Emission Factor = 2.68 kg CO2e/litre).

Calculation: $Emissions_{diesel} = 10000\ litres * 2.68\ kg\ \frac{CO23}{litre} = 26800\ kg\ CO2e$

Equation 7

Scope 2: Economic Input-Output LCA

Assume the company´s economic output is $1 million, with an emission intensity of 0.5 kg CO2e per dollar (considering the energy mix of the region and sector).

Calculation: $Emissions_{economic} = \$1000000 * 0.5kg\frac{CO_2e}{\$} = 500000\ kg\ CO_2e$

Equation 8

Total GHG Emissions

$$Total\ Emissions = Emissions_{diesel} + Emissions_{economic}$$

Equation 9

$$Total\ Emissions = 26800\ kg\ CO2e + 500000\ kg\ CO2e = 526800\ kg\ CO2e$$

Equation 10

In this case, the hybrid LCA model enables the company to carry out a complete analysis of its direct emissions from fuel usage (Scope 1) and the broader economic impact of its production activities (Scope 2), hence the comprehensive knowledge of its total environmental impact (Ramaswami et al. , 2008).

4.4 Data Requirements & Collection Methods for Scope 1 and 2 Emissions

For Scope 1 emissions, accurate data collection is fundamental to assessing direct emissions from operations. This assessment involves:

1. Identification of emissions sources: An inventory of all the direct emission sources of the company, like vehicle combustion, boilers, and manufacturing processes.
2. Quantitative data collection: Precise logging of activity data, such as the quantity of fuel consumed, the number of hours that the equipment is used, and the distance travelled by company vehicles. The obtained data is the first step in determining the amount of emissions.
3. Emission factors application: The application of proper emission factors for different types of activity must be guaranteed. Special concern is given to these factors because of their varying nature.

For Scope 2 emissions, the measurement of indirect emissions that are generated from the purchase electricity, heat, or steam; the key data collection steps are as follows:

1. Energy Usage Data: Statistics about the entire amount of electricity, heat, and steam that has been used. This data is usually derived from utility bills and energy suppliers.
2. Application of Grid-Specific Emissions Factors: Factoring the local or national electricity grid's emission intensity to obtain appropriate emission factors (Ranganathan et al. , 2004).

4.5 Environmentally Extended Input-output Analysis for Scope 3 Emissions

The Environmentally Extended Input-Output Analysis (EEIOA) is the primary model in the evaluation of Scope 3 GHG emissions. This method, one of the main parts of environmental accounting, assists companies in understanding and measuring the emissions that are related to upstream and downstream activities. The EEIOA is an extension of the conventional economic input-output analysis in which environmental aspects are also taken into account. The basic idea of EEIOA is its capacity to connect the economic transactions of different industries with the GHG emissions, which are quite closely related to environmental impacts. The foundation of EEIOA are the national or sectoral economic input-output tables, which are the financial transactions between the differing sectors of the economy at the centre. The tables show the economic transactions and the business relationships between sectors. Thus, they represent the picture of economic interactions and the flow of goods and services across industries. These tables are environmentally oriented in that they contain information on environmental impacts, especially GHG emissions. The extension of the criteria includes the distribution of emissions data to different sectors, according to their economic activities. Hence, EEIOA examines the complexities of the interrelationships among industries. To illustrate, the emissions that are related to the processing of a raw material used in the manufacture of an end-product are taken into consideration in determining exactly this final product´s environmental impact.

Through the combination of economic and environmental facts, EEIOA enables a complete study of Scope 3 emissions. This covers the broad range of indirect emissions sources which include everything from the extraction of materials that are purchased to the end-of-life treatment of sold products, hence their holistic life. In the domain of corporate GHG emissions accounting, EEIOA is a tool that is highly useful in measuring the emissions that are part of a company's supply chain and product lifecycle. This approach helps to gain a comprehensive view of the environmental impact by taking into account not only the direct operations but also the entire economic network of a company. For clarification, the primary benefits of EEIOA are the attention to a broad spectrum of indirect emission sources, the use of easily obtainable economic and environmental data, and the detection of substantial sources of indirect emissions (Kitzes, 2013).

Mathematical Formulation of EEIOA

The EEIOA employs a mathematical framework that enables the quantification of indirect GHG emissions across an organization´s value chain. This formulation is pivotal in translating economic transactions into environmental impacts. The mathematical foundation of the EEIOA is rooted in the interaction between economic activities and their associated environmental impacts. The primary equation used in EEIOA is:

$$GHG\ Emissions = Economic\ Output * Leontief\ Inverse * Emission\ Intensity$$

Equation 11

Here, GHG emissions are calculated by considering the economic output of a company, the inter-industry relationships within the economy (captured by the Leontief Inverse matrix), and the emissions intensity of different economic sectors. In a corporate setting, EEIOA helps in assessing Scope 3 emissions as explained above. This involves mapping out the supply chain and related economic activities, and then applying the EEIOA framework to quantify emissions associated with these activities. The application often requires segmenting the analysis into specific sectors relevant to the organization´s operations and supply chain. This sector-specific approach ensures that the calculated emissions accurately reflect the organization´s unique economic interactions (Kitzes, 2013).

4.6 Data Sourcing for EEIOA

Economic Activity Data

The foundation of EEIOA is built on input-output tables, which are comprehensive data sets detailing the financial transactions and interdependencies among different industries within an economy. These tables are typically sourced from national statistical agencies or international economic organisations. They provide insights into the economic output of each industry sector, forming a matrix that represents the sale and purchase relationships between sectors. Given the dynamic nature of economies, it is crucial to use the most current input-output tables available. This ensures that the analysis reflects recent economic conditions and sectoral interdependencies (Kitzes, 2013).

Environmental Impact Data

Environmental impact data is primarily represented by sector-specific emission intensities. These intensities indicate the amount of GHG emission per unit of economic output for each sector. Sources for emission intensities include environmental databases, government reports, and academic studies. They are often compiled and published by national environmental agencies or international bodies such as the IPCC.

The challenge in data sourcing lies in harmonising economic and environmental data. This requires to ensuring that the economic sectors defined in the input-output tables correspond accurately with the sectors for which the emission intensities are available. Discrepancies in sector classifications or temporal mismatches between the economic and environmental data sets necessitate careful adjustment and reconciliation (Kitzes, 2013).

It is essential to select data that is geographically and temporally relevant to the organization´s operations. For global companies, this might involve using a combination of national and international data sets. The temporal alignment of economic and environmental data is crucial for accurate assessment, necessitating the use of data from corresponding years where possible. Moreover, the reliability of EEIOA significantly depends on the quality of the underlying data. Therefore, it is imperative to source data from reputable and transparent sources, ensuring the credibility of the analysis. Documentation of data sources and methodologies used in data compilation is also vital for the verifiability and replicability of the analysis (Kitzes, 2013).

4.7 Limitations and Challenges in EEIOA

Utilising EEIOA in evaluating Scope 3 GHG emissions is a critical step in comprehensive environmental accounting. Nevertheless, this approach, though it has numerous advantages, also has some weaknesses and problems that must be taken into consideration and solved.

Inherent limitations of Input-Output Tables

Input-output tables inherently aggregate data across economic sectors. The intense aggregation of such data can sometimes hide the environmental impacts of individual companies or products, thus, creating a generalisation that may not be a true reflection of the particular attributes of the different industries. Moreover, economic input-output tables are normally based on the data from a certain year, and thus, they show the economy as a fixed picture. They might not represent the fast changes in the economy or in the technologies and practises of the sectors that can play a major role in the environmental protection (Hertwich & Wood, 2018).

Challenges in Data Integration

Input-output tables process economic as well as environmental data, such as emission intensities, which might impose a great deal of difficulty. Variances in sector classifications, the regions of coverage, and data collection methods can cause inaccuracies and inconsistencies in the analysis. Additionally, the data on environmental impact and the economic data often do not coincide in time. The inconsistencies between years of economic and environmental data are frequent reasons for the unbalanced results of studies. This is especially the case in industries that are changing fast (Wiedmann et al. , 2020).

Methodological Limitations

EEIOA is premised on the assumption of linearity in economic interactions, that is, inputs and outputs are directly proportional. The simplicity of this process may not be applicable to all cases, particularly in non-linear systems where small changes in inputs can lead to significant changes in outputs. Besides that, the methodology spotlights mainly indirect emissions and thus, it may not correctly measure the complexities and nuances of these emissions especially in global supply chains with many layers of transactions (Holding, 2023).

<u>Data Quality and Availability</u>

Also, EEIOA's accuracy is tightly linked to the quality and detail of emission factors for different sectors. From this proceeding restricted access to the detailed and sector-specific emission factors might lead to a weak precision in analysis (Huang et al. , 2009).

4.8 Example EcoCockpit

EcoCockpit is a sophisticated software programme which main function is to help companies in the evaluation and management of their GHG emissions. It is a comprehensive data processing tool designed to meet international standards for carbon footprint calculation, especially the GHG Protocol. Its interface is designed for user-friendliness; thus, organisations are able to input, manage, and analyse various types of environmental data without difficulty. The input data range covers energy consumption, waste generation, and other operational aspects that are significant for environmental impact assessment. Here, the tool´s design focuses not only on the accessibility of its features but also on the accuracy and relevance of the data it processes. Due to its adjustment to the GHG Protocol, its emission calculation is both trustworthy and comparable worldwide. This standardisation is key for companies that work in sectors with complex supply chains and distinct emission sources , for instance, the textile machinery manufacturing sector. When processing data, EcoCockpit can handle data from each scope also reflecting the distinct needs of every organisation which leads to a complete solution for GHG emissions management. Since the software has the ability to be customised, this tool can be used in various industries and is applicable to different company sizes and sectors. Hence, it provides the required environmental impact assessments for small businesses and large corporations.

Besides aiding in the computation and analysis of GHG emissions, EcoCockpit also helps in the reporting part. Its function comprises the generation of comprehensive reports that comply with global reporting standards, and thus it becomes an aid for organisations in their environmental compliance and sustainability reporting requirements (Pichancourt et al., 2018). The design and functionality of EcoCockpit are in accordance with the principles and standards of the GHG Protocol, so that the GHG emissions calculations and visualisation are both globally standardised and credible. This enables organisations to take well-informed and data-driven decisions. This is extremely beneficial for companies that are planning to cut down on their carbon emissions, follow environmental norms, or accomplish their sustainability objectives. Complying with regional and global environmental regulations is especially valuable when interacting with and reporting to international stakeholders. It can be said that EcoCockpit is a real-life example of the GHG Protocol´s theoretical framework applied in a practical way, which turns complicated emission calculation methodologies, as seen above, into a simple and user-friendly tool. It aids the organisation in the detection of emission hotspots, the setting of reduction targets, and the monitoring of progress, which in turn contributes to larger sustainability projects (Green, 2010).

5 Analysis

The era that we are living in is characterised by critical environmental problems. Therefore, the ability to predict and plan future ecological impacts is invaluable. The tool, developed for this purpose, is meant to be a strong analytical tool for modelling GHG emissions in five predictive scenarios, once globally and once specified to Thies GmbH & Co. KG. The tool combines Excel VBA as programming language and mathematical modelling to analyse emissions under different conditions, thus it is useful in the evaluation of environmental policies and technological innovations. The main purpose of the Excel workbook is to provide researchers with a data-driven tool to examine and create strategies that could effectively reduce the effect of GHG on the environment. The need for such a tool is emphasised by the current global effort to fight climate change and to comply with international commitments such as the Paris Agreement. Its goal is the reduction of the GWP well below 2, preferable to 1.5 degrees Celsius. The current global warming is estimated to be 5 degrees Celsius, which is much more than the pre-industrial level (Rogelj et al., 2016). Since the governments were trying to be in line with these goals, it is necessary to have a reliable tool that can simulate the outcomes of policy implementation and technological shifts. Therefore, the Excel workbook comprises several worksheets, each of which is focused on a particular emission scenario. This systematic approach is the way of processing the environmental and technological conditions, which lead to the simulation of various outcomes based on the data inputs that are both established and estimated.

<u>Introduction Worksheet</u>

The introduction worksheet serves as the initial contact point with the workbook. This worksheet utilises explanations in combination with the ability to run the integrated macros. The macros are hardcoded into the workbook, utilising the data input to generate the forecast when run. Hence, this worksheet is used to set up the other worksheets. This worksheet can be said to be the administrative workplace.

<u>Data Worksheet</u>

This sheet serves as the foundation, where essential parameters like growth rates and base year emissions are recorded. These parameters are crucial as they define the boundaries for the projection model, reflecting values recommended by sources such as the IPCC for accuracy and reliability. Initially, this worksheet is generated by running a macro containing fixed values. However, if the need to change values occurs, these values might be implemented within the VBA code or directly in the worksheet. Also, additional variables may be displayed. Hence, this worksheet is subject to change over time.

<u>Scenarios</u>

Each scenario within the workbook is powered by tailored macros that dynamically calculate emissions based on the scenario-specific assumptions:

- “Business As Usual” projects future emissions by extrapolating historical data, assuming no significant policy or technological shifts.
- “Current Policies” scenario employs a logistic growth model to anticipate emission trends under existing regulations.
- “Circular Economy and Waste Reduction”, “Renewable Energy”, and “Investment in Energy Efficient Technology” explore the potential impacts of sustainable practises, alternative, and advanced energy integration.

- "Thies Scenario" employs the constructed scenarios to adjust it to Thies. Here, the expected ecological footprint of Thies and the corresponding compensation and investment costs are explored.

Visual Worksheet

Visual representations such as graphs and charts are automatically generated to facilitate a clear comparative analysis of all scenarios. This visualisation aids in making the complex data more accessible and interpretable for all stakeholders. The statistical method used to develop this workbook is based on sound mathematical principles and models such as exponential and logistic growth functions which are used to estimate future emissions. Furthermore, the incorporation of confidence intervals around the projections not only give them statistical validation, but also offers a quantified measure of any model-based prediction uncertainties. The workbook is not only a theoretical piece of work, but it is also a practical tool designed to be used in real world situations. It can be utilised for:

- Assessing the efficiency of preexisting policies for environmental protection.
- Assessing the role of advanced technology in emission cuts.
- Aiding in academic research and participate in strategic planning process.

Here, we develop a holistic tool to assess the environment that is easy to use, but also powerful enough to deal with the challenges of climate change and sustainability. Through the use of detailed simulations, it provides a platform where assessments are based on scenarios, which supports informed decision-making, which in turn leads to a proactive approach to environmental management and policy formulation.

5.1 Scenario Construction

Business As Usual

The BAU scenario is crucial because it forms the basis for the analytical framework, which purpose is to forecast future GHG emissions. This situation implies the fact that there is no introduction of new policies or technologies. Hence this scenario is a baseline for the comparison of other emission reduction strategies. It is designed to forecast emissions according to historical data and set a basis for the assessment of the effectiveness of policy change and technological progress conducted in other scenarios.

The BAU scenario is structured around these critical assumptions:

1. Stability of conditions: It is expected that the policy framework, technology, and economic activities will not change during the forecast period.
2. Historical emissions data: This is the complete set of historical GHG emissions data, of which the quantity is measured in Gt CO_2e. The data, which is a representation of previous emission patterns, is the basis for making accurate future projections. This historical emissions framework will be validated through the use of global datasets, like those presented by Meinshausen et al. (2011) in their study on GHG concentrations and their projections up to 2300. Such forecasts have the ability to validate the long-term trends that are assumed in the BAU scenario.
3. Extrapolation of emission growth rates: The net growth rate of emissions is calculated from historical data, which is basically the sum of emissions that are expected to be polluted if current practises stay in place. Furthermore, the data will be processed in accordance with the methods that are used to track the past and present emissions trajectories. For example, as

described by Gütschow et al. (2016) in their research paper, which provides an extensive historical emission time series, thus ensuring the accuracy of the projected growth rates.

The scenario employs a systematic approach to project emissions:

- Hardcoding of historical emissions data into the macro is used, which guarantees the reliability of the starting data points and their consistency. Fixed emission data from future years can be incorporated into the array when needed.
- Key parameters such as the start and end year, net growth rate, and standard deviation for calculating the confidence intervals (CI) are retrieved from the "Data" worksheet.
- Future emissions are calculated using an exponential growth model. The formula used is:

$$Emission_{year} = Last\ Historical\ Emission * (1 + Net\ Growth\ Rate)^{(Current\ Year - Last\ Historical\ Year)}$$

Equation 12

- This calculation extends from the last historical data point to the end year defined in the parameters.
- The choice of an exponential model is substantiated by its widespread application in ecological and environmental studies where unregulated growth processes are analysed.
- The exponential growth formula starts with the last recorded emission value as its base and increases it annually by a given growth rate.
- The growth rate is derived from historical data.
- To account for uncertainty in projections, the scenario includes the calculation of a 95% CI around the estimated emissions, enhancing the robustness of the analysis.

$$Lower\ Bound = Emission - (1.96 * Standard\ Deviation * Emissions)$$

Equation 13

$$Upper\ Bound = Emission + (1.96 * Standard\ Deviation * Emissions)$$

Equation 14

<u>Current Policies</u>

The "current policies" (CE) scenario is important to preserve the future emissions of GHG based on the assumption that no additional policy change or technological advancement occurs throughout the forecasted period. This scenario is useful for assessing the performance of the current incentives and offers a more realistic outlook on the possible emissions reduction in the absence of new policies. This refers to all existing policies, energy conservation measures, RE policies as well as targets that are officially recognized up to the current date.

The policies covered in the scenario are the leading worldwide environmental policies such as the Paris Agreement, in which countries agreed to prevent global warming from being below 2 degrees Celsius and to strive to achieve 1.5 degrees (Rogelj et al., 2016). It also includes the European Union's far-reaching climate policies which include the recently agreed target of cutting GHG emissions by at least 55% by 2030 relative to 1990 and achieving net-zero emissions by 2050 (Kelemen, 2010; Rovinskaya, 2022). Furthermore, this scenario discusses the policies and measures of different countries like the Clean Power Plan of the United States and China's National Carbon Trading Scheme, which signify major state efforts in combating climate change and ecological degradation.

The CP scenario relies on two parameters:

1. Emissions baseline: The scenario starts with a base level of emissions, reflecting the most recent comprehensive data available. The base year emissions are the emissions from the reference year from which all future emissions are projected.
2. Growth Rates: The key assumptions, including fixed growth rates, are based on historical data and current policies and strategies. These rates are based on the anticipated trends in emissions as a result of policies and other socio-economic factors.

The analytical approach of this analysis is a combination of linear and non-linear regression models for predicting emissions. This is a blend of logistic and compound growth models due to the nature of the existing policies and their impact on emissions. Moreover, methods of interpolation are used to extrapolate emissions of years with no data, which provides a long and consistent series for analysis.

The logistic growth model is especially useful in cases where growth is assumed to reach a certain point only because of existing limitations in current legislation and technological advancements. This model is quite typical for many natural processes – for instance, the increase in the number of a certain population is fast at the beginning but gradually decreases as the upper limit is reached. When applying the idea of a "carrying capacity" to the CP scenario, the term can be defined as the highest emissions level resulting from the application of current policy measures.

The formula for the logistic growth phase is:

$$P_t = \frac{k}{1 + \exp\left(-b * (year - t_0)\right)}$$

Equation 15

Here, k is the carrying capacity derived from the BAU scenario, b is a parameter determining the curves steepness, and t_0 is the inflection point year where changes in emissions trends are most significant. The steepness parameter is utilized to ensure a smooth transition from the compound growth phase to the logistic growth phase.

For the year prior to the inflection points, the scenario employs a compound growth model:

$$P_t = E_{base} * (1 + r)^{t-2023}$$

Equation 16

Where E_{base} is the base year emissions, and r is the rate of change reflecting CP impacts on emissions growth.

First, emissions are calculated using the compound growth formula where the base is the historical level of emissions, and the exponent is the existing policy factor. After passing through the tipping point, the model enters a logistic phase, indicating a slowdown in the growth of emissions due to policy and technological constraints. This is in accordance with environmental and economic theories that predict two values. On the one hand, the emissions increase due to economic and population growth, and on the other hand the overall emissions peak that occurs under full integration of regulatory measures (Stern, 2007).

<u>Renewable Energy</u>

The "Renewable Energy" (RE) scenario within the thesis represents the future shift in energy consumption through emphasis on RE sources. This scenario can be considered rather relevant because it demonstrates the impact of the increased deployment of RE on GHG emissions over the course of the current century, guided by the following key variables:

1. RE share in 2023: Based on the data from 2023, the share of RE on an international level is set at 30.2%. Currently, the percentage considers the fact that there is an increase in RE installations like; solar energy, wind energy, and hydro energy driven by achieving global sustainability standards.
2. CO_2e savings: Each percent increase in RE share leads to a decrease in the level of GHG emissions by 0.6%. This impact highlights the positive environmental impact of replacing fossil fuels by RE (Pursiheimo et al., 2019).
3. Annual growth factor: The RE share is expected to increase by 5% annually, which shows both the achievable and aspirational growth rates given the current advancement in technology and policies (Saygin et al., 2015).
4. Targeted global RE share: The scenario aims at achieving 80% RE share in 2050 and further incremental increases until 2100. This is in line with the global goals of reducing the carbon footprint and preventing further increases in temperature within an acceptable range (Holechek et al., 2022).

This scenario uses an exponential growth model to project the incremental increase in RE from 2023 to 2100. The mathematical expression for RE share growth is:

$$RE_{Share}(t) = RE_{Share}(t-1) + \big(1 + RE_{Share}(t-1)\big) * k$$

Equation 17

Where $RE_{Share}(t)$ is the RE share in year t, and k is the growth factor representing the annual increase rate adjusted for the diminishing potential for growth as the market approaches saturation.

This model does well in capturing the pattern of RE adoption by factoring in the possibilities of exponential expansion while also considering the natural saturation that occurs once the market is nearly fully saturated. This way, the model changes the growth rate depending on the previous year´s RE share and thus, prevents the projection from getting over 100%. In the practical implementation of the model, the RE share is bounded below 2050, so that the minimum RE share is 80%, which is consistent with global trends in the adoption of RE.

Circular Economy and Waste Reduction

The “Circular Economy and Waste Reduction” (CE&WR) scenario focuses on the possibility of optimising the circularity of processes and decreasing overall GHG emissions through the shift towards a more circular economy. This scenario rests upon several key assumptions on how CE principles will be integrated and approximates the resultant effects on environmental performance through 2100.

First, the scenario has a maximum sustainable level referred to as the carrying capacity, which is 60% circularity in the economy. This is the maximum proportion of the economy’s total material flow which can be cycled back into the economy, without having to draw on fresh materials. This limit is deemed achievable based on today’s innovations and financial capabilities, and the public’s readiness to embrace circular systems (Haas et al. , 2015).

Next, the growth rate of CE integration is assumed to be slightly more than 0.3% annually. This slow increase presents reasonable growth expectations that may be attributed to policy support, technological development, and market uptake of CE practises (Androniceanu et al., 2021).

The CE scenario also applies a logistic growth model to estimate the circularity rate and its rise from the current level to the carrying capacity by the year 2100. This sort of model is useful in a situation such as the CE&WR, where growth will eventually slow because of practical and systemic realities. In the case of CE integration, the model expects a saturation point – referred to as the carrying capacity.

The mathematical expression for the logistic growth is:

$$CE_{Integration} = \frac{L}{1 + \exp\left(-k * (year - x_0)\right)}$$

Equation 18

Where L is the carrying capacity or the maximum level of CE integration achievable, k is the growth rate of integration, and x_0 is the inflection point, so the year when the rate of adoption is highest.

This model is most useful in situations where the overall market for adopting new practises may start to decline as the market becomes saturated or the easier changes are implemented first before moving on to the more challenging market modifications.

<u>Investment in Energy Efficient Technology</u>

The "Investment in Energy Efficient Technology" (IEET) scenario captures how the continuous advancement of energy efficiency would affect the CO_2e emissions trend. This scenario is based on a set of key parameters that characterise the future course of energy efficiency and the resulting impact on CO_2 emission. It depicts progressive improvements and policy measures that are being implemented to increase the efficiency of energy use.

1. Annual improvement rate in energy efficiency: The given scenario assumes an annual increase in energy efficiency of 1.5%. This rate is based on trends that are prevalent in industrialised countries where constant advancements in technology and the implementation of strict energy policies create regular enhancements in energy efficiency.
2. Annual rate at which CO_2e reductions improve: Based on the assumption, it is possible to assert that the CO_2e reduction improvement rate equals 2% per year. This is due to improved technology and efficiency in using energy, resulting in higher CO_2-efficiency factors for emissions per unit of energy used (Javid & Khan, 2019).
3. Initial energy efficiency level in 2023: In this particular case, the baseline value of energy efficiency at the beginning of this scenario in 2023 is estimated at 10%. This baseline provides a snapshot of energy efficiency in the present day across different segments, highlighting the potential for future enhancement.
4. Initial CO_2e emissions reduction level: The initial level of CO_2e emission reduction is 5%. This percentage indicates the current efficiency of presently available technologies and measures in decreasing emission levels as compared to a reference point and past value.

This scenario also uses compound growth to forecast the gradual increase in energy intensity improvement and concomitant decrease in CO_2e emissions from 2023 to 2100. The choice of a compound growth model is informed by its ability to simulate the cumulative effect of yearly incremental improvements in energy efficiency. This model reflects the realistic nature of technological advancements where each year´s improvement builds on the previous year´s advancement, compounding their effects over time.

The mathematical formulation of the compound growth model in this scenario is:

$$Energy\ Efficiency\ Level_t = Energy\ Efficiency\ Level_{t-1} * (1 + Improvement\ Rate)$$

Equation 19

$$CO2e\ Reduction_t = CO2e\ Reduction_{t-1} * (1 + Reduction\ Improvement\ Rate)$$

Equation 20

Where EEL_t represents the level of energy efficiency in year t, improvement $rate$ represents the annual energy efficiency improvement rate, $CO_2 e\ Reduction_t$ represents the percentage reduction in CO_2e in year t, and the RIR represents the effectiveness of emissions reduction improves annually.

This model effectively captures the gradual nature of efficiency improvements which are usually derived from improvements in technology and/or processes. In the case of the scenario, it takes the base of the initial energy efficiency and CO_2e emissions reduction and looks at how these parameters change over a period of time due to continued investments in technologies.

5.2 Scenario Distinction

In this section, a detailed analysis of the data presented in the charts is outlined. This helps to understand the specifics and advantages of each of the emission scenarios. The visualisation in (Appendix 1) clearly depicts a sharp decline in CO_2 emissions under the RE scenario which is evidenced by the high scores obtained in the use of RE sources to reduce the use of fossil energy. In this scenario, by increasing the RE share, emissions can be cut by as much as 50% by 2050. Its time-sensitive nature makes it especially relevant with regard to the current climate change agenda. This becomes evident in the graphical representation where the implementation timeline of the RE emissions scenario differs significantly from others (Appendix 2). It is also seen that around 2022 and 2024, there will be a break in the emissions trend, which could well be due to transition issues as energy systems transition more radically from fossil based too renewable. This disruption may cause higher cost of capital that is needed to implement the structural changes and larges scale transitions to RE (Appendix D). Likewise, the negative rash observed from 2041 to 2044 may be due to periods of technological advancement or policy accelerations, which, although bringing short-term fluctuations, result in sharp emission reductions as these technologies become established (Appendix 1).

In contrast to the sharp fall in emissions in the RE scenario, there is a more gradual yet substantial reduction in emissions considering the IEET scenario. It relies on successive technological advancements in the utilisation of energy in various sectors and expects cumulative CO_2 emissions savings through improving energy use intensity by 1.5% annually. This corresponds to approximately 1 Gt CO_2e emissions savings. While its decline is not as sharp as in other scenarios, its long-term effects on promoting sustainable industrial practises are significant making it a crucial addition to the RE plan.

The CE&WR scenario focuses more on a systematic shift in consumption and production patterns. By gradually applying CE principles, it forecasts a decrease in CO_2 emissions due to better recycling and less waste. This encounters a substantial recycled throughput potentially capable of managing up to 60% of the economy´s material demands by 2100 (Haas et al., 2015). Such a circularity value would lead to as much as 95 Gt CO_2e savings. This scenario´s implementation is not as steep as the RE one, but still steeper than the IEET one, which focuses on long-term reduction and material saving.

Contrastingly, in the case of the CP scenario, although there is a decrease in emissions at the beginning of the century, they stagnate from 2080 onwards due to constraints of the current policy framework and capabilities (Appendix 1). In the global emissions forecast, it can be seen that, the CP scenario performs drastically better than the BAU but also better than the other scenarios. This is due to the combination of multiple emissions reduction strategies that are in place. Hence, as a result of the data analysis, it is possible to conclude that individual scenarios offer a range of opportunities to decrease CO_2 emissions, but a combined integration is a more extensive approach that might be more effective in the long run. As seen in the CP scenario, even though it has a more conservative policy setting compared to the others, the current policy mix using a blended approach can gradually reduce the gap towards more rigorous worldwide goals. In particular, if the RE, IEET, and CE&WR strategies were integrated together, the effect of emissions reduction is maximized under the constraint that only these three reduction strategies exist. Also, under the CP scenario, emissions are depicted to rise steeply in 2080 and 2081 because of saturation, the holistic and advanced implementation of existing policy measures, as well as the delayed enforcement of new and more stringent measures. However, in the post-2080´s, the emissions reduction scenario depicts a "run out" connotation, implying that in the absence of fresh policy innovation or technological breakthroughs, the current measures may meet the stiffer climate goals of the second half of the century. Still, these measures are not expected to handle the rising emissions in the future.

5.3 Integration and Cross-Scenario Analysis

The integration and cross-scenario analysis offer a broad understanding of how each of the strategic initiatives affects GHG emissions and sustainability targets simultaneously. For instance, improvements in the field of RE affect the results of the IEET scenario. A higher uptake of RE can lower the energy intensity needed in production processes and, hence, boost the efficiency of energy saving initiatives. Likewise, the CE&WR scenario is consistent with the emissions reduction attained by the improvement of energy efficiency (Haas et al., 2015; Androniceanu et al., 2021). A comparison of these scenarios shows the level of efficiency and practicality between them. It can be seen that each scenario contributes to the environmental goals when contrasted by comparing the key outputs of CO_2 reduction, economic impact, and technological viability. For instance, although RE may reduce CO_2 by the largest amount in the early stages of this century, CE&WR has several indirect advantages in terms of resource preservation and waste reduction that become significant when the corresponding infrastructure and market acceptance are integrated. The comparative strategy also helps to reveal not only the differences in the contribution of each scenario but also the directions for increasing the positive impact of policies or technologies. For instance, applying the results of the IEET to national energy policies may help boost the implementation of high-efficiency technologies that will reduce emissions as estimated by the RE scenario.

To perform a comparative analysis, we will evaluate the scenarios based on several key criteria; their potential impact on CO_2 reductions, economic implications, feasibility, and technological requirements.

Potential impact on CO_2 reductions:

- BAU: Provides a baseline without additional CO_2 reductions beyond current levels, serves as a control scenario.
- CP: Moderate CO_2 reductions based on existing policies which may not be sufficient to meet international climate targets in the long or short run.
- RE: High initial impact on CO_2 reductions, especially if the RE targets are met (e.g., 80% by 2050), significantly losing value over time.
- CE&WR: Less direct than reductions from energy scenarios, but still most effective once implemented.
- IEET: Provides moderate CO_2 reduction, hard to predict based on uncertain innovations.

Economic Implications

- BAU: Likely the least costly in the short term but potentially expensive long-term due to environmental degradation, compensation costs, and missed opportunities for innovation.

- CP: May incur moderate costs associated with implementing and maintaining existing policies, with some economic benefits from early adaptations.
- RE: High initial investment costs but potential for substantial long-term savings.
- CE&WR: Requires relatively high initial costs in R&D and infrastructure, which can be offset by savings in raw materials and waste management. Still, maintaining infrastructure requires moderate investments over time.
- IEET: Generally cost-effective, offering significant returns on investment.

Feasibility

- BAU: Currently, highly feasible as it requires no change from current practises. However, long-terms costs make it absolutely unfeasible.
- CP: Feasible within the current regulatory framework but may lack ambition for deeper cuts in emissions.
- RE: Feasibility depends on technological advancements and the ability to scale up renewable infrastructure rapidly. Also, acceptance of people plays an important role.
- CE&WR: Feasible under the premise of strong policy support and cultural shifts towards sustainability.
- IEET: Highly feasible as it often involves upgrading existing technologies and practises to stay competitive.

Technological Requirements

- BAU: No new technologies required.
- CP: Depends on the sector; generally moderate technology changes are needed to comply with existing regulations.
- RE: Requires significant technological investment in RE technologies and grid infrastructure.
- CE&WR: Needs advanced recycling and manufacturing technologies as well as processes and supply chains.
- IEET: Relies on the development and deployment of cutting-edge efficient technologies.

5.4 Thies´s Emissions under Scenarios

In this section, we are going to discuss the already declared emissions reduction scenarios. However, now, they are aimed at showing Thies´s environmental impact (Appendix 3). The root of this analysis is the calculation of Thies´s emissions data for the year 2023. The emissions data is calculated utilising holistic data provided by Thies and the analytical tool EcoCockpit. Here, only the available data was utilized. We recorded an emissions value of approximately 6379 tonnes CO_2e. This can be seen in Figure 3. For comparison, the emissions of Thies for the years 2022 and 2021 were calculated. These emissions are 8558 t CO_2e (Appendix 7) and 9619 t CO_2e (Appendix 8) respectively. This massive reduction in emissions is mainly due to the reduction of stainless steel used in production. For the years 2021, 2022, and 2023 approximately 1,718,428 kg, 1441,888 kg, and 1,056,542 kg were used, respectively. However, there was no significant drop in revenue, which is 79 € mil. for 2021, 86 € mil. for 2022, and 74 € mil. for 2023. Besides that, there are other emission reduction strategies that Thies implied. These changes are the implementation of photovoltaic with the end of 2022, a lowered steam boiler pressure in dyeing plants, the replacement of lightning in the exhibition hall, the installation of an air curtain system on one hall door, and the adoption of an automated load management system.

By calculating Thies´s emissions for the latest year, their future emissions as well as expected costs under each scenario can be estimated. This emissions forecast serves as the foundational emission for each scenario. The cost estimate includes direct cost of emissions (15€ per tonne of CO_2 equivalent) and the capital costs of investing in particular technologies and processes (Appendix 4). Hence, the data-driven insights calculated through EcoCockpit can provide good information how Thies should set its environmental objectives. Figure 3 shows the distribution of emissions over the Scopes. The explicit data inputs for this calculation can be seen in Appendix 5. Utilizing this, the scenarios are evaluated based on their potential to reduce emissions and their financial viability to create a dual perspective on the environmental and financial performance of the reduction strategies.

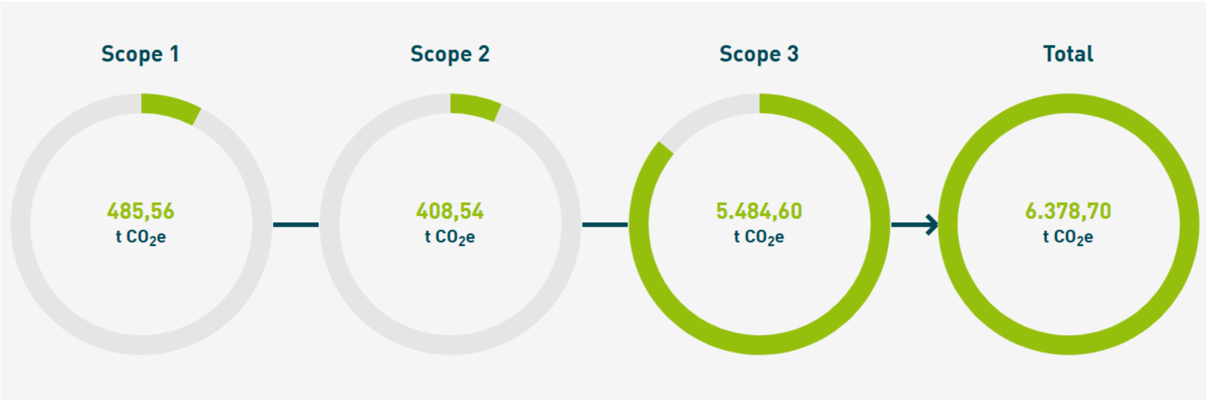


Figure 3: Scope Distinction Thies 2023 (EcoCockpit, n.d.)

Based on the evaluation, an emissions and cost forecast graph are created which provide a quantitative assessment of the projected CO_2 emissions and expected costs, respectively. As for the global BAU scenario, the Thies specific one shows a similar continuous upward trend, emphasising especially the high environmental costs of inaction. In contrast, the other scenarios, although they encounter investment costs in infrastructure and R&D, have lower emissions output as well as lower economic costs. Especially, the RE scenario reflects initial emissions reduction, but at the same time also the highest initial investment. The CP, CE&WR, and IEET scenarios all show a higher emissions forecast than RE where the IEET scenario has the highest. Moreover, the CP and CE&WR scenarios show a quite strong correlation, not only on the emissions forecast but also on the cost forecast. This is a moderate increase in costs with a slightly higher initial investment, a drop around the year 2050, and another moderate increase afterwards. For the CP scenario, this might be due to the reflection of modest policy interventions. On the contrary, the CE&WR scenario requires initial investment in infrastructure, but once the easier changes are implemented, the emissions drop and stabilise over the long term. The RE scenario shows the highest initial costs since the target of 80% RE in 2050 is the most drastic one. However, over time, these costs are offset by the reduced need for emissions compensation costs as fossil fuels become redundant and the infrastructure stabilises. The RE scenarios cost evolution over the years is more unique than the others. It starts with a very high peak, which is falling off quickly as well. The turning point is when the RE capacity of 100% is reached. From that low point on, the costs are rising again since the maintenance cost for infrastructure stays the same, however the compensation cost rises since the maximum CO_2 reduction is reached. Still, for each of these scenarios, the long-term benefits become clear as the economic as well as the environmental cost decrease.

	Mean	
	CO_2e t	Costs
BAU	13,200.15	198,002.27 €
CP	10,465.35	195,189.48 €
RE	8,847.22	201,516.38 €
CE&WR	9,807.14	189,605.38 €
IEET	11,749.85	187,478.72 €

	Std. Deviation	
	CO_2e t	Costs
BAU	5,016.11	75,241.66 €
CP	2,808.77	18,526.22 €
RE	2,455.37	60,978.69 €
CE&WR	2,667.53	20,864.28 €
IEET	3,894.53	57,997.42 €

Table 2: Thies´s av. Emissions and std. Deviation for Emissions and Costs

Additionally, above, one can see the mean and standard deviation for each scenario of emissions and cost forecast for the years 2023 until 2100. It becomes clear that the RE and CE&WR scenarios perform best on average emissions with 8,847 CO_2e and 9,807 CO_2e tonnes and 201,516 € and 189,605 € annually, respectively. Still, the costs for the RE scenario, due to its expected rapid implementation and high investment costs, represents the highest average costs per year. The CP scenario and the IEET scenario perform significantly worse with respect to emissions. However, both perform better on costs than RE and IEET performs slightly better than CE&WR as well. Despite that, it can be concluded that the RE and CE&WR scenarios were the best options to implement when solely reflecting the numbers. The high costs for RE with reflect a scenario where 100% RE is implemented. This rapid improvement is the case for no other scenario. Also, it is important to acknowledge that these costs were the highest potential expenditures when following the ambitious strategy implementations and simultaneously paying the CO_2e compensation costs.

6 Discussion

In this chapter, the findings from the investigation of the carbon footprint management strategies at Thies are critically analysed. A special focus is set on the implications for sustainability within the textile industry. First, we will discuss the research questions that pave the way to answering the knowledge question regarding the integration and effectiveness of CO_2 reduction strategies in textile manufacturing.

The assessment of different environmental emissions reduction strategies, including RE, IEET, and CE&WR, compared to BAU and CP scenarios is a vital perspective for the strategic planning of sustainable development. The RE scenario cost, approximately after the year 2060, constantly rise because the turning point is reached. Here, the energy mix is totally satisfied by RE. Consequently, the emissions rise and so do the compensation costs. Still, it can be observed that the emission reduction is radically higher and quicker than in other scenarios. The graph illustrates this by showing a relatively constant and gradual increase in costs in contrast to BAU which has a steep increase, providing that RE is more economically feasible than conventional energy sources. Furthermore, the cost trend of the IEET scenario is similar to that of RE, with a gradual increase but at a relatively lower slope than BAU. This shows that energy efficiency measures help to cut both emissions and overall operational costs in the long run. Next to that, the graphic enhances a key message, which is that there is a clear opportunity to invest in EET in order to save money in the future rather than continue with the current systems. Also, it is not only recommended to invest earlier but also with high capital. From CE&WR, the cost forecast is similar to the CP forecast but still below, which points to an early but at the same time rather long-term cost advantage. Still, the graph reveals, that in the long run, the costs remain above the RE costs. However, if the circularity is not capped at 60% in the future, it will massively decrease emissions but also costs, since each additional percentage point of circularity has a higher impact on emissions savings. In contradiction to that, the BAU scenario perfectly represents the high cost of compensating emissions as being even higher than investment costs in RE, IEET, or CE&WR. Lastly, the CP scenario suggests that although CP helps to reduce some of the adverse effects of BAU, it does not harness the full cost saving benefits that could be achieved through more stringent sustainability policies. However, it also suggests that a combination of practises is most applicable, be it for costs or emissions savings.

Based on these findings, Thies should consider the elaboration of their sustainable management and focus more on carbon emissions reduction and so the financial performance of the company in the long term. The following points are recommended:

- Prioritise RE and IEET: This prioritisation can be beneficial to achieve long term cost advantages and emissions reduction. Although IEET does not perform best, it is the counterpart to RE. Compared to RE, IEET has lower initial costs but also a lower initial impact. On the other hand, it has greater potential in the long term but also requires higher investments to get there.
- Careful implementation of CE&WR: Although CE&WR has the highest emissions reduction potential, there are more complex drawbacks that might occur. Also implementing circular practises questions the interplay of many stakeholders. Still, the incremental integration of CE&WR will be beneficial, especially in the future.
- Reevaluate CP: The analysis reveals that the CP scenario contributes to global environmental goals. However, there is still much that can be done. This may push for or assume more stringent policies that optimally harness the opportunities of RE and IEET for instance energy recovery as a circular practice.

6.1 Interpretation and Contextualization

The primary research question sets its focus on identifying the most cost-effective and environmentally friendly management strategy for Thies over the long term. The analysis of the data clearly indicates that strategies focused on RE and IEET not only sustain lower environmental cost compared to the BAU and CP scenarios but also show significant long-term economic cost benefits. This addresses the research question by demonstrating the RE and IEET are not only viable but are indeed preferable options for reducing overall emissions and associated costs, which is consistent with findings by Bevilacqua et al. (2007), who noted similar benefits in energy efficiency in manufacturing. Theoretically, the findings reinforce the concept of sustainable development as an integrative component of corporate strategy, suggesting that proactive investment in sustainable technologies is not merely an environmental decision but a financial one as well. In the following, the research questions will be discussed.

<u>1. Primary Sources of CO_2 Emissions</u>

The primary sources of CO_2 emissions in the manufacturing processes of Thies are energy consumption and material use, especially stainless steel. The major contributor to the high energy related emissions are operating machinery and heating processes. Additionally, the transportation of products and employee travel contributes quite a bit to emissions. It can be said that this aligns with regular industry patterns, where energy-intensive processes dominate CO_2 emissions profiles (Bevilacqua et al., 2011; Palamutçu, 2015).

<u>2. Contribution of Different Operational Phases</u>

Each activity that Thies undertakes in each of its phases has a unique impact on the company´s carbon footprint. The manufacturing phase is the most dominant phase in due to its high energy demand. The acquisition of raw materials, especially stainless steel and the transportation of the same also has a significant impact on the indirect emissions categorized under Scope 3. Additionally, the day-to-day business, such as employees´ transport and deliver of final products add to the overall emissions, although not as much as the manufacturing processes do.

<u>3. Mitigation of Primary Sources</u>

To reduce the primary sources of CO_2 emissions, the following measures can be taken; substituting traditional energy sources like coal, oil, and natural gas by cleaner energy sources like solar or wind power can greatly lessen the number of emissions from fossil fuels used in machinery and in heating processes, which is already done by Thies. Next, changing old processes to energy-efficient ones and making necessary adjustments to the production line such as energy management systems can reduce energy use significantly. Also, especially for steel, the related emissions can be minimised when a circular economy is practised (Bevilacqua et al., 2011; Palamutçu, 2015). Here, it must be said that Thies, as a manufacturer of machinery for the wet finishing sector, contributes only to a very small part of the textile industry´s footprint. Still, through upgrading their products continuously, like the Signature Series and the soft-TRD SIII, they enable their customers in the wet finishing sector to produce less environmental harmful textiles.

<u>4. Strategies for Energy Efficiency and RE Integration</u>

In order for Thies to enhance their energy efficiency, they have several options: The introduction of energy efficient machinery and equipment. This would encounter the modernization of equipment, such as the implementation of variable speed drivers (VSDs) in motors to adjust the energy consumption based on the actual throughput rate. Also, regular maintenance and upgrades are essential to operate at peak efficiency. Next, process optimizations like the introduction of lean manufacturing techniques, heat recovery systems, water management, or the overarching integration of a smart grid can be beneficial. Moreover, building and infrastructure improvements like building insulation and owned RE sources can not only reduce energy use but is also costs effective. Besides that, the engagement and training of employees through regular training and incentive programs can contribute to efficiency. However, Thies already implemented some strategies; this is the adoption of 100% ecological electricity purchased, a throttled maximum temperatures in heating and, a lowered steam boiler pressure in dyeing plants, installed motion detectors, and the installation of "smart" heating valves is planned.

5. Improvement of Supply Chain Management and Circularity

To address indirect CO_2 emissions, Thies should focus on the improvement of their supply chain as well as on the circularity of products. First, a supplier collaboration with regular supplier audits can be implemented. This should lead to better communication and coordination. Also, more efficient inventory management like just-in-time Inventory (JIT-I) and demand forecasting can be adopted. However, this requires close supplier connections to deliver materials when needed. An adaptation for Thies´s business plan could be a product-as-a-service (PaaS) model where customers can lease or rent machinery for a specified period of time. Lastly, to encounter circularity, products should be design for durability and longevity, reuse, reduce, remanufacture, and recycle. Thies could optimally work towards a closed-loop supply chain, however, this is quite difficult and time consuming to achieve (Bevilacqua et al., 2007).

6. Barriers for aligning with SDGs

Actual barriers that might occur when aligning with SDGs include financial limitations, technological constraints, regulatory hurdles, cultural and behavioural factors, supply chain inconsistencies, and a lack of staff training or awareness. High initial costs for new technologies and process improvement can be mitigated through green loans, government subsidies, and long-term cost-benefit analysis to justify these investments. Technological issues can be resolved by increasing the company´s R&D budget and partnering with technology vendors. To navigate inconsistent and evolving regulations requires staying engaged with policymakers and participating in regulatory development processes. Changing the traditional thinking and promoting sustainability culture can be done through internal communication, awareness raising activities, and management commitment to sustainability. The increase in consumer demand for sustainable products can be enhanced by engaging in market education efforts and promoting the benefits of sustainable practices.

The answers to these research questions offer a clear and detailed picture of Thies´s and the industry´s current state and possible direction for increasing sustainability. They are satisfactory in several ways: They outline and quantify the major sources of CO_2 emissions and the shares of various operational stages with references to industry standards. The proposes strategies and technologies are based on the existing best practices and offer specific measures that Thies can adopt to improve energy efficiency and incorporate RE technologies. Additionally, the measures for enhancing supply chain management and circularity are clearly outlined, offering a roadmap for reducing indirect emissions. The assessment of the challenges to the implementation of the SDGs is thorough offering actionable solutions to overcome them. However, the answers could benefit from more specific examples and quantitative data to support the proposed strategies. For instance, incorporating information on the anticipated emissions cut from specific interventions or case studies from similar companies that have successfully implemented these strategies would strengthen the recommendations. Furthermore, the answers focus on the strategic level, so a detailed action plan with timeframes, necessary resources, and possible risks would provide a clearer path forward for Thies.

6.2 Reflection on SDG alignment

Through the analysis of Thies´s sustainability report, it becomes evident that Thies supports several of the SDGs. In line with SDG 6 (clean water and sanitation), Thies has developed equipment that uses less water and chemical in the processing of textile, thus improving water quality in textile production. To enhance this alignment, Thies should consider acquiring modern water recycling technologies and enhanced wastewater treatment solutions so as to incorporate them and improve the efficiency of water usage correspondingly. With regard to SDG 9 (industry, innovation, and infrastructure), Thies has embraced the sustainable industrialization agenda by designing efficient textile machinery to increase their customers productivity while minimizing the negative environmental impacts. Their machines continuously improve in the fields of electricity-, energy-, and water usage as well as in reduction of chemical waste. To cope with this goal in the future, Thies should continue to invest in R&D that seeks to develop technologies that reduce emissions and energy use even further. The next steps towards this direction will involve setting up an innovation lab solely focused on sustainability initiatives as well as partnering with technology firms and universities. Regarding the 12th SDG (responsible consumption and production), Thies´s business model is strongly committed to sustainable practices. To improve this alignment, CE has to be integrated at supply chain level. This involves ensuring that products are designed for durability, reuse, and recyclability. Lastly, based on indicators of the 13th SDG (climate action), Thies has effectively reduced the carbon emission of the company by implementing energy efficient technologies, utilizing owned photovoltaic, and buying green energy. As for the improvement of this process, it is proposed to efficient carbon management and smart grids for improved energy efficiency. According to Thies´s standards, they already have implemented several strategies to align with the SDG´s, however, there is still some place for improvement. Since Thies is already well equipped with sustainability practices, one of their main goals could be to align the wet finishing sectors emissions with SDGs through providing ever evolving textile machinery, hence, Thies can deal as an enabler of sustainability.

6.3 Limitations of the Study

In conducting this comprehensive analysis of Thies´s sustainability practises, it is necessary to consider several possible biases that may affect the understanding and generalisation of the outcomes. These limitations will be discussed to give a clear picture of the scope of the study and the potential impact of the recommendations on Thies´s sustainability strategies.

Data Scope and Availability

The primary limitation of this study arises from the gaps in the available data and its scope. Much of the analysis depends on the completeness and accuracy of the data supplied by Thies. A lack of complete data means that only limited insights can be given which in turn could lead to an incomplete understanding of the economic and environmental impact of Thies´s operations. Hence, this could lead to an inappropriate recommendation of emissions reduction strategies but could also provide a screwed picture of Thies´s sustainability. To prevent an underestimation of emissions, a security surcharge of 10% was applied. Still, it does affect each emission source the same. Hence, potential biases in emissions sources were not solved.

Generalizability of Findings

Although the suggested solutions have been based on the data given by Thies and the scenarios examined in the case of Thies, the applicability of these insights to other similar companies in the textile sector might be restricted. Factors like regulatory frameworks, economic constraints, and technological access can very much vary for different companies, which can affect the practicality and effectiveness of certain sustainability initiatives. Furthermore, an emission balance of a company does not have a fixed set and scope of emissions that need to be included. What this means is that different companies can add and discard different emissions sources in their emission balance. Hence, if the exact emission sources between companies is not known, their emission balance is not valuable to be compared. However, the emission balance is rather for comparing successive years of the same company under the prerequisite that the balance reflects the same emission sources and scopes. Still, a partnership between companies would enable a comparison of emission balance.

Technological Assumptions

The study takes into account the feasibility and applicability of incrementally advancing technologies for EET, RE, as well as CE&WR integration. However, the need for implementing such technologies and the company´s ability to integrate such technologies into its business model may not be the same. This could affect Thies´s potential to completely realise the theoretical advantages of reduction strategies.

Financial Constraints

New technologies and processes are always costly to install since they will involve major changes in existing operations. This is especially the case for more drastic and fast-moving changes. Although the financial constraints were acknowledged, Thies´s financial status is not deeply analysed in the study. Therefore, Thies´s financial constraints and its ability to fund sustainable investment may affect the implementation of the suggested strategies. Nonetheless, Thies has the possibility to make use of various subsidies for energy efficiency measures. These include federal, state, and EU funding programmes that offer investment grants of up to 45%.

Bias and Subjectivity

Finally, the analysis of the results and recommendation may contain biases due to the researcher´s subjective judgment on the relevance of specific sustainability indicators. Furthermore, publicly available data for constructing the utilized global scenarios may contain biases as well, due to their long horizon forecasts. These biases can influence the study´s findings and the recommended priorities of initiatives.

6.4 Relevance

The outlined research significantly advances the theoretical understanding of sustainability within the textile machinery manufacturing industry. By employing a hybrid LCA and EEIOA, the study integrates both direct and indirect emissions into a comprehensive evaluation framework. This dual approach not only enhances the precision of emissions measurement but also provides a nuanced view of how different operational processes contribute to the overall carbon footprint. Theoretical contribution of this nature is vital for developing robust models that can be applied across various industries, particularly those with intricate supply chains and significant indirect emissions. This research framework sets a precedent for future academic inquiries into industrial emissions, providing a solid methodological foundation for scholars aiming to explore the environmental impacts of complex manufacturing processes.

The practical implications of this study are extensive and offer actionable insights for both Thies and the broader textile machinery manufacturing sectors but also the industry at large. The study outlines specific strategies for emissions reduction, including the transition to RE sources, the implementation of EET, and the adoption of CE practices. These recommendations are grounded in a detailed analysis of Thies´s current emissions profile, ensuring that the proposed measures are both relevant and feasible. Moreover, the development of the Excel workbook for emissions scenario analysis serves as a practical tool for companies. This workbook allows companies to simulate various emissions reduction strategies, providing a data-driven basis for decision-making and strategic planning. By utilizing this tool, companies can better anticipate the outcomes of different sustainability initiatives, facilitating more informed and effective management of their environmental impacts.

6.5 Data Validation

This section will cross-check the emission data given for the different scenarios with external data sources. This analysis guarantees that the projections are consistent with trends and policies, especially regarding the European Union´s emission reduction measures and international emission reports.

The BAU scenario data shows that emission will continue to rise from 25.5 Gt CO_2e in 2000 to approximately 140 Gt CO_2e by the end of the current century. This scenario makes no alternations to the existing policies and does not consider any technological innovations. The emissions trajectory correlates with the historical and projected emissions data provided by the European Commission which states that in absence of any policy measures, emissions are expected to increase significantly because of the continuous industrialization and energy consumption (European Commissions, 2023). Next, the CP scenario demonstrates the effect of the current legislation and regulations that are currently in force to limit emissions. The data depicts emissions rising from 37.79 Gt CO_2e in 2023 to 75.8 Gt CO_2e in 2100. In the case of emissions, this means limiting the amount of CO_2e to 80 Gt. The EU´s emission Trading System (EU-ETS), a part of the EU climate policy, has been successful in cutting emissions by 15.5% in 2023 compared to 2022 mainly because of the rise in RE and energy efficiency improvement in industry (European Commission, 2023; CDP, 2023). The above-mentioned trend correlates with the projection under the CP scenario and suggests that existing measures. Next, the CE & WR scenario estimates emissions taking into account the application of reduce, reuse, and recycle. The data depicts that emissions are gradually decreasing to 93.8 Gt CO_2e by 2100. This scenario corresponds to the objectives of the European Green Deal since it focuses on the efficient use of resources and CE solution to reach climate neutrality by 2050 (European Commission, 2023). The overall CO_2 emission reduction which is estimated at 1.248 million tonnes in the Ce scenario is in line with the Commission´s goals. Next, the IEET scenario predicts emission cuts that can be attained through improvement sin energy efficiency as intended in the year 2030. The data suggest reduction of emission to 114.29 Gt CO_2e by 2100. This becomes evident in the European Commission data which reveals that there has been a considerable cut in emission in energy intensive industries as a result of efficiency (European Commission, 2023). The last considered reduction strategy is the RE scenario which shows the effect of increasing the contribution of RE sources. The data shows emissions to reduce to 113.26 Gt CO_2e by 2100, implying significant CO_2 reductions from RE deployment. According to the European Commission, there has been a record cut in emissions in 2023 mainly by the power sector transitioning to RE especially wind and solar (European Commission, 2023). Consequently, this scenario is quite consistent with the current tendencies. Lastly, the emission and cost forecast for Thies under the emission scenarios reveals the regional effects of global emission patterns and policies. The emissions reduction and their corresponding costs differ depending on the projection made, which implies that there is the need to develop specific measure that can be used to implement emission reduction gaols at the local level. The information presented for Thies corresponds to the trend in the EU ETS and other international emission reduction programs, which proves the validity of the used methodology (CDP, 2023).

6.6 Implementing Theoretical Findings

The integration of theoretical findings into Thies´s business model is crucial for transforming research insights into practical sustainability initiatives. This sub-chapter provides a clear and comprehensive road map on how the recommended emission reduction strategies are to be integrated into Thies´s operations while being consistent with the company´s strategic plan and industry relevance.

Firstly, it is necessary to bring the theoretical results into correlation with the general strategic concept of Thies. Sustainability should be made a fundamental part of the company´s strategic vision and corporate values. This requires a top-down approach starting with the management´s commitment and support for sustainability practices. Thus, incorporating these principles into the corporate culture of Thies, the company can create conditions in which sustainability is not an add-on, but a natural part of the organization´s activities and management. Based on the initiatives and business development of Thies, it can be concluded that Thies already encapsulates sustainability as part of their business model. Next, for the outlined strategies to be implemented successfully, Thies must develop a sustainability governance structure that will focus on these strategies. This may include the establishment of a Sustainability Steering Committee that will be charged with the responsibility of ensuring that emission reduction measures are incorporated. Some of the members of the committee should come from production, procurement, finance, and marketing departments. It guarantees that sustainability issues are well addressed in all areas of the business since it involves cross-functional approaches. Additionally, "job-enrichment" can be seen as a positive side effect. This principle focuses on enhancing job roles with more meaningful tasks and responsibilities. Therefore, job enrichment leads to higher responsibility and motivation, enhanced skill development, and greater autonomy on employee side and increase productivity, enhanced employee retention, improved quality of work, and enhanced organisational reputation on company side.

Among the most important recommendations, there is a need to switch to the use of RE sources. Thies can start with a feasibility study to determine the prospects of putting up solar, wind, and hydroelectric power plants in the manufacturing facilities of the company. This study should assess costs, possible energy savings, and the environmental impact. From the feasibility study, Thies can identify a step-by-step implementation plan that focuses on high impact projects. Thies already uses 100% green energy and has also incorporated the use of solar panels. Before deciding whether to invest in won-generated Re or to continue purchasing it, the following aspects should be takin into account. The generation of own RE requires a capital investment and is a one-time cost, but in the long run, it can prove to be cost effective, energy secure, and low carbon. It is sustainable and ma be financed by subsidies from the government. However, continuing to purchase RE offers predictable costs, avoids capital expenditures, and allows Thies to focus on core operations. Additionally, continued supplier relationships can help to obtain new technologies and beneficial conditions for cooperation. Thus, a balanced approach, combining expanded internal generation and strategic purchases, could optimize costs savings as well as sustainability. Another important measure is the introduction of energy-saving technologies. Thies should also undertake an energy audit to help in the determination of areas that require optimization on energy use. This audit will identify areas of upgrading the machinery, increasing the efficiency of the processes, and implementing energy management systems. For instance, the upgrade of old equipment with new ones that are energy efficient can help in cutting down the electricity usage. Also, implementing smart energy management systems can optimize energy use and reduce wastage. Next, applying CE solutions means changing the processes and making them as efficient as possible in terms of resources consumption. Thies can adopt the closed-loop system whereby wastes generated are used as raw materials in the manufacturing process. Here, especially steel waste and used machines should be cycled back. This approach has to be done in cooperation with the suppliers and customers in order to make the whole supply chain circular. Thies can also look at product take-back schemes where products at their end of useful life are collected for recycling, upgrading, or remanufacturing. Also, this could encompass such elements as establishing sustainability standards for suppliers and building strategic partnerships with suppliers who are environmentally conscious. Furthermore, Thies can adopt digital supply chain management to improve the visibility of the company´s supply chain and monitor the environmental effects of the supply chain processes.

For the successful implementation of these strategies, it is essential to involve employees at all levels. Thies should develop comprehensive training programs to educates staff on sustainability practices and the importance of reducing emissions. Encouraging employee participation through sustainability initiatives and recognizing their contribution can foster a culture of environmental responsibility within the company. Regular workshops and seminars can keep employees informed about new sustainability trends and technologies. Besides that, it is important to note that having a good monitoring and reporting systems is crucial in order to assess the progress and ensure accountability. Thies should set up concrete KPIs that are linked to sustainability objectives and report on these KPIs periodically. Moreover, transparency in reporting can improve the level of stakeholders´ trust and show that Thies is concerned with sustainability issues. Thus, tools like EcoCockpit can help Thies to carry out the emissions monitoring on a continuous basis to adjust their strategies based on real-time data. In Appendix 9, a detailed implementation plan can be seen which outlines how the theoretical findings can be practically applied within Thies´s business model.

6.7 Recommendations and Future Research

To build on the results of this thesis, future research should be focused on collecting more comprehensive quantitative as well as qualitative data. This data should especially reflect emissions data from suppliers to set up a more sustainable supply chain. This broader data collection could give a better picture of the state of the environment and the efficiency of the textile machinery manufacturers sustainable initiatives, especially for Thies. For further analysis of the effects of the implemented strategies, a longitudinal study on a monthly basis would also be beneficial to access a more detailed picture of the strategy´s performance. This future research could benefit from comparative case studies with other firms in the textile industry as well, but not only machinery manufacturers. This would provide a clearer view of the industry´s trends and differences in sustainability practises across the industry. It might reveal best practises and set standards that Thies could aim to achieve or even exceed. Also, this could explore new technologies in RE and CE that can help Thies identify possible investment opportunities. Additionally, further research in the area of how new technologies can be integrated into existing business models may help to identify more effective implementation methodologies which may reduce both implementation costs and environmental impact. Important is also a detailed financial analysis and costs-effectiveness studies of the proposed sustainability strategies. Applying this could assist Thies and similar companies to determining the financial timelines and break-even points of implementing specific emissions reduction strategies, such as the proposed ones. Lastly, the emissions of Thies can be recalculated, including upstream as well as downstream activities. This will lead to a more holistic picture of Thies environmental impact. Addressing these topics in the future can be very beneficial not only for Thies but also for the sector as a whole. This will help Thies refine its sustainability understanding through utilising an informed approach.

7 Conclusion

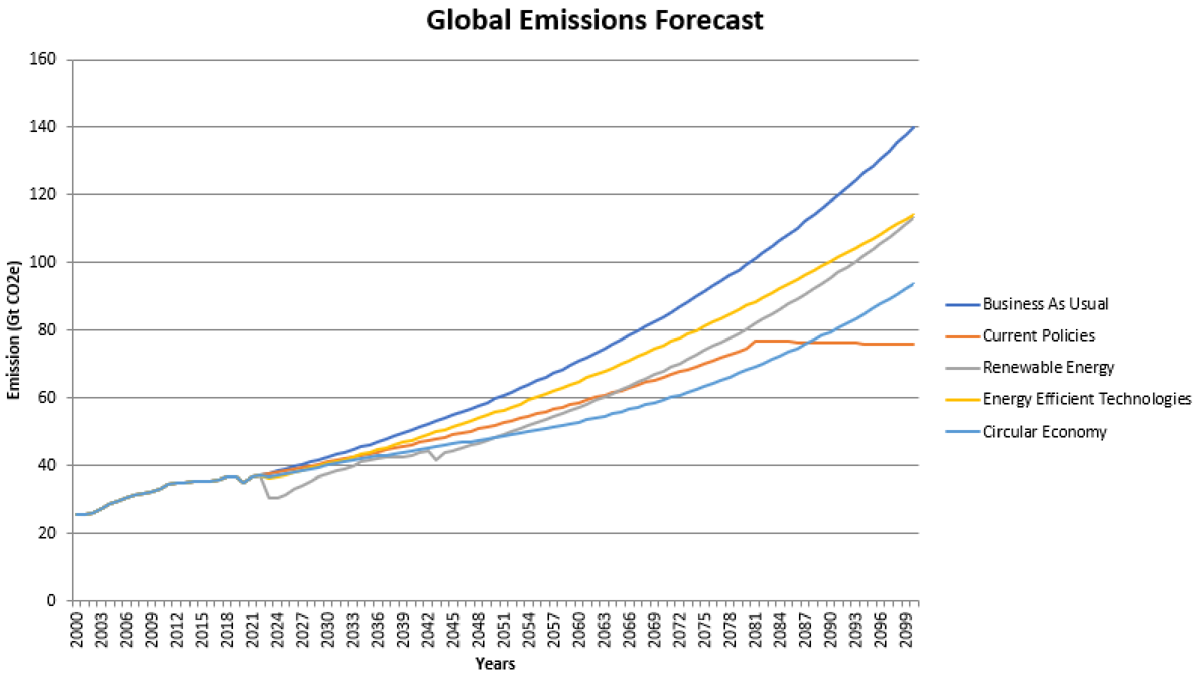
In this section, we will conclude the study by summarising the objectives and key findings including their implications. Also, we will make some concluding remarks concerning the significance of sustainability efforts in the textile industry and the contribution of innovative practises to achieving the SDGs. The main objective of the thesis is to evaluate the carbon footprint of Thies, including the direct and indirect emissions of GHG across all operational facets at the location in Coesfeld. This was utilised to formulate effective strategies for CO_2 reduction. Hence, the study seeks to identify actionable measures that Thies could undertake to ensure the alignment of their business model with the SDGs with, an emphasis on environmental sustainability. Here, it is noticed that Thies already has a strong commitment to sustainability and the SDGs. Thies already implemented some sustainable incentives, namely the adoption of 100% ecological electricity, throttled maximum temperatures in heating and gas, lowered steam boiler pressure in dyeing plants, and installed motion detectors, moreover, the installation of "smart" heating valves is planned. Hence, Thies is willed to contribute to the sustainability of the textile sector although machinery manufacturers naturally have a way smaller carbon footprint than textile producers. Therefore, Thies´s main in sustainability measure is to enable their customers, the wet finishing industry who are responsible for 15% of the fashion industries GHG emissions, to produce more ecologically friendly.

The analysis reveals both, the major contributors to emissions and the most effective strategies for reduction, thus offering a comprehensive framework for improving the company´s sustainability initiatives. One of the two major sources of CO_2e emissions are indirect emissions from manufacturing processes. This includes emissions from purchased electricity consumption as well as heating and cooling processes. Additionally, the high amount of stainless steel used in production processes is a major contributor.

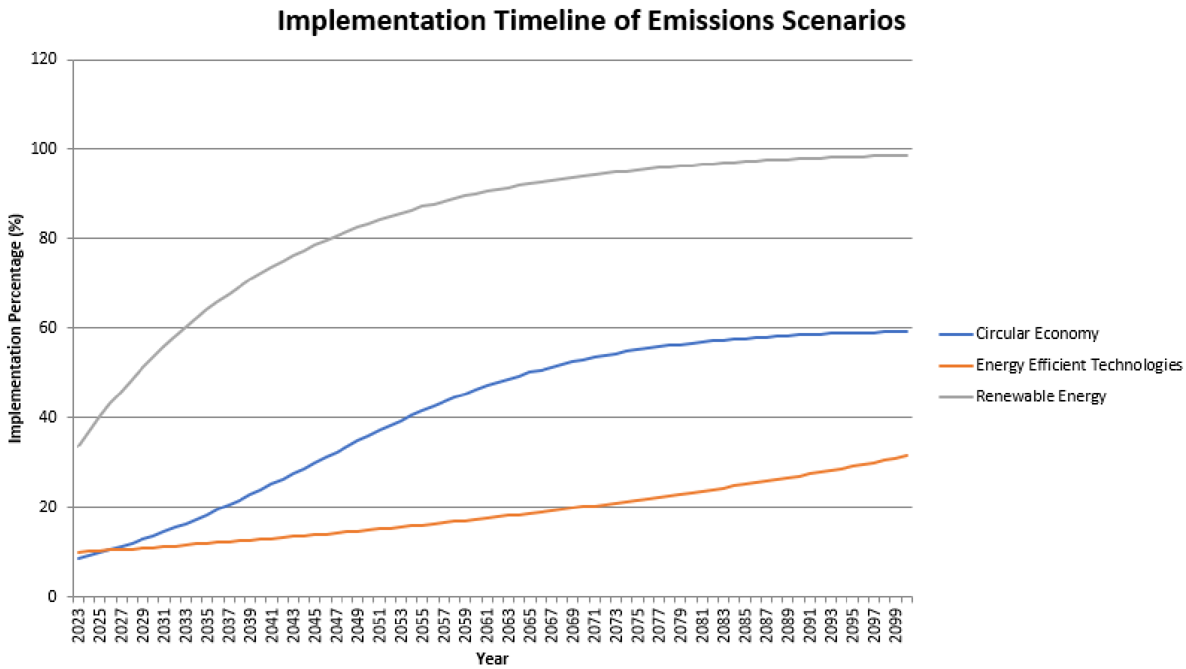
According to these main contributors, the research highlights some strategies that can be adopted to address the challenges of emission reduction. This could be the implementation of company owned RE sources. The transition from conventional energy sources to, for example solar, wind, and hydroelectric power can help minimise indirect emissions from purchased electricity. Linked to this is the need for energy efficient technologies. Additionally, optimising or replacing existing machinery is an optimal way to enhance energy savings. The combination of RE and EET has a great effect on emissions savings, as declared previously. On top of that, energy management systems can be used to identify further opportunities for energy efficiency improvements for instance VSDs or smart grids. Apart from that, it has been established that the implementation of CE can have a beneficial impact on costs and emission reduction. Such practises are waste material recycling, end-of-life recyclability, and reusing by-products. Most optimal would be the establishment of a closed-loop supply chain. Utilising these practises, especially emissions due to stainless steel can be reduced. Important to notice is that these strategies optimally perform together rather than being implemented individually. The adoption of these strategies in a coordinated manner enhances their impact on achieving a reduction in emissions. The proposed strategies are projected to align Thies´s operations more closely, than already exists, with the SDGs but only when implemented and managed effectively.

In conclusion, it can be said that sustainability is not only a regulatory necessity but also economically valuable for companies. Nowadays, environmental responsibility is also requested from companies like Thies. Therefore, committing to continuous sustainable improvement can lead to more sustainable practices and higher economic benefits if performed correctly. This is especially the case for the textile industry, which is one of the main contributors to global warming. Innovative practises such as RE, IEET, and CE&WR are essential to achieving environmental goals. These practises not only reduce the carbon footprint but also drive operational efficiencies and enhance corporate reputation.

8 Appendices



Appendix 1



Implementation Timeline of Emissions Scenarios
120
100
80
60
40
20
0
Implementation Percentage (%)
2023
2025
2027
2029
2031
2033
2035
2037
2039
2041
2043
2045
2047
2049
2051
2053
2055
2057
2059
2061
2063
2065
2067
2069
2071
2073
2075
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2081
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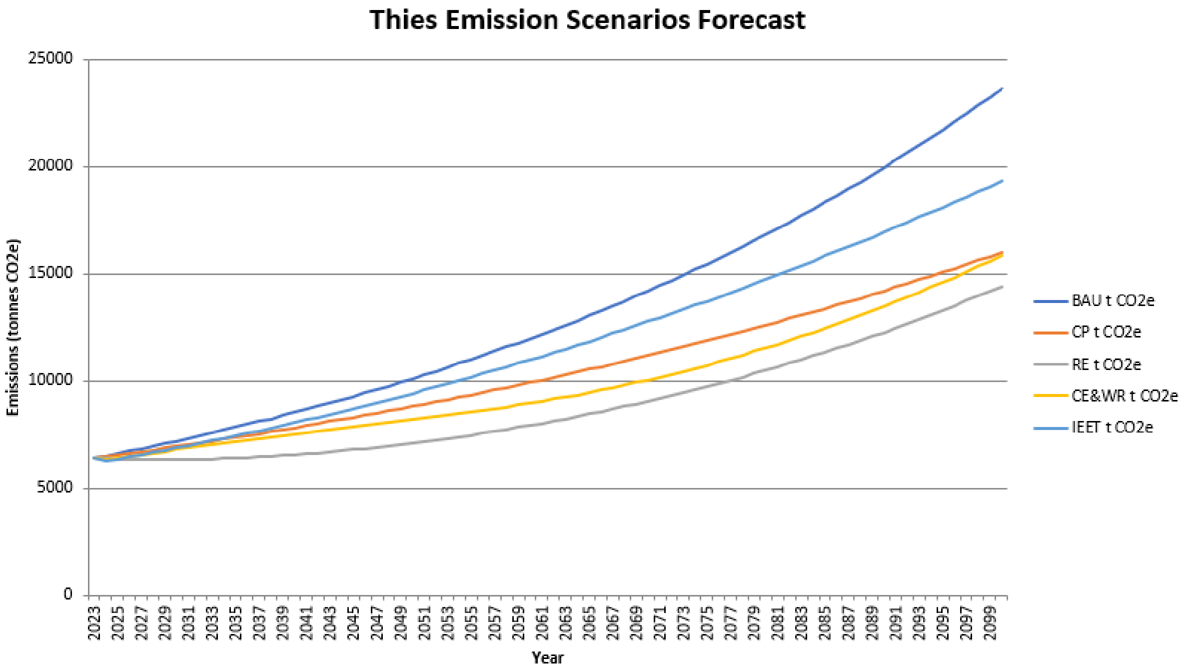
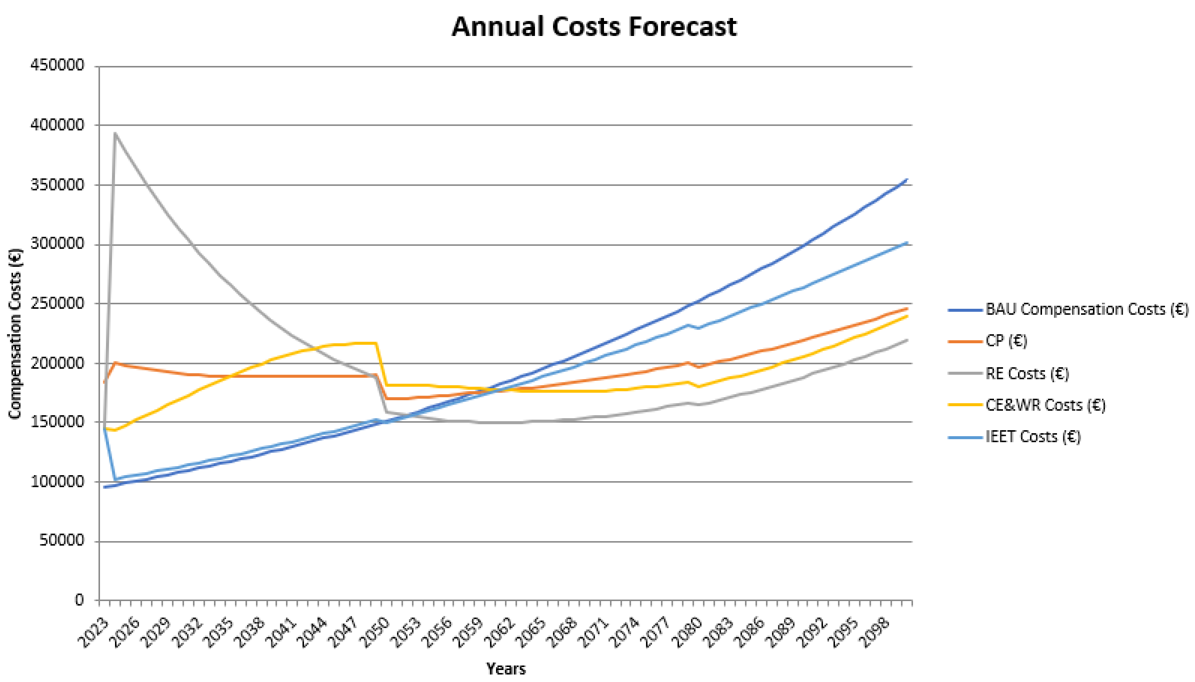
2085
2087
2089
2091
2093
2095
2097
2099
Year
Circular Economy
Energy Efficient Technologies
Renewable Energy

Appendix 2



Thies Emission Scenarios Forecast
25000
20000
15000
10000
5000
0
Emissions (tonnes CO2e)
2023
2025
2027
2029
2031
2033
2035
2037
2039
2041
2043
2045
2047
2049
2051
2053
2055
2057
2059
2061
2063
2065
2067
2069
2071
2073
2075
2077
2079
2081
2083
2085
2087
2089
2091
2093
2095
2097
2099
Year
BAU t CO2e
CP t CO2e
RE t CO2e
CE&WR t CO2e
IEET t CO2e

Appendix 3


Annual Costs Forecast
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
Compensation Costs (€)
2023
2026
2029
2032
2035
2038
2041
2044
2047
2050
2053
2056
2059
2062
2065
2068
2071
2074
2077
2080
2083
2086
2089
2092
2095
2098
Years
BAU Compensation Costs (€)
CP (€)
RE Costs (€)
CE&WR Costs (€)
IEET Costs (€)

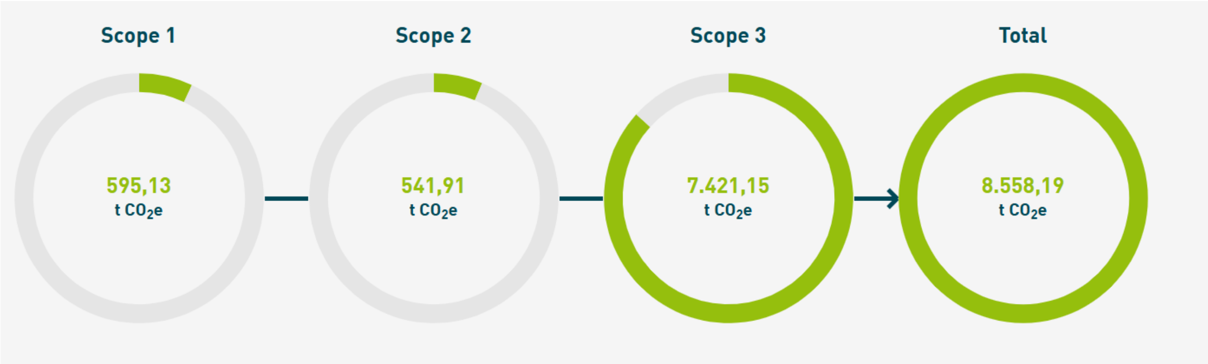
Appendix 4

Issuer	Comment	Amount	KG CO_2e	Data source	Description
Electricity from RE	Chargin Station Car	4,188,488.00 kWh	0	EEW 2022	CO_2-Factor - EEW
Diesel in Liters	-	2,520.00 Liters	3.102	Gemis 5.1	Gasstation/Diesel -DE-2020 (inkl. Bio) + direct emission
Natural Gas	Administration	165,207.00 kWh	0.201	EEW 2022	CO_2-Factor - EEW
Natural Gas	Production	1,991,993.00kWh	0.201	EEW 2022	CO_2-Factor - EEW
Electricity	Data from Thies	1,014,764.00 kWh	0.366	EEW 2022	CO_2-Factor – EEW
Domestic Flight	-	15,263.00 km	0.213	Gemis 5.1	Airplane – Passenger – Inland-DE-2020-Basis
Flight international	-	1,157,169.00 km	0.116	Gemis 5.1	Airplane – Passenger – International-DE
Passenger Train (Diesel-long distance traffic)	Rental Car	110,500.00 km	0.044	Gemis 5.1	Train-Pessenger-long distance – Diesel – DE-2020-Basis
Nitrogen (gaseous)	-	131,864.00 kg	0.075	Gemis 5.1	Xtra-generic/N_2 (gaseous)
Stainless Steel	-	1,056,542.00 kg	4.529	ProBas	Stainless Steel
Waste Water	Dirty and Precipitation Water	6,334,222.00 kg	0	ProBas	Dirty Water – Cleaning – DE-2005
Used Oil	-	145,110.00 kg	0.288	EEW 2023	CO_2 – Factors – EEW
Steel Scrap	-	132,132.00 kg	0.034	Information letter CO_2 factors – Bundesförderung für Energie- und Ressourceneffizienz in der Wirtschaft	-

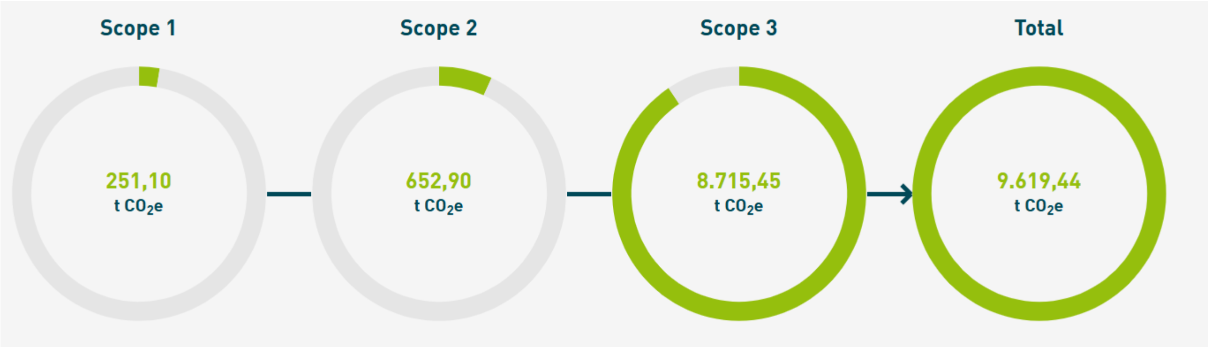
Appendix 5: All Emission Sources and corresponding Factors of Thies

Value	Description	Explanation
8,284.02 kg CO_2e per Employee	Emissions relative to employees	Based on 400 Employees
0.078361 kg CO_2e per €	Emissions relative to Margin	Based on 74,000,000.00€ Margin
637,859.2 Trees	CO_2-Binding	Under the assumption that a tree on a global average, absorbs 10 kg of CO_2 annually. This would be the number of required trees to compensate the emissions.
95,679.1 €	Compensation costs	Under the assumption of an average of 15 € compensation costs per ton of CO_2e. This would be the compensation costs for the total emissions for the year 2023.
5,798,718.7 kg CO_2e	Total emissions without security surcharge	Calculate through data input and their CO_2 equivalents.

Appendix 6: Key Figures Thies



Appendix 7: Scope Distribution Thies 2022



Appendix 8: Scope Distribution Thies 2021

Phase	Action	Timeline	Responsible Parties	Notes
Strategic alignment and vision	Integrate sustainability into the missions and values; demonstrate leadership commitment	Short term (0-6 months)	Senior management	Ensure all decisions and practices reflect sustainability values. Leadership should champion these values.
Organisational structure and governance	Establish a sustainability steering committee with key department representatives	Short term (0-6 months)	Senior management, key department heads	Focus on continuous oversight of initiatives, promoting accountability and collaboration
RE integration	Conduct feasibility study for RE installations; develop phased plan; seek incentives	Medium term (6-18 months)	Sustainability committee, external consultants	Start with feasibility study, guide investments based on findings to optimize outcomes
Enhancing energy efficiency	Conduct energy audit; upgrade machinery; implement smart energy management systems	Medium term (6-18 months)	Operations, sustainability committee	Identify inefficiencies, upgrading and smart systems reduce energy consumption and costs
CE practices	Redesign processes to minimise waste; implement closed-loop systems; explore take-back schemes	Long term (18-36 months)	Operations, procurement, sustainability committee	Redesign production to reduce waste and enhance efficiency. Implement closed-loop systems
Supply chain optimisation	Engage suppliers in sustainable practices; set sustainability criteria; use digital tools	Long term (18-36 months)	Procurement, supply chain management	Monitor and reduce carbon footprint, set clear sustainability criteria for suppliers
Employee engagement and training	Develop training programs on sustainability; encourage participation; hold workshops	Ongoing	HR, sustainability committee	Equip employees with knowledge and motivation to support sustainability goals

Monitoring and reporting	Implement KPIs for sustainability goals; establish monitoring and reporting systems	Ongoing	Sustainability committee, all departments	Track progress towards goals using KPIs and monitoring tools for data-driven decisions
Continuous improvement and innovations	Encourage R&D focused on sustainability; explore new technologies and practices; foster improvement culture	Ongoing	R&D, sustainability committee	Stay ahead with continuous research into new technologies and regulatory requirements

Appendix 9: Strategy implementation plan for Thies

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