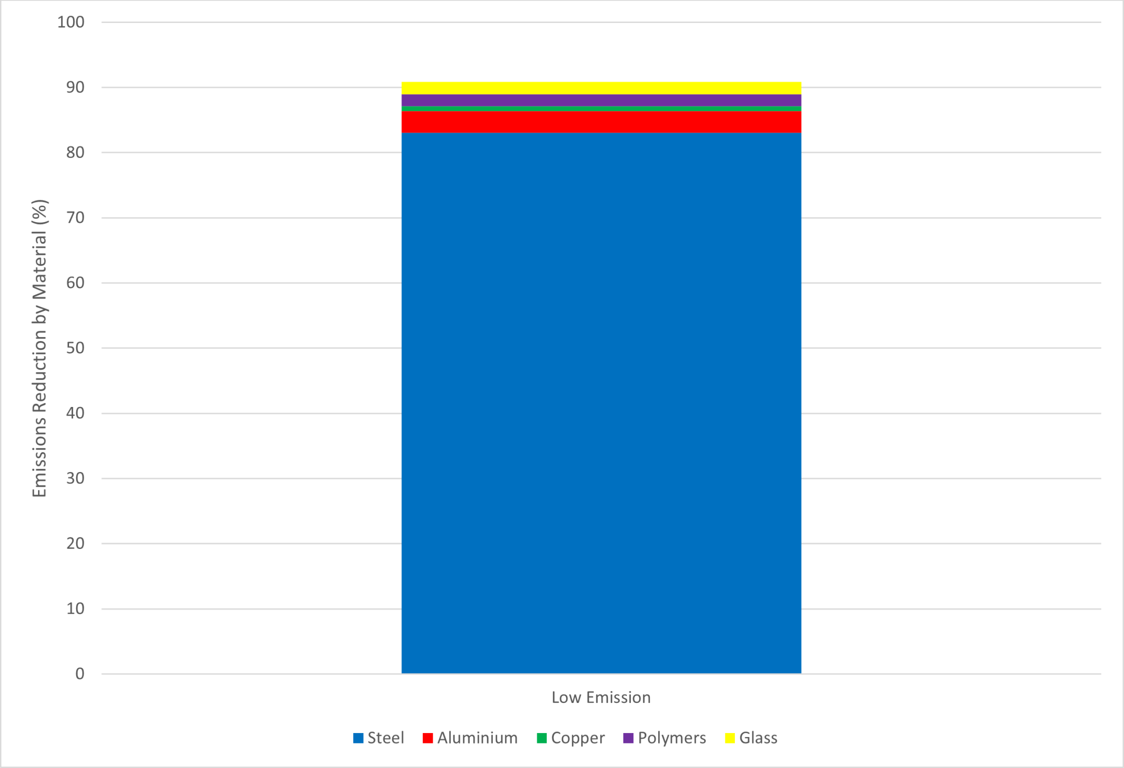

Decarbonizing Industrial Materials: Emissions Reduction and Cost Implications for End Products

Degree project report in Sustainable Energy Systems

Corey Mc Kinley

DEPARTMENT OF SPACE, EARTH, AND ENVIRONMENT

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
www.chalmers.se

Master's thesis 2026

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Cover: Emissions reductions by material for a wind turbine resulting in the lowest total emissions.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2026

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Abstract

Industrial materials, such as steel, aluminum, copper, polymers, and glass, are essential to modern technologies but account for a significant share of global greenhouse gas emissions. Decarbonizing their production is consequently one of the main challenges for climate policy. Existing research has moved in the direction of investigating each material separately, but offers little evidence on the combined effects of simultaneous material decarbonization strategies on finished product costs and emissions. This thesis fills that gap with a case study of decarbonizing all materials in a Vestas V162-6.2 MW wind turbine.

A mixed-methods approach is employed, bringing together life cycle assessment and techno-economic analysis to place quantitative values on emissions savings, cost impacts, and marginal abatement costs of various low-carbon routes to materials production. Four scenarios are built: hydrogen-based direct reduced iron (H-DRI) — hydrogen direct reduction combined with electric arc furnace processing; carbon capture and storage (CCS) — conventional BF-BOF with post-combustion CCS; a cost-minimization scenario — prioritising biomass-enhanced EAF and high shares of secondary feedstock; and an emissions-minimization scenario — selecting the lowest-emission option available for each material.

Findings show that material emissions could be abated up to 90.9% below baseline, and the extra cost is under 1% of the assumed turbine capital cost (€6.0 million). Steel possesses the highest absolute abatement potential, yet cost-reducing cuts in emissions are offered by aluminum and polymers. High costs of abatement, but low climate effects, are found in copper and glass. The analysis distinguishes sharp differences in cost-effectiveness across materials.

Keywords: Sustainable, Energy, Decarbonization, Emissions, Materials, Cost, Consumers.

Acknowledgements

I want to use this moment to express my gratitude to my supervisor, Anna Hörbe Emanuelsson, for her invaluable guidance, constructive criticism, and encouragement throughout the entire process of this thesis. Her expertise, hard work, patientence and comprehension have been decisive in the elaboration of this work.

I want to give a special gratitude to the Department of Energy Technology at Chalmers University of Technology for creating a favorable research environment and for making it possible with the facilities that made this study possible.

Finally, I express my gratitude to my family and friends for their tolerance and support during this time. Their motivation has been instrumental to the success of this work.

Corey Mc Kinley, Gothenburg, August 2025

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BF/BOF	Conventional Blast Furnace – Basic Oxygen Furnace
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
DR/EAF	Direct Reduction with Natural Gas – Electric Arc Furnace
EAF	Electric Arc Furnace
ETS	Emissions Trading System
EU	European Union
EW	Electrowinning
GHG	Greenhouse Gas
H-DR/EAF	Hydrogen Direct Reduction – Electric Arc Furnace
I-EAF	Improved Electric Arc Furnace with Biomass
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
$MtCO_2$	Million Tonnes of Carbon Dioxide
REP	Refunded Emission Payments
SR/BOF	Smelting Reduction – Basic Oxygen Furnace

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1

Introduction

The global average temperature continues to rise, and with it, a growing need to reduce greenhouse gas emissions across all sectors of the economy to mitigate the consequences of climate change. The industrial sector, particularly the production of raw materials such as steel, aluminum, and cement, is a major contributor to this challenge due to its huge carbon footprint. In the European Union (EU), the energy-intensive sectors contribute approximately 22% of the total carbon dioxide (CO_2) emissions [1]. With the EU ramping up its climate ambition, decarbonizing the industrial sectors is now a priority. At the same time, shifting to decarbonized production methods in these industries calls for high upfront investments and raises economic concerns for producers and policymakers. Transitioning to decarbonized production methods often entails high upfront capital investment and elevated operational costs, which can reduce industrial competitiveness, especially in global markets where low-cost, carbon-intensive materials remain dominant. These cost increases may be passed on to downstream industries and consumers, potentially triggering inflationary pressures or decreasing public support for climate policy.

The shift to low-emission technologies, such as hydrogen-based steel production and renewable-powered aluminum production, offers tremendous opportunities to reduce industrial emissions. These technologies are typically higher in capital (CAPEX) and operating (OPEX) expenditures compared to conventional technologies. More and more studies have investigated various aspects of this transition. For example, analysis of the carbon pricing contribution to industrial decarbonization [2], discussion of carbon-intensive industries' abatement options [3], and estimated the cost of reducing emissions from specific materials like steel [4]. Other research specified financial tools to achieve deep emission reductions [5].

While such studies are highly beneficial in providing perspective into specific technologies and markets, they do not treat materials in a combined analysis, failing to speak to the collective effect of lowering emissions from several materials in a single end-use product. Consequently, there exists a gap in our understanding of how full material decarbonization affects emissions as well as the final product price.

This thesis closes this gap by examining the cost-effectiveness of using decarbonized materials in a Vestas V162-6.2 MW wind turbine as a case study of decarbonizing all turbine materials. Rather than focusing on a single material, the study considers the overall effect of substituting conventional materials with their decarbonized alternatives. By applying a simplified attributional lifecycle assessment (LCA) methodology, this research analyzes the trade-off in decarbonizing material production for end-products with the related economic implications. The analysis is based on current emission intensities and material prices. With the addition of a multi-material perspective, this thesis contributes to existing knowledge by examining the emissions and cost effects of decarbonizing material production on the end-products. The findings assist industry stakeholders and policymakers in developing more effective approaches to emissions reduction with economic sustainability.

1.1 Background

The reduction of CO_2 emissions has been the world's number one climate policy target, and particularly for the EU. The EU Emissions Trading System (ETS) is one of the leading drivers in this direction by capping industrial emissions and forcing companies to purchase permits for each ton of CO_2 they emit. By attaching a price to emissions, the system incentivizes cleaner production methods like hydrogen-based steelmaking and renewable-powered electrolysis for aluminum.

However, the deployment of these technologies remains an economic challenge. The CAPEX required to build new infrastructure, such as hydrogen-based furnaces, electric smelters, or carbon capture systems, and to retrofit existing facilities, is often remarkably high. These upfront costs, combined with increased OPEX from higher energy demands, labor, and chemicals for Carbon Capture and Storage (CCS), make decarbonized production significantly more expensive than conventional processes.

Rising costs are a concern for both producers and policymakers, especially when the price premium must be passed along the value chain to consumers. If consumers do not accept the higher prices, industries that made large investments risk being uncompetitive. Industry sectors such as steel, aluminum, and plastics are especially affected because their production processes are highly energy-intensive and emission-intensive, making decarbonization both technically challenging and economically costly in places with low renewable energy production.

While there are technical solutions to decarbonization, market penetration of such technologies is often impeded by high investment requirements, unclear policy incentives, and low consumer willingness to pay a green premium. For example, manufacturers may not want to adopt decarbonized materials when companies in other countries are allowed to produce conventionally and cheaply, or regulatory incentives [22]. Therefore, the transition to decarbonized materials is as much a market force and policy design challenge as it is a technical one. In order to address this, there has to be a coordinated combination of policy instruments like carbon pricing, subsidies, and green public procurement in order to bridge the cost difference and enable broader industry uptake.

1.2 Aim

This thesis quantifies the cost impact of the application of decarbonized materials in the production of end products. Through the examination of the cost of producing traditional and decarbonized materials, this study assesses the effect on prices for an industrial product, such as the V162-6.2 MW wind turbine. The results guide industry players and policymakers on how emission reductions can be synchronized with cost competitiveness.

1.3 Limitations

This thesis involves the decarbonization of some of the most significant industrial materials in the EU, namely steel, aluminum, copper, glass, and plastics, due to their high emission intensities and their key roles in manufacturing and infrastructure. Other materials and industries that contribute to global emissions, such as cement or textiles, are not covered by this study.

An important limitation relates to the availability and quality of cost and emissions data. Emissions data for material production are largely drawn from the Inventory of Carbon and Energy [6], which gives cradle-to-gate carbon intensities according to Scope 1 and Scope 2 emissions. This approach excludes Scope 3 emissions, such as those from upstream supply chains or downstream transport and disposal. For consistency, Scope 1 and 2 boundaries are applied uniformly across materials. While more comprehensive figures exist in select cases, such as copper production reports including Scope 1–3 emissions of up to 4.5 kg CO_{2e}/kg, comparable data across all materials was not consistently available. For consistency, Scope 1 and 2 boundaries were applied uniformly across materials and thus sticking with the ICE data.

Cost data for decarbonized alternatives are likewise compiled from a combination of industry reports, peer-reviewed studies, and forward-looking techno-economic models. Data for emerging technologies, in particular, are sometimes limited to expert estimates or early pilot projects, which introduces uncertainty in both cost and performance projections.

Furthermore, this study is focused on greenhouse gas (GHG) emissions and direct production-related cost impacts. It does not account for broader environmental effects such as land use change, water depletion, or toxicity, nor does it perform a full LCA. The analysis is limited to emissions from material production and the influence of material choices on end-product costs and avoidance costs.

The study excludes the concrete used in the wind turbine foundation, which can represent substantial embodied carbon; this emission should be noted when interpreting the overall emissions reduction potential.

This analysis assumes that any marginal cost increases are passed entirely to end users, thereby preserving producer profit margins; in practice, limited profit margins and consumer willingness to pay may constrain implementation.

1.4 Specification of the Issue Being Investigated

This thesis investigates the economic effects of using decarbonized industrial materials for manufacturing end-products. The V162-6.2 MW wind turbine serves as a case study to assess how replacing conventional materials such as steel, aluminum, copper, glass, and polymers with their low-emission alternatives affects both production costs and the final product price.

At the center of the analysis is a comparison of operating and capital costs of conventional and decarbonized production pathways of materials, triggered by the need to explain economic trade-offs between emissions reductions and cost effects in energy-intensive manufacturing industries. The findings are meant to help policymakers and industry actors to facilitate more informed choices towards a climate-compatible industrial transition.

2

Methodology

This thesis applies a mixed-methods approach combining quantitative modelling to calculate the impact of material decarbonization on a wind turbine's emissions and cost profile. The methodology has five main elements: system boundary definition and functional unit, baseline data collection for material costs and emissions, decarbonization option modelling, scaling up impacts to the wind turbine level, and calculation of the impact of policy mechanisms.

2.1 System Boundary and Functional Unit

The system boundary includes only the material production stage of an onshore wind turbine in terms of emissions due to the processing and extraction of primary materials. It excludes downstream activities such as component production, transportation, installation, use, and dismantling. The system boundary also excludes the concrete used in the wind turbine foundation, which can represent a substantial source of embodied carbon. The functional unit is a single V162-6.2 MW wind turbine. It was selected for representative size to examine embodied emissions in the material of the wind turbine, as well as cost aspects.

2.2 Material Inventory and Emission Factors

A comprehensive material inventory was established based on the industry source provided by Vestas [7]. Materials considered include steel and iron, aluminum alloys, copper alloys, glass composites, and polymer materials. Steel and iron make up most of the mass of the wind turbine (688 tonnes of 801 tonnes total), with contributions from the other materials making up the final 14%. A few materials were left out, which include: electronics, lubricants, and other materials, as they had little emissions and very little weight.

Emission factors (in tCO_{2e} per tonne of material) were sourced from the Inventory of Carbon and Energy database [6] and the World Steel Association [8]. These factors represent cradle-to-gate emissions associated with primary material production. Table 2.1 summarizes the emission factors applied.

Table 2.1: Emission factors for primary materials used in the reference wind turbine

Material	Emission Factor (tCO_{2e}/t)	Source
Steel	1.91	World Steel Association, 2023
Glass Composites	0.91	ICE, 2023
Copper	3.81	ICE, 2023
Aluminum	9.16	ICE, 2023
Polymers	3.31	ICE, 2023

While all materials are considered in the emission accounting, the economic modelling focuses on those with identifiable decarbonization options and available cost data: steel, aluminum, copper, polymers, and glass composites. Each of the materials is analyzed for both emissions reductions and associated cost implications. With this data, we can analyze the amount of CO_{2e} emitted from each material per wind turbine to gain a better understanding of where the emissions are coming from. Figure 2.1 shows that steel makes up 79.8% of all CO_{2e} emissions in one wind turbine.

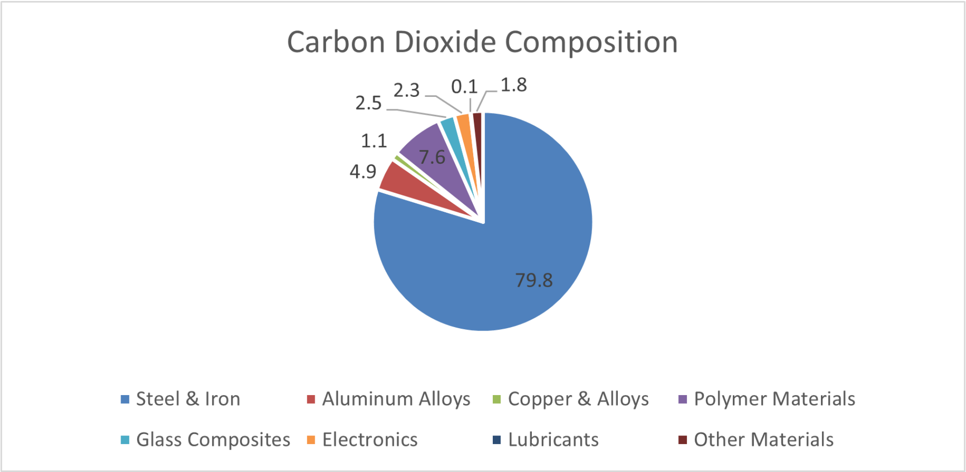

Figure 2.1: CO_{2e} emissions per material for one V162-6.2 MW wind turbine

2.2.1 Cost-effectiveness Evaluation

Each decarbonization option is evaluated in terms of its emissions intensity (tCO_{2e} per tonne of material) and production cost (€/tonne), compared against conventional baselines.

For costs, the baseline production cost for each material is:

$$C_{\text{baseline}} = c_{\text{conv}} \times m_{\text{turbine}} \tag{2.1}$$

where c_{conv} is the sum of conventional production cost and annualized investment cost (€/tonne), and m_{turbine} is the total mass of that material in the wind turbine. The cost difference for a low-emission option is:

$$\Delta C = (c_{\text{lowC}} - c_{\text{conv}}) \times m_{\text{turbine}} \tag{2.2}$$

where c_{lowC} is the low-emission production cost including annualized investment. In graphical representation, $\Delta C > 0$ indicates higher cost relative to the conventional option, while $\Delta C < 0$ indicates cost savings.

For emissions, the baseline emissions are:

$$E_{\text{baseline}} = e_{\text{conv}} \times m_{\text{turbine}} \tag{2.3}$$

where e_{conv} is the emissions intensity of the conventional option ($\text{tCO}_{2\text{e}}$/tonne). Low-emission option emissions are:

$$E_{\text{lowC}} = e_{\text{lowC}} \times m_{\text{turbine}} \tag{2.4}$$

The relative emissions reduction can be expressed either per material:

$$\text{Reduction}_{\text{material}}\ (\%) = \frac{E_{\text{baseline}} - E_{\text{lowC}}}{E_{\text{baseline}}} \times 100 \tag{2.5}$$

or as a share of the total turbine baseline emissions:

$$\text{Reduction}_{\text{turbine}}\ (\%) = \frac{E_{\text{baseline}} - E_{\text{lowC}}}{E_{\text{baselineTot}}} \times 100 \tag{2.6}$$

where $E_{\text{baselineTot}}$ is the sum of E_{baseline} for all materials.

Cost-effectiveness is then assessed using the avoidance cost (AC) framework:

$$\text{AC} = \frac{C_{\text{lowC}} - C_{\text{baseline}}}{E_{\text{baseline}} - E_{\text{lowC}}} \tag{2.7}$$

The AC (€/$\text{tCO}_{2\text{e}}$) represents the additional cost required to avoid one tonne of CO_2 through substitution with a low-emission option; lower values indicate more economically efficient abatement, and negative numbers indicate cost savings.

2.2.2 Scaling to the Wind Turbine Level

The material-level cost and emissions results from the subsection above are aggregated to estimate the total impact of decarbonization on a V162-6.2 MW wind turbine. For each material i, the cost difference (ΔC_i) and emissions avoided are taken from the earlier calculations and summed to give the turbine-level totals:

$$\text{Total Emissions Avoided } (\text{tCO}_{2\text{e}}) = \sum_i \left(E_{\text{baseline},i} - E_{\text{lowC},i}\right) \tag{2.8}$$

$$\text{Total Cost Increase } (\text{€}) = \sum_i \Delta C_i \tag{2.9}$$

This aggregation accounts for the mass of each material in the turbine's bill of materials and applies the same cost and emissions intensities as defined in the material-level assessment.

To contextualize the economic impact, the total cost increase is compared to the assumed CAPEX of a single wind turbine:

$$\text{Cost Impact (\%)} = \frac{\text{Total Cost Increase}}{C_{\text{turbine}}} \times 100 \tag{2.10}$$

Where C_{turbine} is the average installed cost for a V162-6.2 MW unit. Although no project-specific CAPEX data is available for the Finnish installation referenced in a Vestas project that built a 192 MW wind farm [19], industry estimates for utility-scale onshore wind turbines range from US$1.0–1.25 million per megawatt [20]. This yields a range of US$6.2–7.75 million for a 6.2 MW turbine, equivalent to €5.46–6.82 million using a fixed USD/EUR exchange rate of 0.88. A midpoint of €6.0 million is adopted for modelling purposes. This approach enables a direct link between material-level decarbonization pathways and their implications for turbine-wide emissions and costs, allowing assessment of trade-offs at the system scale.

3

Materials and Emissions

This study considers the embodied carbon emissions associated with material production for a V162-6.2 MW wind turbine. The scope is limited to emissions generated during the extraction, processing, and manufacture of materials prior to construction. Emissions from transport, installation, maintenance, or decommissioning are outside the scope of this analysis.

Steel and iron dominate the carbon footprint due to their extensive use in the tower, nacelle frame, and rotor hubs. Although used in smaller quantities, materials such as polymers, aluminum, and electronics contribute significantly due to their high emission intensities. Table 3.1 summarizes the mass, emission factors, and resulting CO_2 emissions for each material.

Table 3.1: Material emissions breakdown for a V162-6.2 MW wind turbine.

Material	**Mass (kg)**	**Emission Factor (kg CO_2e/kg)**	**CO_2e (kg)**	**Share (%)**
Steel & Iron	688,059	1.91	1,314,192.69	79.8
Aluminum Alloys	8,811	9.16	80,708.76	4.90
Copper & Alloys	4,806	3.81	18,310.86	1.11
Polymer Materials	37,647	3.31	124,611.57	7.56
Glass Composites	44,856	0.91	40,818.96	2.48
Electronics	6,408	6.00	38,448.00	2.33
Lubricants	801	2.30	1,842.30	0.11
Other Materials	9,612	3.00	28,836.00	1.75
Total	**800,000**		**1,647,768.14**	**100.00**

For each of the materials, steel, aluminum, copper, polymers, and glass composites, decarbonized production options were identified from industry roadmaps and academic literature. These options vary in technological maturity, emissions reduction potential, and economic cost.

3.1 Steel and Iron

Steel and iron account for nearly 80% of total emissions. This is primarily due to the high mass of steel used in the wind turbine structure and its relatively high emission intensity. Most emissions come from the integrated blast furnace–basic oxygen furnace (BF–BOF) route, where coal-derived coke is used as a reducing agent, leading to significant CO_{2e} generation [21]. Steel has several decarbonization options.

These include biomass-enhanced electric arc furnaces (I-EAF), hydrogen-based direct reduction followed by electric arc furnaces (H-DR/EAF), and Top Gas Recycling Blast Furnace – BOF with CCS (TGRBF/BOF + CCS). The results show scenarios for all of these options.

3.2 Aluminum Alloys

Despite being used in smaller quantities, aluminum alloys contribute to nearly 5% of emissions in the turbine due to their high production energy requirements. The Hall-Héroult process used in primary aluminum production is particularly carbon-intensive when powered by fossil-based electricity. Decarbonizing this sector requires decarbonized electricity and technological improvements in production methods [22]. Aluminum decarbonization is mainly driven by two strategies: renewable-powered electrolysis, such as hydropower or wind, and exchanging primary production for secondary production, which has significantly lower emissions. Both options are included in the modelling.

3.3 Copper and Alloys

Copper represents a smaller share of the turbine by mass but still contributes over 18 tonnes of CO_{2e}. These emissions arise primarily from the smelting and refining of sulfide ores, where both thermal and chemical processes emit greenhouse gases. Emission intensities vary widely across regions depending on ore quality and the energy sources used in production [23]. Copper decarbonization options include electrorefining with renewables, electrowinning with renewables, and exchanging primary production for secondary production. Electrorefining purifies impure copper anodes from smelting into high-purity cathodes using an electrolytic cell, while electrowinning produces copper directly from leach solutions without smelting. Two of the options are considered for emissions and cost implications, with electrowinning left out because of data availability.

3.4 Polymer Materials

Polymer-based components contribute over 124 tonnes of CO_{2e}, roughly 7.6% of total emissions. Derived from fossil feedstocks, their manufacturing involves high-temperature cracking and polymerization, both of which are energy-intensive. Without systemic changes to production and end-of-life treatment, polymers will remain a significant emissions source [24]. Polymers present several emerging decarbonization options. These include: 100% chemical recycling, 100% bio-based polymer production, 50/50 mixes of mechanically recycled and virgin feedstocks, and renewable energy-powered polymer production from conventional feedstocks. In this study, chemical and mechanical recycling are considered in the modelling because of data availability.

3.5 Glass Composites

Glass composites used in blades contribute about 2.5% of the total emissions. Although the emission intensity per kilogram is low, the large mass used in rotor blades makes this category non-negligible. The energy demand of glass fiber production is primarily linked to the prolonged high temperatures required for melting raw materials [6]. Glass composites can be decarbonized through electric melting furnaces powered by renewable electricity, hydrogen-fueled kilns, and carbon capture and storage integrated into conventional gas-fired melting systems. Hydrogen-fueled kilns were excluded due to data availability.

3.6 Decarbonization Options

The decarbonization options, summarized in Table 3.2, illustrate the large variation in achievable emission factors across materials and technologies. Steel offers the largest absolute reduction potential, with hydrogen-based direct reduction (H-DRI + EAF) and biomass-enhanced EAF (I-EAF) able to cut emissions to near zero. In contrast, blast furnace routes with CCS reduce emissions substantially compared to conventional BF–BOF production, but remain more carbon-intensive than electrified routes. For aluminum, the difference between secondary production and renewable-powered electrolysis highlights the importance of recycling in lowering emissions. Copper also benefits significantly from recycling, though even renewable-powered electrorefining does not reduce emissions to the same extent. Polymers can be decarbonized through chemical or mechanical recycling, though these options achieve only partial reductions. Glass production can be decarbonized through renewable-powered electric furnaces or CCS-equipped kilns, both of which substantially reduce emissions compared to conventional gas-fired furnaces.

Overall, Table 3.2 underscores that deep decarbonization depends strongly on both material type and technology pathway. While some options already deliver near-zero emission intensities, others only achieve smaller reductions. These differences shape the abatement cost landscape and determine which options are most effective for reducing the embodied emissions of a wind turbine. The next chapter applies these emission factors to the V162-6.2 MW turbine case to quantify the potential reductions and associated costs at the product level.

Table 3.2: Emission factors for selected decarbonization options of the materials compared to conventional production.

Material	Option	Emission factor (kg CO_{2e}/kg)	Reduction vs. conventional (%)
Steel	H-DRI + EAF	0.025	98.7
Steel	BF-BOF + CCS	1.065	44.2
Steel	I-EAF	0.005	99.7
Steel	DR-EAF	0.89	53.4
Aluminum	Secondary aluminum	1.90	79.3
Aluminum	Renewable electrolysis	4.00	56.3
Copper	Secondary copper	0.99	74.0
Copper	Renewable electrorefining	1.50	60.6
Polymers	50% mech. recycled	1.81	45.3
Polymers	Chemical recycling	2.91	12.1
Glass	Renewable electric furnace	0.33	63.7
Glass	CCS	0.18	80.2

3.7 Scenario Design

To assess the implications of material decarbonization, four scenarios were constructed that apply different options across steel, aluminum, copper, polymers, and glass composites. Each scenario reflects a distinct strategic choice: focusing on hydrogen-based steelmaking, relying on carbon capture and storage, minimizing costs, or minimizing emissions. The scenarios are summarized in Table 3.3.

Table 3.3: Decarbonization options applied to each material in the four scenarios.

Scenario	Steel	Aluminum	Copper	Polymers	Glass
H–DRI	H–DRI + EAF	Secondary aluminum	Secondary copper	Mechanical recycling	CCS
CCS	BF–BOF + CCS	Secondary aluminum	Secondary copper	Mechanical recycling	CCS
Low Cost	I–EAF	Secondary aluminum	Secondary copper	Mechanical recycling	Renewable electric furnace
Low Emission	I–EAF	Secondary aluminum	Secondary copper	Mechanical recycling	CCS

The **H–DRI** scenario emphasizes deep decarbonization of steel through hydrogen-based direct reduction, while keeping other materials on low-emission options, which will be described in the low-emission scenario. The **CCS** scenario instead applies carbon capture to conventional blast furnace–BOF steelmaking, combined with low-emission options for the other materials. The **Low Cost** scenario prioritizes options with the lowest cost increase per material, selecting I–EAF with biomass for steel and maximizing secondary production for aluminum and copper, mechanically recycling for polymers, and the electric furnace for glass. A limitation of the I–EAF route is that it requires scrap or pre-reduced iron (DRI/HBI) as input, rather than processing iron ore directly, which constrains its scalability due to limited scrap availability. Finally, the **Low Emission** scenario uses the most emission reduction options available, combining I–EAF with biomass for steel, secondary production for aluminum and copper, mechanical recycling for polymers, and CCS-equipped glass furnaces.

For aluminum and copper, secondary production is modeled as a 40% recycled and 60% primary mix. In the **Low Cost** scenario, the primary share is produced using conventional methods, reflecting the least expensive pathway. In contrast, the **H–DRI**, **CCS**, and **Low Emission** scenarios assume that the primary share is produced through renewable-powered electrolysis (aluminum) and renewable-powered electrorefining (copper), achieving deeper emission reductions.

4

Results

This section presents the outcomes of decarbonizing all materials used in the V162-6.2 MW wind turbine, focusing on a lowest-emission scenario in which each material is produced using the lowest-emission technology from 3.3.

4.1 Lowest-Emission Scenario

Figure 4.1 shows the percentage reduction in emissions by material under the lowest-emission scenario.

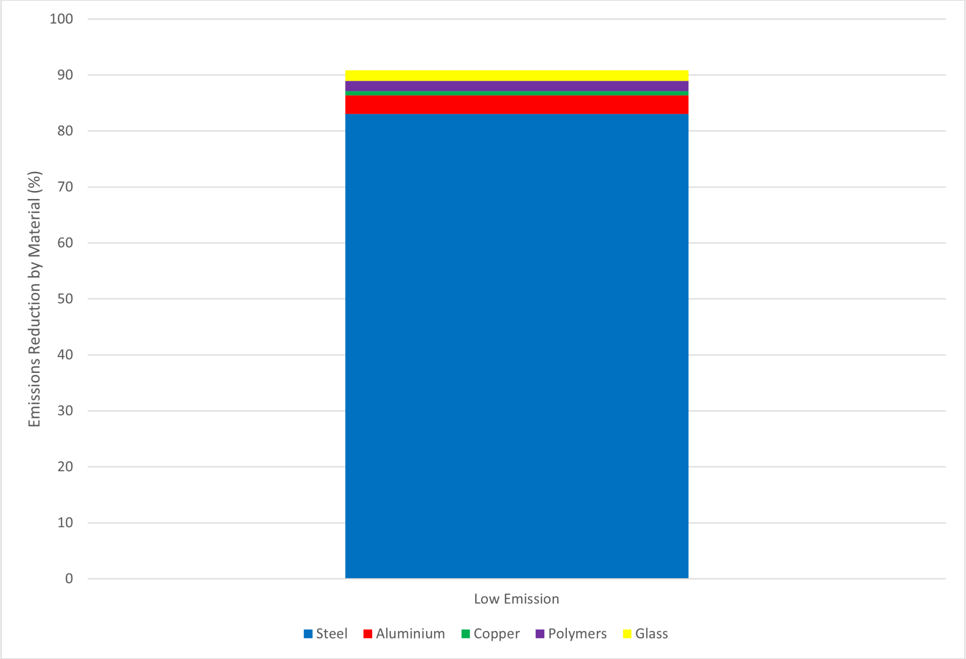

Figure 4.1: Emissions reduction by material percentage.

Under the lowest-emission scenario, all major materials, including steel, aluminum, copper, polymers, and glass composites, are to be produced using the technology that emits the least amount of carbon, as shown in Table ref tab:scenarios. The resulting total emissions are summarized in Table 4.1. Total material-related emissions from the wind turbine decrease by **90.9%**, from 1,578 tonnes CO_{2e} in the baseline case to just over 144 tonnes CO_{2e} in the lowest-emission case.

Table 4.1: Material-related emissions under the lowest-emission decarbonization scenario.

Material	Baseline (kg CO_2e)	Lowest-emission (kg CO_2e)	Reduction (%)
Steel & Iron	1,314,193	3,440	83.0
Aluminum	80,709	27,843	3.3
Copper	18,311	6,229	0.8
Polymers	124,612	96,376	1.8
Glass Composites	40,819	10,317	1.9
Total	**1,578,644**	**144,205**	**90.9**

4.2 Cost Impact of Lowest-Emission Material Substitution

Decarbonising materials to their most emission reduction options not only reduces carbon but also slightly alters the overall cost of producing the wind turbine. Rather than viewing relative percentage reductions for each material, this section contrasts the absolute increase in turbine manufacturing costs under the lowest-emission scenario.

Figure 4.2 shows the cost rise by turbine, by material. Steel, copper, and glass increase costs, whereas aluminum and polymers yield low-cost decreases from growing use of secondary production and cheaper recycling. Summed across, the results show a small net increase.

Figure 4.2: Cost increase per turbine under the lowest-emission material decarbonization scenario, by material contribution (percentage of total turbine CAPEX).

The total cost of turbine production rises from €436,223 in the baseline to €489,427 in the lowest-emission scenario. This corresponds to a **+12.2% increase in material costs**, which translates to less than **1% of the overall turbine capital cost**. In other words, near-complete decarbonization of materials can be achieved with negligible impact on the competitiveness of wind power.

4.3 Avoidance Cost Analysis for Lowest-Emission Case

Avoidance cost, expressed in euros per ton of CO_{2e} avoided, provides a useful metric for comparing the cost-effectiveness of emission reductions across materials. It is calculated as the additional (or reduced) cost of adopting a decarbonization option divided by the emissions avoided relative to the baseline. Negative values indicate that an option both lowers costs and reduces emissions, while positive values indicate that emission reductions come at an increased cost. Figure 4.3 illustrates the avoidance costs for each material under the lowest-emission scenario.

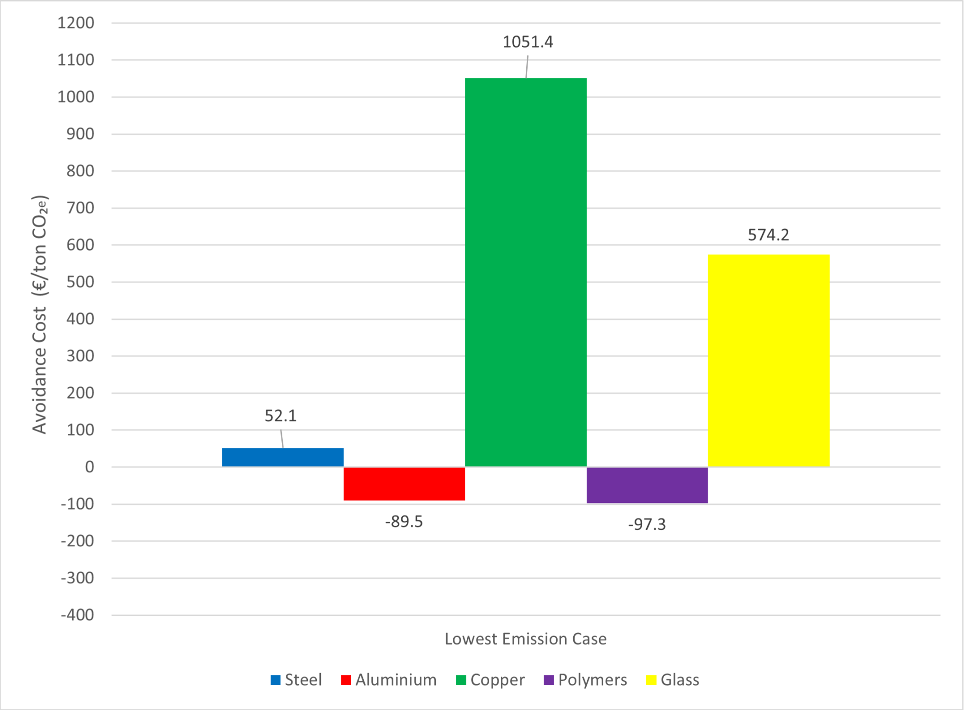

Figure 4.3: Avoidance costs (€/kg CO_{2e} avoided) for lowest-emission technologies.

Aluminum and polymers yield negative avoidance costs of -€89.5/tCO_{2e} and –€97.3/tCO_{2e}, respectively. This indicates that switching to these decarbonization pathways both lowers overall costs and reduces emissions. Steel exhibits a positive avoidance cost of €52.1/tCO2e, reflecting the additional expense of improved electric arc furnaces using biomass. Despite this premium, steel delivers the largest absolute emission reduction (1.31 million kg CO_{2e} avoided), making it highly impactful in total abatement potential. Copper has the highest avoidance cost at €1,051.4/tCO_{2e}, because the comparatively small emission reduction of about 12 tonnes CO_{2e} is paired with a large cost increase €20 469. Glass also performs poorly, with an avoidance cost of

€574.2/tCO_{2e}, from low emission reduction of 30.5 tonnes CO_{2e} and a significant cost increase of €18 753. In summary, aluminum and polymers offer pathways that both cut emissions and reduce costs, steel achieves deep reductions at additional cost, and copper and glass emerge as the least cost-effective options for decarbonization.

4.4 Scenario Results

This section compares the four decarbonization scenarios (H–DRI, CCS, Low Cost, and Low Emission) in terms of emission reductions, cost increases, and avoidance costs. Together, the figures illustrate how the choice of technology pathways for each material influences both environmental and economic outcomes.

4.4.1 Emissions Reductions by Scenario

Figure 4.4 shows the percentage reduction in material-related emissions under each scenario, disaggregated by material. Steel dominates the reductions in all cases, reflecting both its large share of total emissions and the effectiveness of low-carbon steelmaking pathways. The H–DRI and Low Emission scenarios achieve reductions of around 90%, while CCS yields a much smaller overall reduction, below 50%. The low cost scenario used the same steel as the low emission option, indicating that large-scale emission reductions can still be achieved when prioritizing cost minimization. Contributions from aluminum, copper, polymers, and glass are comparatively smaller but remain visible across scenarios.

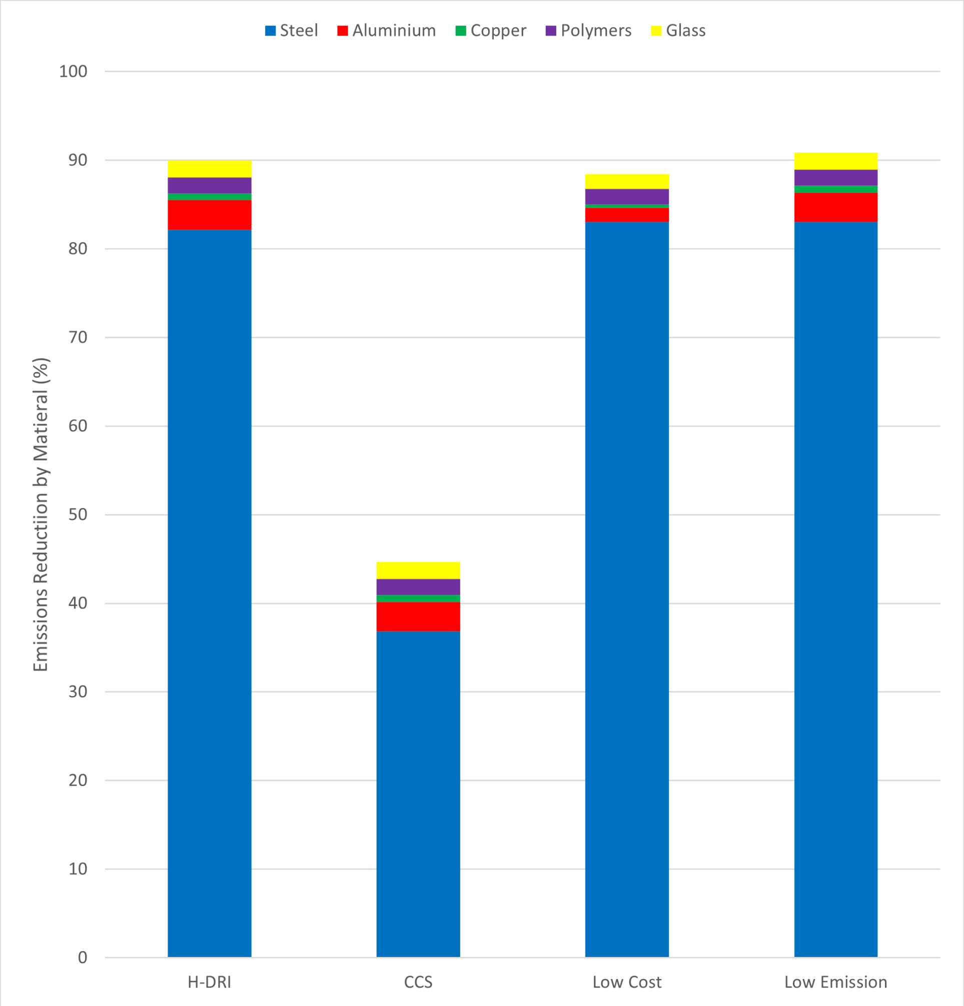

Figure 4.4: Emissions reduction by material across the four decarbonization scenarios.

4.4.2 Cost Increase by Material

Figure 4.5 presents the cost increases by material under each scenario. Steel, copper, and glass generally drive cost increases due to the higher expense of their options. By contrast, aluminum and polymers often show small cost savings, particularly in the Low Cost and H–DRI scenarios, where greater reliance is placed on secondary production or recycling. These results refer only to the cost of the materials, thus not including the costs related to constructing the wind turbine (those broader construction costs are shown in Figure 4.2). This highlights that decarbonization does not uniformly increase costs; some options cut both costs and emissions.

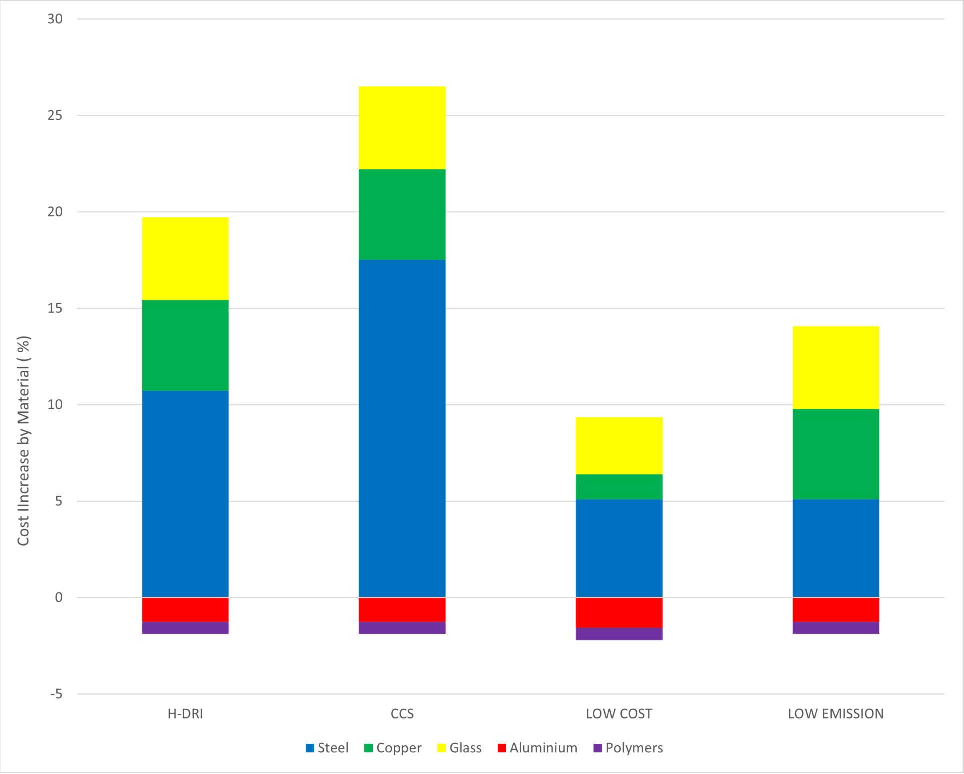

Figure 4.5: Cost increase by material across the four scenarios.

4.4.3 Total Cost Increase per Turbine

The total cost increase per wind turbine under each scenario is shown in Figure 4.6. The H–DRI and CCS scenarios have the highest overall cost increases, reflecting the use of advanced but capital-intensive technologies. The low emission scenario shows has almost has high costs, while the Low Cost scenario achieves substantial emission reductions with the lowest additional expense. This makes Low Cost a particularly attractive option from an economic perspective, as it balances large emission cuts with minimal cost impact.

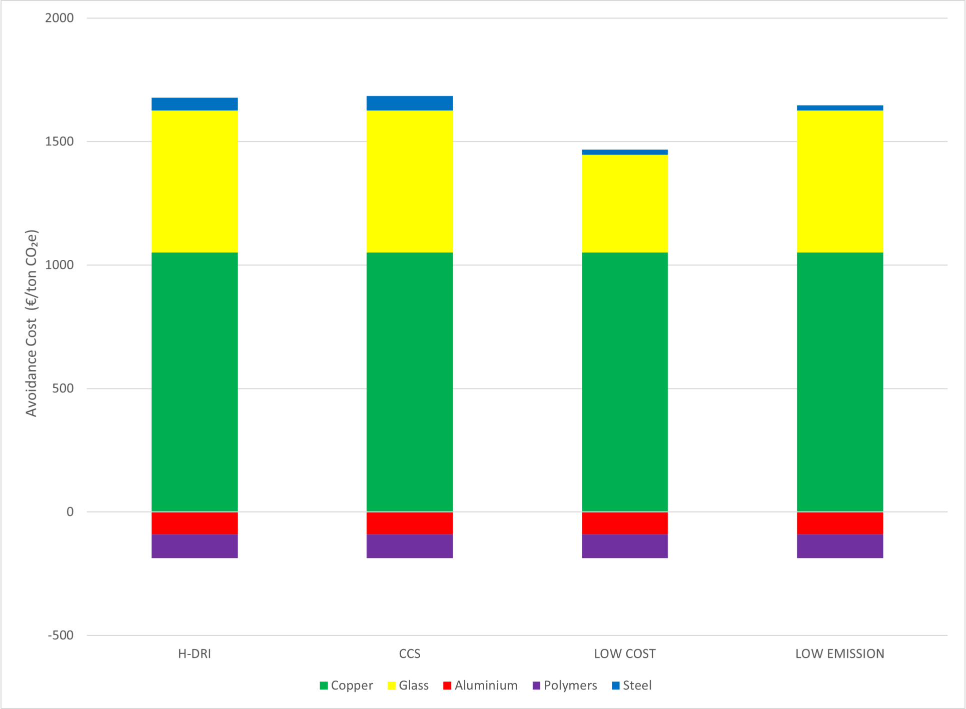

Figure 4.6: Total cost increase per turbine across the four scenarios.

4.4.4 Avoidance Costs by Material

Finally, Figure 4.7 shows the avoidance cost per material across the four scenarios. Negative avoidance costs are observed for aluminum and polymers in several cases, indicating pathways that both save money and cut emissions. Steel shows positive avoidance costs across scenarios, but these are accompanied by the largest absolute emission reductions, making steel central to overall abatement. Copper and glass exhibit the highest avoidance costs, especially in the Low Emission scenario, confirming that these materials are comparatively expensive to decarbonize relative to the emissions avoided.

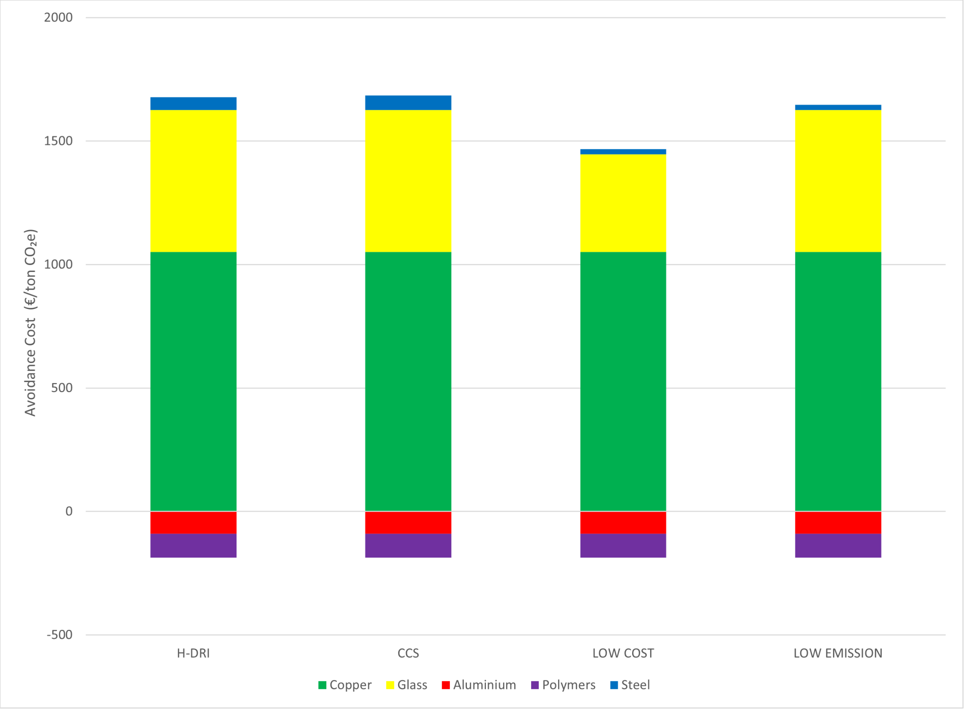

Figure 4.7: Avoidance costs by material across the four scenarios.

5

Discussion

Reducing emissions in the high-emitting sectors is crucial in achieving net-zero levels. Enshrined in the production of wind turbines are steel, aluminum, copper, polymers, and glass, which are the main drivers of emissions. The technical and economic impacts of replacing carbon-intensive materials with low-carbon materials were the subject of the thesis. This chapter discusses the findings, comparing across materials, evaluating the affordability of decarbonization measures, and considering broader system and policy-level implications.

5.1 Summary of Findings

5.1.1 Relative Impact of Material Substitution

The study shows that steel offers by far the largest potential for greenhouse gas emissions savings. This is primarily due to its dominant mass fraction in wind turbine production and its 79.8% share of baseline emissions. The transition to hydrogen-based direct reduction with electric arc furnaces (H–DRI + EAF), the primary decarbonization strategy of steel, cuts the current level of emissions from 1.31 million kg CO_{2e} to only 17,200 kg CO_{2e} per turbine, reducing the level by 82.2% from steel alone. The result is aligned with Haapala and Prempreeda (2014), who emphasize that the manufacturing phase, mainly spearheaded by steel in the tower, accounts for the overwhelming share of wind turbine life-cycle environmental effects [13].

Once steel emissions are largely eliminated, the distribution of residual emissions shifts considerably. In the lowest-emission scenario, polymers account for two-thirds (66.8%) of the remaining footprint, equal to 96 kg CO_{2e}. This reflects the limited abatement potential of mechanical recycling relative to other pathways. Aluminum contributes around 19% (27.8 kg CO_{2e}), while glass contributes 7% (10.3 kg CO_{2e}). Copper is the smallest contributor at 4% (6.2 kg CO_{2e}).

These results highlight two points. First, after steel is decarbonized, polymers become the largest residual source of emissions and thus the next priority for further reductions. Second, percentage shares alone can be misleading: while glass and copper appear to take on larger relative shares once steel is decarbonized, their absolute contributions remain very small in comparison. For this reason, the case for decarbonizing these materials is less about immediate climate benefit at the turbine level and more about longer-term change in industrial decarbonization strategies.

5.1.2 Cost vs. Emissions Trade-Offs

The avoidance cost calculations reveal large cost-effectiveness differences among the materials. Steel has a positive avoidance cost of €16.9 per tonne CO_{2e} avoided because the relatively high hydrogen-based steel costs compared with the baseline. While the premium exists, steel yields the highest absolute emission reduction in the calculations, and hence, it is the most necessary of the overall material decarbonization.

Whereas aluminum and polymers have negative avoidance costs of around -€104 and -€97 per tonne CO_{2e} avoided, respectively. Decarbonization reduces costs as well as emissions in both instances. The latter is largely due to the substitution of primary production with the use of secondary production in aluminum and the take-up of mechanical recycling in polymers. These findings thus suggest that some decarbonization options can become economically and environmentally positive.

Copper and glass are the least economical options. Copper incurs the highest avoidance cost with €1,694 per tonne CO_{2e} avoided because of relatively low emission reduction of approximately 12 tonnes of CO_{2e} with a high marginal cost increase of over €20,000. Glass also has a high avoidance cost of €615 per tonne of CO_{2e}, mainly because of limited reduction of the order of 30.5 tonnes of CO_{2e} with an added cost of almost €19,000.

Overall, materials fall into three categories when both reduction potential and additional cost are considered. Aluminum and polymers emerge as win–win options: their low-emission routes lower both carbon and total material cost, thanks to high recycling rates and modest process upgrades. Steel, by contrast, delivers the largest absolute emission cuts over one million kilograms per turbine because of its dominant volume; however, adopting hydrogen-DRI or biomass-EAF increases production costs substantially. Copper and glass sit at the other end of the spectrum: their low-emission pathways reduce only a few tonnes of CO_{2e} per turbine while adding tens of thousands of euros in material cost. This comparison emphasizes the need to prioritize decarbonization measures by weighing each material's absolute emission reduction potential against its relative cost impact.

5.2 Barriers and Limitations

The findings suggest that transition options with low emissions are possible from a technical perspective, but some barriers impede adoption. Technological readiness is one. Though hydrogen-based steel production and CCS-fitted furnaces are underway, much of this technology is at early adoption levels. This puts a limit on how fast they can be scaled up at an industrial level. Infrastructure can also be a barrier with hydrogen fuel chains, CCS storage locations, and sophisticated recycling complexes can be bottlenecks for transitioning industries. Uncertainty in data is another barrier: factors of emissions in new technology are still calculated from limited research, which reduces the strength of estimates of avoidance costs. Market inertia is another. Companies may be reluctant to change material due to perceived risk, qualification issues, or ambiguity in clear customer demand. These points in no way invalidate the study's findings but suggest better grounds upon which the transition's pace may be slower than purely technical possibilities would promise.

Whilst this paper provides an end-use material-level analysis, some of the limitations of the methodology should be taken into account. First, the analysis assumes perfect substitution of traditional with low-carbon materials. The modelling is therefore simplified but may overestimate near-term change feasibility, as sectors tend to adopt decarbonization measures incrementally. Second, the modelling uses static parameters that do not account for dynamic effects such as learning curves, future carbon price scenarios, or interruptions in the supply chain. These may decrease or boost future costs relative to current-day estimates. Third, the study's focus is limited to material production-based material-level embodied emissions. Larger environmental impacts, such as land use, water use, or toxicity, are excluded. These exclusions mean that whilst the findings are strong in direction, absolute numbers should be interpreted as indicative rather than directive. Most significantly, the findings remain valid under the assumptions defined, and they provide useful guidance when exploring decarbonization priorities.

5.3 Implications for Industry and Research

The results indicate that low-carbon materials become more realistic, but only with the timing and scale of deployment contingent on industry leadership and enabling policy. For the wind turbine sector, the study finds that significant cuts in emissions become achievable, especially through decarbonizing steel. But this is contingent on concurrent advancements in hydrogen infrastructure, recycling, and CCS deployment. For research, future studies could expand on this material-level analysis by incorporating dynamic system modelling of technology deployment, interactions with circular economy strategies, and supply chain transparency tools such as digital product passports. These directions would complement the present analysis by placing material substitution within a broader systemic context.

6

Conclusion

The analysis demonstrates that substituting conventional, emission-intensive materials with low-emission production options in a V162-6.2 MW wind turbine can reduce material-related emissions by 90.9% (for the five materials analyzed) while increasing turbine material costs by €53,204, which corresponds to 0.89% of the assumed turbine capital cost (€6.0 million) as reported in Section 2.2.2. These results indicate that deep reductions of emissions are technically feasible under current technology trajectories, though deployment at scale depends on infrastructure, market, and policy conditions. Steel accounts for the largest share of both the turbine's baseline emissions and its abatement potential, since hydrogen-based direct reduction combined with electric-arc-furnace processing can nearly eliminate steel-related CO_{2e} emissions. Aluminium and copper can deliver substantial reductions when combined with high recycling shares and low-carbon power; polymers and glass show more limited additional abatement potential under the pathways modelled.

These routes depend on concurrent development of hydrogen supply networks, CO_2 transport and storage facilities, and expanded recycling systems. Scaling these infrastructures alongside production technologies is required for the emissions savings identified here to be fully realised. The results therefore show that near-complete decarbonization of materials in a V162-6.2 MW wind turbine is achievable with a small overall cost impact when the marginal material cost increases are passed through; realising this potential requires timely investments, supportive policy measures, and further technology deployment.

Overall, the transition to low-emission materials in wind turbine production is necessary and feasible. Achieving reductions at scale requires a combination of industrial investment, technology innovation, and targeted policy support. Adopting these measures at scale would reduce the embodied emissions of renewable energy infrastructure and accelerate progress toward global net-zero goals.

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