Energy Prices Affecting Construction

The Extent to which Fluctuating Energy and CO_2 Prices Affect Material Costs for a Concrete versus a Timber Dwelling

MASTER THESIS

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BOUWGROEP DIJKSTRA DRAISMA

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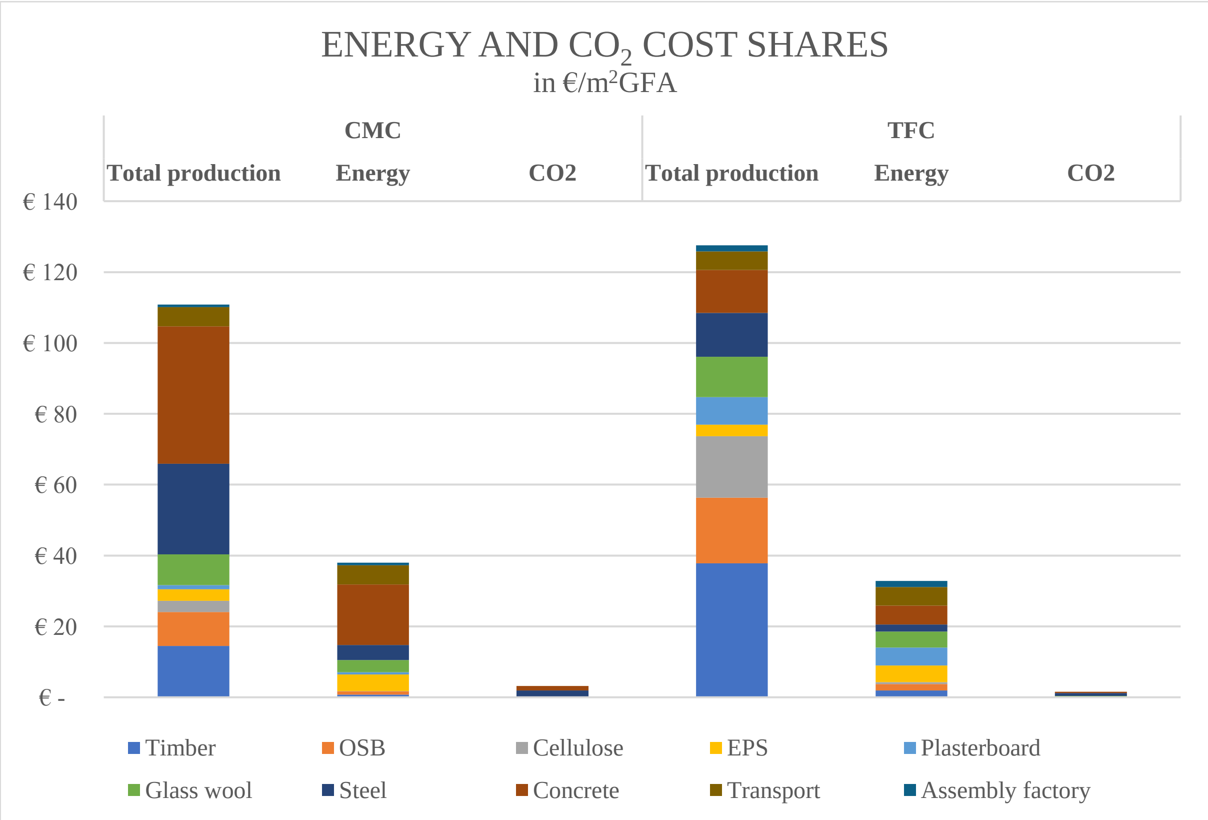
Executive Summary

Timber-based constructions can sequester CO_2 and replace energy-intensive concrete and steel structures, promising to be effective for reaching the CO_2 reduction targets of the Dutch construction sector. However, financial feasibility poses a barrier to large scale adoption of timber-based constructions, despite that timber-based constructions generally entail reduced energy demand and CO_2 emissions compared to concrete and steel based counterparts. Therefore, construction company Bouwgroep Dijkstra Draisma (BGDD) aims to find a tipping point at which a Timber Frame Construction (TFC) dwelling is financially competitive to its Concrete and Masonry Construction (CMC) counterpart, under rising energy and CO_2 prices. Hence, the following Research Question (RQ) is formulated: *'How do energy and CO_2 prices determine the competitiveness between CMC and TFC production in the Netherlands?'*

To structure this study, three Sub Questions (SQs) were formulated entailing the comparison of a CMC and a TFC variation of a land-bound dwelling regarding 1) difference in energy and CO_2 demand through an energy and CO_2 analysis, 2) difference in production costs through a cost analysis and 3) the impact of fluctuating energy and CO_2 prices on production costs with an impact analysis.

The results of SQ1 disclose that energy demand for the CMC is 22.8% higher than for the TFC (145 GJ and 118 GJ), primarily due to coal intensive concrete and steel use. Furthermore, the CMC constitutes 74% more CO_2 emissions as a result of intensive coal use for its materials production (48%). Moreover, production of TFC materials entails a significant share of biomass use (counted as a CO_2 neutral fuel) in the energy mix (19%).

What is more, the results of CO_2 are displayed in the figure below, disclosing that TFC total production costs per m^2 Gross Floor Area (GFA) are 15% higher compared to the CMC and vice versa for energy costs as part of production costs (128 €/m^2GFA and 111 €/m^2GFA for total production costs; 37.94 €/m^2GFA and 32.88 €/m^2GFA for energy costs). Also, CO_2 costs under the EU ETS are negligible for both dwellings, constituting < 3% of total production costs even for the CMC.



What is more, the impact analysis in SQ3 discloses that the total production costs for the CMC and TFC can respectively increase with 17.3% and 17.6% if a scenario occurs in which energy prices for all energy carriers peak based on an extrapolation imitating 2021 - 2022 fluctuations. Furthermore, both TFC and CMC are most sensitive to the NG prices and second most sensitive to diesel prices. Also, the impact analysis disclosed that the CMC is slightly more sensitive to coal and electricity prices than the TFC. Hence, the tipping point at which production costs for CMC and TFC would be equal occurs when coal- and electricity prices increase by > 700%, which is not deemed plausible.

The answer to the RQ is therefore that the CMC and TFC are roughly equally sensitive to fluctuating energy and CO_2 prices and that tipping point based on these fluctuations is not realistic.

What is more, the results of this study are subject to several limitations: Firstly, the configurations for the CMC and TFC could be chosen differently as e.g. finding alternatives for abundant use of (NG intensive) mineral wool and plasterboard in the TFC might yet yield a plausible tipping point. Secondly, using different values for embodied energy of materials within a the significant range of potential possible values (depending on context regarding data, geography and production technology) could alter the results to such extent that it exceeds robustness of the model to marginal deviations in embodied energy values. Lastly, the used energy mix has been subject to several assumptions including the use of 1) typical energy content values for energy carriers as found in literature and 2) the EU electricity mix for emissions and cost calculations of electricity, while the resolution of electricity mixes involved in materials production is more refined in reality.

Nevertheless, this study has provided several valuable insights. Firstly, it contradicts the finding of Sathre (2007) that a timber-based dwelling is less sensitive to CO_2 prices than its concrete counterpart. The difference in results of both studies can be explained by differences in 1) case-study dwellings, 2) geographic scope, 3) date of study, 4) CO_2 tax mechanisms, 5) starting point for energy prices and 6) used materials prices. Secondly, this study discloses that the Cross Laminated Timber (CLT) based dwelling proposed by Staatsbosbeheer (2022) and van der Lugt & Harsta (2021) poses an overestimated CO_2 sequestration potential for timber-based constructions, as the TFC contains only 1/3 of the timber used in a CLT dwelling, entailing 2/3 less CO_2 sequestration from timber use.

Then, to expand this field of study, future research is suggested on 1) different configurations of the case-study dwelling, 2) embodied energy values that specifically for construction materials used in the Dutch construction sector and 3) exact energy content and electricity mixes corresponding to the cross-border production chains of the construction materials.

Finally, several policy recommendations for the government and construction companies are raised. Firstly, the government could 1) improve the MPG score system ensuring fair material scores for bio-based materials, 2) establish mandates and subsidies for timber-based constructions, and 3) stimulate awareness and education regarding timber-based construction, both for professionals and consumers. Secondly, construction companies could 1) seek to reduce transport distances of materials supply to reduce transport costs, 2) reduce plasterboard- and mineral wool content in a TFC for reduced energy costs and 3) find alternatives to the reinforced concrete floor with EPS insulation.

Keywords: timber construction, energy analysis, CO_2 analysis, energy prices, construction materials

List of Abbreviations

BAU	Business As Usual
BF	Blast Furnace
BGDD	Bouwgroep Dijkstra Draisma
CMC	Concrete and Masonry Construction
CH_4	Methane
CO_2	Carbon dioxide
CBS	Central Bureau for Statistics in NL
CLT	Cross Laminated Timber
EAF	Electric Arc Furnace
EoL	End of Life
EPS	Expanded Polystyrene (insulation foam)
EU	European Union
EU 27	27 European Union countries (ex. UK since 1-2-2020)
EUA	1 emission allowance of 1 tCO2-eq under the EU ETS
EU ETS	European Emission Trading System
FU	Functional Unit
GJ	Gigajoule
GFA	Gross Floor Area
GHG	Greenhouse gas
HTP	Human Toxicity Potential
kWh	Kilowatt hour
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LHV	Lower Heating Value
LUC	Land Use Change
MCS	Monte Carlo Simulation
MDF	Medium Density Fibre Board
MJ	Megajoule
MS	Modified Silane
MSR	Market Stability Reserve of the EU ETS
MPG	Milieu Prestatie Gebouwen
NG	Natural Gas
NMD	Nationale Milieu Database
N_2O	Nitrous Dioxide
OSB	Oriented Strand Board
PCF	Product Carbon Footprint
PFC	Perfluorocarbons
Prefab	Pre-fabrication
PVC	Polyvinylchloride
TFC	Timber Frame Construction
SQ	Sub Question
tkm	Tonne*kilometer

1. Introduction

In order to reach the targets of the Paris Agreement, the Netherlands have formulated stringent CO_2 restrictions for their construction sector. This study investigated whether increasing energy and CO_2 prices could benefit development of timber-based constructions that can be used a measure to reduce the climate impact of the Dutch construction sector.

1.1 Societal and Scientific Background

In 2020, buildings and the construction sector were responsible for 37% of global CO_2 emissions (IEA, 2021a). Furthermore, the EU construction sector constitutes half of EU total resource extractions and despite being a global leader in recycling of construction waste, the sector is responsible for one-third of all EU waste production (C. Zhang et al., 2022). Moreover, with improved energy performance of modern buildings, embodied energy of a building (the energy required for extraction, processing, manufacturing and delivery of construction materials; Level, 2021) constitutes an increasing and prominent share of the environmental impact of a building throughout its lifetime (van der Lugt & Harsta, 2021). Especially concrete and steel production constitute a significant share of CO_2 emissions for the production of construction materials (respectively 55% (1.6 Gt) and 32% (0.95 Gt); Idem). Thus, to mitigate the environmental impact of the construction sector, it is important to find alternatives to the current use of concrete and steel. This quest is specifically valuable for the Dutch construction sector, because continuing business as usual (BAU) depletes its CO_2 budget until 2030 to stay under 1.5 °C already in 2026 (Sobota et al., 2022).

Opportunities for Industrial Timber Frame Constructions

A promising approach for improving the environmental performance of the construction sector is to use timber frame constructions (TFC; see section 2.1).

Regarding timber use, wood products consist for generally 50% of carbon (Lamlom & Savidge, 2003), which is sequestered by trees through photosynthesis. Therefore, timber constructions can function as a carbon sink that sequesters CO_2. According to Staatsbosbeheer (2022) and van der Lugt & Harsta (2021), roughly 55 m^3 of wood is required for 1 timber dwelling. Assuming a wood density of 500 kg/m^3 (Matmatch, n.d.; based on Pine), 2.75 Mt CO_2 can be sequestered when constructing 100,000 timber dwellings. This amount would represent 81% of the Dutch target to reduce 3.4 Mt CO_2 in the built environment in 2030 compared to BAU (*Klimaatakkoord*, 2019). However, this example is not pragmatic nor realistic as carbon sequestration does not count for the reduction targets in the Dutch built environment. The example is merely meant to provide a perspective on the amount of CO_2 that could potentially be stored in the built environment. Furthermore, if omitted concrete would be included in this calculation – assuming 135 t of concrete for a typical Dutch dwelling (Beijers, 2021) with an emission intensity for concrete of 100 kg CO_2 /t (Portland Cement Association, n.d.) – another 1.35 Mt of CO_2 could be reduced annually. Hence, the substitution of concrete for pinewood in the construction of all dwellings until 2030 entails a CO_2 reduction that exceeds targets for the built environment.

What is more, the use of timber products can contribute to the Dutch ambition to create a circular economy in 2050 (Dijksma & Kamp, 2016). This requires biobased products (wood for timber) from the biocycle because raw materials from the techno cycle (required for concrete and steel production) are non-renewable (R. H. Crawford & Cadorel, 2017). Nevertheless, cascading construction materials can contribute to a circular economy, but finitely sourced materials can never be 100% circular. Moreover, timber is relatively suitable for cascading due to its options for high quality re-use and energy recovery through incineration (van Stijn, 2021). Also, Van der Lugt & Harsta (2021) state that accessible iron reserves might become scarce before 2090 if current extraction rates are extrapolated.

What is more, worldwide demand for sand to produce concrete has pressured availability of certain sand-types, driving overexploitation and environmental damage in certain regions (Torres et al., 2017; Tweedie, 2018). Therefore, a shift towards renewable biobased construction materials is essential for a circular economy (Appendix I elaborates further on circularity in the construction sector).

Lastly, TFC elements are often constructed off-site (Prefab) due to its light weight compared to concrete and steel, which allows for better transport- and on-site handling performances (de Vries et al., 2022; Tykkä et al., 2010; van der Lugt & Harsta, 2021). What is more, compared to conventional construction methods, prefabrication entails better time-efficiency, reduced waste intensity (up to 15%) and reduced cost over runs due to resilience to weather conditions (Dineshkumar & Kathirvel, 2015; Shahzad et al., 2014; C. Zhang et al., 2022). Therefore, an additional benefit to industrial TFC development is that it can contribute to the ambition to build 100,000 (affordable) dwellings annually (Ministerie van Binnenlandse Zaken en Koningkrijksrelaties, 2022).

Reluctancy Regarding Constructing with Timber

Despite the potential benefits of industrial timber construction, concrete and masonry constructions (CMC) are currently dominant in Europe (van der Lugt & Harsta, 2021).

An important reason for this is inertia in the construction and housing sector that is caused by a lack of experience with- and capacity for industrialized timber constructions as 80% of materials used in the built environment in Europe constitute concrete, mortar and steel (de Vries et al., 2022; Tykkä et al., 2010; van der Lugt & Harsta, 2021). A shift towards timber construction requires different skills, expertise and equipment, which makes construction companies reluctant towards adopting it (de Vries et al., 2022). Moreover, industrialisation is only feasible for larger construction companies that have the resources and sufficient sales volumes to be profitable (Neelamkavil, 2009). What is more, project developers and housing cooperatives are reluctant in commissioning timber constructions due to worries regarding risks of fire, acoustics and durability of timber constructions (Papa, 2022). See Appendix III for an elaboration on this.

Furthermore, the Milieu Prestatie Gebouwen (MPG) score is the only tool that officially mandates the use of environmentally friendly construction materials in the Netherlands. The score is expressed in €/m^2 Gross Floor Area (GFA)*year, based on 1) 'shadowcosts' (read: externalities expressed in €), 2) the expected lifetime (time a material can fulfil its function) and 3) the End of Life (EoL) scenario (e.g. landfill or recycle) of each material in the building. Shadowcosts are defined in the Nationale Milieudatabase (NMD) by a Life Cycle Analysis (LCA). From July 2021 onward, buildings are required to achieve a score > 0.8 €/GFA*year (RVO, 2021). There are however three factors that undermine the representation of bio-based materials as an environmentally friendly construction material in the NMD: 1) CO_2 storage capacity of biobased products is not accounted for in the LCA that defines the shadowcosts (van Stijn, 2021), 2) biobased products score high on Human Toxicity Potential (HTP) in the LCA, which has a significant but questionable weight (Beijers, 2021) and 3) the lifetime of timber products in the NMD is mostly defined < 100 years (NMD, 2022b), while timber can last longer if humidity is kept < 20% (de Vries et al., 2022; Hens, 2013). These factors currently infirm the effectiveness of the MPG in stimulating the adoption of timber products in the Dutch built environment.

Lastly, public controversy deters the transition towards mainstream timber construction. Worries exist regarding environmental damage caused by wood harvesting, land use change (LUC), biodiversity loss and the availability of wood (See Appendix II for an elaboration on this). What is more, critics note that sequestered carbon in TFC can be released at the EoL stage when incinerated, compromising its environmental benefits. However, the extent to which these worries are valid exceed the scope of this study.

Tipping Points for Adoption of Timber Frame Constructions

Klas & Jonsson (2009) foresee improved economic performance of TFC when the construction sector 1) shares experiences within the sector and 2) involves more in the timber frame network. Then, van der Lugt & Harsta (2021) state that financial competitiveness between a timber and concrete based construction depend on design parameters, technical details and regional properties. Then, Tykkä et al. (2010) adds that potential TFC uptake in the construction sector differs significantly per country, based on traditions, culture and policies. Also, several timber based constructions have proven their cost-effectiveness, which is crucial for the development of industrial TFC as construction costs are a competitive necessity (Tykkä et al., 2010). E.g. Arumägi & Kalamees (2020) demonstrated a single story industrial TFC complying to Nearly Zero Energy Building (NZEB) regulations that could be built for 1390 €/m^2 in Estonia, which is what an average building in the Netherlands costed in 2021 (Academia, 2021). Furthermore, Skaio in Germany is built with timber and facilitates affordable social housing (van der Lugt & Harsta, 2021). Nevertheless, significant adoption of TFC dwellings in the Dutch market remains absent as CMC are generally more cost-effective (de Vries et al., 2022; Klimstra, 2022).

Nässén et al., (2012) and Sathre & Gustavsson (2007) defined an approach for researching the dynamics behind cost-effectiveness of a TFC compared to a CMC by identifying energy and CO_2 costs required for the production of construction materials. They found that increased prices for energy and CO_2 cause a relative decrease in costs for a wood-based construction compared to its conventional CMC counterpart. This approach can be used to explore the tipping point at which a TFC can financially compete with a CMC. Moreover, the dynamics between cost-effectiveness and CO_2- and energy prices is currently of significant relevance due to recent price increases caused by current geo-political tensions and the energy transition.

1.3 Knowledge Gap

A study that assesses the development potential of industrial TFC dwellings in the context of fluctuating energy and CO_2 prices in the Netherlands is not available. Dutch studies that generated lifecycle impacts of TFC- compared to CMC dwellings rely mostly on standardized data and therefore miss the resolution required for an accurate energy and CO_2 cost analysis that would be applicable for the Dutch construction sector; e.g. Beijers (2021) used Ecoinvent data for an LCA and Life Cycle Costing (LCC) but did not account for energy costs throughout the full production chain. The studies of Nässén et al. (2012) and Sathre & Gustavsson (2007) do offer insights in the effect of energy and CO_2 prices on prices for construction materials, but they focus on the Swedish construction sector. Moreover, they use outdated values for standardized energy inputs as established by Tillman & Björklund (1997). Also, Nässén et al. (2012) use outdated electricity- and CO_2 price prognoses of respectively < 60 €/MWh and < 40 €/t in 2030, while Dutch electricity prices are expected to stay near 100 €/MWh until 2026 (Zicht Op Energie, 2022) and CO_2 prices are expected to increase to 129 €/t in 2030 (Pietzcker et al., 2021). Hence, results of Nässén et al. (2012) and Sathre & Gustavsson (2007) are not usable for the Dutch construction sector.

This study seeks to fill that knowledge gap by comparing the cost-effectiveness of producing an industrial- TFC and CMC under fluctuating CO_2- and energy prices, aiming to use relevant and up-to-date data for the Dutch construction sector. This entails an approach based on Nässén et al. (2012) and Sathre & Gustavsson (2007) that includes 1) energy use for the assembly phase of construction modules to account for prefabrication, 2) updated energy and CO_2 prices and 3) materials data that is compatible with the Dutch construction sector. In light of this, the following research questions (RQs) have been formulated:

1.4 Research Questions and Scope

Main Research Question:

How do energy and CO_2 prices determine the competitiveness between CMC and TFC production in the Netherlands?

Sub Question 1: What is the difference in energy demand and CO_2 emissions for the production of a CMC and TFC?

Sub Question 2: What is the difference in energy and CO_2 costs as part of total materials production costs between a CMC and TFC?

Sub Question 3: How are production costs of a CMC and TFC impacted by fluctuating energy and CO_2 prices and when is a price equilibrium between both variants reached?

This study entails a Dutch ground-bound dwelling (See Section 4.2). Furthermore, the study is limited to the Dutch construction sector but does include foreign resource and material producers. The, the timeframe for this study is between 2022 and 2030 and therefore, the EoL of the buildings is not taken into account. Also, the use-phases of both TFC and CMC are assumed to be equal with regard to energy consumption (both versions abide to EU Nearly Zero Energy Building regulations) and are thus excluded from the analysis. Furthermore, the lifetime of construction materials is not accounted for as this study focusses on the production process of both building approaches. Then, the cement, steel, plasterboard and fibre-glass industry are subject to the EU Emission Trading System (EU ETS) and corresponding CO_2 costs are calculated based on this system as elaborated on in section 3.2. Also, prices for energy carriers are based on industry and consumer prices found online, where taxation schemes regarding energy carriers are not accounted for. What is more, waste management, LUC, biogenic carbon uptake, offsetting and soil carbon stock are excluded from this study. Lastly, 'production' of a CMC or TFC entails 1) materials production, 2) transport of materials from supplier to assembly factory and 3) assembly of a dwelling in the factory (See Figure 12).

1.5 Societal and Scientific Relevance

The societal relevance of this study is that disclosure regarding cost-effectiveness of a TFC or CMC under rising energy and CO_2 prices can provide the necessary incentive for construction companies in to 1) adopt industrial TFC construction or 2) continue improving the (environmental) performance of the CMC. This is relevant for society as the direction that the construction sector chooses has a significant impact on Dutch sustainability goals (see section 1.1). Furthermore, policy makers can use this study to assess the extent to which subsidy schemes can stimulate industrial TFC construction to compete with industrial CMC.

Then, the scientific relevance of this study is that it identifies the energy and CO_2 dynamics that are present behind a cost analysis for either TFC or CMC construction in the Netherlands. The scientific domain already conducted LCAs and LCC for both construction approaches, but these lack a refined data resolution relevant for a Dutch construction company (see section 1.3). The novity in this study is that it discloses the effect of energy and CO_2 prices in the Netherlands on construction costs for a TFC and CMC. This approach allows for the identification of a tipping point at which TFC and CMC become economically competitive. These results can supplement the scientific domain with a quantitatively expressed reciprocity between energy and CO_2 prices and the costs of a TFC or CMC.

2. Industrial CMC and TFC

This section provides details and context regarding industrial CMC and TFC as these are the objects of study for this study. The section starts with a description of a CMC (2.1) and TFC (2.2). Then, part of the assembly process of the BGDD factory is explained (2.3). Moreover, several operational CMC and TFC factories in the Netherlands are presented in Appendix IV.

2.1 Concrete and Masonry Construction

A prefabricated concrete and masonry dwelling typically consists of a concrete casco that ensures structural integrity and a masonry façade that provides aesthetics, insulation and weather-proofing (Bouwgroep Dijkstra Draisma (2020); See Figure below).

A prefabricated (reinforced) concrete casco ensures rapid construction-times and minimal finishing layers for casco elements (Spaansen, 2022). A concrete casco consists mostly of a ground floor, separating walls (for terraced dwellings), stabilizing walls, inner walls and mezzanine floors (Idem). In a concrete casco, electricity, water piping and space for ventilation systems can already be integrated (Buildingsupply, n.d.). See Appendix V for more details on concrete production.

A masonry wall consists of materials (e.g. bricks, stones, tiles, ceramic- or glass blocks) that can be cemented together with mortar, stacked as 'dry set masonry' or reinforced with a backbone of a strong material such as steel (McMahon, 2022). Masonry walls are highly durable, can be a cheap building method if local resources are used and are confer fire protection (Idem).

The masonry façade of the prefab CMC in this study constitutes a prefab outer wall that is finished with stone strips that are glued to the a cement-fibre surface with MS Polymer glue (Verboom, 2021). The façade is connected to the concrete casco and traditional roofing with tiles and batten are used to make the structure watertight.

Figure 1 CMC construction as assembled and constructed on-site by BGDD *Source: BGDD (n.d.)*

2.2 Timber Frame Construction

The most used timber construction for housing is a timber frame construction (TFC) that uses rectangular beam frames for the structure of walls, floor and roof (Hens, 2013; Thoma et al., 2018; van der Lugt & Harsta, 2021), which can be seen as a 'timber casco' when compared to the CMC (Section 2.1). These frames are filled with isolation and sealed with Oriented Strand Board (OSB), Medium Density Fibre Board (MDF) or multiplex for further structural stability (Hens, 2013; van der Lugt & Harsta, 2021). Upright beams reach either from floor-to-floor ('platform frames': efficient to construct but structurally less stable) or from floor to the roof sheet ('balloon frames': more stable but complex to construct). Then, both timber- or poured concrete floors can be used for TFC depending on climate and soil conditions. The TFC that is subject of this study has an outer wall with a stone strip finish that is aesthetically identical to the industrial CMC in this study (See 4.2 Case Study Dwelling).

In North-European countries, prefab is the norm for TFC (Tykkä et al., 2010). A typical TFC construction factory uses digital joinery machines (for drilling and screwing) and computer assisted sawing machines to construct prefab TFC modules, which are then mostly assembled manually (Thoma et al., 2018; Tykkä et al., 2010). The most used wood species for TFC in the Netherlands is coniferous (van Stijn, 2021).

Maintenance of a correctly designed airtight and moisture tolerant TFC without thermal bridging, hardly differs from required maintenance of a CMC; depending on outdoor finish (Hens, 2013). See Appendix III for an elaboration on the quality and fire-safety of TFC.

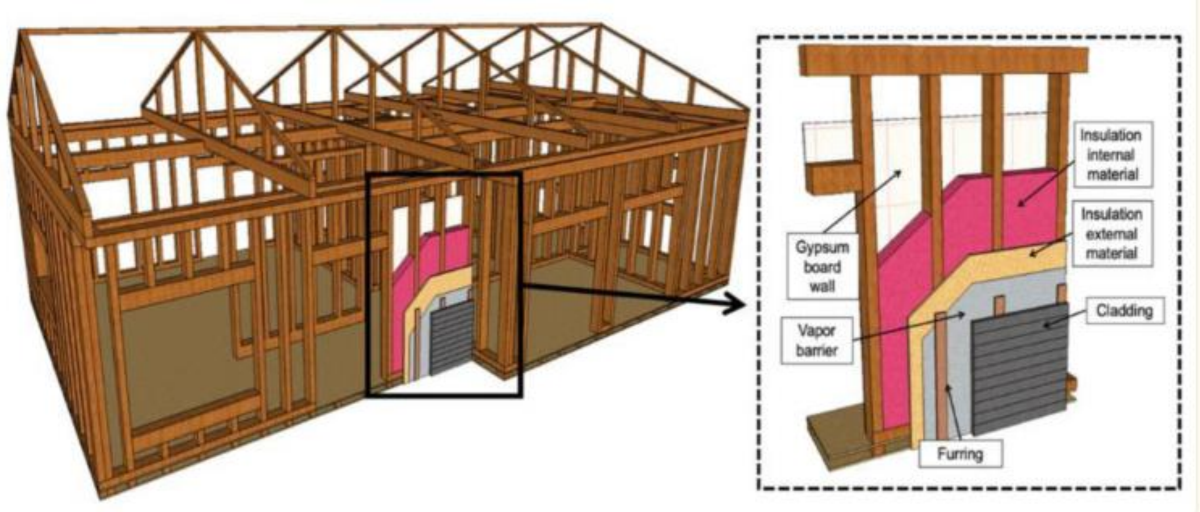


Figure 2 Schematic of a timber frame construction with wall configuration on the right (Cabral & Blanchet, 2021)

2.3 Assembly of Construction Elements in Factory

A construction factory for assembling construction elements is a building that primarily functions as a shelter against wind, rain, moisture and temperature for machines, robots and human laborers (Kim et al., 2009).

Primary materials (Section 3.3 for CMC and TFC) are transported to such construction factory where they are used to make construction elements. These elements include roofs, walls, facades and floors. The elements also gain the required windows, window frames, installation pipes, electronics and insulation.

Figure 3 below provides an impression of the construction factory of BGDD in which the CMC are assembled. This figure displays the production-line for outer-facades, with 1) framing station with automated OSB stapling, 2) butterfly table I for electronics installation, 3) butterfly table II for electronics installation from the other side, 4) assembly table for windows and panels, 5) clinker tile laying robot, 6) drying room and 7) finishing lane for final assembly (BGDD, 2022). The finished outer-facades are then connected to the casco to form a wall element.

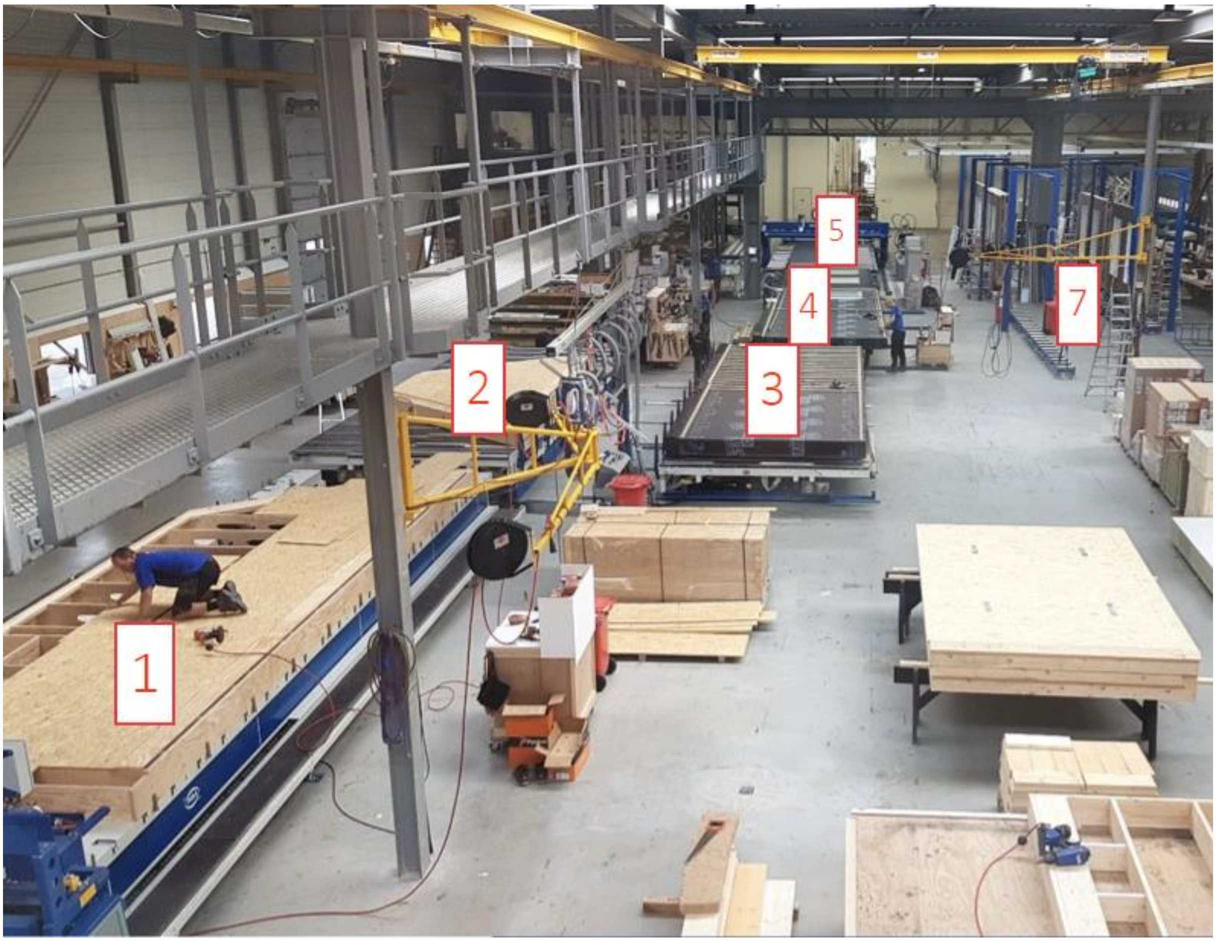


Figure 3 Construction factory at construction company BGDD *Source: BGDD (2022)*

Factory performance is typically expressed in [annual product output], for the CMC- or TFC factory this entails [annual amount of dwellings] or [annual amount of materials processed in meters]. The energy use of a factory is often expressed as [m^3/year] for NG and [kWh/year] for electricity.

3. Concepts Used In This Study

This section includes a theoretical background with concepts that improve understanding of the methods used to answer the RQs. Firstly, concepts for a cost analysis in construction are explained in 3.1 Cost Analysis. Furthermore, the EU ETS is explained in Section 3.2, which is required to understand the CO_2 cost component in the cost analysis. Then, to determine energy and CO_2 for producing a TFC or CMC, concepts for an energy and CO_2 analysis are treated Section 3.3. Lastly, Section 3.4 describes the theoretical background regarding the impact analysis, which is used to determine the robustness of the cost analysis under fluctuating energy prices.

3.1 Cost Analysis

Cost calculations are a vital part of developing and ultimately constructing real estate, as they 1) improve plans by identifying errors before construction starts, 2) allow to make better bid comparisons between contractors and 3) improve risk control (Ramos, 2020).

Figure 4 displays a general cost-overview for building a physical structure (Ramos, 2020; Sikkema, 2022).

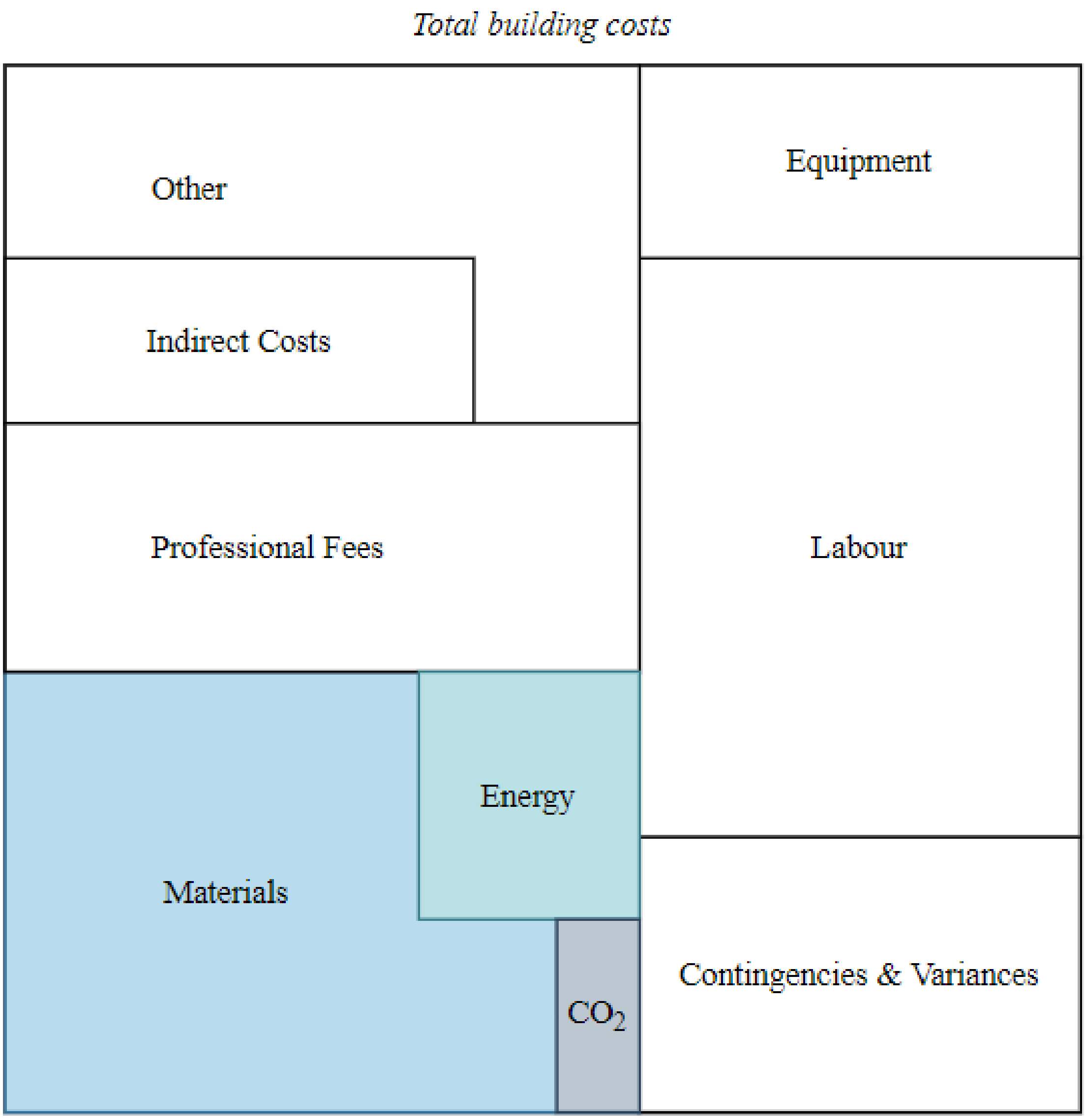


Figure 4 General cost-overview for building a physical structure; developed in consultation with a BGDD calculator

The costs in this figure entail:

- Contingencies and Variances: Reserves allocated to cover unexpected conditions; e.g. delays or inclement weather.
- Equipment: Depreciation, rental or lease of machines; e.g. cranes or earth movers.
- Indirect Costs: E.g. insurance, legal bills, inspection fees or overhead costs.
- Labour: Wages and related costs.
- Materials: Supplies ranging from screws and nails to concrete and wood.
- Professional Fees: Architecture, design and engineering costs.
- Other: E.g. demolition, disposal or government mandates.

Energy and CO_2 costs for materials are usually not calculated separately.

Figure 5 below displays the levels of accuracy in construction cost estimating, ranging from low accuracy order of magnitude cost calculations to high accuracy definitive cost calculation.

Level	Name	Accuracy	Purpose/Use	Common Method
Level 1	Order of magnitude	Very low	Screening decision	Analogous, parametric, expert judgment, factoring
Level 2	Feasibility	Low	Go/No-go decision	Parametric, factoring
Level 3	Preliminary	Moderate	Budget authorization, design decision	Bottom-up - unit cost assembly level
Level 4	Substantive	High	Bid/tender, control	Bottom up - unit cost detailed
Level 5	Definitive	Very high	Bid/tender, check estimate, control, performance evaluation	Bottom up - unit cost detailed

Figure 5 Levels of Accuracy in Construction Cost Estimations *Source: Ramos, 2020*

For the CMC and TFC, data for a bottom-up construction cost estimation detailed at unit cost is available (Section 3.6 builds on this). A bottom-up construction cost estimation entails a granular approach in which costs for all aspects (see list above) are calculated for each stage of the project (Ramos, 2020). Generally, bottom-up estimates are time consuming due to the large number of data included. However, if detailed data is available, the output of a bottom-up estimation is deemed to be accurate up to the point that it can be used for e.g. tender bids or performance evaluations.

3.2 EU Emissions Trading System

Cement-, mineral wool insulation-, steel- and PVC producing companies in the EU fall under the EU Emissions Trading System (EU ETS). This means that CO_2 emissions emitted for the production of these construction materials constitute a share of the production costs. Moreover, the CO_2 price under the EU ETS is expected to increase. Therefore, the share of CO_2 costs in the industrial TFC and CMC are calculated in this study (Section 4.5), to account for rising CO_2 prices under the EU ETS.

The EU ETS is a greenhouse gas emissions trading scheme that was launched in 2005 as a tool to meet EU emission reduction targets. It uses a 'Cap and Trade' system in which the cap for CO_2 emission of the system decreases annually and continues to decrease by 2.2% per year from 2021 onwards (European Commission, 2015a). System participants share emission allowances under this cap (Idem). This group includes over 11,000 of the largest CO_2 emitting companies (primarily energy producers and heavy industry) in the EU, Iceland, Liechtenstein and Norway; covering 40% of EU GHG emissions (European Commission, n.d.; European Environment Agency, 2019). Total emissions under the EU ETS have been reduced by 43% since deployment of the system (Kerstine, 2021). Furthermore, the system allocates emission allowances (EUA) for individual EU ETS participants, where surpluses or deficits can be traded between companies and an auction until the allocated EUA are met (Figure 6). 1 EUA is the allowance to emit 1 tonne of CO_2-eq (European Commission, 2021a). Lastly, a Market Stability Reserver (MSR) can trade EUA at an auction to ensure stability of the EUA price. In 2021, 57% of EUA were purchased from auctioning (European Commission, 2021a).

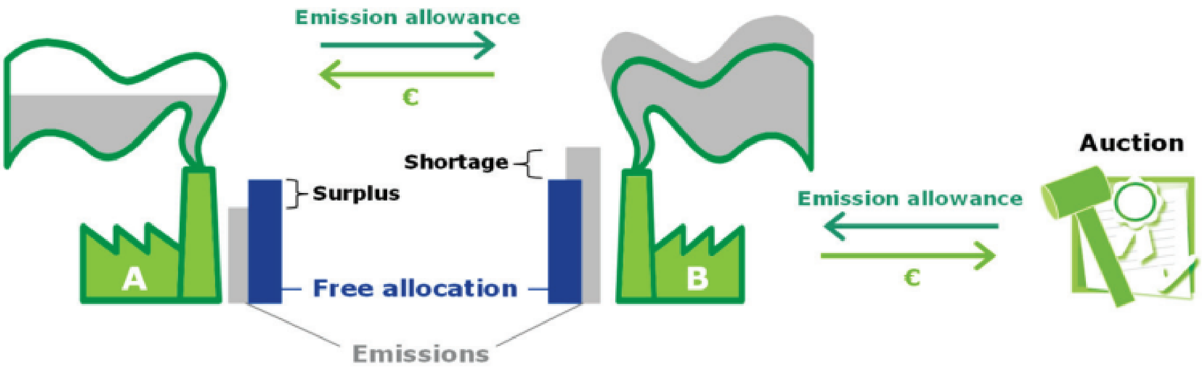


Figure 6 EU ETS ' Cap and Trade' system with emission trading between companies and auction (EU ETS Handbook, 2015)

The amount of EUA for each company is related to the benchmark performance of the 10% best performing companies; these companies gain all allowances for free, while the least CO_2 efficient companies need to purchase EUA until the benchmark is met (European Commission, 2011). This forces them to 1) reduce emissions or 2) purchase additional allowances. Benchmarks update for each product every 5 years and current benchmarks can be found in: European Commission (2021e). Furthermore, to prevent carbon leakage to outside the EU, free allowances are granted to companies that are at risk of relocating outside the EU if CO_2 costs exceed the benefit of staying in the EU. Industrial manufacturing companies often gain free allowances due to this mechanism, while power producing companies are not eligible for free allowances related to carbon leakage.

In 2015, the cement sector proposed that benchmark updates should only be performed for industries where the gap between best and worst performers is widest (European Commission, 2015b). Moreover, they argue that EU-wide emission reduction targets should be divided better between emitters in the EU, as industries under the EU ETS now carry a relatively large burden in the EU climate ambitions. They also argue that EU ETS revenues should be unlocked for innovations in the cement industry (Cembureau, 2021). Based on this and other stakeholder inputs, the EC has implemented a 'Modernisation Fund' from 2021 onwards (European Commission, 2021c). This fund provides EUA for low-carbon innovations.

3.3 Energy and CO_2 Analysis

Now that the cost analysis and EU ETS are explained, this section describes concepts used for the energy and CO_2 analysis (Section 4.4) in order to calculate energy demand and CO_2 emissions that are used for the energy and CO_2 cost calculations in Section 4.5. These concepts include Primary to Useful Energy, Embodied Energy, Transport Energy, Life Cycle Assessment and Emission Scopes.

3.3.1 Primary to Useful Energy

Generally, there are four stages in which energy can be measured (Ritchie, 2022). These stages range from its primary form at the source to the amount of useful energy that is ultimately provided to the user (Figure 7). The moment of measuring an amount of energy that is used for the same application, can provide significantly different results due to conversion losses. Therefore, one of the four stages should be mentioned when interpreting energy correctly. The first stage is primary energy which entails energy as available at the source; e.g. unburned coal or crude oil. Secondary energy indicates that primary energy was transformed to a transportable form; e.g. refined oils or electricity. Final energy is the energy that is delivered to the consumer; e.g. petrol at the fuel pump or electricity entering a dwelling. Useful energy is the energy that is actually utilized for a function; e.g. an amount of light from a lightbulb or an amount of kinetic energy.

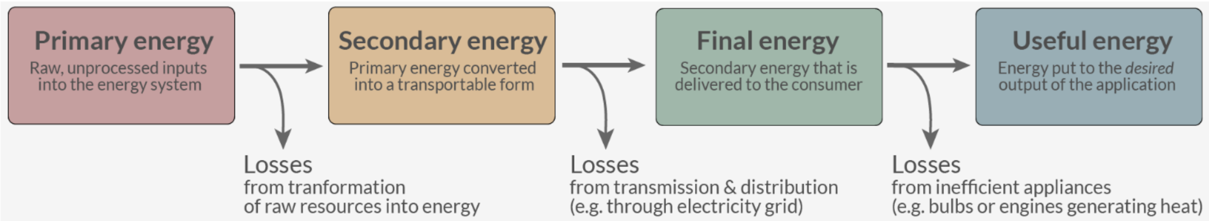


Figure 7 Four different stages in which energy can be measured *Source: Ritchie (2022)*

3.3.2 Embodied Energy

To quantify energy requirement for construction materials, the concept of embodied energy is used. This concept entails tot energy required for extraction, processing, manufacturing and delivery of construction materials (Level, 2021). Embodied energy is considered to be an indicator for the overall environmental impact of construction materials, but unlike a Life Cycle Assessment (LCA), it only considers the front-end energy intensity of a construction material instead of its full life cycle. Hence, embodied energy can be used as data input for an LCA. Calculating embodied energy requires insight in the production processes of materials (See Appendix IV) and numerous sources, resulting in a value expressed typically as [GJ/m^3].

Embodied energy accounts generally for 20% of a building's energy use, but this number decrease as buildings become more energy efficient (Level, 2021; van der Lugt & Harsta, 2021). Higher embodied energy does however not always translate into decreased environmental performance as products with high embodied energy can increase energy efficiency of a building (e.g. mineral wool insulation).

3.3.3 Transport Energy

Transport energy is often expressed as a function of distance and load. This load can either be an amount of passengers, volume or mass. For construction materials, transport is generally weight-limited for products with a density > 250 kg/m^3 and volume limited for products with a density of < 250 kg/m^3 (P & O, 2013). The unit of expression of transport energy for passengers, volume and mass, is respectively [passenger*km], [m^3*km] and [t*km]. The latter constitutes the transport of 1 tonne of goods (including packaging and tare weights of intermodal transport units) over a distance of 1 km (Eurostat, 2021).

3.3.4 Life Cycle Assessment

To determine the CO_2 emissions from the production of different construction materials, a Product Carbon Footprint (PCF) can be established. A PCF is a means for measuring, communicating and managing GHG emissions related to a certain product. A PCF is based on an LCA, but focuses on the single issue of Global Warming Potential (GWP) (de Schryver & Zampori, 2022). Several prominent PCF calculation methodologies are available, building on existing ISO standards for LCA: ISO 14040 and ISO 14044.

The general structure of an LCA follows 4 steps, as displayed in Figure 8 below (Whitehead et al., 2015). In the first step, the goal and scope define te study goals. During this step, a Functional Unit (FU) is defined as the unit of comparison (Stamatiadou, 2015). A FU can be a product, service or system whose impacts can be calculated by a LCA. A common FU is e.g. 100 kcal, 1 m^2 of GFO or 1kWh of light. This allows different products that fulfil the same FU to be compared (e.g. the CMC and TFC that fulfil an amount of m^2). Also, a system boundary is established in this step. The system boundary defines a separation between lifecycle processes of the product that are in- or excluded in the LCA. Then, a Life Cycle Inventory (LCI) is used to (visually) describe process flows and the system boundary for the life cycle of the products that fulfil the FU. Furthermore, at the step for impact assessment selection, relevant environmental impacts for the goal and scope of the study are selected (CO_2 for a PCF). These impacts are quantified for each product that fulfils the FU. Lastly, resulting impact scores for the products are compared and interpreted.

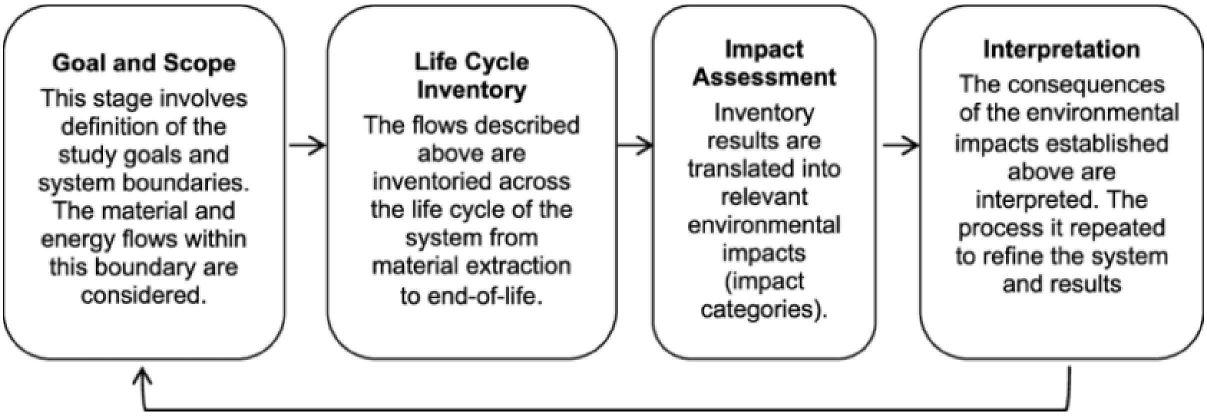


Figure 8 The four steps of a life cycle assessment (Whitehead et al., 2015)

Common process flows for construction products are displayed in Figure 9 below. Stages A1 – A5 constitute the development of a construction; from resource extraction to final assembly of the building. Then, stages B1 – B7 constitute the use-phase of a building. Lastly, stages C and D constitute the EoL stage of a building, in which resources can be generated for re-use or recycling.

Product / Manufacture Stage [A1-A3]			Construction Process Stage [A4-A5]		Use [B1-B7]							End-of-Life Stage [C1-C4]				Benefits & Loads Beyond [D]
					Building Fabric					Operation of the Building						
Raw Material Extract / Process / Supply	Transport	Manufacture	Transport to the Site	Assembly / Install in the building	Use / Application of Installed Products	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operational Water Use	Deconstruction / Demolition	Transport to Waste Process	Reuse-Recovery-Recycle	Disposal	Reuse-Recovery-Recycle Potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Cradle-to-Gate			Gate-to-Grave													
Cradle-to-Grave																
Cradle-to-Cradle																
System Boundaries																

Figure 9 Life cycle stages in service of a FU of construction products as part of an LCI (Koseci, 2018)

Ecoinvent 3 Database for LCI

Ecoinvent 3 is a database that contains data regarding environmental impacts of a diverse range of products from sectors ranging from global to regional levels, constituting more than 18,000 datasets to be used for LCI (Ecoinvent, n.d.). These datasets contain data on human activities and industrial- or agricultural processes, entailing: amounts of natural resources withdrawn from the environment, emissions released to water, soil and air, products demanded from other processes (e.g. electricity) and quantities of waste produced. For each dataset, several impact assessment methods are available, containing impact categories ranging from climate change and human toxicity to water use and depletion of fossil fuels. Datasets are provided as individual unit process data ensuring comprehensive documentation and transparency regarding the underlying computed environmental impacts. The Ecoinvent database is mostly used with Simapro software.

3.3.5 Emission Scopes

CO_2 emissions can occur directly from combusting e.g. a litre of NG for heat. These direct emissions are called Scope 1 emissions (Bernoville, 2022). Furthermore, when purchasing a cup of hot coffee, no direct emissions occur for enjoying the heat of the coffee. However, the coffee was still heated earlier, for which e.g. also a litre of NG was combusted or electricity might have been used to heat the coffee. Emissions occurring indirectly from purchasing thermal energy or electricity are called Scope 2 emissions (Idem). What is more, to allow the production of a hot cup of coffee, emissions have occurred when making the machine or pot for coffee making, when building the building in which the coffee was made and when extracting and transporting NG or electricity to heat the cup of coffee. These remaining indirect emissions both upstream and downstream are called Scope 3 emissions. Note that Scope 3 emissions also includes waste treatment and EoL scenarios.

3.4 Impact Analysis

Impact analyses are used to identify exposure to risk factors and aid in the development of setting priorities for risk management (Frey & Patil, 2002). An impact analysis can therefore provide the basis for planning adaptation measures (Idem). This concept lies at the heart of this study as the development of TFC to replace CMC can potentially provide an adaptation measure for construction companies to mitigate risks involved in rising energy prices.

To measure impact, sensitivity analysis methods can be used. These are classified in 3 categories: 1) Mathematical Methods that assess sensitivity of an output to the range of variation in an input (e.g. nominal range sensitivity or break-even analysis), 2) Statistical Methods that involve running simulations in which inputs are assigned a probability distribution (e.g. Monte Carlo simulation) and 3) Graphical Methods that provide a visual representation of how an output is affected by variations in inputs; mostly used to complement the former two methods (Frey & Patil, 2002).

Sensitivity analyses can be performed with different software programs ranging from manual mathematical sensitivity analyses in e.g. Excel to using e.g. @Risk software specifically for a Monte Carlo Simulation (MCS). Both Excel and @Risk can be used for visual presentations of sensitivity analyses.

3.4.1 Monte Carlo Simulation

A MCS uses probability distributions as parameter in- and outputs. A probability distribution is a statistical function that defines the likelihood of a parameter to obtain a certain value (Frost, 2022). A probability distribution is typically expressed as X ~ N($\bar{x}$, σ), where X is the name of the parameter, ~ indicates that it follows a distribution, N signifies the distribution, $\bar{x}$ is the mean value of the dataset, and σ is the standard deviation in the dataset (Idem).

Standard Deviation

As displayed in the expression above, the mean and standard deviation (σ) define the probability distribution of a parameter. A standard deviation indicates the dispersion of a dataset relative to its mean (Investopia, 2022). The equation for standard deviation is expressed in Eq. 1 below:

Eq. 1) $$\text{Standard Deviation } (\sigma) = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n-1}}$$

Where:

x_i = Value of the i[th] point in the data set

$\bar{x}$ = Mean value of the data set

n = Number of datapoints in the data set

Furthermore, the reader is expected to be able to calculate the mean of a dataset.

4. Methods

This section describes the methods that are used to generate results that are used to answer the RQs. In 4.1 Analytical Framework, a general overview of the analytical framework is provided describing general data requirements and results format per RQ. Then, 4.1.1 Data Gathering follows on the analytical framework with a more detailed description of data requirements per SQ with corresponding details regarding data sources. Furthermore, before the gathered data could be used for calculations, 4.2 Case Study Dwelling and 4.3 Case Study Assembly Factory provide specifics on 1) the case study dwelling, entailing the resulting FU that was used for calculations and the material quantities that were used for respectively the CMC and TFC variation of this dwelling and 2) the assembly factory entailing production performance and energy data for both types of dwelling assembly (CMC and TFC). Then finally, Sections 4.4 – 4.6 contain an explanation of the calculation methods: the Energy and CO_2 Analysis in Section 4.4, the Cost Analysis in Section 4.5 and the Impact Analysis in Section 4.6.

4.1 Analytical Framework

Figure 10 displays the used research framework to determine the extent to which CMC and TFC are financially impacted by fluctuating energy and CO_2 prices. Final use and prices of energy and CO_2 and materials were defined in an Excel model for SQ1 and SQ2 (Sections 4.4 and 4.5), allowing for an impact analysis in SQ3 (Section 4.6). The FU of these construction systems is 1 casco of a dwelling, referred to as *building* as elaborated on in Section 4.2 and Table 2. Note that for the cost analysis, this FU is 1 m^2 GFA in *building*; using this FU ensured confidentiality regarding precise cost prices for elements produced by BGDD. Furthermore, the research scope was limited to a cradle-to-gate approach; use- and EoL-phase were excluded from this study (See Section 3.3.4).

The results of SQ1 provided data on energy use and CO_2 emissions throughout the production chain for each construction approach (Section 4.4). SQ2 built on data from SQ1 to determine 1) total materials costs, 2) energy costs- and 3) CO_2 costs for both construction approaches (Section 4.5). Then, SQ3 used the Excel model established in SQ1 and SQ2 to perform an impact analysis in @RISK software, so that the financial impact of fluctuating energy and CO_2 prices could be quantified (Section 4.6).

SQ1 and SQ2 required data from the case study at 1) the construction company, 2) literature & public data (including Ecoinvent 3) and 3) consultation of material suppliers for the buildings. SQ3 only required data from the latter two. SQ1 and SQ2 provided results that were respectively formatted as GJ/*building* (SQ1), tCO_2/*building* (SQ1), and €/m^2GFA (SQ2) for each construction approach (See Figure 10). Specifics on data requirement are elaborated on in the following section.

This methodology was appropriate because it provided a universal framework that was applicable to both construction approaches, yielding outputs in the same units. This allowed for a direct comparison between CMC and TFC. In the following paragraphs, the research framework is dissected further.

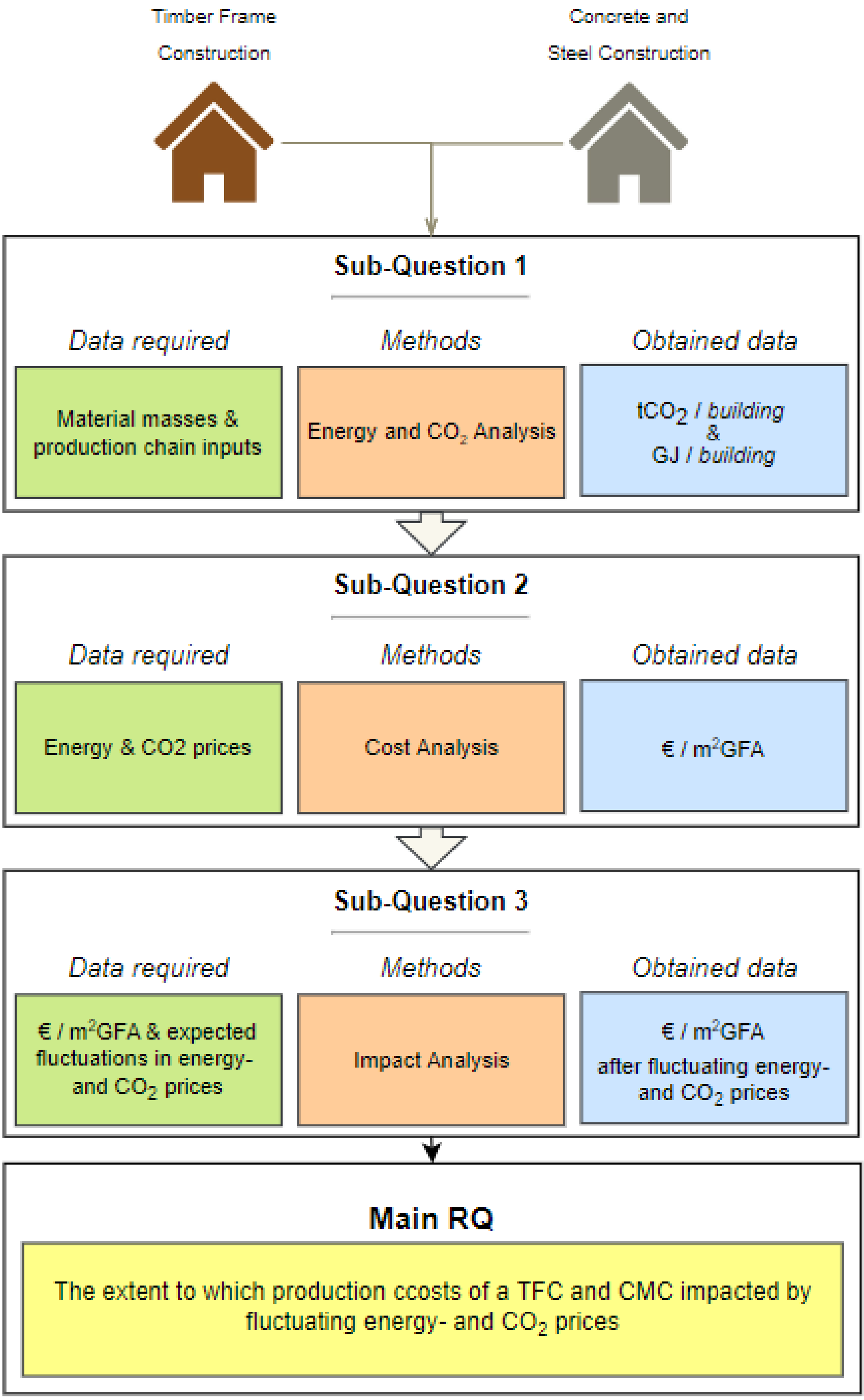


Figure 10 Analytical Framework to research the extent to which industrial- TFC and CMC are financially impacted by fluctuating energy and CO_2 prices

4.1.1 Data Gathering

Data for the research framework is gathered according to the overview displayed in Table 1. More details regarding individual data sources is provided in the following sections that describe the methods for SQ1, SQ2 and SQ3, and in Appendices V, VI, VII and VIII.

Table 1 Data gathering of required data for each sub-question; construction company = Dijkstra Draisma, Suppliers = Van Nieuwpoort Beton & NordicTimber, Literature and internet entails a mix of grey and academic literature

	Required insight	Required Data	Data Source
Sub Question 1	Amount of construction materials for full building	Technical drawings	Construction company
		Materials in construction elements	Construction company
			Suppliers
	Energy requirement for construction materials	Primary or final energy use for (production steps in) producing construction material	Literature and internet
		Energy mix used per construction material	Ecoinvent database
			Literature and internet
	Energy requirement for transport	Transport distances	Suppliers
			Construction company
		Transport modes	Suppliers
			Construction company
		Energy performance transport modes	Literature and internet
	Energy requirement for assembly	Annual energy use in factory	Construction company
		Annual production volume in factory	
		Energy mix for factory	
	CO_2 emissions for producing full dwelling	Energy requirement and energy mix for full building	See above
		Emission factors	Literature and internet
Sub Question 2	Costs of materials	Costs of construction materials	Construction company
		Costs of labour	
		Costs of machines and external services	
	Energy costs in materials	Energy requirement and energy mix for full building	SQ1
		Price of energy carriers	Literature and internet
	CO_2 costs in materials	CO_2 emissions that fall under EU ETS	European Commission
		Price of CO_2 under EU ETS	Literature and internet
Sub Question 3	Volatility of energy and CO_2 prices	Historic prices of energy carriers and CO_2 under EU ETS	Literature and internet
	Impact of energy and CO_2 costs in materials	Energy and CO_2 costs in materials	SQ2

4.2 Case Study Dwelling

Figure 11 below displays the two storey dwelling with pointed roof that can either be built as prefab-CMC or TFC. This dwelling casco is used as a FU for the energy and CO_2 analysis (SQ1) and 1 m^2 of GFO for this dwelling casco is used as FU for the cost- and impact analysis (SQ2 and SQ3). This section elaborates on the dwelling casco as FU and corresponding materials used for the CMC or TFC.

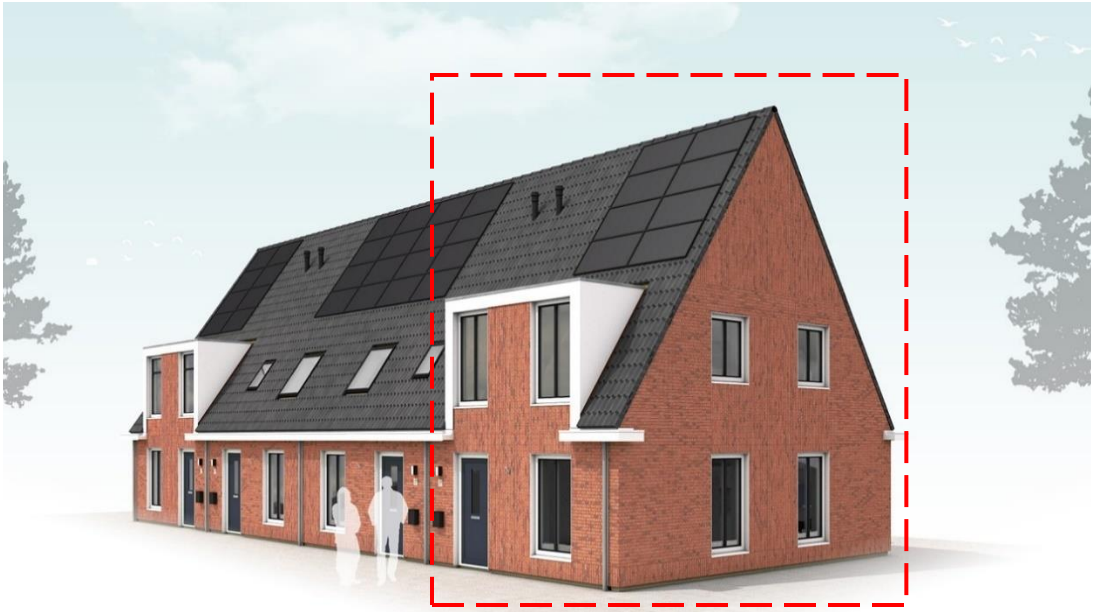


Figure 11 Two storey dwelling with pointed roof that serves as case study dwelling for this study. It has been constructed with the prefab CMC approach and is expected to be produced with the TFC approach until 2030.

The FU entails a the dwelling casco displayed in figure 11 with dimensions, energy performance and aesthetics (with stone strip finish) as provided under discretion by BGDD. The CMC requires more construction elements (39 compared to 34) for a structurally equal dwelling. This is because the outer and inner walls in the TFC are produced as 1 element. The construction elements for the TFC version are 100% assembled at the construction company, while the CMC uses floor-, inner-wall- and separating wall modules from external suppliers.

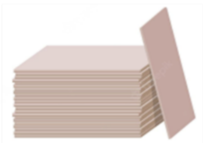
Table 2 below displays the included and excluded elements for this study. Installations, interior and finishings were excluded as these take up a large share of the costs, while being identical for both construction approaches as well as replaceable for alternatives according to the taste of inhabitants. Furthermore, the impact of energy and CO_2 prices is limited for these elements. Therefore, they have not been part of this study. Also, tapes, kit, glues, nails and screws were excluded from the energy and CO_2 analysis. This study rather focuses on the casco elements of each construction approach, which differs significantly between the CMC and TFC.

Table 2 Construction elements in the CMC and TFC in- and excluded for the scope of this study; the resulting primary materials in these elements can be found in Table 3

Included elements for study	**Excluded elements for study**
Foundation pillars	Toilet units
Ground floor	Stairs
First floor	Kitchen
Attic floor	Fuse box
Outer walls	Sanitary unit
Inner walls	Rainwater drainage
Facade	Installation skid
Roofing	Outside roof finishings
	Windows

Quantities of included primary materials (Appendix V) per construction approach are included in Table 3 below:

Table 3 Total casco construction materials in [m^3] for both construction approaches sourced from the construction company

		 **CMC**	 **TFC**
Timber[1]		3.6 m^3	9.4 m^3
OSB[2]		2.0 m^3	4.0 m^3
Cellulose[3]		6.1 m^3	17.3 m^3
Mineral wool[4]		25.2 m^3	32.9 m^3
Reinforcing steel[5]		0.26 m^3	0.13 m^3
Plasterboard		0.8 m^3	4.9 m^3
Concrete		39.2 m^3	12.2 m^3
EPS[6]		8.8 m^3	8.8 m^3

[1]Includes batten and beams for wall, roof and floor structure
[2]Includes 9mm and 11mm panels
[3]Used for wall insulation with a density of 45 kg/m^3
[4]Used for roofing insulation with a density of 45 kg/m^3
[5]Used for foundation structure in both TFC and CMC (95 kg/m^3) and for the CMC for reinforcement in floor modules (14 kg/m^2) and wall modules (40kg total) with density assumed at 8000 kg/m^3
[6]Used under concrete ground floor as insulation

4.3 Case Study Assembly Factory

The CMC and TFC are processed in an assembly factory (Section 2.3**)**, from materials (Table X) to construction elements and finally to complete dwellings.

The CMC factory is currently operational, providing an output of nearly 20,000 m of beams used in elements (Table 4). Concrete elements for this factory are delivered by external suppliers. This set-up allows for a capacity of 300 dwellings per year. Energy use in the factory includes NG for heating and electricity that is 100% sourced from wind-power (Saathof, 2022).

The TFC factory is in its development phase. Hence, exact energy consumption is unknown. Therefore, an estimation was made based on the extrapolation of the projected output of beams used in elements. The results of this extrapolation are found in Table 4 below. The capacity of this factory is lower than the capacity of the CMC factory because this factory also assembles the timber-based construction elements that replace the concrete elements in the CMC (which were assembled by external suppliers).

Table 4 below displays the capacity-, electricity consumption- and NG use per year for the factory that assembles construction elements for the CMC and TFC. This data was granted by the construction company.

Table 4 Capacity-, electricity consumption-, and NG use per year for the factory that produces construction elements

	Factory for CMC elements	Factory for TFC elements	Unit
Capacity	300	250	[dwellings/year]
Element output	18,886	39,267	[m/year]
$E_{NG,building}$*	14,031	29,173	[m^3/year]
$E_{electricity}$*	127,363	264,807	[kWh/year]

*Based on two-year average

4.4 Sub-Questions 1: Energy and CO_2 Analysis

For the energy and CO_2 analysis a partial LCA similar to the PCF as described in Section 3.3.4 was used. The goal was to identify the energy demand and CO_2 emissions for the production of 1 dwelling (CMC or TFC). The FU is 1 dwelling with a non-publicly disclosed GFA (note that the cost calculations in Section 4.5 provide €/m^2 GFA as desired by the construction company).

Furthermore, the corresponding LCI is disclosed in figure 12 below. The system boundary is separates phases A1 - A3 from a full lifecycle (See Section 3.3.4). Then, the impact assessment was limited to energy demand and CO_2 emissions, which were calculated according to the equations described in the rest of Section 4: respectively Eq. 2 and Eq. 7 express the part within the system boundary mathematically for the energy demand and the total CO_2 emissions of a dwelling. Lastly, LUC, biogenic carbon uptake, offsetting, soil carbon stock, resource requirements and waste generation are outside the scope of this study (See Section 1.4) and were thus not accounted for.

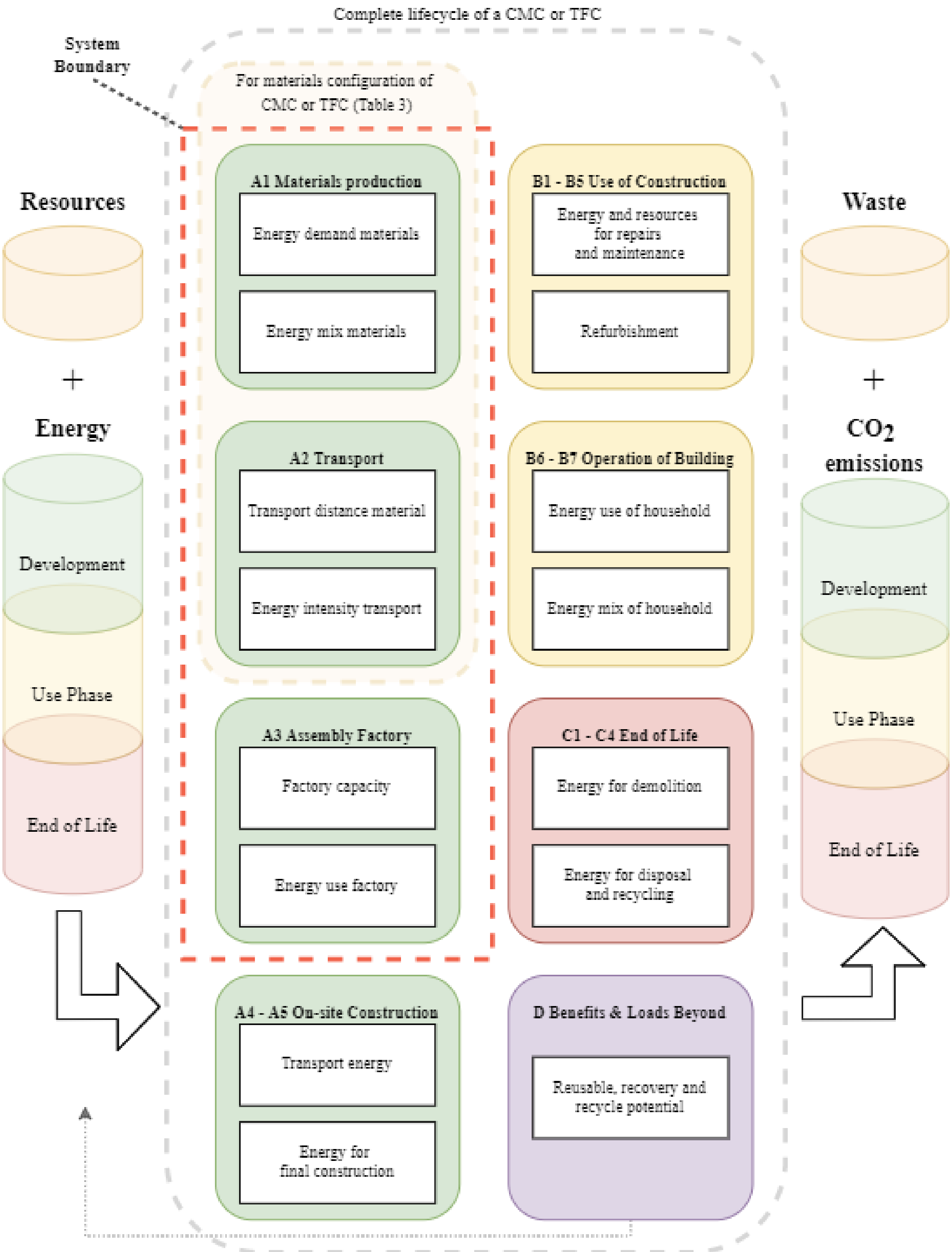


Figure 12 LCI for a CMC or TFC with energy and resources input; CO_2 emissions and waste output; and a system boundary encapsulating phases A1 – A3 as subject of this study

4.4.1 Energy Requirement for each Construction Approach

The energy requirement for 1 dwelling consists of 1) energy used for the production of construction materials, 2) energy used for transport from material suppliers to the assembly factory of the construction company 3) energy use at the assembly factory to assemble 1 dwelling.

The total final energy demand for each building approach was then calculated by Eq. 1 below:

Eq. 2) $$E_{building,\mathrm{final}} = M_{building} + T_{building} + F_{building}$$

Where:

Index *building* is either *CMC* or *TFC*

$E_{building,\mathrm{final}}$ = Total final energy demand for *building* in [GJ]

$M_{building}$ = Final energy requirement for materials production in *building* - defined in Eq. 3 - in [GJ]

$T_{building}$ = Final energy requirement for materials transport in *building* - defined in Eq. 4 - in [GJ]

$F_{building}$ = Final energy requirement in assembly factory for *building* - defined in Eq. 5 - in [GJ]

4.4.1.1 Energy Requirement for Materials Production

Figure 9 displays calculation steps for the final energy demand calculations of the CMC and TFC. Literature provided primary- and final energy demand for material production (without energy mix). Primary energy was converted to final energy by using corresponding conversion efficiencies based on the energy mix (derived from Ecoinvent 3) of each material production process. Then, embodied energy and energy mix per material allowed for the calculation of final energy requirement for materials production $M_{building}$. What is more, the energy mix of $M_{building}$ was calculated in Eq. 4 for further calculations regarding CO_2 emissions and costs (Section 4.5 and 4.6). Combined, $M_{building}$, final energy requirement for assembly ($F_{building}$), and final energy requirement for transport ($T_{building}$), were used to calculate total final energy requirement ($E_{building,\text{final}}$).

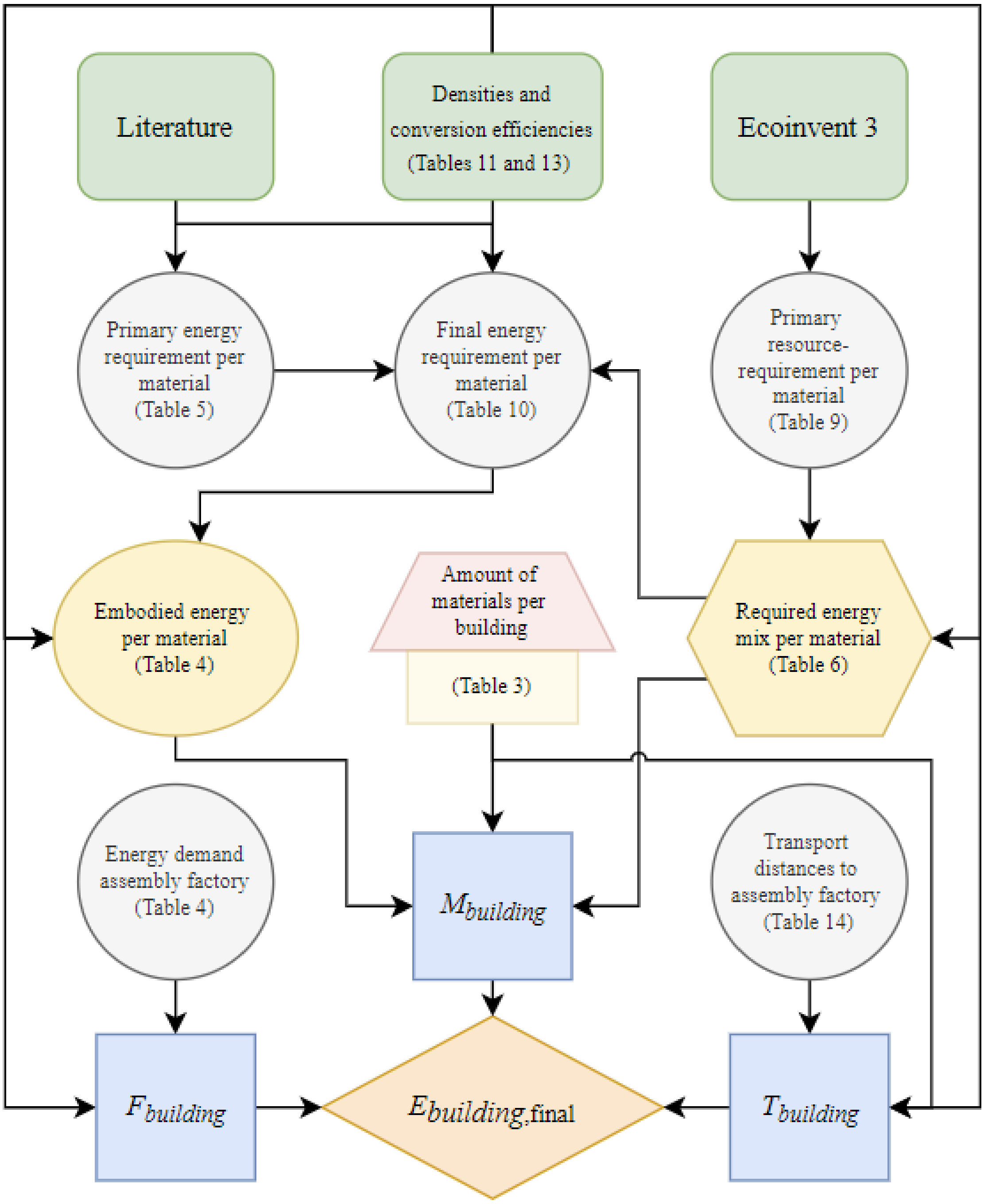


Figure 13 Calculation steps for final energy requirement calculations of a CMC or TFC with corresponding table-numbers

Eq. 3 below displays the calculation for final energy requirement of materials production. The output of this calculation is used again to calculate the corresponding CO_2 emissions from materials production in Eq. 8.

Eq. 3) $$M_{building} = \sum_m Qty_{m,building} * e_m$$

Where:

Index *building* is either *CMC* or *TFC*

Index *m* stands for 'material' which represents either *Timber*, *OSB, Cellulose, EPS, Plasterboard, Mineral Wool, Reinforcing Steel* or *Concrete*

$M_{building}$ = Final energy requirement for materials production in *building* in [GJ]

$Qty_{m,building}$ = Quantity of material *m* in *building* - as found in Table 3 - in [m^3]

e_m = Embodied energy requirement of material *m* - as found in Table 5 - in [GJ/m^3]

Table 5 on the next page displays embodied energy demand for each construction material *m* in each *building*. Details regarding production processes of each material can be found in Appendix V and the conversion from each literature source to embodied energy is described in Appendix VI.

Table 5 Embodied energy of construction materials as derived from literature with upper- and lower limit indicated in third column if found in literature (See Appendices IV and V for details)

Material	**Used parameters**	**Value**	**Source**		**Embodied Energy *e* [GJ/m^3]**
Timber	Final energy use harvesting Sweden	82 MJ/m^3	Athanassiadis, (2000)	→	[+4.01][1] 1.734 [-0.006][2]
	Final energy use Pine drying	1 GJ/m^3	Garrahan (2011)		
	Final energy use sawing	652 MJ/m^3	Donahue et al. (2021)		
OSB	Primary energy consumption OSB production Ireland	5579MJ/ m^3	Murphy et al. (2015)	→	[+2.75][3] 2.7 [n.a.]
Cellulose	Primary energy requirement cellulose production Switzerland	3.7 MJ/kg	Isofloc (2014)	→	[+0.014][4] 0.07 [-0.028][4]
EPS	Final energy requirement EPS production Switzerland	1393 MJ/m^3	Kingler (2011)	→	[+0.295][5] 1.393 [-0.76][5]
Plasterboard	Embodied Energy Plasterboard	8.6 GJ/m^3	Crawford (2019)	→	[+2.95][6] 3.8 [-0.4][9]
Mineral wool	Final energy use mineral wool production	17 GJ/t	Krijgsman & Marsidi (2019)	→	[n.a.] 0.765 [-0.578][7]
Steel	Specific energy consumption EU steel	13.6 GJ/t	Odyssee-Mure (2019)	→	[+75.2][8] 108.8 [-10.4][9]
Concrete	Final energy requirement concrete production	794 MJ/t	Average of The Concrete Centre (2019) and Guidetti (2017)	→	[+0.949][10] 1.826 [-0.563][11]

[1] Upper limit entails high energy use from kiln drying based on higher moisture content (Ananias et al., 2012) and < 2000 data (Sathre, 2007)
[2] Lower limit entails Polish lumber harvesting with assumed 31 km to sawmill (Lijewski et al., 2017)
[3] Upper limit based on strong board energy costs calculated with 50% conversion efficiency (Institut Bauen und Umwelt, 2020)
[4] Upper and lower limit based on density ranges of respectively 30 kg/m^3 and 60 kg/m^3 (Isofloc, 2014)
[5] Upper and lower limit based on density ranges of respectively 15 kg/m^3 and 40 kg/m^3 (Isolatiewerken, 2021)
[6] Upper limit is based on web page (Greenspec, 2022)
[7] Lower limit is based on lowest found density for mineral wool of 11 kg/m^3 (Isolatie-info, 2021)
[8] Upper limit based on 1986 report of Hoogovens in Ijmuiden (van Buuren & Ronde, 1986)
[9] Lower limit based on < 2000 data used in Sathre (2007)
[10] Upper limit based on value found in Guidetti (2017)
[11] Lower limit based on values found at The Concrete Centre (2019)

In the process of determining the embodied energy from heterogenous literature data (Appendix V), the energy mix for each construction material was calculated and displayed in Table 6 below. See Appendix V for a context regarding the production process of each material.

Table 6 Ecoinvent materials energy demand data converted to shares of energy carriers based on total final consumption for the production of each material (See Appendices V and VI for context of calcuations with regards to the production processes of materials)

Material	Diesel	Coal*	NG*	Biomass*	Electricity
Sawnwood, beam, softwood, dried (u=20%), planed {Europe without Switzerland}| planing, beam, softwood, u=20% | Cut-off, S	1%	4%	2%	89%	3%
Oriented strand board {RoW}| market for oriented strand board | Cut-off, S	3%	15%	18%	60%	4%
Cellulose fibre {CH}| cellulose fibre production | Cut-off, S	5%	26%	20%	0%	49%
Polystyrene foam slab for perimeter insulation {CH}| processing | Cut-off, S	10%	5%	76%	0%	9%
Plasterboard{CH}| production | Cut-off, U	3%	19%	45%	0%	33%
Glass wool mat {CH}| production | Cut-off, S	3%	12%	67%	0%	18%
Reinforcing steel {GLO}| market for | Cut-off, S	3%	64%	5%	0%	29%
Concrete, 50MPa {RoW}| concrete production 50MPa | Cut-off, S	9%	55%	22%	0%	14%

*for heat conversion

With the energy mix- and the embodied energy of each construction material, the share of energy carriers as part of $P_{building}$ was calculated by Eq. 4 below:

Eq. 4) $$Energyshare_{bulding,C} = \frac{\sum_m Qty_{m,building} * e_m * Energyshare_{m,C}}{M_{building}} * 100\%$$

Where:

Index *building* is either *CMC* or *TFC*

Index *C* is either *diesel, coal, NG, biomass or electricity*

$Energyshare_{bulding,C}$ = The total share of energy carrier *C* in *building* in [%]

$M_{building}$ = Final energy requirement for materials production in *building* - defined in Eq. 3 - in [GJ]

$Energyshare_{m,C}$ = Relative share of energy carrier *C* for material *m* - as found in Table 6 - in [%]

4.4.1.2 Transport Energy Requirement of Construction Materials

Eq. 5 below displays the calculation to calculate final energy requirement for transport per construction material. This entails transport from the factory that delivers semi-finished products to the factory of the construction company that assembles the construction elements for the dwellings. The energy that is required for transportation of raw materials to produce semi-finished products is assumed to be covered by the embodied energy for the construction materials as displayed in Table 5. Furthermore, all transport is assumed (in consultation with the construction company and suppliers) to be performed by a heavy truck with a trailer.

Eq. 5) $$T_{building} = \sum_m Qty_{m,building} * D_m * \rho_m * \frac{EI}{1000} * \eta_{diesel}$$

Where:

Index *building* is either *CMC* or *TFC*

Index *m* stands for 'material' which represents either *Timber*, *OSB*, *Cellulose*, *EPS*, *Plasterboard*, *Mineral Wool*, *Reinforcing Steel* or *Concrete*

$T_{building}$ = Final energy requirement for transport of materials in *building* in [GJ]

$Qty_{m,building}$ = Quantity of material *m* in *building* - as found in Table 3 - in [m^3]

D_m = Transport distance of material *m* – as found in Appendix X (Table 9) – in [km]

ρ_m = Density of material *m* – as found in Table 14 – in [kg/m^3]

EI = Energy Intensity of a heavy truck with trailer of 1.1 [MJ/tkm] (Klein et al., 2021)

η_{diesel} = Conversion efficiency of diesel - as found in Table 12 - in [%]

4.4.1.3 Assembly Factory Energy Requirement

The construction company factory that produces the construction elements runs on NG and wind-powered electricity (See Section 4.2). Eq. 6 displays the calculation that was used to determine final energy requirement to assemble construction elements for 1 *building*. For this equation, input data from Table 4 is used.

Eq. 6) $$F_{building} = \frac{E_{f,NG,building} * u_{NG} * \eta_{NG} + El_{f,building} * 3.6}{C_{building}}$$

Where:

Index *building* is either *CMC* or *TFC*

$F_{building}$ = Final energy requirement in assembly factory for *building* in [GJ]

$E_{f,NG,building}$ = Annual NG use at the factory of *building* - defined in Table 6 - in [m^3/y]

u_{NG} = Energy density of NG – as found in Table 12 – in [MJ/m^3]

η_{NG} = Conversion efficiency of NG - as found in Table 12 - in [%]

$El_{\mathrm{f},building}$ = Annual electricity use at the factory for *building* in [kWh/y]

$C_{building}$ = Production capacity of factory for amount of *buildings* [amount/y]

4.4.2 CO_2 Emissions of Producing CMC and TFC

In this section is explained how Scope 1 and 2 emissions (See Section 3.3.5 are calculated for the production of the CMC and TFC. The final energy required for the production of *building* (Eq. 2) was converted back to primary energy so that the emissions could be calculated with the corresponding Emission Factors (EF) as displayed in Table 13 in Appendix VII. Then, Eq. 7 below was used to calculate the total amount of carbon emissions per building:

Eq. 7) $$Emissions_{building,\mathrm{total}} = E_{building,\mathrm{materials}} + E_{building,\mathrm{transport}} + E_{building,\mathrm{factory}}$$

Where:

Index *building* is either *CMC* or *TFC*

$Emissions_{building,\mathrm{total}}$ = Total emissions for producing 1 *building* in [t CO_2]

$E_{building,\mathrm{materials}}$ = Total emissions from materials production for *building* in [t CO_2]

$E_{building,\mathrm{transport}}$ = Total emissions from transport of materials to the factory for *building* in [t CO_2]

$E_{building,\mathrm{factory}}$ = Total emissions from assembly of *building* in the factory in [t CO_2]

4.4.2.1 Materials Production Emissions

Eq. 7 displays the calculation for the production of building materials based on the energy mix required for the production of all materials in *building*:

Eq. 8) $$E_{building,\mathrm{materials}} = \sum_{C,building} EF_C * M_{building} * \frac{Energyshare_{bulding,C}}{\eta_C} + E_{building,\mathrm{calc}}$$

Where:

Index building is either CMC or TFC

Index *C* is either *diesel, coal, NG, biomass or electricity*

EF_C = Emission Factor for each energy carrier *C* - as found in Table 13 - in [kgCO_2/GJ]

$M_{building}$ = Final energy requirement for materials production in *building* - defined in Eq. 3 - in [GJ]

$Energyshare_{bulding,C}$ = Relative share of energy carrier *C* for *building* in [%]

η_C = Conversion efficiency of energy carrier *C* - as found in Table 12 - in [%]

$E_{building,\text{calc}}$ = Total emissions from calcination process for *building* in [t CO_2]

4.4.2.2 Calcination Emissions

Calcination emissions for concrete production were calculated by Eq. 9 below:

Eq. 9) $$E_{building,\text{calc}} = e_{conc} * Qty_{conc,building} * \frac{Energyshare_{conc,C}}{\eta_C} * EF_C * ES_{cement} * ES_{calc}$$

Where:

Index *building* is either *CMC* or *TFC*

Index *C* is either *diesel, coal, NG, biomass or electricity*

e_{conc} = Embodied energy of concrete in - as found in Table 4 - in [GJ/m^3]

$Qty_{concrete,building}$ = Quantity of concrete in *building* - as found in Table 3 - in [m^3]

$Energyshare_{conc,C}$ = Relative share of energy carrier *C* in concrete – Table 6 - in [%]

η_C = Conversion efficiency of energy carrier *C* - as found in Table 12 - in [%]

EF_C = Emission Factor for each energy carrier *C* - as found in Table 13 - in [kgCO_2/GJ]

ES_{cement} = Emissions share of cement in concrete - found in Jansen (2020) - constituting 80%

ES_{calc} = Emissions share of calcination in cement - found in Rubenstein (2012) - constituting 50%

4.4.2.3 Transport Emissions

Eq. 10 below displays the calculation for emissions from transport between suppliers of materials and the assembly factory:

Eq. 10) $$E_{building,\text{transport}} = EF_C * \frac{T_{building}}{\eta_{diesel}}$$

Where:

Index building is either CMC or TFC

EF_C = Emission Factor for each energy carrier *C* - as found in Table 13 - in [kgCO_2/GJ]

$T_{building}$ = Final energy requirement for materials transport in *building* – defined in Eq. 4 - in [GJ/m^3]

η_{diesel} = Conversion efficiency of diesel - as found in Table 12 - in [%]

4.4.2.4 Assembly Factory Emissions

Eq. 11 below displays the calculation for emissions at the assembly factory for *building:*

Eq. 11) $$E_{building,\text{factory}} = EF_C * E_{NG,building} * \frac{u_{NG}}{\eta_{NG}}$$

Where:

Index building is either CMC or TFC

EF_C = Emission Factor for each energy carrier *C* - as found in Table 13 - in [kgCO_2/GJ]

$E_{NG,building}$ = Annual NG use at the factory of *building* – defined in Table 6 - in [m^3/y]

u_{NG} = Energy density of NG – as found in Table 12 – in [MJ/m^3]

η_{NG} = Conversion efficiency of NG - as found in Table 12 - in [%]

4.5 Sub-Question 2: Cost Calculations

For SQ2, a bottom-up cost estimation detailed at unit cost was conducted (See Section 3.1). In calculations for SQ2, only costs of materials and their corresponding energy and CO_2 costs were calculated.

Firstly, data from Tables 3 and 14 (Appendix VIII) were used to calculate the total primary materials costs of both construction approaches (CMC versus TFC). After total material costs were calculated, costs were calculated for 1) all required energy inputs in the production chain (Appendix V) and 2) CO_2 requirement for materials producers that fall under the European EU ETS (See Section 3.2); these calculations were based on results from SQ1. Finally, the results of SQ2 (energy and CO_2 costs) were used as variables for the impact analysis in SQ3 (Section 4.6). The costs were expressed in €/m^2 GFA as desired by BGDD.

4.5.1 Total Materials Costs

Firstly, total material costs were calculated to disclose the relevance and impact of energy and CO_2 costs in the context of the total material costs. The costs were calculated for 1 m^2 of GFA to ensure confidentiality for BGDD that facilitated costs data. The price of each *building* was calculated by Equation 12 below:

Eq. 12) $$P_{building} = \frac{\sum_{m,building} Qty_{m,building} * P_m}{GFA}$$

Where:

Index *building* is either *CMC* or *TFC*

$P_{building}$ = Total pice of materials in *building* in [€/m_2 GFA]

$Qty_{concrete,building}$ = Quantity of concrete in *building* - as found in Table 3 - in [m^3]

P_m = Price of material *m* – used prices -as displayed in Table 14 - in [€/m^3]

GFA = Gross Floor Area as defined under discretion by the construction company in [m^2]

4.5.2 Energy Costs

Energy costs for each *building* were calculated by Eq. 13 below:

Eq. 13) $$P_{E,building} = C_{m,building} + C_{t,building} + C_{f,building}$$

Where:

Index *building* is either *CMC* or *TFC*

C_m = Energy costs of materials in *building* in [€/m^2 GFA]

C_t = Energy costs of transport in *building* in [€/m^2 GFA]

C_f = Energy costs of factory in *building* in [€/m^2 GFA]

Then, energy costs for the materials production were then calculated by Eq. 14 below:

Eq. 14) $$C_{m,building} = \frac{\sum_{building,C} \frac{Energyshare_{bulding,C} * M_{building}}{\eta_C} * P_C}{GFA}$$

Where:

Index *building* is either *CMC* or *TFC*

Index *C* is either *diesel, coal, NG, biomass or electricity*

$Energyshare_{bulding,C}$ = The total share of energy carrier *C* in *building* - calculated by Eq. 4 - in [%]

$M_{building}$ = Final energy requirement for materials production in *building* - defined in Eq. 2 - in [GJ]

η_C = Conversion efficiency of energy carrier *C* - as found in table 12 - in [%]

P_C = Price of energy carrier *C* - as displayed in Table 13 - in [€/GJ]

GFA = Gross Floor Area as defined under discretion by the construction company in [m^2]

Next, energy costs for the transport of construction materials were then calculated by Eq. 15 below:

Eq. 15) $$C_{t,building} = \frac{\frac{\left(\frac{T_{building}}{u_{diesel}}\right)}{\eta_{diesel}} * P_{diesel}}{GFA}$$

Where:

Index *building* is either *CMC* or *TFC*

$T_{building}$ = Final energy requirement for transport of materials in *building* in [GJ]

u_{diesel} = Energy density of diesel – as found in Table 12 – in [MJ/l]

η_{diesel} = Conversion efficiency of diesel - as found in Table 12 - in [%]

P_{diesel} = Price of diesel - as found in Table 13 - in [€/L]

GFA = Gross Floor Area as defined under discretion by the construction company in [m^2]

Lastly, energy costs for the assembly factory were then calculated by Eq. 16 below:

Eq. 16) $$C_{f,building} = \frac{\left(\frac{\left(\frac{\left(\frac{\left(\frac{E_{\mathrm{f},NG,building}}{u_{NG}}\right)}{\eta_{NG}}\right)}{3.6} * P_{NG} + El_{\mathrm{f},building} * P_{el,factory}\right)}{Cap_{building}}\right)}{GFA}$$

Where:

Index *building* is either *CMC* or *TFC*

$E_{\mathrm{f},NG,building}$ = Annual NG use at the factory of *building* in [m^3/y]

u_{NG} = Energy density of NG - as found in Table 12 - in [MJ/m^3]

η_{NG} = Conversion efficiency of NG - as found in Table 12 - in [%]

P_{NG} = Price of NG - as found in Table 13 - in [€/kWh]

$El_{\mathrm{f},building}$ = Annual electricity use at the factory for *building* in [kWh/y]

$P_{el,factory}$ = Price of electricity for the BGDD factory – as found in Table 13 - in [€/kWh]

$Cap_{building}$ = Capacity of factory for *building* – found in Table 4 - in [amount/y]

GFA = Gross Floor Area as defined under discretion by the construction company in [m^2]

4.5.3 CO_2 Costs

This section explains how the CO_2 costs for both construction approaches under the EU ETS were calculated. Despite having calculated the total CO_2 emissions for each construction approach before in Section 4.4.2 CO_2 Emissions of Producing , the CO_2 cost calculation is based on benchmark emission values (See Section 3.2 EU Emissions Trading System) for each construction material that falls under the EU ETS as reported by corresponding materials producers.

Materials that fall under the EU ETS include: Plasterboard, mineral wool, Steel and Cement (See Section 3.2). The difference between the benchmark and the current industrial standard determine the amount of CO_2 costs. These benchmarks and corresponding current industrial practices are displayed in Table 7 below.

Table 7 Benchmark CO_2 emissions per construction material as defined under the EU ETS (left) and the current practice for CO_2 emissions for these construction materials (right)

Material	**Benchmark*** in tCO_2/t	**Current practice** in tCO_2/t	**Source**
Plasterboard	0.11	0.16	ETEX (2020)
Mineral wool	0.532	0.9	Krijgsman & Marsidi (2019)
High alloy steel	0.268	1.85	Hoffmann et al. (2020)
Grey cement clinker	0.693	0.83	IEA (2021b)

*from European Commission (2021d)

Furthermore, to convert CO_2 costs from grey cement clinker production to concrete in the CMC and TFC, a 73% clinker in cement content was assumed (IEA, 2021b) and a 20% cement content was assumed for C50 concrete (based on contact with concrete supplier Van Nieuwpoort and Zimmermann & Lehký (2015)).

CO_2 costs were then calculated by Eq. 17:

Eq. 17) $$P_{carbon,building} = \frac{\sum_{building,m}(I_{cp,m} - I_{b,m}) * P_{CO_2} * Qty_{m,building}}{GFA}$$

Where:

Index *building* is either *CMC* or *TFC*

Index *m* stands for 'material' which represents in this case either *Plasterboard*, *Mineral Wool*, *Reinforcing Steel* or *Concrete*

$I_{cp,m}$ = CO_2 intensity of the current practice *cp* for material *m* in [tCO_2/t]

$I_{b,m}$ = CO_2 intensity of the benchmark practice *b* for material *m* in [tCO_2/t]

P_{CO_2}= Price of CO_2 being set at 83 – based on Ember (2022) - in [€/tCO_2]

$Qty_{m,building}$ = Quantity of material *m* in *building* - as found in table 3 - in [m^3] or [t]

GFA = Gross Floor Area as defined under discretion of the construction company in [m^2]

4.6 Sub-Question 3: Impact Analysis

To determine the resilience of the material prices that were calculated in SQ2, an impact analysis was performed using a MCS with @RISK software (See Section 3.4). @Risk calculated the distribution of material prices for the CMC and TFC (output parameters) based on probability distributions for energy and CO_2 prices (input parameters). The distribution of input prices was defined with standard deviations (σ) and means ($\bar{x}$) of historic energy and CO_2 prices. @Risk was then used to calculate the material prices 10,000 times with different combinations of energy and CO_2 prices, providing the probability distribution of material prices. The results of this simulation provided a probability distribution in €/GFA for material costs, based on probability distributions of energy and CO_2 costs for both construction approaches.

4.6.1 Defining Probability Distributions

Fluctuating energy prices were computed by defining a probability distribution for the price of each energy carrier based on historic energy prices. Based on historic prices, their corresponding standard deviation (σ) and mean ($\bar{x}$) were calculated (See Section 3.4).

The resulting standard deviations and means for energy and CO_2 prices (used as @Risk inputs) with their corresponding calculation metrics and sources are displayed in Table X below:

Table 8 Metrics used to define fluctuations in energy and CO_2 prices

	Diesel	**NG**	**Biomass***	**Coal**	**Electricity****	**CO_2**
Unit	€/L	€/kWh	€/kWh	€/t	€/kWh	€/t
Period measured	July 2021 – July 2022	Q1 2021 – Q1 2022	2015 - 2050	Jan. 2021 – Dec. 2021	2020 Q1 – 2021 Q4	Aug 2021 – July 2022
Resolution (n)	25	5	3	12	4	12
High	2.20	0.095	0.03489	136.37	0.12	95.0
Low	1.46	0.029	0.02877	55.09	0.10	55.0
Most recent	2.07	0.10	0.02877	132.62	0.12	83.0
Mean ($\bar{x}$)	1.77	0.057	0.03133	90.90	0.10	74.2
Std. Dev. (σ)***	0.2597	0.02503	0.00318	31.6506	0.01312	13.7996
Source	CBS (2022)	CBS (2022b)	Heat Roadmap (2017)	CBS (2022a) & European Commission (2021c)	UK Government (2022)	Tradingeconomics (2022)

*Measured period and resolution are relatively broad due to a lack of available public data; Ecofys (2016) also encountered this problem

**EU average for medium-sized industry
***Calculated with Eq. 1 (Section 3.4)

4.6.2 Calculating Tipping Point

Based on the outcome of the impact analysis, the tipping point at which an energy price configuration yields equal production costs between the CMC and TFC was calculated. This was done by identifying the two energy carriers that have a dominant impact on the cheaper variant (based on the results of the impact analysis) between the CMC and TFC. The prices of these two energy carriers were then increased in the Excel model until the production costs of the CMC and TFC were equal.

5. Results

The results for the three SQs are presented in the following sections.

5.1 Sub-Question 1: Energy and CO_2 Analysis

Figure 14 below displays the total final energy requirement for the CMC and TFC of respectively 145 GJ and 118 GJ . The main energy demand in the CMC is from concrete and steel use. The main energy demand in the TFC is from concrete and timber use. What is more, the OSB energy demand in the TFC and CMC also constitutes a significant energy demand of respectively 10.8 GJ and 5.6 GJ. Furthermore, cellulose insulation constitutes the lowest energy demand in both cases: respectively 0.4 GJ and 2.3 GJ in the CMC and TFC. Then, a prominent difference between the CMC and TFC is the difference in energy demand for plasterboard of respectively 2.3 GJ and 18.5 GJ. Lastly, the energy demand form EPS is identical for both construction approaches because both construction approaches use the same ground floor insulation.

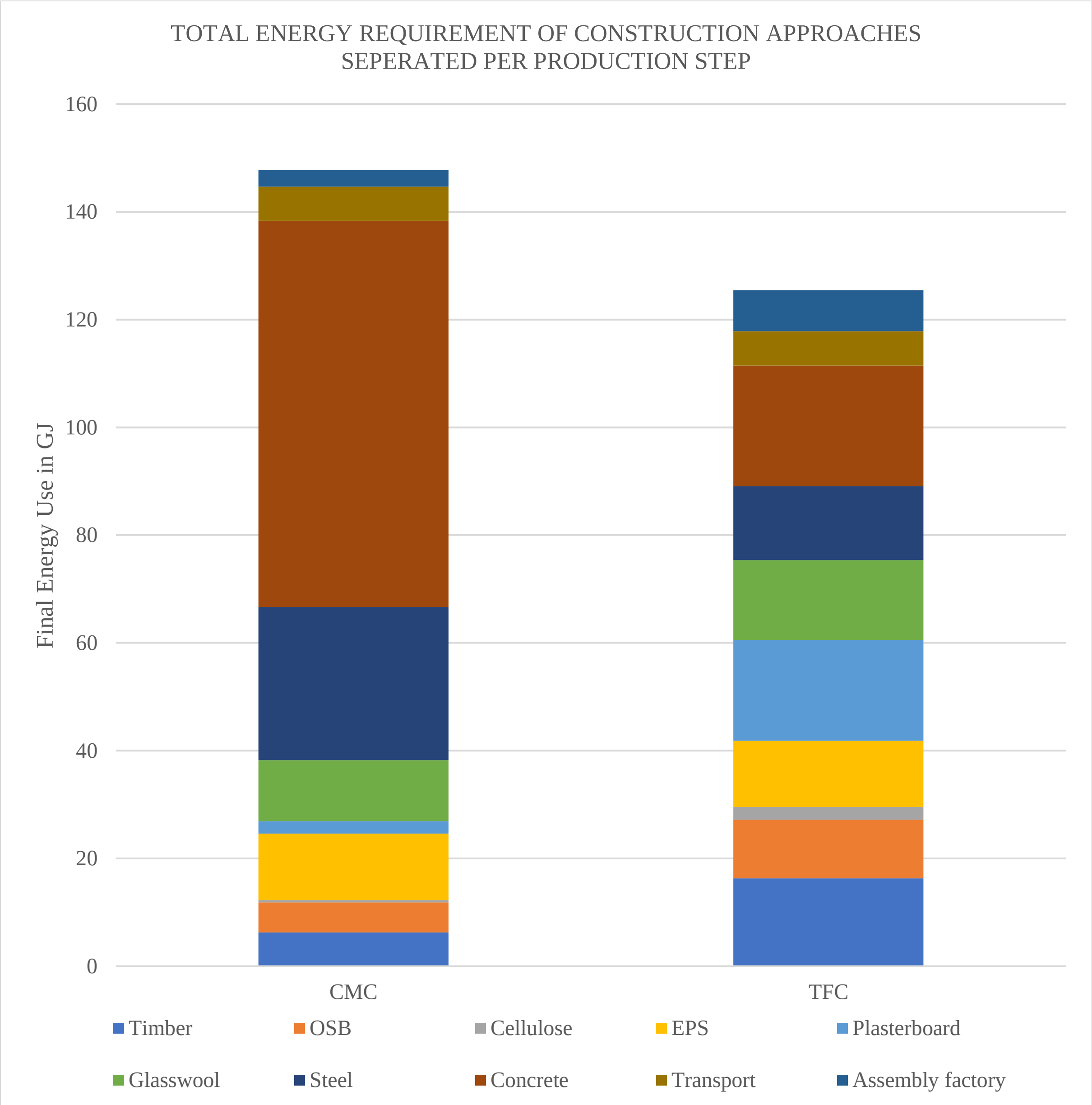


Figure 14 Total final energy requirement per construction approach for CMC and TFC in GJ. The final energy requirement for 1 dwelling is displayed for each construction material, based on their quantities in Table 3

Then, figure 15 below displays the final energy demand and energy mix per construction material for each construction approach. Coal and electricity are dominant energy sources for concrete and delivered respectively 45.2 GJ and 9.3 GJ for the concrete used in the CMC. Energy use for steel production is also dominated by coal and electricity with a total energy demand of respectively 17.88 GJ and 8.05 GJ for the CMC. Timber production requires primarily biomass as energy carrier, with a biomass demand of 20.99 GJ for the TFC. Furthermore, plasterboard, mineral wool and EPS production constitute a prominent share of energy demand for the TFC, with a respective demand of 18.71 GJ, 14.81 GJ, and 12.31 GJ that is primarily sourced from NG. Lastly, diesel use provides a limited share in the energy mix of all construction materials.

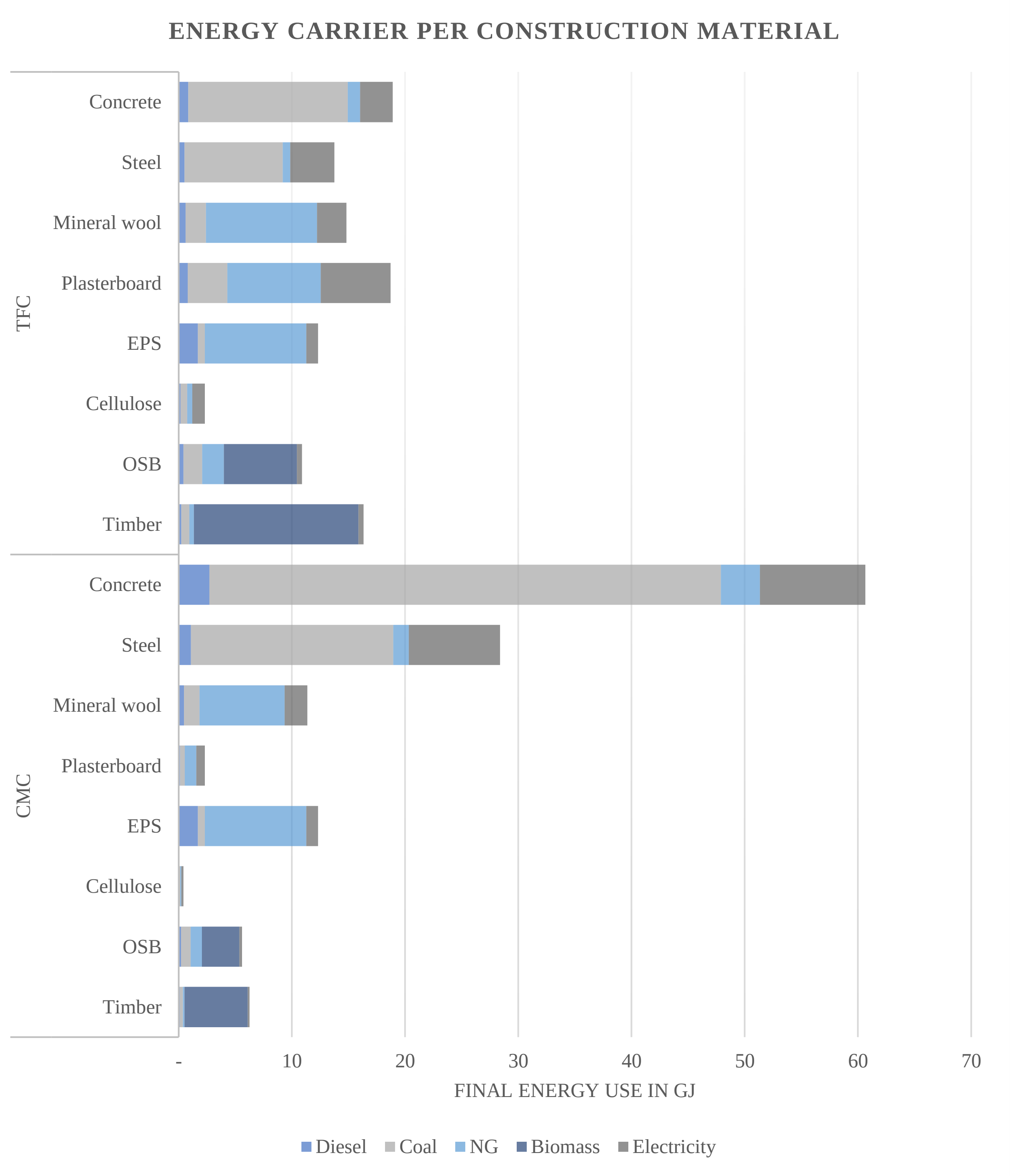


Figure 15 Energy mix per construction approach: constituting final energy use per energy carrier for each construction material

Furthermore, figure 16 below displays the relative energy share of the CMC and TFC based on the total final energy use for the production of their construction materials. Both construction approaches have the lowest share of energy from diesel (5%). The highest (48%) and shared highest (28%) energy share for respectively the CMC and TFC is from coal use. The shared highest (28%) and second highest (17%) energy share for respectively TFC and CMC is from NG use. Electricity use is similar for both construction approaches (16% and 17%). Lastly, biomass constitutes the third highest (19%) and second lowest (6%) final energy share for respectively the TFC and CMC.

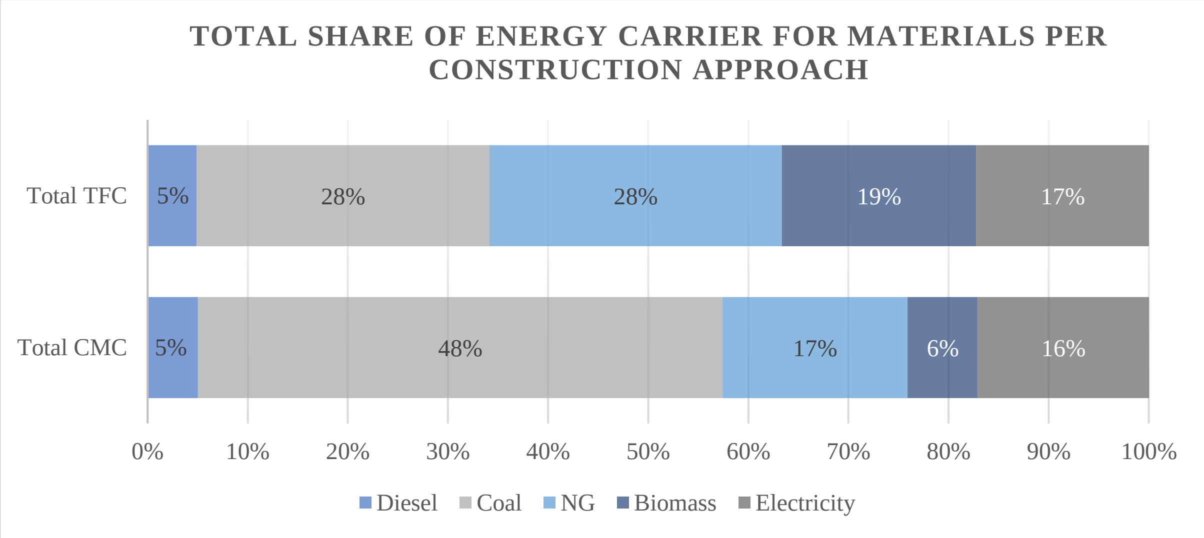


Figure 16 Relative share of energy carrier based on total final energy use per construction approach, excluding factory and transport energy

Figure 17 then displays the CO_2 emissions for the CMC and TFC per material. Total CO_2 emissions for the CMC and TFC are respectively 23.1 tonne and 13.3 tonne, excluding emissions from biomass. Biomass emissions can be regarded as CO_2 neutral due to regrowth of trees and are therefore displayed transparently with a dotted line. Concrete provides most of the CO_2 emissions in both construction approaches, constituting respectively 15.1 tonne and 4.7 tonne for the CMC and TFC. These include calcination emissions calculated by Eq. 9. Then, steel constitutes the second- and third largest share of CO_2 emissions of respectively 4.0- and 1.9 tonne CO_2 for the CMC and TFC. Both concrete and steel emissions are primarily caused by coal burning for respectively the rotary kiln and BOF (See Appendix V). Furthermore, biomass emissions represent a prominent share of CO_2 emissions of respectively 2.0- and 4.6 tonne CO_2 for the CMC and TFC. These emissions are primarily from the production of timber and OSB (See Table 6 and Appendix V). Additionally, timber and OSB emissions from remaining fuel sources represent a minor share of respectively 0.09- and 0.32 tonne for the CMC and respectively 0.23 and 0.61 tonne for the TFC. These remaining fuel sources entail primarily coal and also for a significant part NG for OSB. What is more, emissions from mineral wool production represent 1.3- and 1.6 tonne CO_2 for the CMC and TFC respectively. Their main emissions source is NG (See Appendix V). Next, EPS emissions are identical due to the same amount of EPS used in both construction approaches. Then, plasterboard emissions are only significant in the TFC with values of 0.2- and 1.9 tonne CO_2 for respectively CMC and TFC. The main emission sources for plasterboard are coal and NG (See Appendix V). Lastly, cellulose provides minor CO_2 emissions of 0.04 tonne and 0.23 tonne for respectively CMC and TFC, primarily from coal.

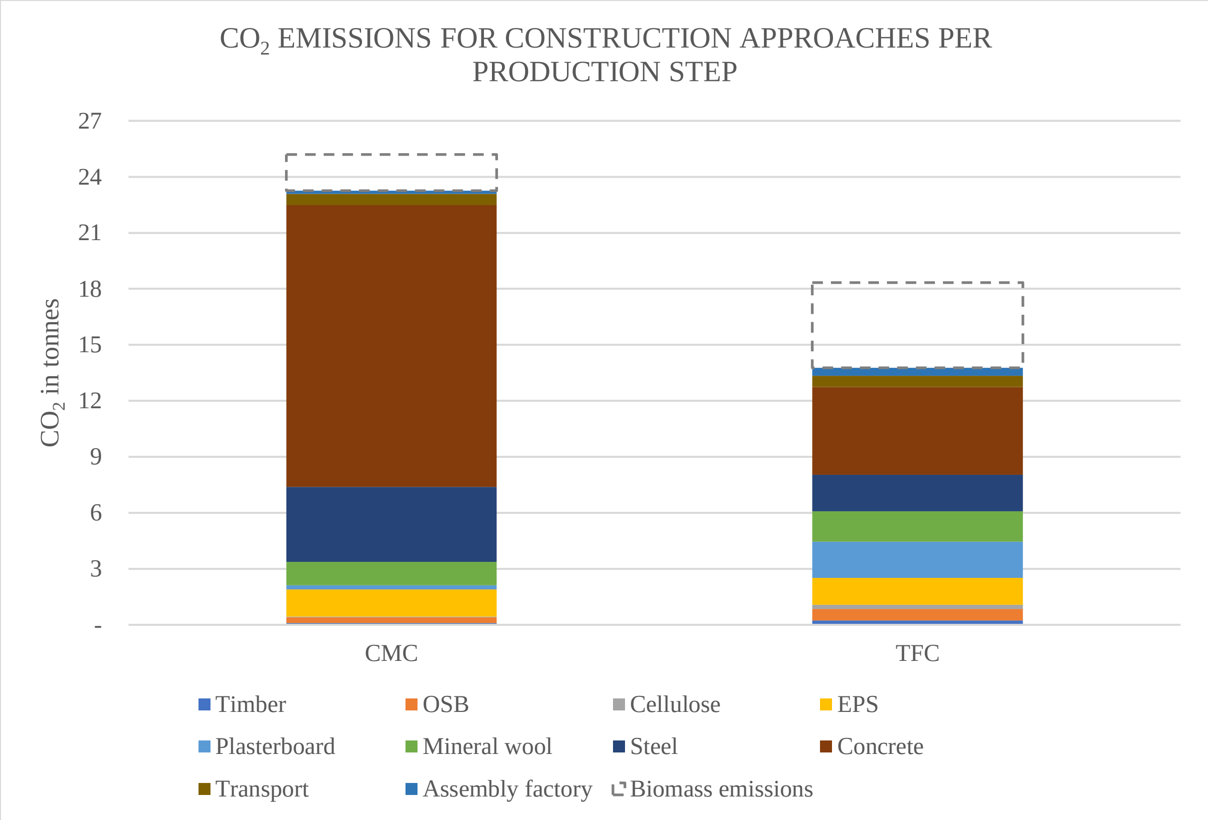


Figure 17 CO_2 emissions for CMC and TFC sourced per construction material based on final energy demand for each construction material + calcination for concrete. Biomass emissions are visualized separately as these are typically regarded as CO_2 neutral

5.2 Sub-Question 2: Cost Analysis

Figure 18 below displays the energy and CO_2 costs (right two bars) as part of the total materials costs that includes energy and CO_2 costs (left bar) for the CMC and TFC, in [€/m^{2}GFA]. The total materials costs for CMC (110.79 €/m^{2}GFA) are lower than those of the TFC (127.54 €/m^{2}GFA). Nevertheless, the total energy and CO_2 costs of the CMC (37.94 €/m^{2}GFA and 3.22 €/m^{2}GFA respectively) are higher than those of the TFC (32.88 €/m^{2}GFA and 1.6 €/m^{2}GFA respectively). Material costs for the CMC are primarily from concrete and steel, while the materials costs for the TFC are more fragmented; this also holds for the energy and CO_2 cost-divisions for both construction approaches. However, CO_2 costs are negligible for both construction approaches. What is more, transport provides a significant and similar energy cost share for both the CMC and TFC of respectively 5.37 €/m^{2}GFA and 5.25 €/m^{2}GFA. For the CMC, the energy and CO_2 costs for concrete are most significant and constitute respectively 17.3 €/m^{2}GFA and 1.3 €/m^{2}GFA. Also, steel in the CMC requires significant energy and CO_2 costs of respectively 4.18 €/m^{2}GFA and 1.69 €/m^{2}GFA. Then, the largest material cost for the TFC is from timber use at 37.80 €/m^{2}GFA, closely followed by the remaining materials starting at 18.60 €/m^{2}GFA for OSB. However, high costs of timber and OSB are barely caused by their energy costs. Furthermore, the highest energy cost shares in the TFC are also from concrete and steel. Also, energy costs from plasterboard in the TFC are significant at 5.01 €/m^{2}GFA due intensive NG use (See Appendix V). Lastly, mineral wool constitutes a significant energy cost share in the TFC of 3.52 €/m^{2}GFA, also due to intensive use of NG (See Appendix V).

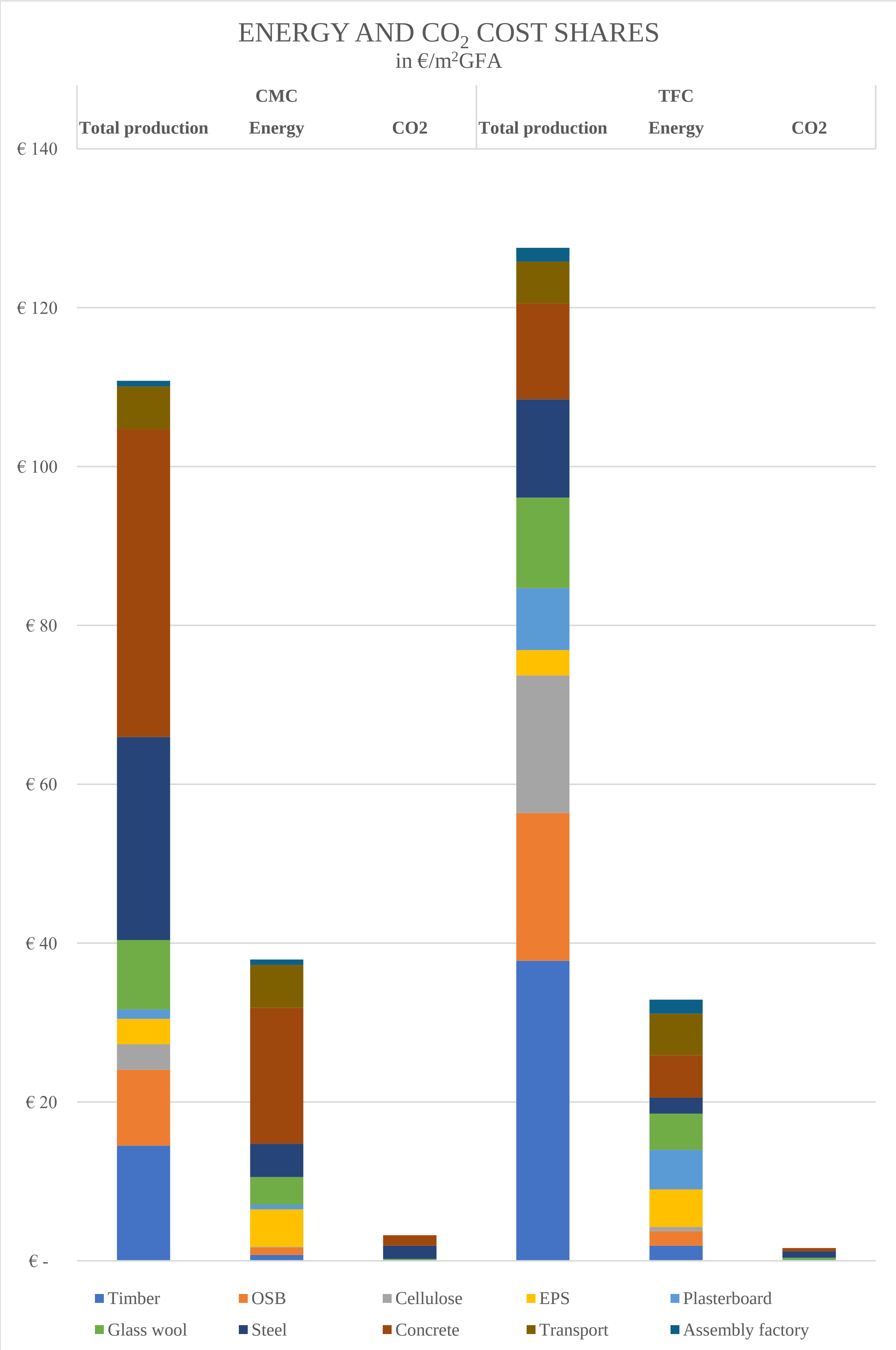


Figure 18 Energy and CO_2 costs per construction material, as part of total material costs for CMC and TFC

5.3 Sub-Question 3: Impact Analysis

Figure 19 below displays the normal distribution of materials costs for the CMC as calculated 10,000 times by @Risk software with different input quantities for energy costs as picked at random within the boundaries of the standard deviation (Section 4.6). 95% of the values for materials costs are located within a lower- and upper boundary of respectively 100.03 €/m^{2}GFA and 121.7 €/m^{2}GFA, with 110.79 €/m^{2}GFA as the calculated current production price of the CMC, including energy and CO_2 costs. The figure discloses that a combination of the lowest fuel prices could potentially cause the production price to drop to 90 €/m^{2}GFA for the CMC and vice versa to 130 €/m^{2}GFA for 'high' fuel prices. In other words, the defined fluctuations in fuel prices (Appendix IX) can cause an 17.3% increase or decrease in total materials costs for the CMC.

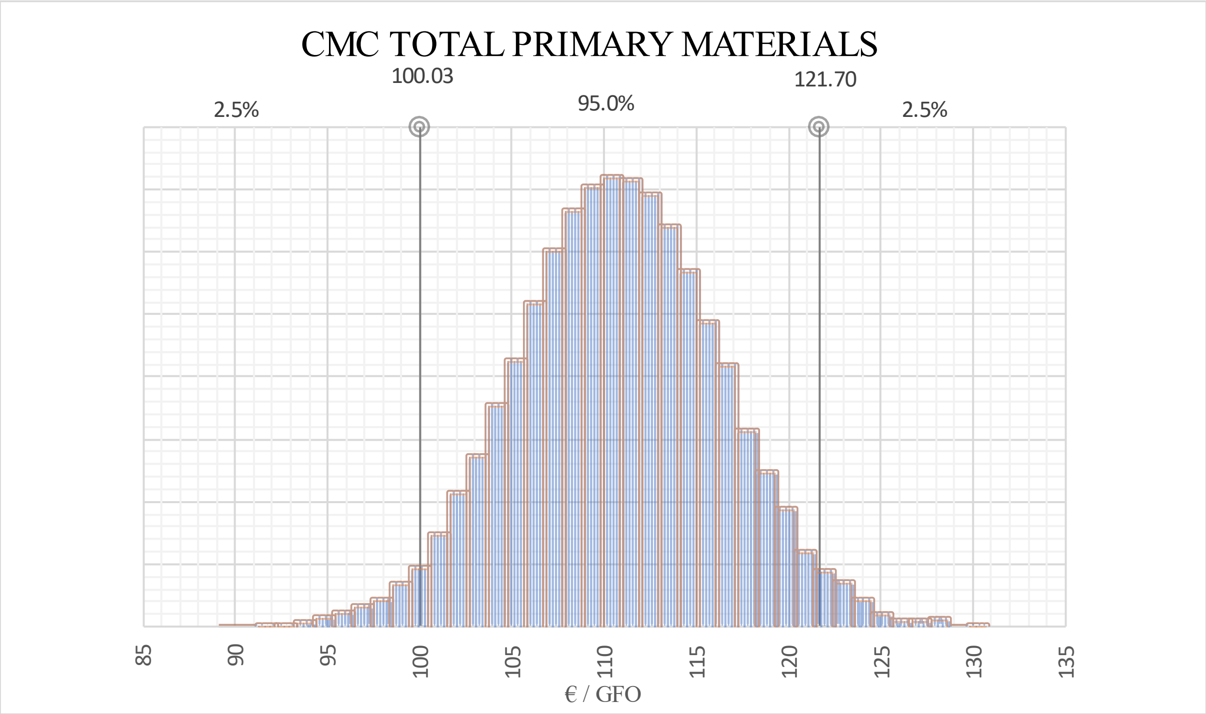


Figure 19 Distribution of TFC production costs based on 10,000 calculations in @Risk with random fluctuating energy and CO_2 prices defined in Appendix VIII

Then, figure 20 below displays the impact per input parameter on the production costs of the CMC. The figure discloses that the NG price has the most significant impact on materials costs, causing material prices to deviate between 101.62 €/m^{2}GFA and 119.89 €/m^{2}GFA when the NG price fluctuates between 0.04 €/kWh and 0.16 €/kWh (with 0.1 €/kWh as standard value; see Appendix IX). This constitutes a maximum impact of 8% from NG. Furthermore, the diesel price has the second largest impact on CMC materials price. Then, there is no significant impact from fluctuating electricity prices on the production costs of a CMC. Also, the CO_2 price does not have a significant impact on the production costs of a CMC. Lastly, the impact of price fluctuations of biomass is lowest.

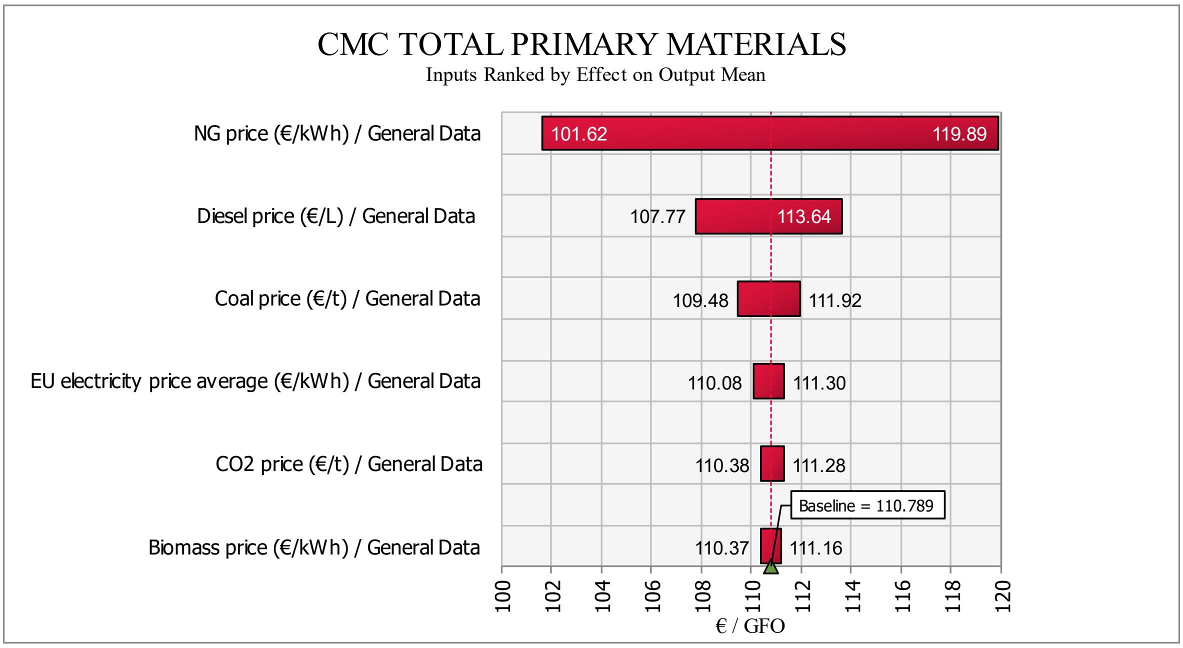


Figure 20 Sensitivity of CMC production costs to fluctuations of different energy and CO_2 prices

Figure 21 below then displays the normal distribution of materials costs for the TFC. 95% of the values for the calculated materials costs (See methods section) are located within a lower- and upper boundary of respectively 116.00 €/m^2GFA and 139.13 €/m^2GFA, with 127.54 €/m^2GFA as the calculated current production price of the TFC, including energy and CO_2 costs. This means that a combination of the lowest fuel prices could potentially cause the production price to drop to 105 €/m^2GFA for the TFC and vice versa to 150 €/m^2GFA for the highest fuel prices. In other words, the defined fluctuations in fuel prices (Appendix IX) can cause a 17.6% increase or decrease in total materials costs for the CMC.

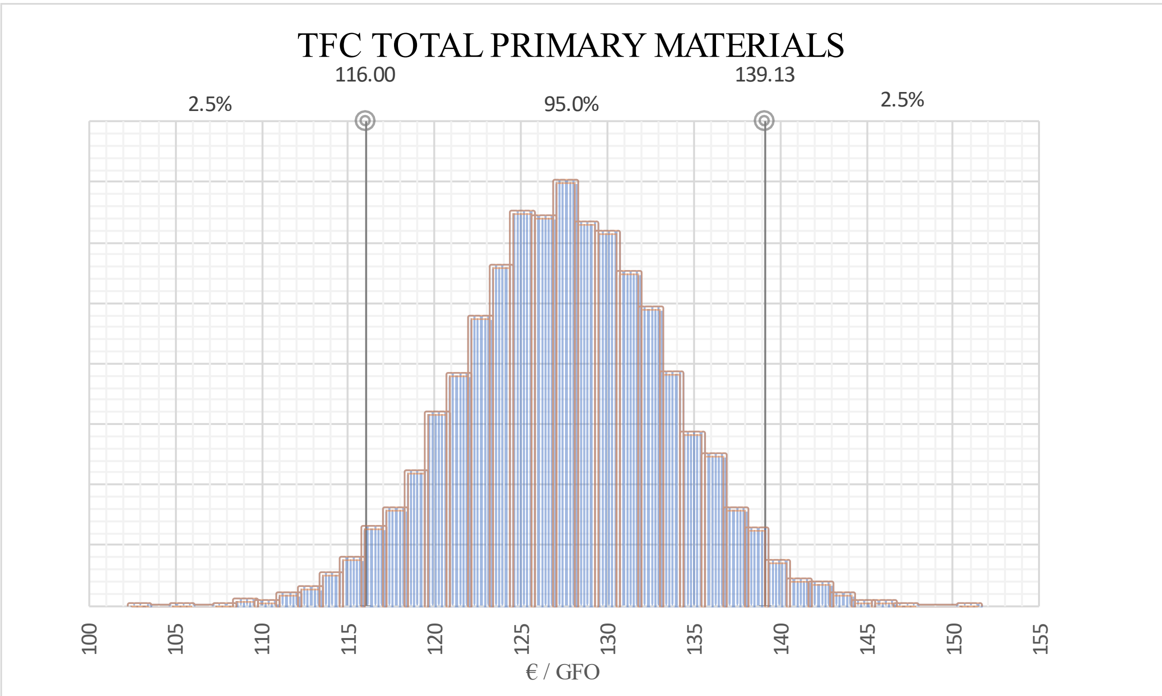


Figure 21 Distribution of TFC production costs based on 10,000 calculations in @Risk with random fluctuating energy and CO_2 prices defined in Appendix VIII

Lastly, figure 22 below displays the impact of the input parameter on the production costs of the TFC. The figure discloses that the NG price has the most significant impact on materials costs, causing material prices to deviate between 117.44 €/m^{2}GFA and 137.68 €/m^{2}GFA when the NG price fluctuates between 0.04 €/kWh and 0.16 €/kWh (Appendix IX). This constitutes a maximum impact of 8% from NG. The second largest impact on the TFC production price is from diesel. Then, the price of the remaining energy carriers and CO_2 barely have a significant impact with the lowest impact from biomass. The coal price has a minor impact on the price of the TFC.

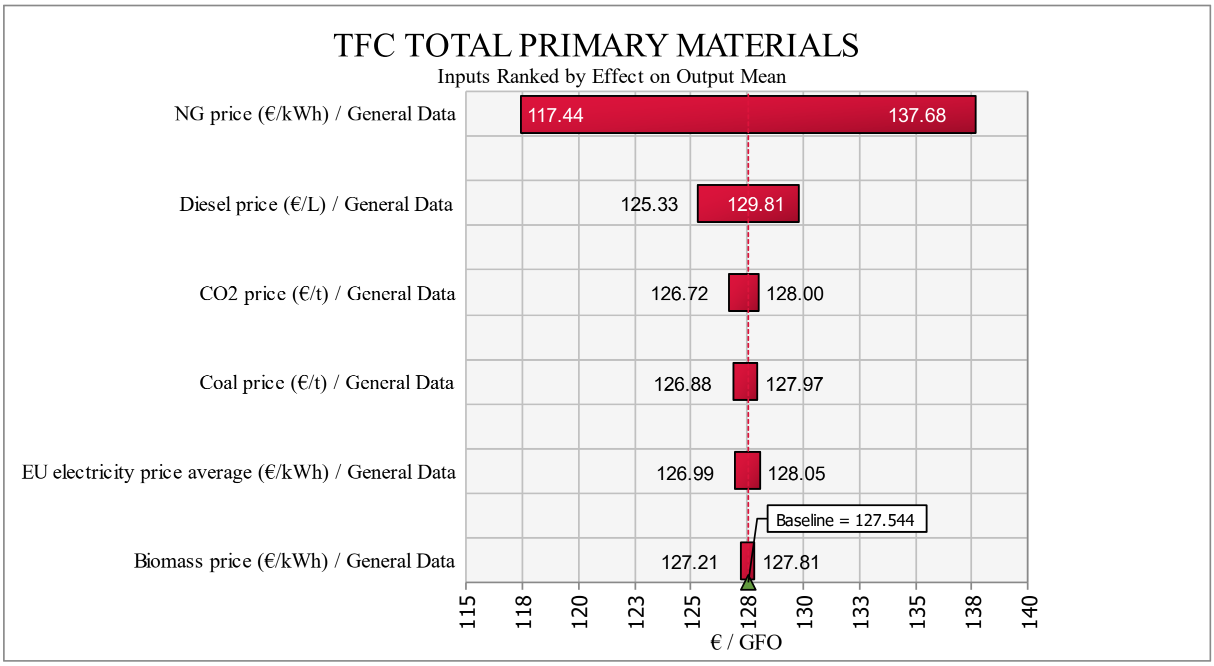


Figure 22 Sensitivity of CMC production costs to fluctuations of different energy and CO2 prices

5.3.1 Tipping Point

The energy carriers that are used (See Section 4.6.2) to explore the tipping point are coal- and electricity price (increasing prices for the remaining energy carriers would only increase the cost-gap between the CMC and TFC). The tipping point at which costs for producing the CMC and TFC are equal occurs when coal- and electricity prices are increased to respectively 1000 €/t coal and 0.95 €/kWh. These prices entail an increase in coal- and electricity prices - compared to the base energy prices as displayed in Table 12 in Appendix VII - of respectively 754% and 764%. The impact of these price increases on the CMC and TFC production costs are displayed in Figure 23 on the next page:

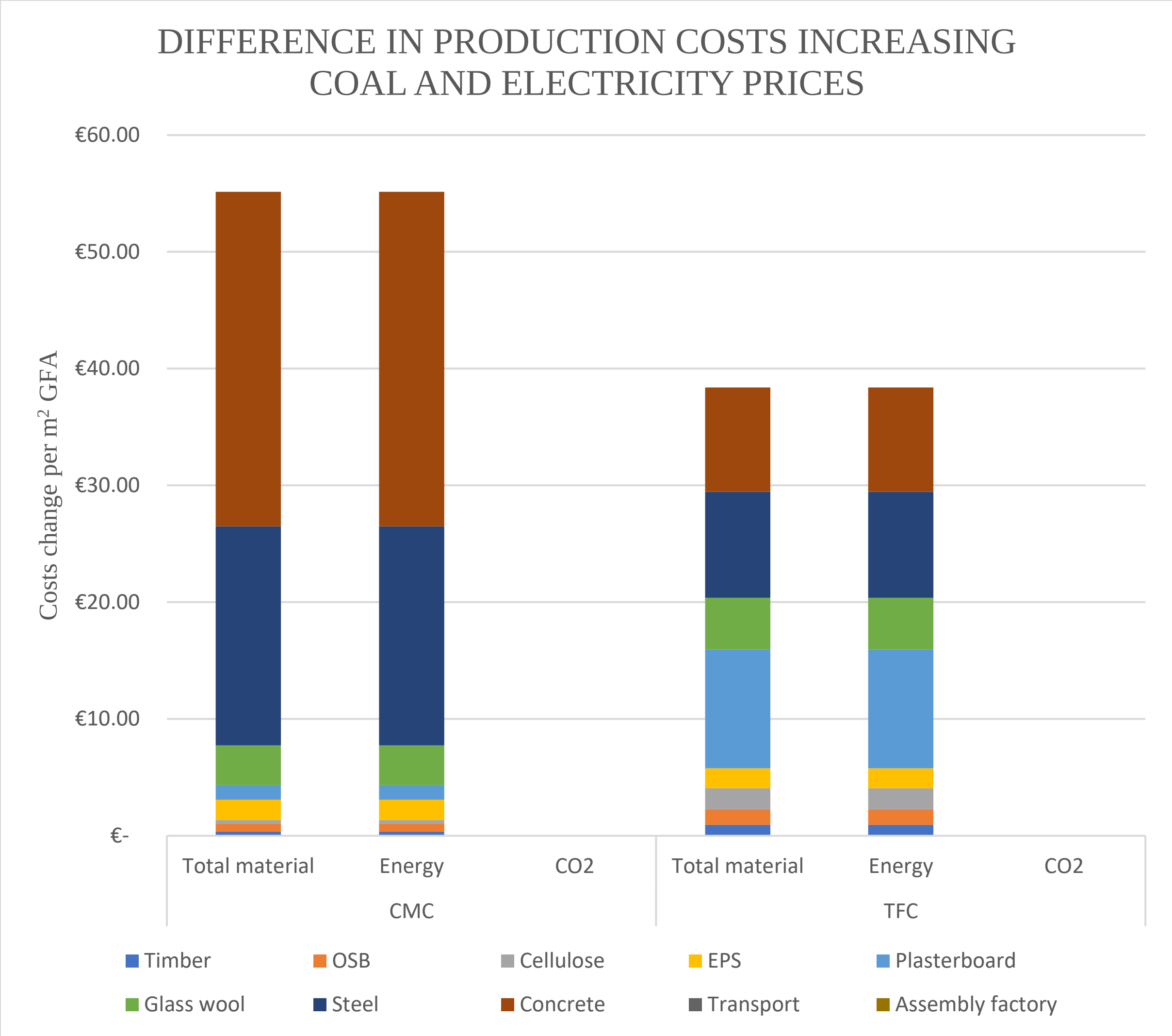


Figure 23 Changes in production costs after price increases of coal and electricity, leading to the tipping point at which the CMC and TFC are both 165.94 €/m²GFA

Figure 23 displays that the most significant cost increases after increasing the price of coal and electricity occur in steel- and concrete production for the CMC. Furthermore, in the TFC, this most significant cost increase occurs in the production of plasterboard. Nevertheless, the net cost increase is larger in the CMC than in the TFC. Moreover, the cost-increase displayed in the figure is the exact cost increase that causes the tipping point at which the CMC and TFC are equal in price at 165.94 €/m^2 GFA, which constitute a total production cost increase for the CMC and TFC of respectively 49.8% and 30.1%.

5.4 Excel Model

An additional result of this study was that the Excel model that was made could be used by BGDD employees as a tool to calculate the impact of fluctuating energy prices on different types of constructions. This tool calculates differences in materials costs for a building based on changes in energy prices. For this study, primary materials for the CMC and TFC were inserted in the model, but the impact of fluctuating energy prices on materials costs can also be modelled for other buildings. The tool can be provided by requesting it via harmjaapdejong@hotmail.nl.

6. Discussion

In this section, an extensive interpretation of the results is provided. Firstly the RQs are answered based on the results presented in the previous section. Then, a sensitivity analysis is presented to determine the reliability of the results generated by the Excel model. Furthermore, limitations to this study are discussed. Next, a comparison with literature and suggestions for future research are raised. Lastly, policy recommendations for both construction companies and the Dutch government are formulated in the final part of this section.

6.1 Answer to RQs

Regarding SQ1 '*What is the difference in energy demand and CO_2 emissions for the production of a CMC and TFC?*', Figure 14 discloses that the CMC demands 22.9% more energy than the TFC and Figure 17 disclosed that the CMC emits 73.7% more CO_2 than the TFC. Important to note is that the difference in energy demand is smaller than the difference in CO_2 emissions as 34.4% of emissions for the TFC are biomass-sourced and thus counted as CO_2 neutral (while biomass does count as energy demand). Moreover, significant energy demand in the TFC is from plasterboard, mineral wool and the concrete ground floor. Nevertheless, energy demand from the reinforced concrete casco of the CMC still exceeds energy demand of the TFC.

Regarding SQ2 '*What is the difference in energy and CO_2 costs as part of total materials production costs between a CMC and TFC?*', Figure 18 discloses that costs of the CMC compared to the TFC for total materials, energy and CO_2 are respectively -15.1%, 15.4% and 101.3%. These results disclose that total materials production cost of the CMC is cheaper, despite entailing higher energy costs and a significant difference in CO_2 costs. The absolute difference in CO_2 costs is however marginal. Furthermore, energy costs for the TFC are relatively low due to lower energy demand as disclosed by SQ1 and a high share (19%) of relatively cheap biomass energy, despite the high share of relatively expensive NG demand (28%) intensively required for mineral wool, EPS and plasterboard production. Lastly, CMC energy costs are relatively high due to 1) the vast coal demand for concrete and steel production, despite the relatively low price per J of coal (Prices are displayed in Table 13) and 2) a significant electricity demand for steel production in EAF (Appendix VI), which is an expensive energy carrier and 3) significant diesel use costs for concrete production; 9% of energy use with energy costs per J > 10x that of coal (See data in Tables 6 and 13).

Regarding SQ3 *'How are production costs of a CMC and TFC impacted by fluctuating energy and CO_2 prices and when is a price equilibrium between both variants reached?'*, Figure 19 and Figure 21 disclose that the impact of fluctuating energy and CO_2 prices is nearly equal between the CMC and TFC (17,3% and 17,6% respectively), primarily driven by changes in NG and diesel price. Despite similar sensitivities to overall fluctuations in energy and CO_2 prices, Figure 20 and Figure 22 disclose that the TFC is more sensitive to price changes in CO_2 and biomass compared to the CMC, while the CMC is relatively more sensitive to price changes in coal and electricity. Furthermore, the impact of price changes of NG is equal between the CMC and TFC (constituting a maximum of 8%). Figure 23 therefore discloses that a tipping point entailing equal production costs of the CMC and TFC is reached if coal and electricity prices would rise more than 7x, which is not deemed plausible.

The answer to the main RQ '*How do energy and CO_2 prices determine the competitiveness between CMC and TFC production in the Netherlands?*' is therefore that both energy and CO_2 prices do not provide an impact on the competitiveness between a TFC and CMC of sufficient significance to cause a plausible tipping point at which the production costs between the CMC and TFC become equal. This is because increased plasterboard (for fire safety) and mineral wool (for insulation) use in the TFC (compared to the CMC) demands significant quantities of expensive NG for materials production.

6.2 Reliability of Results

Because the results of the Excel model might be subject to deviations in parameter inputs, it is useful to test the reliability of the results through a sensitivity analysis. Therefore, the Excel Model has been tested by altering input parameter that have a mathematic relation with the model outputs.

The production costs in €/m^{2}GFA could be subject to deviations in embodied energy values found- and converted from literature (See the found ranges in Table 5). Furthermore, the used value for transport intensity is based on transport by a large truck with trailer as this mode of transport is common for transport of construction materials to the factory (de Vries et al., 2022). In reality however, different modes of transport might occur for different occasions entailing different transport configurations. To account for this and the significant impact of transport energy demand (See Figure 18), energy intensity for the mode of transport is also chosen as an input parameter for the sensitivity analysis. What is more, parameters that are excluded from the sensitivity analysis are conversion efficiencies (Table 12), emission factors (Table 13) and densities (Table 14) because these values are relatively stable. Lastly, to test the impact of using material variations for prominent materials (next section), density variations of concrete, EPS, plasterboard and mineral wool are included.

Figure 24 displays sensitivity of production costs (representing the results of the model as displayed in Figure 18) to a 40% deviation of the before mentioned input parameters. This figure discloses that both construction approaches are most sensitive to deviations in values for embodied energy of concrete (ignoring the NG line). This effect is strong especially for the CMC with its voluminous concrete casco. When extrapolating the high range for embodied energy for concrete in Table 5, the 52% (+0.969) increase for embodied energy in concrete leads to respectively a 6.6% and 2.2% increase in production costs for the CMC and TFC, as disclosed by the results of the sensitivity analysis. If this high range value had been used as base-value for the model, the upper ranging values in the impact analysis results in Section 5.3 had been raised to 138.0 €/m^{2}GFA and 153.3 €/m^{2}GFA for the CMC and TFC respectively (compared current values at 130 and 150 respectively). For the CMC this means that the impact of price fluctuations on production costs can potentially cause a cost increase of 24.6% instead of 17.6%. Nevertheless, it is not likely that a 24.6% price increase occurs as this entails the use of the highest found value for embodied energy for concrete combined with the low probability (<5%) that all energy prices develop to the highest value as formulated in Appendix VIII.

What is more, following this reasoning for the impact of the embodied energy value of timber on production costs of the TFC, it can be concluded that the high and unlikely upper limit of a 231% increase (+4.01; Table 5) would cause a relatively limited TFC production cost increase of 3.5%. This is due to the limited volume (<10m^3) of timber that is required even for a TFC frame (See Table 3).

Furthermore, the effect of alternative transport modes for delivery of construction materials from suppliers to the construction factory can have a significant impact on production costs of a dwelling. Figure 24 discloses that energy intensity for transport is has the second largest impact on results calculated by the model; a 40% deviation in energy intensity for transport causes respectively a 2.1% and 1.8% deviation in production costs of the CMC and TFC. This impact is lower for the TFC as its total used materials are lighter (less concrete and steel, more timber) than the CMC, despite longer transport distances for timber (See Table 15).

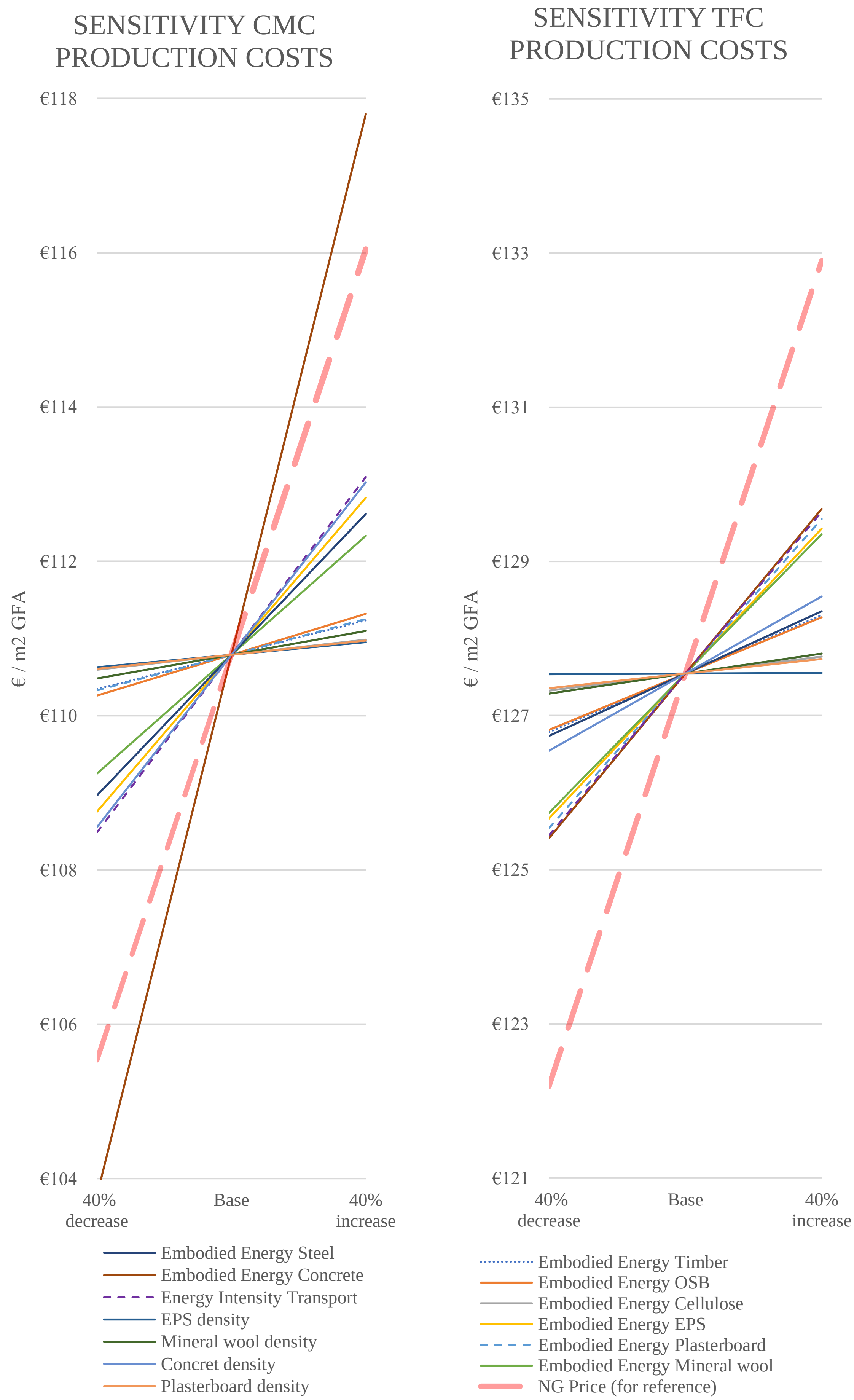


Figure 24 Sensitivity of the calculation results to changes in parameter inputs, including embodied energy- and transport energy intensity values; the red striped line is the sensitivity of the production costs to changing NG prices for reference

6.3 Limitations to This Study

In this section, different limitations to the study are discussed regarding the chosen case study dwelling, the energy and CO_2 analysis and decisions made regarding energy carriers and CO_2 emissions.

6.3.1 Materials Choices

The dwelling described in 4.2 Case Study Dwelling provides several limitations to the study as its material choices are limited to the CMC and TFC version selected in consultation with BGDD (Table 3). There are however other configurations available for the case study dwelling that could provide different results. An example of such configuration would be to include bio-based insulation options such as cattail or hemp insulation to replace mineral wool as insulation material, causing decreased NG demand especially for TFC production (See Figure 18) and hence reduce the impact of fluctuating NG prices. Nevertheless, mineral wool is currently one of the most used insulation materials in the Netherlands due to its beneficial price, (sound) insulation and fire retarding properties (Viveen, 2022).

What is more, further options for the CMC and TFC configuration are to use different variations of the construction materials constituting different densities and properties. This is however only impactful for concrete, as the impact of variations for cellulose, OSB, timber and steel would be limited (See corresponding sensitivity to embodied energy in Figure 24: where embodied energy is based on density of materials). Therefore, lighter concrete could potentially reduce the impact of fluctuating energy prices on production costs of especially the CMC. Examples of available lightweight concrete are 1) Lightweight Aggregate Concrete (LWAC) with 12% reduced density for LC50/55 concrete (similar to C50 concrete used for the dwellings in this study; see Table 14) when using lightweight sand compared to conventional sand and 2) lightweight concrete enriched with shale, clay, ash perlite, volcanic pumice or slate, providing up to 23% density reduction compared to conventional concrete (SpecifyConcrete, 2019; Thienel et al., 2020). Using the former lightweight concrete to replace the currently used concrete might however not provide significantly different results as most energy-use in concrete is from cement production (See Appendix V). Furthermore, using the latter lightweight concrete to replace concrete used for this study can potentially significantly impact the results as the listed materials for enrichment can to a certain extent replace cement (de Brito & Kurda, 2021; SpecifyConcrete, 2019) and thus reduce embodied energy value for such lightweight concrete.

6.2.2 Energy and CO_2 analysis

The energy and CO_2 analysis raises several further limitations to the conducted study with regards to embodied energy, energy carriers and CO_2 emissions.

Embodied Energy

Embodied energy as described in Table 5 was limited to available literature regarding the production process of each construction material (Appendix 5). By using different literature sources for different primary construction materials while aiming to calculate homogenous values (based on the same starting points and calculation rules) for embodied energy, several limitations emerged: 1) data from literature was mostly subject to energy conversion calculations before embodied energy for a material could be calculated (due to differences in energy stages that were mentioned – See 3.3.1 Primary to Useful Energy), which entailed several assumptions that are discussed more extensively later in this section and 2) literature sources provide different data values that form a range of potential embodied energy values for each material (Table 5).

An alternative approach to establishing Table 5 would be to directly use the Ecoinvent database (See Appendix VI). However, Ecoinvent does not contain data for each specific EU county in which suppliers of BGDD operate, which makes extracting data from literature sources that do generally provide information regarding desired EU countries (E.g. Swedish Lumber) the preferred approach. Nevertheless, data from Ecoinvent is useful to supplement lacking data from literature when calculating embodied energy, which is why the Ecoinvent database is still used when establishing Table 5. Nevertheless, the best approach would be to directly gather all energy demand data from suppliers. This was however not feasible within the scope of this study as contact with suppliers disclosed that most suppliers do not have energy demand data available (even internally).

Then, the second limitation resulting in ranges for embodied energy is linked to context specific deviations (e.g. geography or material variation) between production approaches of construction materials. Therefore, the best value in each range is chosen based on date of publication and the extent to which the context in literature matches the material supply chain of a Dutch construction company.

Energy Mix and Energy Carriers

Several decisions regarding energy carriers, the used energy mix and CO_2 emissions calculations have been made.

Firstly, the energy mix (Table 6) is derived from energy demand data from the Ecoinvent database. As discussed before, this database is not the preferred source of data for construction materials used by a typical Dutch construction company. However, for determining the energy mix of construction materials, within the scope of this study, the Ecoinvent database is the most complete and detailed source available. Alternatively, the energy mix for the production of different materials could be calculated by 1) literature data or 2) primary data from the industry. These both approaches are however not compatible with this study. Firstly, finding a complete set of up to date and relevant literature data for embodied energy regarding each material proved challenging and therefore finding enough data on the specific energy carrier for the production of each material is deemed unfeasible for the scope of this study. Nevertheless, several sources disclosed information regarding the energy mix for materials production: (Ananias et al., 2012; Donahue et al., 2021; IEA, 2021c; Institut Bauen und Umwelt, 2020; Krijgsman & Marsidi, 2019; Madlool et al., 2011; Martelaro, 2016; Rubenstein, 2012; Sathre & Gustavsson, 2007; van Oostenrijk, 2022) These sources have been used to confirm the accuracy of the calculated energy mixes in Table 6. Secondly, gathering energy mix data directly from each materials supplier exceeds the scope of this study due to the same reasons mentioned in the previous section.

Additionally, to establish the energy mix for each construction material (Table 6), oil is assumed to be solely converted to diesel, neglecting oil used for e.g. petrol or lubricants. This assumption is made to simplify the energy mix used in this study (note that petrol is missing from the mix), because the scope of the study does not allow for tracking each oil-based product in the production process of each construction material. Therefore, assuming oil to be only used for conversion and burning of diesel yields significant time-saving, without significantly sacrificing accuracy of the results (as oil is a minor energy carrier in the energy mix of materials production; see Table 6 and Table 10). Furthermore, the assumption that oil is solely converted to diesel entails that all production processes that use oil, make use of diesel powered machines. In many cases this assumption is valid, as heavy industry relies significantly on heavy diesel powered machinery such as tractors, trucks and generators.

What is more, the energy content for different energy carriers (Table 12) are based on typical values found in literature. These values can however deviate (slightly) in reality. E.g. biomass is currently used in this study as an energy carrier with the same conversion efficiency as the thermal efficiency from coal burned in a kiln (50%; Kline Consulting, 2022) and with a LHV based on oven dried timber (18.7 MJ/kg; Blok & Nieuwlaar, 2020). In reality however, efficiencies and heating values for biomass burning can deviate depending on biomass type, moisture content, pre-treatment and conversion medium. The Ontario Ministry of Agriculture (2011) and Blok & Nieuwlaar (2020) formulate a LHV for biomass between 14 – 19 MJ/kg. This study assumed an energy content based on dry wood residues, but the type of biomass used for energy demand of materials can vary per production process. Nevertheless, it is beyond the scope of this study to track the exact energy content values for each energy carrier in each material production process as deviations in energy content per energy carrier is limited (biomass is the most extreme case). Moreover, the impact of altering the energy content of biomass in the model on production costs of CMC and TFC is limited due to the relatively low price of biomass (Table 13), limited use of biomass as fuel (Table 6) and limited use of material volume of materials with high use of biomass as fuel (Timber and OSB; Table 5).

Lastly, the average electricity mix of the EU 27 (Figure 43) is used to determine 1) the energy mix of materials (Table 6), 2) the EF of electricity use and 3) the industrial electricity price. The EU 27 electricity mix contains e.g. a significant share of polluting Polish and German coal power and clean Swedish and French hydro and nuclear power (IHA, 2021; Statista, 2021; World Nuclear Association, 2022). Hence, the electricity mix per country can vary significantly, which has an impact on its corresponding EF and price. The point in calculating the correct emissions and price from electricity demand per material is not to determine the exact electricity mix for a source country – which is certainly feasible - but rather to determine the respective country of origin for electricity demand. This is challenging as the Netherlands imported respectively 24%, 16% and most of the remaining part of its sawn softwood from Germany, Sweden and a mix of EU countries + Russia (Probos et al., 2020). A similar situation applies to the supply of the other construction materials to Dutch construction companies (even though certain materials can be sourced more reliably than timber; which has not been further explored as it does not fit the scope of this study). This means that a construction material might be sourced from different countries year-on-year, depending on availability and price. To account for this unreliability in determining a correct electricity mix, using the EU 27 electricity mix ensures a middle ground regarding emissions and price calculations for electricity demand.

6.4 Comparison with Literature and Future Research

This section provides a discussion after comparing the results of this study with findings and claims from Sathre (2007) and Staatsbosbeheer (2022) and van der Lugt & Harsta (2021). In the last part of this section, several recommendations for future research are provided.

6.4.1 Comparing Impact of Energy and CO_2 prices on Materials Costs

The results of this study partly contradict the findings of Sathre (2007) that concluded that the impact of rising energy and CO_2 prices is larger for concrete dwellings than for its timber counterpart. However, differences between the set-up of both studies frustrate a direct comparison of results (E.g. due to 1) incompatibility of geographic scope; Sweden and the Netherlands, 2) case-study building; apartments and ground-bound dwelling and 3) timeframe; 2007 and 2022). Nevertheless, certain elements of both studies can be compared to shed new light on the results of this study. Therefore, the Excel Model (See 5.4 Excel Model) is used to compare several parameters from the model with results from Sathre (2007). Figure 25 displays the share of energy and CO_2 costs for materials production (entailing materials that are used in both studies) as part of the total costs of the materials under different taxation schemes. In this figure, *Sathre Zero Energy Tax* entails Swedish energy prices without any tax, *Sathre High Carbon Tax* entails a carbon tax of 379 €/tCO_2, *This Study No Carbon Tax* entails energy prices for EU industry with a CO_2 price under the EU ETS of 0 and *This Study High Carbon Tax* entails a CO_2 price under the EU ETS of 379 €/tCO_2.

The figure shows firstly that the share of energy and CO_2 for steel and lumber costs before and after the increased CO_2 prices are similar in both studies. This can partly be attributed to the similarly used energy demand values in Sathre (2007) and this study of respectively 98.4 GJ/m^3 versus 108.8 GJ/m^3 for steel and 1.504 GJ/m^3 and 1.734 GJ/m^3 for timber. Moreover, a similar % of coal use in the production of steel of respectively 50.4% and 64% (See Table 6) is used as both studies assumed 50% ore-based and 50% scrap metal-based steel production. Furthermore, the values for concrete without carbon tax differ significantly between both studies. This could be attributed to a significantly increased diesel and coal price between 2007 and now (EEA, 2017), as diesel and coal constitutes a significant cost-share for concrete production (diesel because it is currently more than 10x as expensive as coal and it constitutes 9% of concrete production; see Tables 6 and 13). The figure also discloses that the increased CO_2 price under the EU ETS with the benchmark-mechanism (See 3.2 EU Emissions Trading System) is significantly less effective for concrete production than the carbon tax on all emissions proposed by Sathre (2007). The relative lack of impact from the carbon price under the EU ETS is in line with the findings of this study that rising CO_2 costs have limited impact on production costs of the CMC and TFC as displayed in Figure 20 and Figure 22. However, the EU ETS does have a significant impact on the price of steel (see Figure below), which can be attributed to the more stringent benchmark restrictions for steel production (See Table 7). Lastly, costs of energy and CO_2 for plasterboard production are significantly higher in this study than in Sathre (2007), both with and without a high carbon price. The reason for this is uncertain as the energy demand value for plasterboard production in this study is comparable to Sathre (2007) (3.8 GJ/m^3 and 3.4 GJ/m^3). The difference could therefore be attributed to differences in total material prices, which are undisclosed in Sathre (2007).

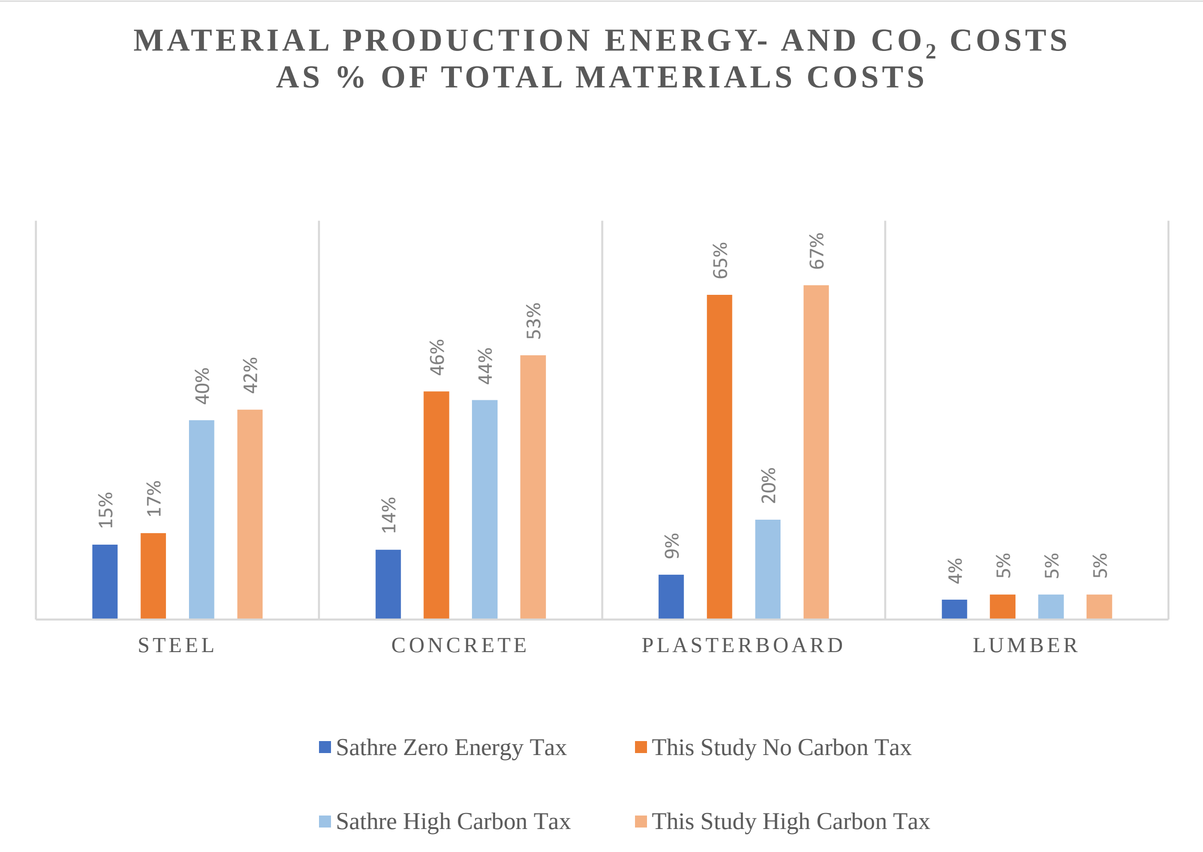


Figure 25 The costs of energy and CO_2 as part of total material costs compared between Sathre (2007) and this study; Sathre Zero Energy Tax entails Swedish energy prices without any tax, Sathre High Carbon Tax entails a carbon tax of 379 €/tCO_2, This Study No Carbon Tax entails energy prices for EU industry with a CO_2 price under the EU ETS of 0 and This Study High Carbon Tax entails a CO_2 price under the EU ETS of 379 €/tCO_2

6.4.2 Built Environment Climate Targets

Besides seeking to identify the economic feasibility of developing the TFC compared to the CMC, the results of this study shed further light on environmental benefits of building TFC instead of CMC. Based on the calculation example of Staatsbosbeheer (2022) and van der Lugt & Harsta, (2021) (Section 1.1), the climate targets in the built environment for 2030 could almost be met within 1 year solely by carbon sequestration by constructing 100,000 timber-based dwellings (the Ministerie van Binnenlandse Zaken en Koningkrijksrelaties (2022) aims to construct 100,000 dwellings anually and the climate target for the built environment entails a CO_2 of 3.4 Mt in 2030). Moreover, the target could already be exceeded in 1 year when accounting for the concrete and steel that would be omitted when constructing with timber. Nevertheless, note that this remains an illustrative calculation example as most emissions from producing concrete and steel occur beyond Dutch borders and CO_2 sequestration in timber does not account towards the emissions reduction goal.

Furthermore, the results of this study raise nuance to this calculation example as Table 3 displays that a typical Dutch timber dwelling (the TFC) requires 9.4 m^3 of timber and 4 m^3 of OSB, in contrast to the 55 m^3 of timber used for the timber-based dwelling raised by Staatsbosbeheer (2022) and van der Lugt & Harsta (2021). This is because their timber dwelling entails a Cross Laminated Timber (CLT) casco (comparable to the functionality of the concrete casco in the CMC). A CLT casco for a typical Dutch ground-bound dwelling (e.g. the dwelling described for this study) is structurally however overdone (and rather used for multi-storey constructions) and therefore, using more of the expensive timber (See prices in Table 14) than necessary, compromises economic viability of the dwelling (de Vries et al., 2022; Papa, 2022). Hence, to reduce costs, the TFC uses only 13.4 m^3 of timber (just enough for structural integrity) and the remaining of the casco is filled with insulation.

When comparing environmental performance of the TFC to a CLT-based dwelling, building 100,000 TFC could sequester 0.67 Mt CO_2 (treating OSB as mass-timber). This is only 24% of the value calculated from numbers raised by Staatsbosbeheer (2022) and van der Lugt & Harsta, (2021) for a CLT variant. Furthermore, Figure 17 displays that production of a TFC emits 13.3t CO_2, mainly from the reinforced concrete floor with EPS insulation and then from mineral wool insulation and plasterboard use. This means that the TFC is not a carbon sink as it sequesters less CO_2 (6.7t per dwelling) than that it requires for its production (13.3t). And even though emissions for the production of a CLT-based dwelling were not accounted for in the calculation example, the emissions to produce this casco would only be 1.35t CO_2 (if extrapolating the timber emissions in Figure 17 to the 55 m^3 timber CLT casco). This implies that the CLT-based dwelling is indeed a carbon sink, despite excluding remaining construction materials from this carbon footprint calculation.

When combining the limited sequestration capacity of the TFC with the CO_2 savings it generates compared to the CMC, another estimation can be made for the contribution that the adoption of timber-based dwellings for the construction sector can have on its climate targets. Figure 17 discloses that building a TFC instead of CMC would save 9.8t of CO_2 emissions, amounting to an annual emissions reduction of 0.98 Mt when building 100,000 dwellings annually. Therefore, the TFC could provide an annual CO_2 reduction of 2.33 Mt when combining the sequestration effect with substituting the CMC variant. This would not cover the complete target of 3.4 Mt CO_2 reduction in 2030 within 1 year (while building 100,000 CLT-based dwellings would). However, building dominantly TFC dwellings until 2030 (I.e. for the coming 8 years) does ensure that a CO_2 reduction equal to the climate target for the built environment is met, even without accounting for carbon sequestration.

Nevertheless, incentives for TFC development have to exceed the advantage that the TFC has over the CMC in the light of rising energy and CO_2 costs, as this study disclosed that a cost-equilibrium between the CMC and TFC is only reached if coal and electricity prices rise beyond a factor 7.5 compared to current prices, which is unlikely to occur. Therefore, the following sections describe recommendations for future research and policy development.

6.3.3 Recommendations for Future Research

This section provides recommendations for future research based on new insights and limitations emerging from this study.

Firstly, Section 6.2.1 raised several limitations regarding configurations used for the case-study dwelling that was used in this study. In future research it would be important to expand the case-study dwelling towards multiple variations of the case-study dwelling to research the extent to which the findings of this study would apply to these different variations. Eg. Beijers (2021) used a similar case-study dwelling that entailed the use of MDF instead of OSB. He found however that MDF use caused significantly higher MPG score (0.1693 €/m^2 GFA) compared to the same case-study dwelling equipped with OSB (0.0428 €/m^2 GFA) to replace MDF. Similar differences could occur regarding the impact of energy prices on production costs of the CMC and TFC when variations of the case-study dwellings would be researched. Thus, suggested alternative dwellings to include in such research (as elaborated on in Section 6.2.1) entail 1) a TFC with chipboard or MDF as a replacement to OSB due to significant differences in environmental impact found by Beijers (2021), 2) a TFC with reduced use of plasterboard due to the high energy costs in plasterboard, 3) the replacement of mineral wool with a bio-based alternative such as cellulose, hemp, wood-fibre or cattail due to the high NG demand for the production of mineral wool and 4) alternatives to concrete such as lightweight concretes or concretes with reduced energy demand (e.g. with ash or other mineral powders to replace cement (de Brito & Kurda, 2021; Tikkanen et al., 2015)) due to the significant impact of concrete density and embodied energy of concrete on the results of this study (See Figure 24). The Excel model generated for this study (Section 5.4) could then be built upon to include these options, ensuring significant timesaving.

Secondly, Figure 24 disclosed the sensitivity of the production costs of the CMC and TFC to embodied energy values, while Section 6.2.2 emphasised the limitations of this study in determining accurate embodied energy values. Therefore, it is advised that future research accounts for this by finding a universal method for calculating embodied energy. Furthermore, to increase accuracy of embodied energy values for materials in the Dutch construction sector, future research should incorporate tighter cooperation with materials suppliers to gain primary data regarding production processes of materials. Moreover, further transparency regarding production chains of construction materials used in the Netherland provides better accuracy regarding transport distances from suppliers to factories, improving reliability of energy demand values from transport. Future research aiming to establish a universal method for calculating embodied energy could build on and complement currently established concepts such as the materials passport or NMD which provide data regarding circularity and environmental impact of construction materials (Madaster, 2022; NMD, 2022a).

Thirdly, as discussed in 6.2.2 and building on the previous point, it is suggested to expand the used research format of this study beyond using the EU 27 average electricity mix. This provides a deeper understanding of the impact of changing electricity prices on construction materials, especially for materials with a high electricity demand such as cellulose, plasterboard and steel (See Figure 6). Clarity regarding exact supply chains of materials to the Netherlands provides a basis for determining the correct electricity mix for each material, which impacts the values of calculated energy costs and CO_2 emissions for producing a material. Also, the EU electricity mix is expected to change drastically in the coming decades due to the energy transition (McKinsey, 2010). Hence, this should be accounted for when future research builds on this study.

6.4 Policy Recommendations

The benefit of TFC development regarding the climate targets for the built environment have been extensively disclosed and discussed in this study. Moreover, van der Lugt & Harsta (2021) have emphasized the benefit that occupants experience from living in timber dwellings (be that CLT constructions). Nevertheless, reluctancy in wide-scale adoption of timber dwellings still exists due to obstacles 1) in the perception of durability and fire safety and 2) regarding the price of timber dwellings (as discussed in Section 1.1). The latter justly so, even under price fluctuations of energy and CO_2 as the results of this study have disclosed. Nevertheless, there are several policy incentives that can spark the further adoption of industrial TFC dwellings. These policy incentives can come both from the government as well as from construction companies.

6.4.1 Government

As disclosed in this study, the financial benefit of the TFC compared to the CMC under rising energy and CO_2 prices (with the dwelling configurations as described in 4.2 Case Study Dwelling), is not enough to provide a fundamental reason for the market to adopt TFC on a large scale. Nevertheless, the government can incentivize the adoption of timber constructions. This can firstly be done by improving the MPG score system (See 1.1). The MPG system does not necessarily require more stringent score requirements, but 1) monitoring of LCA calculations for the NMD should be improved to ensure realistic EoL scores for materials, 2.1) calculation rules should be adjusted such that carbon sequestration for timber products is accounted for, 2.2) the disproportionate effect of HTP on scores of biobased products should be re-evaluated and 2.3) the lifetime of timber products should be calculated more accurately.

Furthermore, mandates for timber constructions could be established. An important example of such mandate is the covenant initiated by the metropolitan area of Amsterdam, stating that 20% of newly built constructions should be timber-based (*Green Deal Houtbouw Duurzaam uit de crisis*, 2021). However, special care should be taken when establishing guidelines for such mandates as the definition of 'timber-based' can be a significant source of debate. E.g. the covenant of the metropolitan area of Amsterdam defines a timber-based ground-bound dwelling as a dwelling where 80% (volume basis) of the supporting structure is bio-based. For the TFC used in this study, this percentage is not feasible due to the reinforced concrete floor structure (See Table 3). It seems thus that this covenant only allows a ground-bound mass-timber CLT casco (as proposed by Staatsbosbeheer (2022) and van der Lugt & Harsta, (2021) and discussed in 6.3.2), which rather decreases viability and disallows thrift regarding timber application in the built environment. Nevertheless, a similar covenant could be considered nationwide, or potentially EU-wide. However, sustainable forest-capacity should be considered when increasing the scale of such covenant (See Appendix II – Ecological Controversy Regarding Timber Construction).

Then, a subsidy on biobased construction materials could be considered to cover the cost-gap between producing a CMC versus a TFC (currently 16.75 €/m^2GFA; See Figure 18). By consulting the Excel model (See 5.4 Excel Model), it was calculated that a subsidy of 30% on timber and OSB can close the cost gap between the CMC and TFC (Based on prices in Table 14) with: a CO_2 price under the EU ETS of €130 as expected to occur in 2030 (Pietzcker et al., 2021), a doubling of electricity prices to 0.3 €/kWh and accounting for the current coal price at 5-9-2022 of €450/t (Trading Economics, 2022).

Lastly, the government could consider stimulating awareness and conduct educational programmes regarding timber construction, as de Vries et al. (2022) and Tykkä et al. (2010) see a significant obstructor for adoption of timber constructions by construction companies in the lack of skills, experience and expertise of timber constructions. Also, reluctancy from real-estate developers regarding adoption of timber constructions due to worries about fire-safety and acoustics (Papa, 2022) could be eliminated if government-initiated awareness campaigns that rebuttal these worries were conducted effectively. Such awareness campaigns and educational programs should on the one hand ensure that the non-financial benefits of timber constructions are emphasized, and on the other hand they should be transparent about potential risks of large-scale timber sourcing (See Appendix II), ensuring that decision makers are aware of the type of timber they use for their projects; this should stimulate the use of certified timber (e.g. FSC or PEFC).

6.4.2 Construction Companies

Construction companies that are open to the adoption of timber constructions take part in an important puzzle of finding a configuration of a timber construction that can financially compete with its concrete and steel counterpart. Due to the rising energy prices combined with energy intensive use of steel and concrete, it was expected that this study would identify a realistic tipping point at which timber buildings could become a cheaper option. This tipping point does however not occur within realistic margins (See 5.3.1 Tipping Point) for the currently used case study dwelling (See 4.2 Case Study Dwelling). Nevertheless, this study disclosed several measures that construction companies could take to succeed in finding a cheaper timber alternative to their concrete and steel-based dwellings under increasing energy prices.

Firstly, transport distances from suppliers to construction factories should be minimized as the largest energy cost component for the TFC is diesel costs for transport (See Figure 18). Specifically for BGDD, when looking at transport distances in Table 15, it could be beneficial to find timber suppliers closer to Dokkum, ensuring reduced diesel costs for transport. E.g. Germany is a prominent supplier of timber to the Netherlands (Probos et al., 2020); it could therefore be beneficial to find a German timber supplier when adopting industrial TFC production.

Secondly, despite its important fire retarding properties, the use of plasterboard in a timber dwelling should be minimized, as plasterboard constitutes the second highest energy cost in a TFC (after transport, see Figure 18). This is because plasterboard contains a significant embodied energy value of more than twice the embodied energy of concrete (See Table 5). Moreover, plasterboard is significantly impacted by increasing energy and CO_2 prices as 1) nearly half of the energy demand for the production of plasterboard stems from (expensive) NG (See Table 6 and Appendix V) and 2) the plasterboard industry falls under the EU ETS due to its intensive calcination emissions (See Appendix V).

Thirdly, an alternative to mineral wool insulation should be found, as energy demand for producing mineral wool is significant (See Table 5) and expensive due to dominant use of NG in the production process (See Table 6 and Appendix V). Alternatives to mineral wool are readily available for slightly higher prices, entailing use of cellulose, hemp, wood fibre and cattail (Eco-home, 2022; Jochenschulz, 2020; Verboom, 2021). These prices might however be competitive if the NG price increases further.

The last measure that construction companies can take to reduce costs of a TFC under increasing energy prices would be to find an alternative to the reinforced concrete floor with EPS insulation. This last measure would has the most impact on energy and absolute costs of a TFC (See Figure 18), but this is also a measure with significant challenges and compromises regarding structural stability and durability of the structure (van der Lei, 2022). However, a start could be made by identifying alternatives to the EPS insulation, which on its own contributes a significant share of the energy costs of a TFC (See Figure 18).

7. Summary and Conclusions

Large scale adoption of timber-based constructions in the Netherlands entails promising effects regarding CO_2 reduction targets for the construction sector. However, several barriers regarding this adoption were posed in literature and financial feasibility is one of these. To find scenarios in which a timber-based dwelling would be financially competitive to its concrete and masonry counterpart, a hypothesis emerged based on recently rising energy and CO_2 prices under the EU ETS, entailing that a TFC could possibly financially outcompete a CMC due to constituting lower embodied energy and CO_2 emissions.

To test and quantify this hypothesis, this study has aimed to find a tipping point at which a ground-bound industrial TFC dwelling is equal in production costs compared to its identical CMC counterpart, under increasing energy and CO_2 prices. The main RQ of this study is therefore: *'How do energy and CO_2 prices determine the competitiveness between CMC and TFC production in the Netherlands?'* This study is structured according to 3 SQ entailing the comparison of CMC and TFC variation of the case-study dwelling, regarding 1) difference in energy and CO_2 demand through an energy and CO_2 analysis (Section 4.4), 2) difference in total production costs through a cost analysis (Section 4.5) and 3) the impact of fluctuating energy and CO_2 prices on production costs with an impact analysis (Section 4.6).

The results of SQ1 disclose that energy demand for the CMC is 22.8% higher than for the TFC (145 GJ and 118 GJ), primarily due to significant coal intensive concrete and steel use. Energy demand for the TFC is more dispersed between materials, of which primarily mineral wool, plasterboard, OSB, timber, concrete, EPS and steel. Furthermore, the CMC constitutes 74% more CO_2 emissions due to intensive coal use (48%) and a significant share of biomass (counted as CO_2 neutral fuel) in the energy mix for TFC production (19%).

Then, the results of SQ2 disclose that TFC total production costs are 15% higher compared to the CMC and vice versa for energy costs as part of production costs (127.54 €/m2GFA and 110.79 €/m2GFA for total production costs; 37.94 €/m2GFA and 32.88 €/m2GFA for energy costs). Also, CO_2 costs under the EU ETS are negligible for both dwellings, constituting < 3% of total production costs even for the CMC.

What is more, the impact analysis in SQ3 discloses that the total production costs for the CMC and TFC can respectively increase with 17.3% and 17.6% if a scenario occurs in which energy prices for all energy carriers peak based on an extrapolation of 2021 - 2022 price developments on current energy prices. The impact analysis also disclosed that both TFC and CMC are most sensitive to the NG prices and second most sensitive to diesel prices due to high prices and intensive use of both energy carriers (especially NG). Then, the impact analysis disclosed that the CMC is slightly more sensitive to coal and electricity prices than the TFC. Hence, the tipping point at which production costs for CMC and TFC would be equal occurs when coal- and electricity prices would increase by > 700% to respectively 1000 €/t and 0.95 €/kWh, which is not deemed plausible.

The results therefore indicate that the CMC and TFC are roughly equally sensitive to fluctuating energy and CO_2 prices and that it is not realistic that a tipping point occurs at which production costs of both variations under rising energy and CO_2 prices become equal. This is due to increased use of plasterboard and mineral wool in the TFC to substitute for the concrete casco of the CMC (a more extensive answer to the RQs can be found in Section 6.1 Answer to RQs).

What is more, the results calculated with the Excel model are relatively robust to deviations in input parameters, except for deviations in embodied energy values for concrete, as disclosed by a sensitivity analysis performed on the Excel model.

Furthermore, it is important to note that the results of this study are subject to several limitations: Firstly, configurations for the CMC and TFC could be chosen differently as e.g. an alternative to NG intensive mineral wool in the TFC might provide a significant difference to the sensitivity of production costs of the TFC to NG prices. Secondly, embodied energy values of materials might deviate depending on context of specific supply chains. Lastly, the used energy mix has been subject to several assumptions including the use of 1) typical energy content values for energy carriers as found in literature and 2) the EU electricity mix for emissions and cost calculations of electricity.

Additionally, this study has provided context regarding existing literature. Firstly, it contradicts the finding of Sathre (2007) that a timber-based dwelling is less sensitive to CO_2 prices than its concrete counterpart. The difference in results of both studies can be explained by differences in 1) case-study dwellings, 2) geographic scope, 3) date of study, 4) CO_2 tax mechanisms, 5) starting point for energy prices and 6) used materials prices. Secondly, this study disclosed that the CLT-based dwelling proposed by Staatsbosbeheer (2022) and van der Lugt & Harsta (2021) pose an unrealistic potential for the impact of timber-based constructions on climate targets for the built environment. Despite the significant potential for carbon sequestration and CO_2 savings through substitution of concrete and steel, the limited timber-content in the TFC yield only 24% of the CO_2 sequestration potential of financially unfeasible CLT variants.

Then, to expand this field of study, future research is suggested on 1) different configurations of the case-study dwelling, 2) embodied energy values specifically for construction materials used in the Dutch construction sector and 3) exact energy content and electricity mixes corresponding to the cross-border production chains of construction materials.

Finally, several policy recommendations for the government and construction companies are raised. Firstly, the government could 1) improve the MPG score system ensuring fair material scores for bio-based materials, 2) establish mandates and subsidies for timber-based constructions, and 3) stimulate awareness and education regarding timber-based construction, both for professionals and consumers. Secondly, construction companies could 1) seek to reduce transport distances of materials supply to reduce transport costs, 2) reduce plasterboard- and mineral wool content in a TFC for reduced energy costs and 3) find alternatives to the reinforced concrete floor with EPS insulation.

Ultimately, uncertainty regarding the development of energy prices are not going to constitute a major role in enabling large-scale adoption of the TFC subject of this study. Nevertheless, increased research on and experience with timber-constructions can certainly provide insight on the extent to which benefits of timber-based building can be harvested for society.

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Appendices

This section contains content ranging from used data for calculations to conceptual context that is non-essential for understanding the conducted research in the main text. It is however advised to read- or at least scan through the Appendices to gain a deeper understanding of the subject covered in this study.

Appendix I – Circularity in Construction

The most sustainable building is a building that does not require to be newly constructed (Sobota et al., 2022). Therefore, re-using construction and demolition waste for new buildings (CDW) is a promising principle for a sustainable construction sector. Circular construction requires a new approach to CDW that is based on the 3Rs principles of the ''spaceship theory'' developed by ecological economist Kenneth E. Boulding in 1966: reduce-reuse-recycle (C. Zhang et al., 2022). A first priority regarding CDW is to reduce the amount of waste produced. If CDW is unable to be reduced, it should be reused and if re-use is not possible, CDW should be recycled. This approach is expanded by the Ladder van Lansink,(Maurits, 2015) which includes the preference to recover energy from used materials over incineration, if recycling of the material is not possible. The worst option is landfilling, which is only an option if incineration is not possible (see Figure 26).

Figure 26 Recycling of used products according to the Ladder van Lansink (Maurits, 2015)

CDW recovery was around 90% in the EU in 2018 due to its effective Waste Framework Directive 2008/98/EC; in contrast, CDW recovery in China was less than 10% (C. Zhang et al., 2022). However, most recovered materials are downcycled, meaning that the production of new materials still requires additional resource extraction (van der Lugt & Harsta, 2021). Table 9 below displays CDW categories and their corresponding properties regarding circular construction.

Table 9 Circular potential of CDW (de Brito & Kurda, 2021; Sobota et al., 2022; van der Lugt & Harsta, 2021; C. Zhang et al., 2022)

	CONCRETE	METAL	BRICKS	GLASS AND MINERALWOOL	PLASTICS	WOOD
REUSABILITY	Pre-fabricated elements are reusable; rarely seen in practice due to non-universal design	Complete elements can be reused	Long lifetime, but poorly reusable due to mortar use	Panels and panes can be reused	Pipes and claddings can be reused	Complete elements can be reused
RECYCLABILITY	Can be downcycled in new concrete, dikes and under roads	Can be re-melted to produce new material at high energy cost	Can be downcycled for new concrete, dikes and under roads	Can be downcycled to feedstock for new products (e.g. be used as aggregate for concrete)	Recyclable as new plastic products under absence of additives	Can be 1) recycled as feedstock in low tier wood products or 2) downcycled as organic mulch or compost for gardening
ENERGY RECOVERY	N.a.	N.a.	N.a.	N.a.	Can be incinerated for energy recovery	Can be incinerated for energy recovery
INCINERATION AND LANDFILLING	Landfilling can be avoided	Landfilling should never be considered	Landfilling can be avoided	Landfilling can be avoided	Should not be incinerated without energy recovery	Should not be incinerated without energy recovery

The extent to which a material contributes to circularity in the construction sector is highly dependent on the configuration in which the material is used. The following principles are identified to address these end-of-life issues by realising minimal resource use and better reuse and recyclability: 1) Long lasting design, 2) design for dismantling before demolition, 3) light weight design and 4) design for recycling by allowing demolished material to be used directly as raw material for new building materials (Hendriks & Dorsthorst, 2001; C. Zhang et al., 2022).

Currently, reuse and high quality recycling is rare in the construction sector, requiring further technological innovation, quality certificates and standardization (C. Zhang et al., 2022). A questionnaire conducted at construction contractors, demolition companies and CDW processing companies disclosed that 1) the largest setback is caused by logistical challenges and 2) the most significant opportunities lie in on-site operations dismantling operations (Ghaffar et al., 2020). Also, mobile robotic sorting and reprocessing machines with artificial intelligence and internet connection provide a potential breakthrough for circularity in construction (Idem).

Lastly, Adams et al., 2017 disclosed through industry interviews that the another significant challenge to design for end-of-life issues is the lack of incentives to design for end-of-life issues of construction materials. Yet, McKinsey and Accenture estimated that a transition towards a circular economy potentially provides an economic benefit of 1.8 trillion euro in 2030 in the EU (van der Lugt & Harsta, 2021). Redistribution of this benefit for end-of-life design of construction materials therefore seems to be of primary importance for a shift towards a circular construction sector.

Appendix II – Ecological Controversy Regarding Timber Construction

Regarding environmental impact, Werner & Richter (2007) performed a literature study that synthesises LCA comparisons between wooden construction products and functionally equivalent products from different materials. They identified reduced- energy use, CO_2 emissions and solid waste of wood compared to competing products. Furthermore, incineration of wood products can cause higher impacts of acidification and eutrophication in exchange for thermal energy recovery. What is more, composed wood products (OSB, MDF etc.) require a high energy use due to the production of fibres, glues and resins. Also, Bukauskas et al. (2019) state that environmental performance of applying biobased construction materials depends on regional resource availability, processing capacity and transport. Especially transport might pose significant emissions due to low packing efficiency of untreated wood. Nevertheless, Börjesson & Gustavsson (2000) found that primary energy input for material production of CMC was 60-80% higher than for TFC materials. And an LCA conducted by Beijers (2021) disclosed that an OSB and CLT based mass timber dwelling requires only 38.3% of CO_2-eq for material production compared to an equivalent traditional Dutch dwelling. However, if MDF was used instead of OSB, the traditional dwelling performed better. Yet, including biogenic carbon storage in an LCA results in negative CO_2-eq emissions for a timber construction (Beijers, 2021; Švajlenka et al., 2017; van der Lugt & Harsta, 2021). Lastly, regarding timber products, energy is a key input for powering the equipment needed in milling lumber and the kiln drying process is typically the most intensive energy requirement at a sawmill, followed by sawing and material handling (Forest Products Laboratory 2010).

Regarding LUC, Börjesson & Gustavsson (2000) state that TFC requires approximately two times the amount of land to produce construction materials than CMC, assuming that all primary energy use required for material production is biofuel. Yet, Forster et al. (2019) disclosed that expansion of forestry onto marginal lands in UK for construction timber can mitigate 2.4 kt CO_2 eq. per ha over 100 years by carbon sequestration in trees and construction materials. They warn however that up to half of this effect can be compromised if this forestry expansion causes beef production to replace to Brazil.

Regarding forest capacity and biodiversity loss, to maintain both timber harvest as well as biodHuston & Marland (2003)ns exist. Huston & Marland (2003) state that biodiversity and carbon sequestration in forests for timber can provide a win-win if degraded land is used for reforestation. Furthermore, Betts et al. (2021) proposes three options: 1) high yield tree plantations can free up forest land for conservation, 2) compromise wood yield intensity for biodiversity richness in an 'ecological forestry approach' and 3) install 'Triad' zoning where an area is divided in three zones each with its own management objective (reserve, ecological and intense forestry). Messier et al. (2011) disclosed that triad zoning in Quebec is economically viable and ecologically preferrable. What is more, respectively 83% and 100% of all sawnwood and coniferous wood used in the Netherlands is sustainably sourced and certified by the Forest Stewardship Council (FCS) or the Program for the Endorsemen(van der Lugt & Harsta, 2021)FC) (van der Lugt & Harsta, 2021). Moreover, European forests are expected to be able to sustainably supply a growing timber demand until 2050 through a further increase in production capacity and a potential to increase forest area with 40-50% (van der Lugt & Harsta, 2021). After all, EU forests currently produce 23% of global timber demand only with 2% of global forest area (Idem).

Appendix III - Quality of Timber Constructions

The most important difference between a CMC and TFC is that TFC is light weight due to low densities in coniferous woods between 430 – 780 kg/m^3 (Engineering Toolbox, 2004a) compared to concrete densities between 1750 – 2400 kg/m^3 (The Physics Factbook, 2001).

Air cavities in timber stimulate thermal building performance with respective measured thermal conductivities (λ) for dry balsa, softwood, concrete and steel (Cross Timber Systems, n.d.; van der Lugt & Harsta, 2021). Furthermore, these air cavities allow timber to absorb and release water. Hence, TFC is prone to damage from moisture as 20% moisture content in the material causes mould to colonize timber and at 30% moisture content, bacterial rot and fungi attacks can occur (Hens, 2013). However, use of ventilation, rain-tightness, outside cladding and vapour barriers prevents this issue (Cabral & Blanchet, 2021; Hens, 2013). When kept under 20% moisture content, timber can have a lifetime of >1400 years (van der Lugt & Harsta, 2021). Finally, reduced weight of timber makes TFC prone to noise transmission (de Geetere & Ingelaere, 2014). This can however be cost-effectively solved by detaching construction elements (van der Lugt & Harsta, 2021) or installing noise-reducing materials in the structure such as sand, gravel, gypsum board, mineral wool or wood fibre cement boards (de Geetere & Ingelaere, 2014).

Regarding fire safety, timber is flammable in contrast to concrete and steel. Nevertheless, timber burns at predictable rates that allow for better assessment for when a structure loses its strength (van der Lugt & Harsta, 2021). The EN13501-1 ranks reaction-to-fire ratings for materials, ranging from A (non-combustible) to F (highly flammable)(Euro Classification, n.d.). Timber with a density of > 350 kg/m^2 (coniferous) fall under class D-s2-d0, meaning that it contributes to fire (D) with average smoke production (s2) and without producing burning droplets (d0) (van der Lugt & Harsta, 2021). Accounting for these properties, TFC is considered fire-safe for up to three storeys with an inside finish of gypsum board and a party wall with wood wool cement board and fire stoppers between the building leaves (Figure 27) (Hens, 2013; Structural Timber Association, 2020).

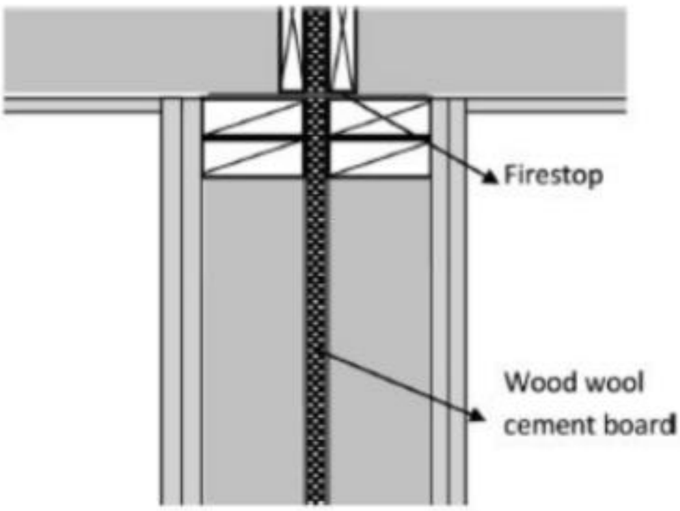


Figure 27 Fire safe wall and floor construction for terraced TFC constructions up to three stories (Hens, 2013)

Appendix IV - CMC and TFC Factories in the Netherlands

Several construction companies in the Netherlands have started or are developing the production of industrial CMC and TFC. Figure 28 displays an image inside the TFC factory of construction company VDM in Drogeham (Friesland), in which elements for their dwellings as displayed in Figure 29 are produced. Regarding the VDM factory, benefits of industrial TFC production compared to their conventional TFC development include flexibility in design, comfort and efficiency regarding energy use, efficient and rapid construction process, consistent high quality, independence to weather conditions and affordability (VDM, 2022). Furthermore, VDM can produce 3 types of land-bound dwellings in their factory, which can be modified with different finishes and details. Furthermore, Figure 30 displays the production of TFC wall elements in the 'Morgen Wonen' factory of construction company VolkerWessels in Rijssen. Figure 31 then displays an image of a TFC produced in the 'Morgen Wonen' factory by construction company VolkerWessels (MorgenWonen, n.d.). In the Morgen Wonen factory, elements for either land-bound CMC, TFC and apartments can be produced with the benefits mentioned for the VDM factory and additional options regarding detachability and reusability of materials to improve circularity of the produced structures (Idem). Then, Figure 32 displays a construction element ready for transport as produced in the factory in Almelo developed for construction company Plegt Vos, producing elements for either CMC or TFC dwellings. Their factory has a capacity of producing elements for up to 30 dwellings per week, ensuring limited labour requirements and allowing for 95% waste and 5% cost (expected to increase to 20%) reduction compared to conventional construction approaches (Plegt Vos, 2022a, 2022b). Also, construction companies Heijmans and BAM are developing a TFC factory at which an expected capacity of 800 – 1000 dwellings per year from 2023 onwards (BAM, 2022; Heijmans, 2021). Lastly, Figure 33 displays the construction factory of BGDD in Dokkum (where the case study CMC for this study is produced) with a capacity to produce elements for 300 dwellings per year ((BGDD, 2018); See 4.3 Case Study Assembly Factory).

Figure 28 VDM Prefab dwellings factory in Drogeham (Friesland) *Source: VDM (2022)*

Figure 29 VDM Wonen finished TFC dwellings *Source: VDM (2022)*

Figure 30 Inside the VolkerWessels TFC factory Morgen Wonen *Source: MorgenWonen (n.d.)*

Figure 31 Finished TFC dwellings produced by VolkerWessels in their 'Morgen Wonen' factory Source: MorgenWonen (n.d.)

Figure 32 Plegt Vos prefab TFC elements ready for transport from the Plegt Vos *Source: Plegt Vos (2022)*

Figure 33 View inside the CMC production factory of construction company BGDD *Source: BGDD (2018)*

Appendix V – Production Processes of Primary Construction Materials

This section describes the production process of different primary construction materials that are subject of study for this study. It provides insight into how the embodied energy and energy mix for the production of each construction material as displayed in Appendices VI and VII were formed.

1. Timber

This study has assumed, in consultation with suppliers of the construction company, that the timber used in the CMC and TFC is sourced from Sweden. In 2018, Sweden was the 3rd largest sawn wood exporter globally (Swedish Wood, 2022). This amounted to a total of 7 Mtonne of sawn-wood exports, constituting > 70% softwood. Swedish softwood is either Spruce (whitewood) or Pine (redwood), which are both coniferous species (Idem). Compared to hardwood, softwood has a low density, rapid growth rate and therefore lower price (Middleton, 2020). Due to its affordability and its strength, it is widely used for interior mouldings, manufacturing of windows, construction framing and as a resources for panel goods such as plywood or OSB (Idem).

Figure 34 below displays the production process from forest to sawn wood. When a tree is roughly 300mm thick at the stem, it is harvested, felled, debranched by a diesel-powered harvester. Then, typically, a 70 m^3 diesel truck is used to transport the trees to the sawmill (Jongerling, 2022). The tree is then cut in to three sections: butt log, middle log and top log (Swedishwood, 2022). The debarked and debranched tree elements are then sawn. A common method for sawing coniferous trees is block-sawing (sawing off rounded sides), followed by re-sawing the rectangular shape in to planks and beams. Planks and beams that are purposed for smooth handling and finishes are then shaved. Shaving is however not applied to the timber used in the CMC and TFC. Furthermore, barks, chips, shavings and branches are repurposed for panel goods or biofuels. Tree residues are also often repurposed as fuel at the sawmill to provide electricity or heat for drying (Mac, 2019). Next, the freshly sawn timber is dried from 30% - 160% moisture content to the target moisture content of 16% to prevent mould and rot. Lastly, the dried timber is checked and wrapped before shipping (Swedishwood, 2022).

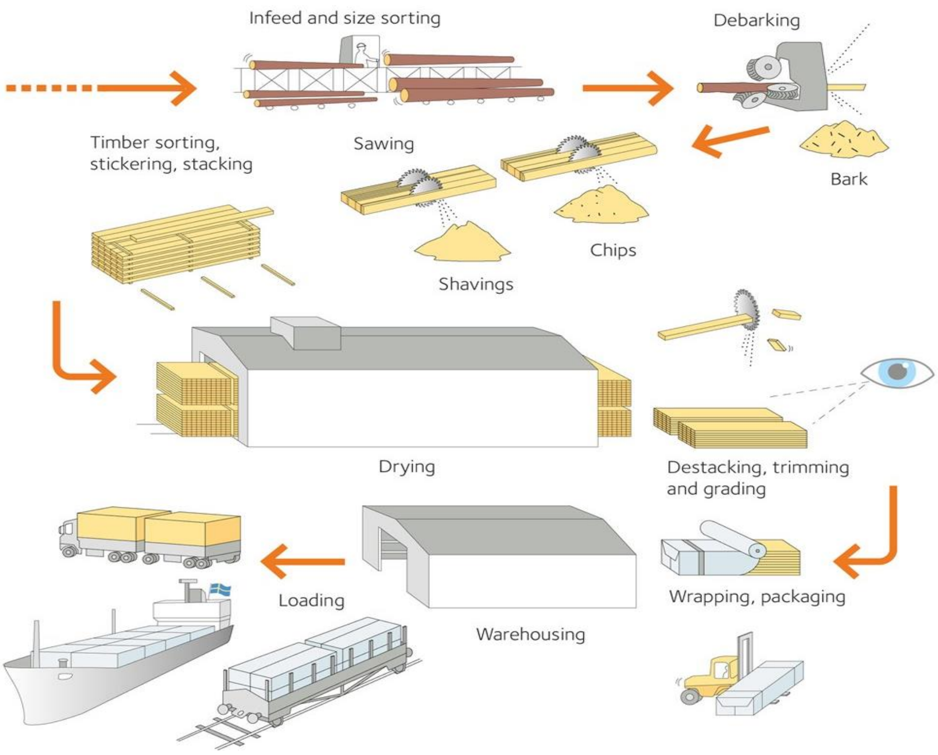


Figure 34 The sawn wood production process from forest to sawn wood product *Source: Swedishwood (2022)*

2. Oriented Strand Board

OSB panels are widely used in construction as they resist deflection, warping and distortion through heat-curing and pressing of waterproof adhesives with rectangularly shaped wood strands. The OSB panels are often used for structural and non-structural uses in floors, roofs and walls of light-frame wood constructions. Wood strands in OSB are 8 to 15 cm long, sourced mainly from crooked, knotty and deformed trees (Naturallywood, n.d.). The strands are mixed with up to 10% chemical mixture that consists of (semi) water resistant thermosetting glues: Urea Formaldehyde (UF), Melamine Urea Formaldehyde (MUF) Phenol Formaldehyde (PF) and Isocyanate (PMDI); (European Panel Federation, 2018; Gündüz et al., 2011; Naturallywood, n.d.; Oldhand, 2017).

Figure 35 (Processing-wood, n.d.; Weyerhaeuser, 2016) below displays the production process of OSB panels. Firstly, logs are harvested and sorted equal to the production process of timber beams (Section 2.6.1). Then, bark is removed as it is unsuitable for OSB panels. Next, a strander produces strands from the wood chips, which are sorted on size and then dried in a drum dryer; often heated with bark and wood-residue (Murphy et al., 2015). Furthermore, during blending, the glue mixture is added and evenly distributed to the strands. The mixture is then aligned such that the weight and proportions of the spread mat is evenly distributed before pressing. At the pressing station, heat and pressure provide curing for the glue and the desired thickness for the OSB panel. Lastly, at the finishing line, the OSB panels are cooled, sized and stored before shipment.

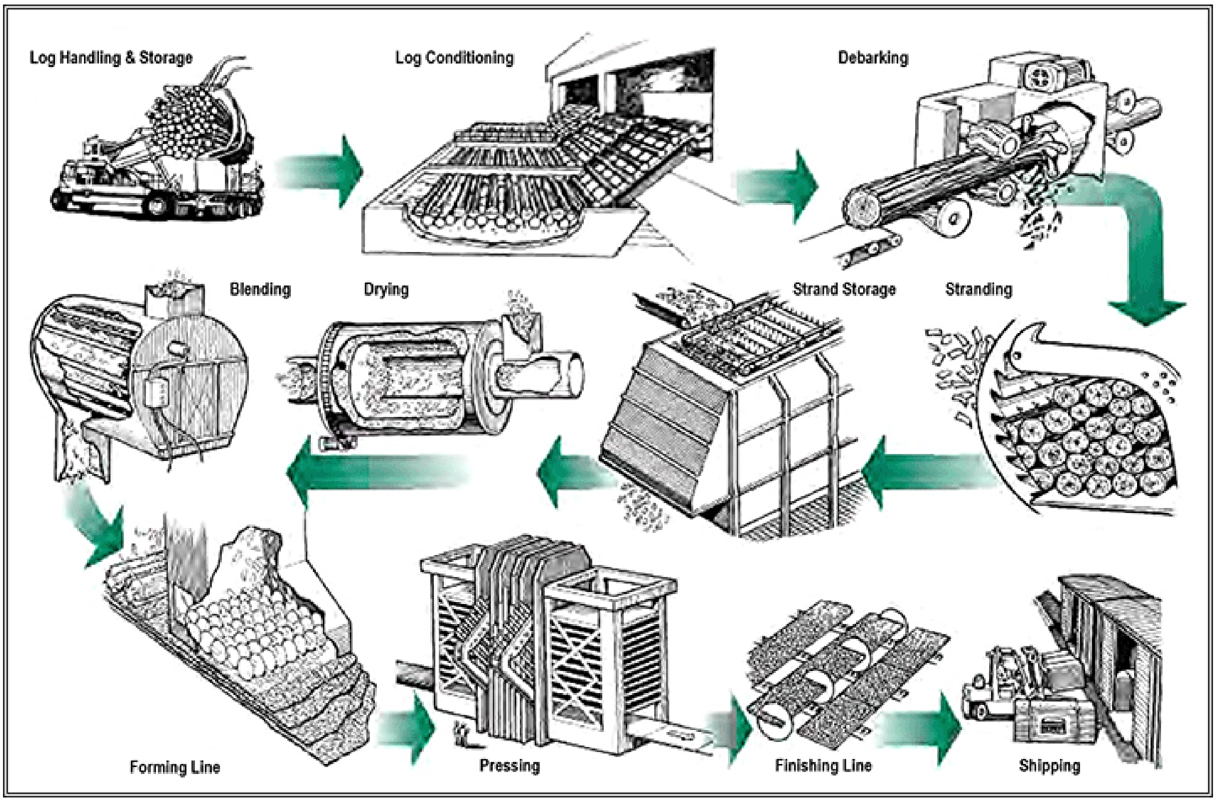


Figure 35 A typical production process for OSB panels *Source: Weyerhaeuser (2016)*

3. Cellulose Insulation

Cellulose is an abundant renewable resource that consists of monosaccharide $(C_6H_{10}O_5)_n$ bonds that constitute cell walls in plants. It also constitutes the structure of paper, which is often sourced from trees. After cellulose served its structural purpose in paper, the paper can be broken down so that the cellulose can be used again in cellulose insulation to trap air and generate a thermal insulation barrier. This is why old newspapers are converted to insulation. Recycled newspapers generate cellulose with significant noise-insulation properties and a thermal insulation performance (λ) of 0.04 W/mK (Eco-Bouwers, 2019), close to the performance of mineral wool. To prevent fire-hazard and ensure pest-control, cellulose insulation is treated, up to 15% by volume, with boric acid, borax, or ammonium sulfate (Ringler, 2021). Cellulose insulation can then be applied in three ways: 1) loose fill insulation that can be blown in to cavities, 2) densely packed panels that can be installed similar to mineral-wool panels and 3) wet-spray cellulose constituting a binder so that it can be sprayed directly to a surface preventing air-leaks (Shine, 2021). For the CMC and TFC, loose fill insulation cellulose is used.

Figure 36 below displays the production steps for producing cellulose insulation from used paper. These steps are derived from (Pearce, 2015) Firstly, the primary mixer removes metal from the paper with a magnet so that it can be processed by the shredder. The shredder then shreds the paper to pieces of roughly 5 cm in diameter surface area. The shredded paper is then mixed with a first batch of chemicals (often boric acid) after which it continues to the fiberizer that shreds the mixed paper to pieces of 4 mm. These pieces are then mixed again with chemicals (e.g. again boric acid). The finished cellulose is then tested for fire-safety by exposing it to a flame. If the test is successful, cellulose insulation is packed in rectangular batts, rolls or loose in bags; ready for transport. The machines used in this production process are powered by electricity (Shredders, n.d.; Verboom, 2021).

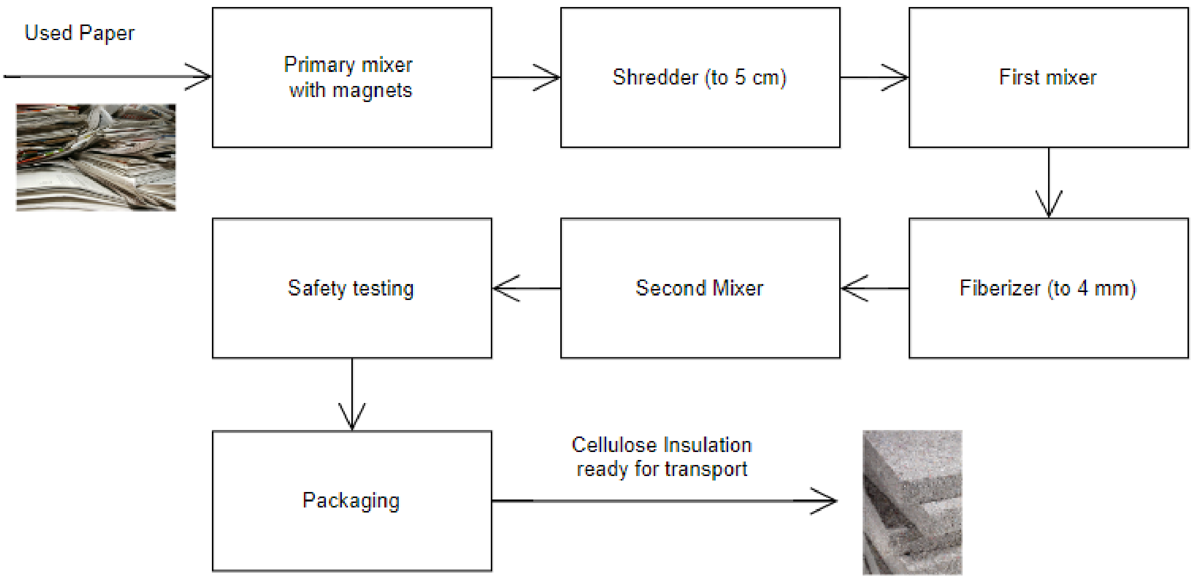


Figure 36 Production steps for producing cellulose insulation from used paper as derived from Pearce (2015)

4. EPS Insulation

EPS is a commonly used insulation material in construction, especially for floors and cavity walls. It contains polystyrene (a polymerized styrene), which is a solid hard plastic that is often used in products for e.g. food packaging, appliances, electronics, toys or gardening pots (Chemicalsafetyfacts, 2022). When steam and pentane is added to polystyrene, expanding air gets trapped in the structure to form EPS with up to a 98% air-content (Chemicalsafetyfacts, 2022; D. Zhang, 2021). EPS is a suitable insulation material due to its durable structure and its resistance to chemicals, bacteria and pests (Flax, 2015). Furthermore, due to the closed cell structure, EPS provides relatively low water-absorption and vapor permanence while maintaining a rigid structure (Insulationcorp, n.d.). The thermal insulation performance (λ) of EPS varies between 0.032- and 0.036 W/mK (Isolatieshop, 2021).

Figure 37 below displays the production process from styrene (a by-product of petroleum and NG refining) to EPS (Styro, n.d.). First, the polystyrene beads are impregnated with pentane as foaming agent and heated to 90 °C with steam to pre-foam, expanding the polystyrene 20 – 50 times its original size (D. Zhang, 2021). The beads are then stored for 6-12 hours to reach equilibrium. Lastly, the beads are conveyed to the mold where they can be mixed with a fire retardant such as a brominated polymeric compound (Idem). In the mold, the beads are exposed to steam again so that they bind together.

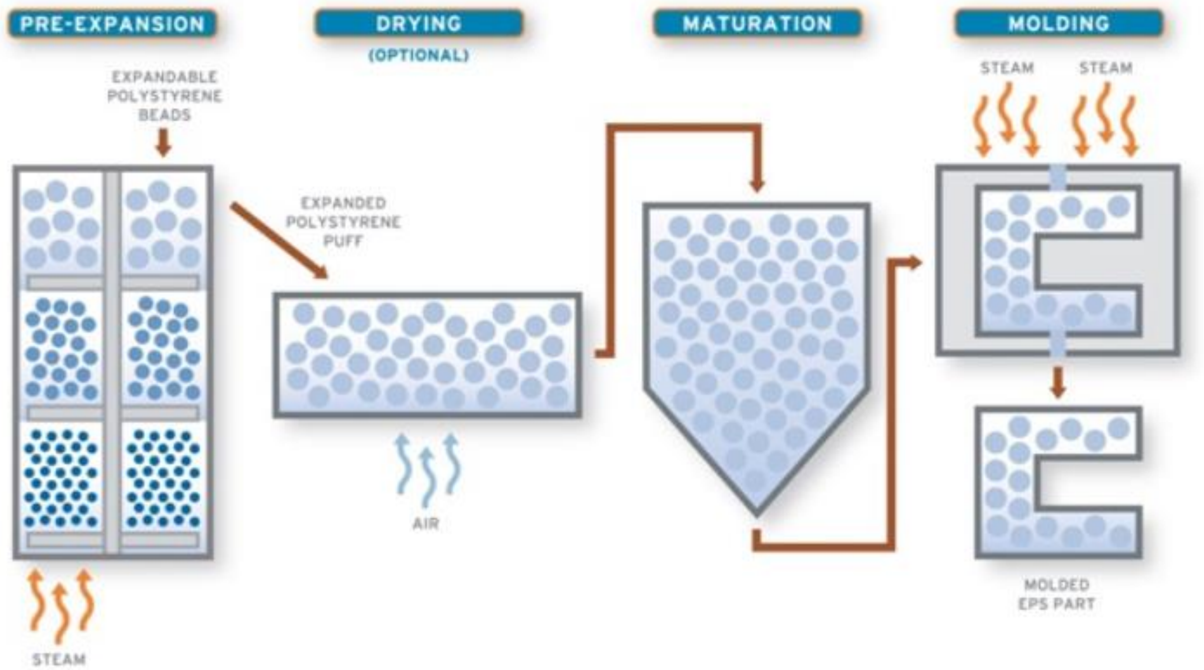


Figure 37 Production process from polystyrene to EPS *Sourced: Styro (2022)*

5. Plasterboard

Plasterboard panels (or referred to as sheetrock, gypsum board, drywall, wallboards or gyprock) are made of gypsum (calcium sulfate dihydrate: $CaSO_4 \cdot 2H_2O$) that is pressed between two paper sheets which are called liners (Siniat, 2020). The panels are typically used as finish in interior walls and ceilings. Plasterboard panels are called a 'drywall' construction, as it is a quicker alternative to traditional wet lath and plaster finishes. Due to the capacity of gypsum to lock in water (21% weight basis), plasterboard finishes ensure fire protection and can be a used to control vapour, moisture and water (Idem). Furthermore, plasterboard contributes to thermal- and acoustic insulation. At the end of its life, plasterboards can be 100% recycled after paper and screws are removed (Idem).

Figure 38 below displays a typical production process for plasterboard panels based on (Savoly & Elko, 2015; Yoshino-Gypsum, n.d.). Firstly, crude gypsum rock is baked in a furnace, removing 2/3 of its crystallized water content at 120 °C ~ 150 °C; this constitutes the calcination process. The resulting products of calcination are steam and calcined gypsum, which is grinded to a powder. When water is added to the calcined gypsum powder, it hardens again. Before that is done, several additives can be added to the calcined gypsum powder: 1) Accelerators such as sugars or ammonium sulfate to shorten setting-time after water is added, 2) Retarders (a carboxylic acid group: -COOH) to decrease setting-time after water is added, 3) Boric Acid to increase strength and over-drying resistance of the gypsum and 4) Starch to improve bonding of gypsum to the paper sheets. After additives are mixed, water is added to the calcined gypsum and the slurry is pressed between two liners. The calcined gypsum then crystalizes in to the liners as the water is encapsulated in the gypsum structure. The resulting solid plasterboard panels are then dried and cut in the required size before shipping .

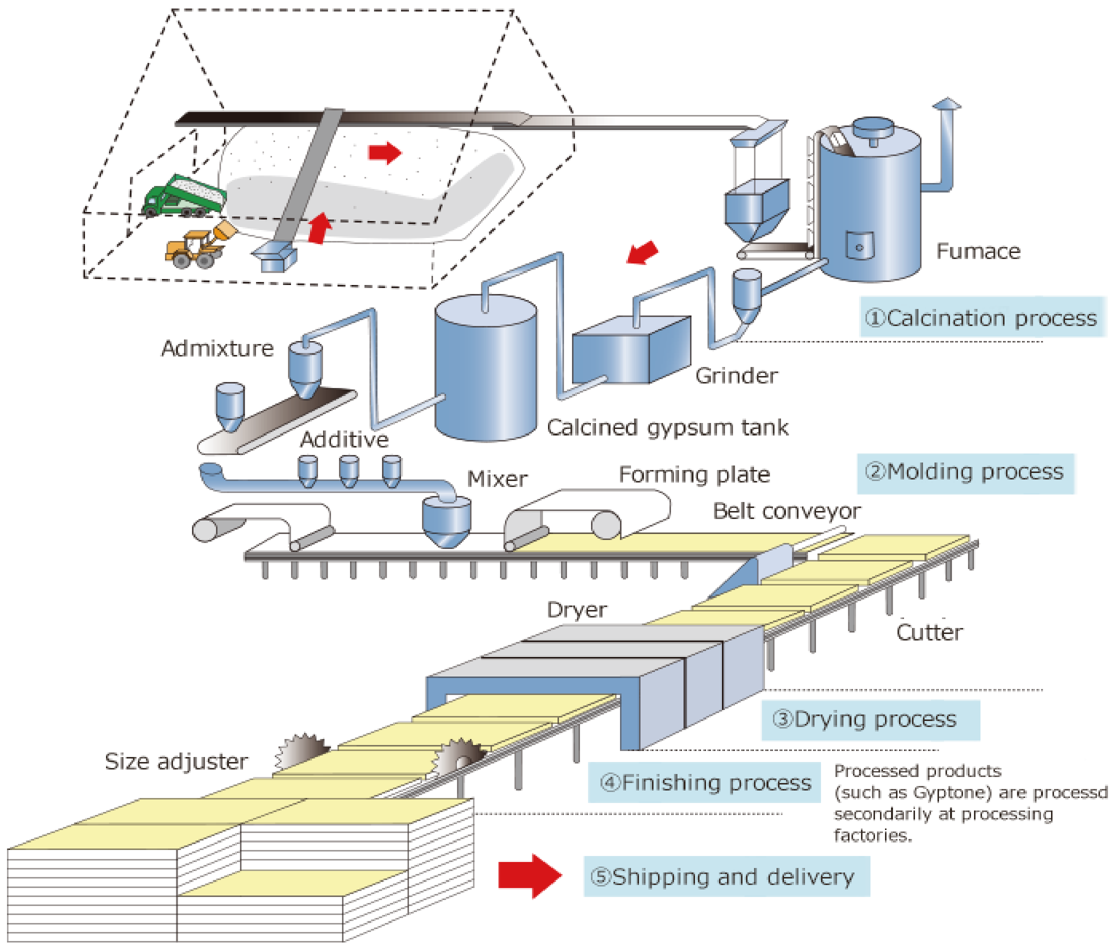


Figure 38 An overview of the production process of plasterboard panels *Source: Yoshino-Gypsum (n.d.)*

6. Mineral Wool

Mineral wool is a name for fibre materials that are formed by melting raw materials at high temperatures, after which the material is spun into delicate fibres (Knauf, n.d.). Mineral wools are used as a multi-purpose thermal and acoustic insulation material in e.g. buildings, pipework of installations or vessels (Krijgsman & Marsidi, 2019). It is also used as a growing medium for plants (Idem). The most common types of mineral wools are Stonewool, Slagwool (also named Rockwool) and Glasswool; all three are manufactured in similar processes and have similar properties (Knauf, n.d.).

Figure 39 below displays the production process of glasswool as this is the primary mineral wool used in the CMC and TFC. This flowchart displays the production process of Saint Gobain in Etten-Leur (NL), with an annual production of around 60 kilotonne as described by Krijgsman & Marsidi (2019). First, a mix of cullet, sand, soda-ash and limestone is melted in a gasfurnace at 1400 °C. Then, the molten glass mixture is fiberized in a centrifuge, after which it is sprayed with a binder that provides improved handling quality and durability of the fibres. The fibres are then compressed into mats and cured at 200 °C. Lastly, the mats are cut to size and packaged, ready for transport.

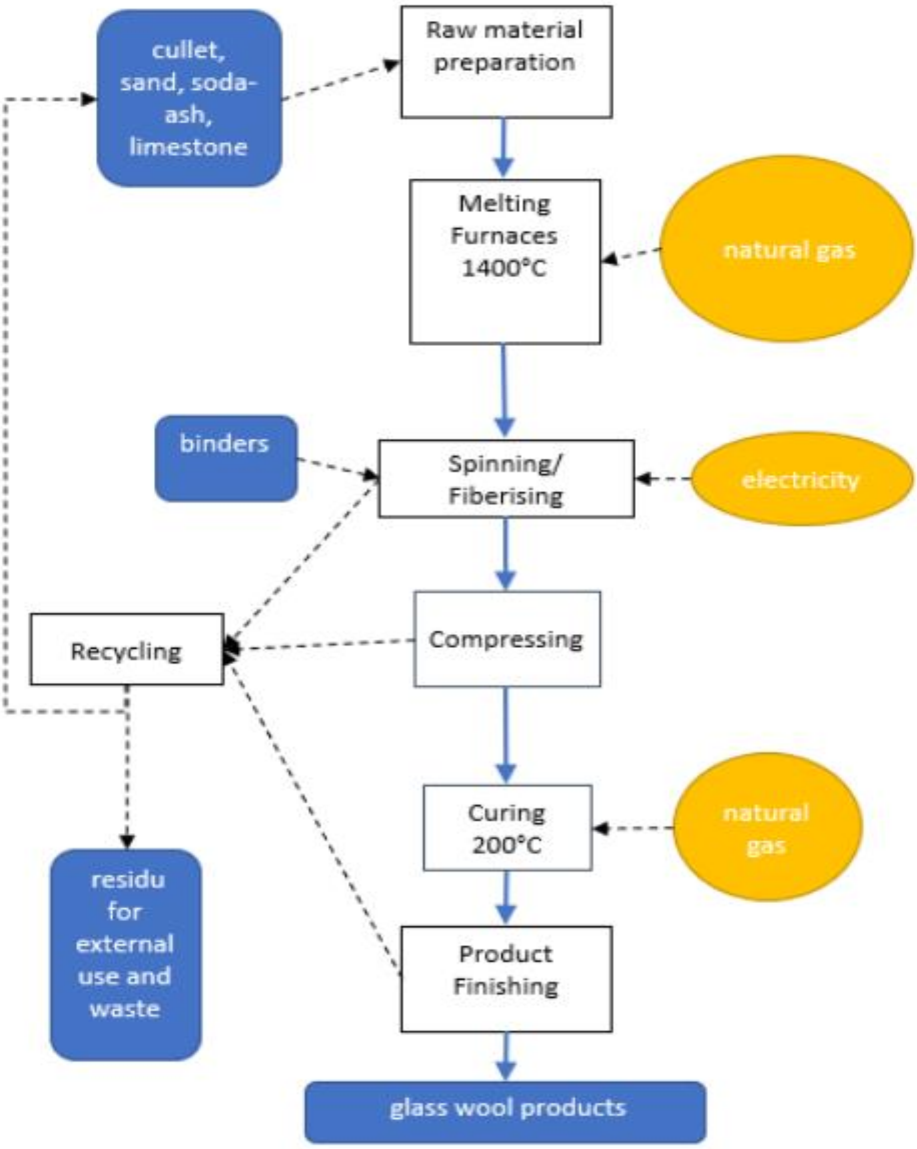


Figure 39 Production process of glasswool as based on the Saint Gobain production facility in Etten-Leur (NL), as described by Krijgsman & Marsidi (2019)

7. Reinforcing Steel

Reinforcing steel consists of cylindrical carbon steel bars of a diameter between 8 mm – 20 mm, often called 'rebar' (Wijngaarden, 2020). Concrete is poured on to a reinforcing steel structure to improve its tensile strength. Reinforcing steel is especially effective for enforcing concrete due to its significant tensile strength and its coefficient of thermal expansion similar to concrete (Bestbar, 2019). Reinforcing steel can be either made from 1) iron ore with a Basic Oxygen Furnace (BOF) or 2) scrap metal with an Electric Arc Furnace (EAF). In the EU, 40% of steel is produced from recycled scrap metal with an EAF and the latter 60% with a BOF from iron ore (Odyssee-Mure, 2019).

Figure 40 below displays the production process for reinforced steel with either a BOF or EAF. In the BOF route, iron ore, limestone and pulverized coal are added to the blast furnace from the top after which they form molten pig iron at the bottom, containing carbon, silicon and manganese (Kumar Dey, 2021). Then, in the BOF, oxygen is blown through the molten pig iron where gas from carbon escapes the mixture and a ferrous-manganese silicate slag is formed, which is called the Acid Bessemer Process (Idem). To regulate the temperature some scrap metal is added, as well as spiegeleisen or ferromanganese to remove hydrogen and especially oxygen from the steel mix, after which molten steel is the final product leaving the BOF (Idem). The EAF directly heats scrap metal by two electrodes that form an electric arch (Nieto, 2019). Sometimes, gas burners are used to assists with heating the scrap iron in the EAF to remove impurities. Then, finishing additions are made in the casting ladle before the molten steel is poured and solidified in a continuous caster. The semi-finished cast iron (often slabs or bars) are ready to be used to form a finished product such as reinforcing steel bars.

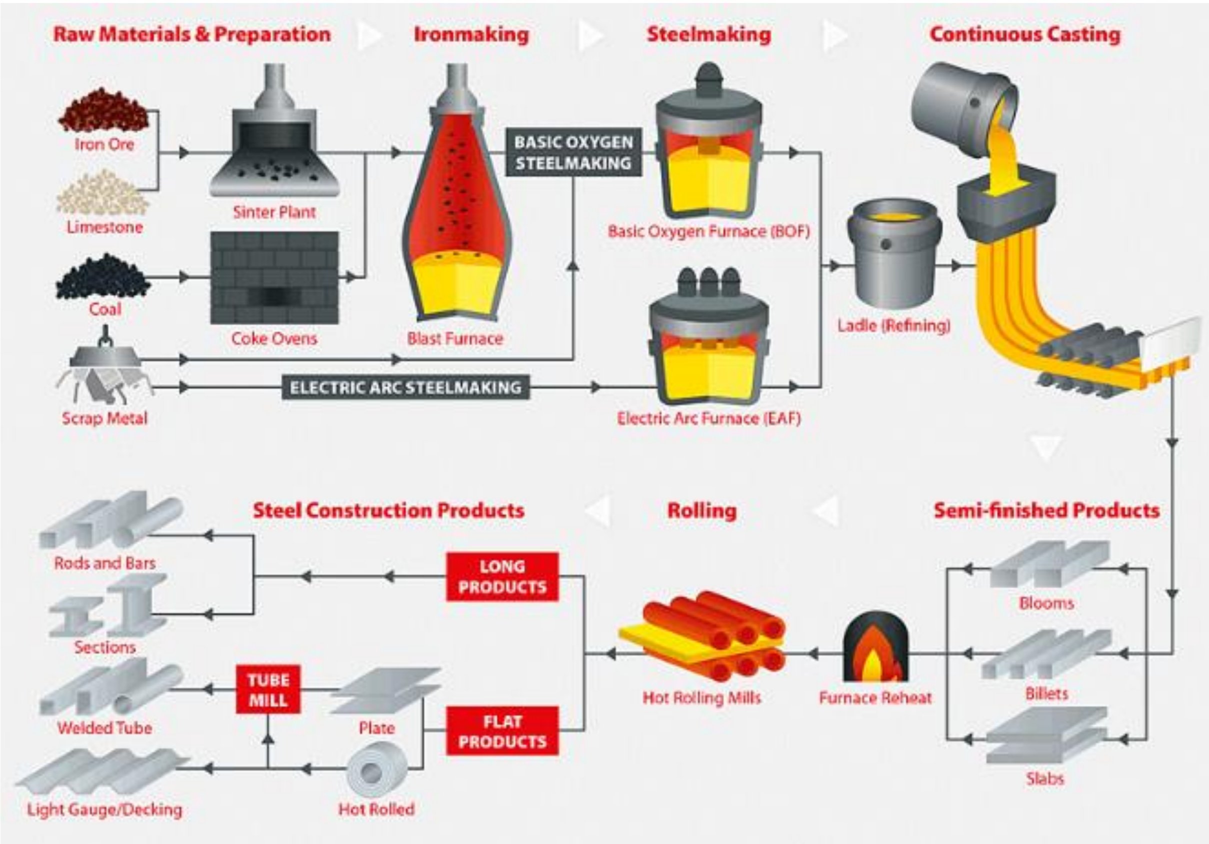


Figure 40 Producion process of reinforcing steel rods by either a BOF or EAF *Source: Nieto (2019)*

8. Concrete

Concrete is a hardened construction material that consists of a chemically inert material (mostly a mix of sand, gravel and crushed stone), a binder (cement), chemical additives (admixture; to improve handling and durability of concrete and cement) and water (Madehow, 2022). After drying, concrete acquires a stone-like consistency which is suitable for constructing roads, bridges, water supply, sewage systems or buildings. Adding a reinforcing steel (or rebar) structure to a concrete element provides significantly increased tensile strength to the vast amount of compression strength that a concrete element can tolerate, enabling the largest constructions that humans have ever built. Figure 41 below displays a schematic of a concrete production, which constitutes the mixing of the above mentioned materials until the desired type of concrete is produced (Chrysostomou et al., 2015).

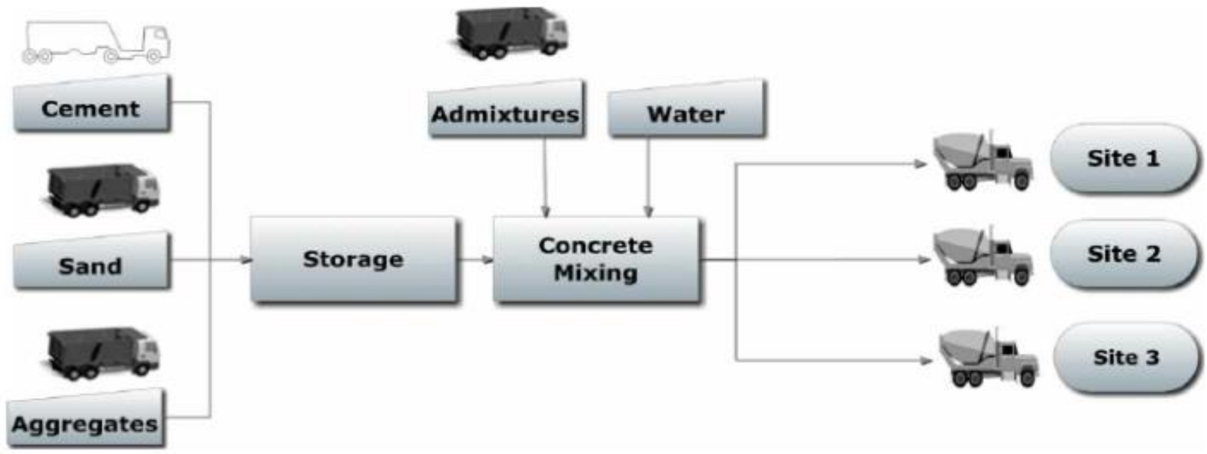


Figure 41 Production process of concrete from cement, water and a combination of chemically inert materials as aggregates such as sand, gravel, crushed stones or recycled (crushed) concrete Source: Chrysostomou et al., 2015

An important part of the production process of concrete is the production process of cement. Moreover, cement production constitutes typically 80% of CO_2 emissions in concrete production; the rest is from transport and mixing (Jansen, 2020). Therefore, the production process of cement is also described in this section. An overview of the production process of cement is displayed in figure 42 below. First, clay and limestone are grinded and transported to silos, ready to be fed to the kilns in the required proportions. Mixing can either be performed in a wet- or dry process: the main difference is that in the wet process the clay and limestone are 1) grinded and washed separately and 2) mixed after washing to be stored as a wet paste instead of a dry powder (Chemicalengineeringworld, 2020). The mixture is then preheated and fed to the rotary kiln which heats the mixture from 400°C in the upper part of the kiln up to 1700°C in the lower part (Idem). The rotary kiln is typically fuelled by powdered coal or oil. During the middle part of the kiln (from 850°C), the calcination of limestone takes place, in which it decomposes in to calcium oxide and carbon dioxide:

Eq. 18) *Calcination of limestone* $$\mathrm{CaCO_3} \rightleftharpoons \mathrm{CaO} + CO_2$$

Calcination of limestone represents typically 50% of CO_2 emissions in the production of cement (Rubenstein, 2012). In the lower part of the kiln, aluminates and silicates fuse together to form lumps (5-10mm) of hard stones that are called clinkers (Chemicalengineeringworld, 2020). Clinkers are then cooled and stored before they are mixed and grinded with gypsum in the cement mill. Gypsum is added to retard the setting process of cement (and concrete), as it is able to trap water (See Section 2.6.5). After the clinker and gypsum are mixed and grinded to form cement powder, it is stored and ready for transport.

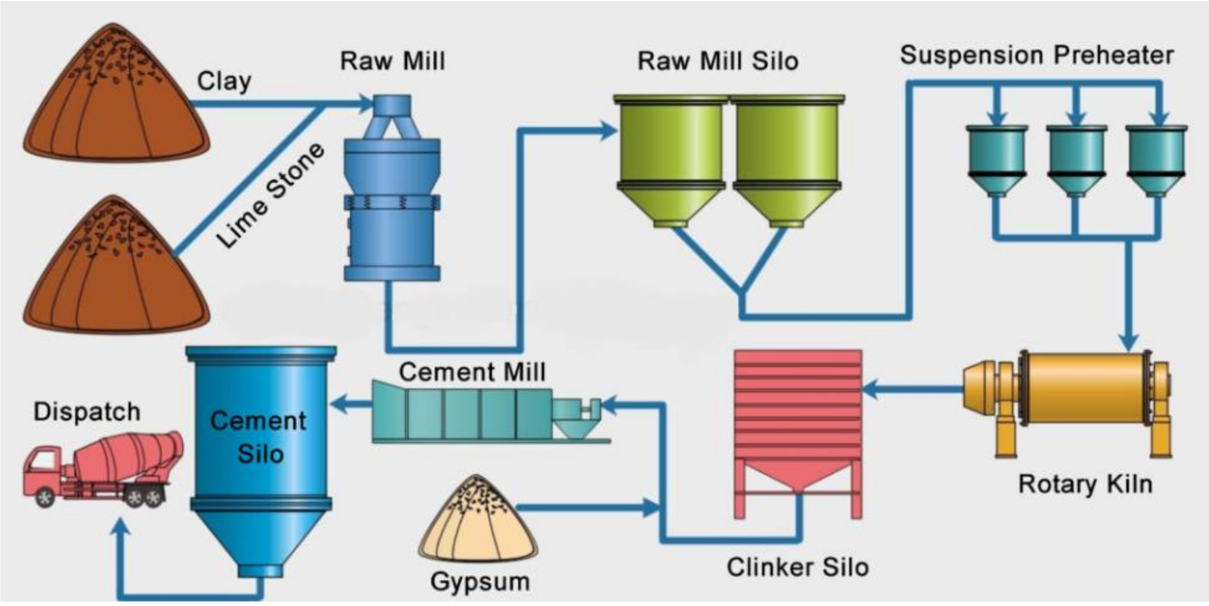


Figure 42 Production process of cement which is used as feedstock for concrete   Source: Chemicalengineeringworld (2020)

Appendix VI – Determining Embodied Energy for Materials

The conversions from primary or final energy demand (See Section 3.3.1) to embodied energy for the different construction materials, were executed using the data in Figure 43 and Tables 10 and 11 below and Tables 12, 13 and 14 in Appendix VII.

Firstly, where possible, a conversion from final energy consumption to embodied energy was performed with the materials density values as listed in Table 14 in Appendix VII.

Secondly, several sources only provided primary energy data (see Table 5); the conversion from primary energy to embodied energy required the identification of the energy mix so that the conversion to final energy and ultimately to embodied energy could be made with the corresponding efficiencies for each energy carrier in the energy mix of a material. This energy mix was however not consistently available in literature or from suppliers. Therefore, the Ecoinvent database has been used to track the used energy mix (where possible for EU or Switzerland) for producing the construction materials. The method for converting primary energy to embodied energy was as following:

The energy mix for the production of embodied construction materials is derived from the inventory for the corresponding materials in the Ecoinvent database (Table 10 below).

Box 1. Possible alternative approach for calculating final energy demand per construction material

The Ecoinvent database could also be used to calculate specific energy content for each construction material with data from Table 10 and 11. In this study however, the use of Ecoinvent was limited to identifying the relative energy mix in the production of each construction material (Table 6). This energy mix was rather used to determine embodied energy use based on values found in literature (Table 5). This is because absolute values from literature were deemed to be more relevant to the EU materials market. Ecoinvent could however also provide data that is for a certain extent applicable to the EU market, providing a possible alternative calculation approach. Ultimately, both calculation approaches have been tested and provided a similar outcome to the study.

Table 10 Primary resource requirement for 1 m³ of construction material according to the Ecoinvent database and generated with Simapro software

Material [1 m^3]	Oil [kg]	Uranium [g]	Coal* [kg]	NG [m^3]	Geoth. [MJ]	Biomass [MJ]	Solar [MJ]	Hydro [MJ]	Wind [MJ]
Sawnwood, beam, softwood, dried (u=20%), planed {Europe without Switzerland}| planing, beam, softwood, u=20% | Cut-off, S	9.7	0.34	13.0	3.3	1.3	15201	0.1	35.0	21.4
Oriented strand board {RoW}| market for oriented strand board | Cut-off, S	52.7	0.54	90.6	42.3	5.4	17674	0.2	156.2	33.7
Cellulose fibre {CH}| cellulose fibre production | Cut-off, S	0.9	0.05	1.8	0.6	0.1	3.4	0.0	18.3	1.4
Polystyrene foam slab for perimeter insulation {CH}| processing | Cut-off, S	36.1	0.34	6.7	31.8	0.5	17.6	0.0	53.6	2.9
Plasterboard{CH}| production | Cut-off, U	9.8	0.65	22.1	18.9	0.2	421	0.2	211.0	21.6
Glass wool mat {CH}| production | Cut-off, S	2.1	0.39	5.7	7.1	0.5	28.5	0.0	144.6	9.3
Reinforcing steel {GLO}| market for | Cut-off, S	763	18.0	615.0	659.3	145.3	2266	13.7	52516	1249
Concrete, 50MPa {RoW}| concrete production 50MPa | Cut-off, S	26.4	0.23	45.2	7.9	2.3	41.8	0.1	71.0	14.3

*entails both brown- and hard coal

These primary resource- and energy inputs per construction material were then converted to final energy per energy carrier with data from Tables 12, 13 and 14 (Appendix VII), as displayed in Table 11 below:

Table 11 Final energy use per m^3 construction material as derived from Table 10 with conversion efficiencies from Table 12 (Appendix VII)

	Final Energy Use in [MJ/m^3]				
Material	**Diesel**	**Coal***	**NG***	**Biomass***	**Electricity****
Sawnwood, beam, softwood, dried (u=20%), planed {Europe without Switzerland}| planing, beam, softwood, u=20% | Cut-off, S	51.9	154.7	86.1	3200	101
Oriented strand board {RoW}| market for oriented strand board | Cut-off, S	281.1	1133.5	1317.9	4423	315
Cellulose fibre {CH}| cellulose fibre production | Cut-off, S	4.6	18.1	14.0	0	33
Polystyrene foam slab for perimeter insulation {CH}| processing | Cut-off, S	192.4	69.8	1013.5	0	117
Plasterboard{CH}| production | Cut-off, U	52.5	226.9	537.3	0	400
Glass wool mat {CH}| production | Cut-off, S	11.3	33.1	180.2	0	48
Reinforcing steel {GLO}| market for | Cut-off, S	4,000	67,200	4,800	0	30,400
Concrete, 50MPa {RoW}| concrete production 50MPa | Cut-off, S	141.0	568.5	231.0	0	140

*For heat conversion
** Includes electricity generated from coal, uranium, NG, biomass and renewables based on the EU electricity mix as elaborated on in the rest of this section; conversion efficiencies from Table 12 in Appendix VII were used for this

Important to note is that the indicated share of electricity (in Table 11) constitutes a mix that represents the EU average as displayed in Fig. 43 below. The electricity share (as in Table 11) was determined by 1) summing the amount of electricity generated by renewables and nuclear (from Table 10 and converted with data from Table 12) and 2) then adding NG, coal and biomass (also from Table 10 and converted with data from Table 12) until their respective shares as defined in Fig. 43 were represented in the electricity mix.

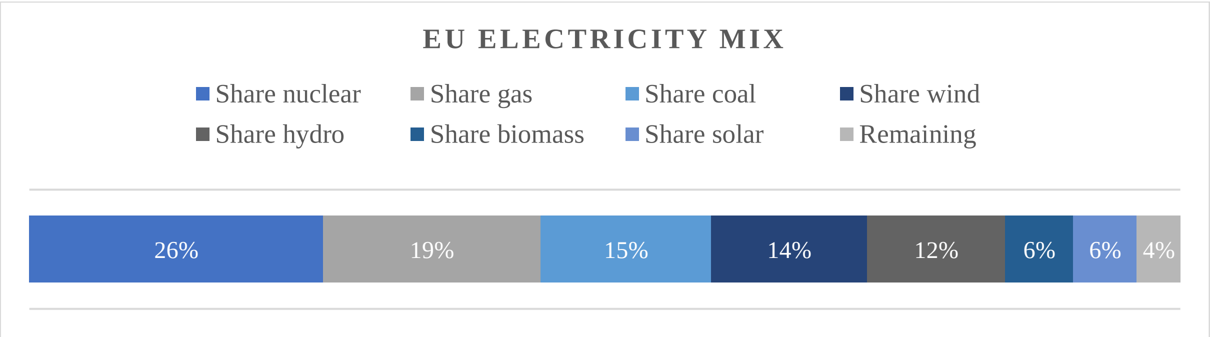


Figure 43 Average EU electricity mix in 2021 as derived from Statista, 2021b to be used as mix for composing the electricity share in Table 8

The resulting final energy per energy carrier was then converted to the energy mix (in % shares) per material as displayed in Table 6 (Section 4.4.1). The conversion efficiencies in Table 12 (Appendix VII) were again used.

Mind that two last alterations for establishing Table 6 were made to improve accuracy of the energy mix for each material:

1) The electricity share in mineral wool production was set to 18% as stated in the study that Krijgsman & Marsidi (2019) made for PBL, which contains accurate data for glass wool production for the Netherlands which is deemed to have better relevance compared to Ecoinvent data constituting Swiss glass wool production.
2) The electricity share in steel production was set to 29% to account for respectively 40% EAF and 60% BOF in the EU steelmaking industry (Eurofer, 2020).

Finally, the mix (Table 6, Section 4.4) was used to convert primary energy (found in literature) to embodied energy as displayed in Table 5 (Section 4.4).

Appendix VII – Data Sheet: Energy Carriers

This section displays conversion efficiencies, energy densities, EF and prices of energy carriers as used in calculations of this study (Sections 4.4.1, 4.4.2 and Appendix VI).

1. Energy Densities and Conversion Efficiencies

Table 12 below displays the conversion efficiencies and energy densities as used in calculations of this study (Sections 4.4.1, 4.4.2 and Appendix VI).

Table 12 Conversion efficiencies used for 1) calculations from primary- to final energy demand shares as displayed in Table 8 and 2) calculations from embodied energy demand to primary energy demand for EF calculations

Parameter	Quantity	Source
Energy density diesel* u	36.0 MJ/L	Engineering Toolbox (n.d.-a)
Energy density NG* u	65.19 MJ/m^3	Engineering Toolbox (n.d.-a)
Biomass energy content*	18.7 MJ/kg	Blok & Nieuwlaar (2020)
Electricity content uranium	45 MWh/kg	Euronuclear (n.d.)
Energy density coal*	26.1 GJ/t	Engineering Toolbox (n.d.-b)
Conversion efficiency diesel engine truck	44%	Lutsey (2015)
Conversion efficiency coal to electricity	33%	Hitchin (2018)
Conversion efficiency coal to heat in kiln	50%	Kline Consulting (2022)
Solar to electricity	20%	TNO (n.d.)
Wind to electricity	40%	EPA (2013)
Geothermal to electricity	12%	Zarrouk & Moon (2014)
Hydro to electricity	90%	USBR (2005)
Crude oil to diesel conversion rate	28.6%	EIA (2021)
Conversion efficiency NG to heat	50%	Mickey (2017)

*Based on Lower Heating Value

2. Emission Factors and Energy Prices

Table 13 below displays the EF and current energy prices of each energy carrier as used in calculations of this study.

Table 13 Used emission factors for different energy carriers

Energy carrier	Emission Factor [$kgCO_2$/GJ]*	Source	Price	in [€/GJ]	Source
Coal	95	Blok & Nieuwlaar (2020)	132.62 €/t	5.08	CBS (2022a) & European Commission (2021c)
Biomass	109	RVO (2019)	0.029 €/kWh	10.36	Heat Roadmap (2017)
Electricity EU	70.27	EEA (2021)	0.124 €/kWh	44.78	UK Government (2022)
Natrual Gas	56	Blok & Nieuwlaar (2020)	0.10 €/kWh	27.78	CBS (2022b)
Diesel	74	Blok & Nieuwlaar (2020)	2.07 €/L	57.43	CBS (2022)
Electricity BGDD	0	Saathof (2022)	0.068 €/kWh	24.48	Saathof (2022)

*Based on Lower Heating Value

Appendix VIII – Data Sheet: Materials

This section provides data of primary materials as used in calculations in Section 4 of this study.

1. Material Prices and Densities

Table 14 below displays the material costs that are used for the total materials cost-calculations in Section 4.5 of this study. Furthermore, the table displays material densities that were used to convert embodied energy (Section 4.4.1), energy mix per construction material (Appendix VI) and prices of materials (Section 4.4.2). Prices for NG and electricity purchase for the assembly factory can be found in Table 13 in Appendix VII.

Table 14 Prices of construction materials as delivered to the assembly factory in €/m³

Material	**Price per m³**	**Density ρ [kg/m³]**	**Source***
Timber**	€650	470	Engineering Toolbox-b (2004)
OSB	€757	600	WPIF (2014)
Cellulose	€85	800	British Gypsum (2022)
EPS	€58	45	Isolatie-info (2021)
Plasterboard	€256	45	Isofloc (2014)
Mineral wool	€56	33	Kingler (2011)
Steel	€15,882	8000	Civilsguide (2021)
Concrete***	€160	2300	Geocentrix (2004)

* Source only applies to densities; prices are sourced from suppliers from BGDD
** Coniferous, EU sourced
*** C50 strength grade

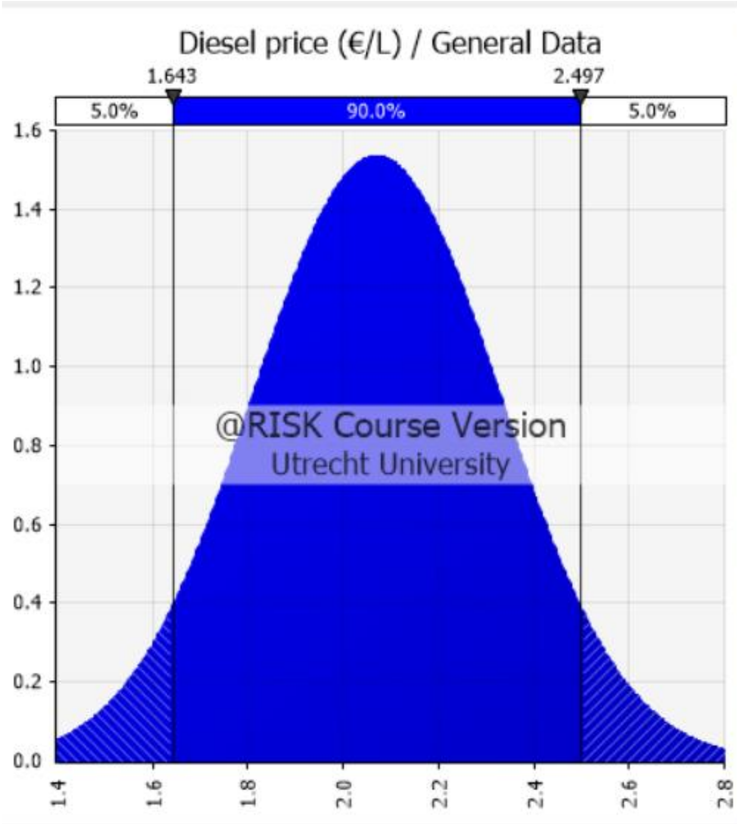
2. Transport Distances of Materials

What is more, Table 15 below displays the transport distances to transport materials from suppliers to the factory at the construction company. Transport distances are based on information from suppliers and the production company regarding the locations of their production facilities. This data is used as input data for final energy use calculations (Section 4.4.1) and energy cost calculations (Section 4.4.2). Transport is assumed to be by heavy truck with trailed, which entails an energy intensity of 1.1 MJ/tkm (Klein et al., 2021).

Table 15 Transport distances to transport semi-finished products to assembly factory of the construction company to produce construction elements

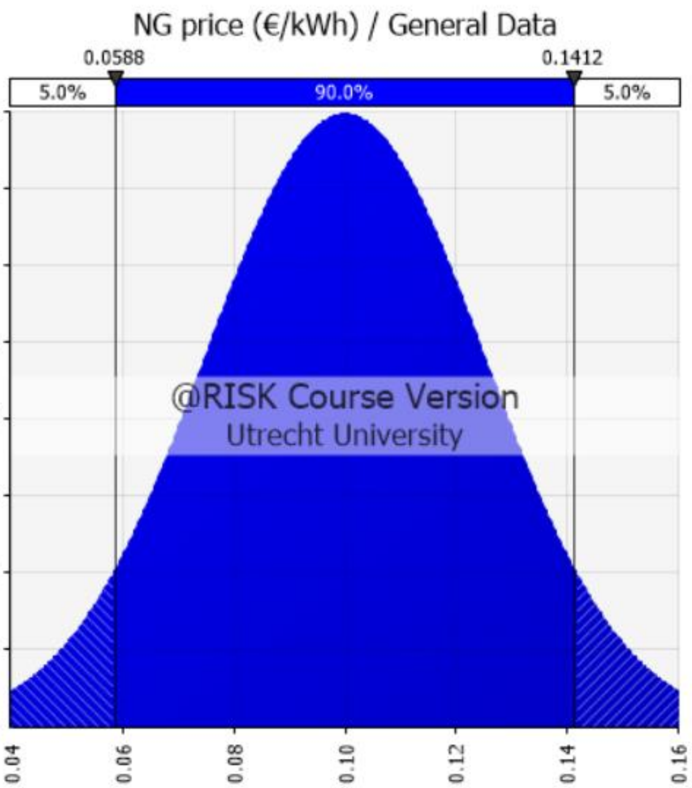
Material	**From**	**To**	**Distance [km]**
Timber	Rörvik (SE)	Dokkum (NL)	932
OSB	Genk (BE)	Dokkum (NL)	356
Cellulose	Hombeek (BE)	Dokkum (NL)	336
EPS	Goor (NL)	Dokkum via Kampen (NL)	212
Plasterboard	Oosterhout (NL)	Dokkum (NL)	243
Mineral wool	Roermond (NL)	Dokkum (NL)	305
Steel	Ijmuiden (NL)	Dokkum via Kampen (NL)	233
Concrete	Kampen (NL)	Dokkum (NL)	111

Appendix IX – Distribution of Input Parameters for Impact Analysis



Statistics	Normal
Minimum	−∞
Maximum	+∞
Mean	2.0700
Mode	2.0700
Median	2.0700
Std Dev	0.2597
Skewness	0.0000
Kurtosis	3.0000
Left X	1.643
Left P	5.0%
Right X	2.497
Right P	95.0%
Dif. X	0.8543
Dif. P	90.0%
1%	1.4658
2.5%	1.5610
5%	1.6428
10%	1.7372
20%	1.8514
25%	1.8948
30%	1.9338

Figure 44 Normal distribution of diesel based on historic price fluctuations



Statistics	Normal
Minimum	−∞
Maximum	+∞
Mean	0.10000
Mode	0.10000
Median	0.10000
Std Dev	0.02503
Skewness	0.0000
Kurtosis	3.0000
Left X	0.0588
Left P	5.0%
Right X	0.1412
Right P	95.0%
Dif. X	0.08234
Dif. P	90.0%
1%	0.04177
2.5%	0.05094
5%	0.05883
10%	0.06792
20%	0.07893
25%	0.08312
30%	0.08687

Figure 45 Normal distribution of NG based on historic price fluctuations

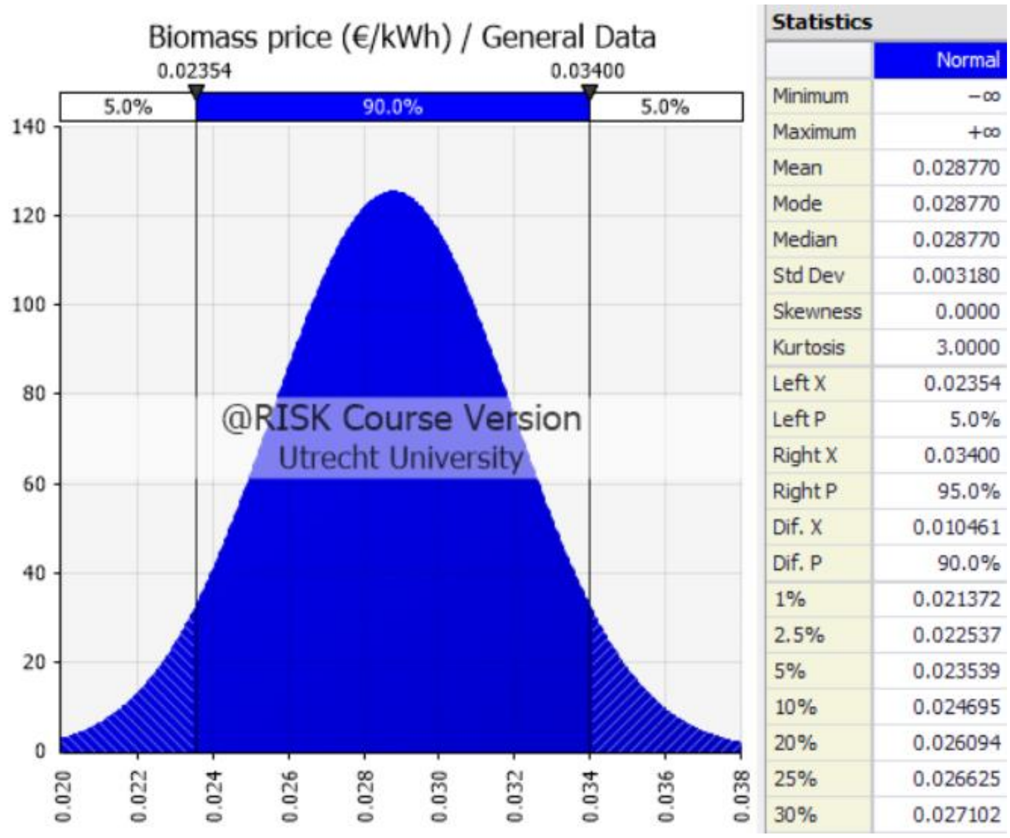


Figure 46 Normal distribution of biomass based on historic price fluctuations

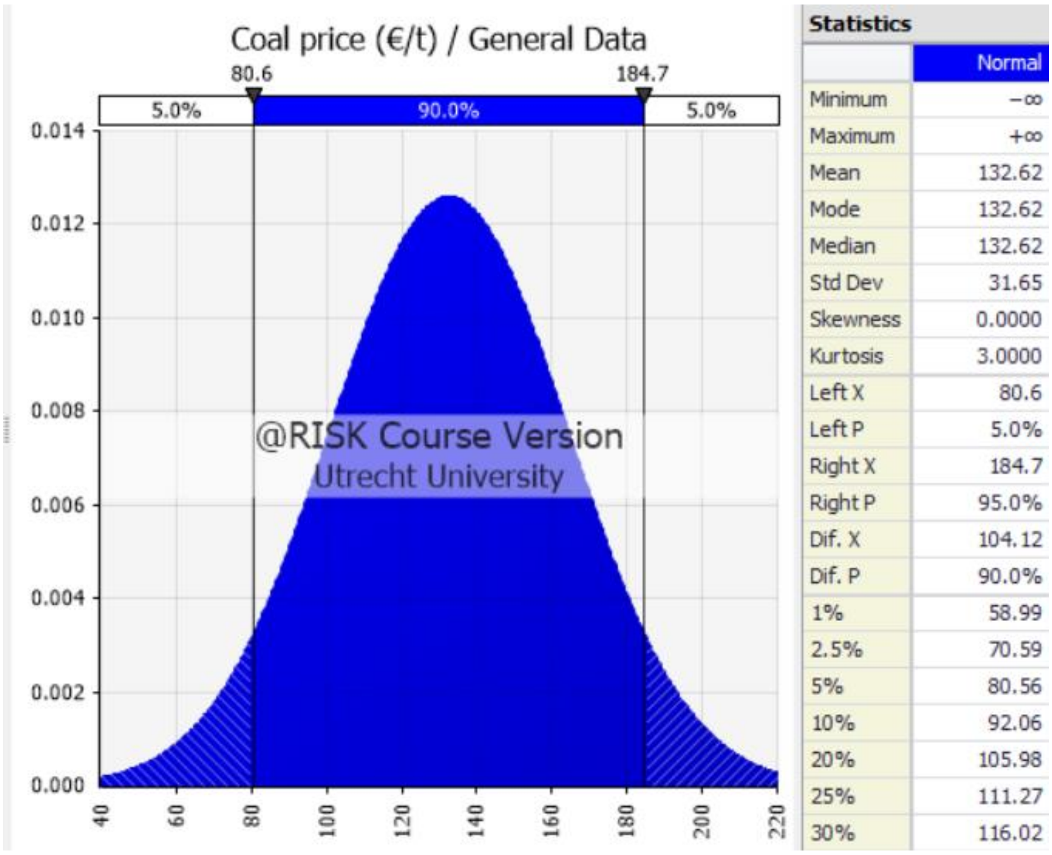


Figure 47 Normal distribution of coal based on historic price fluctuations

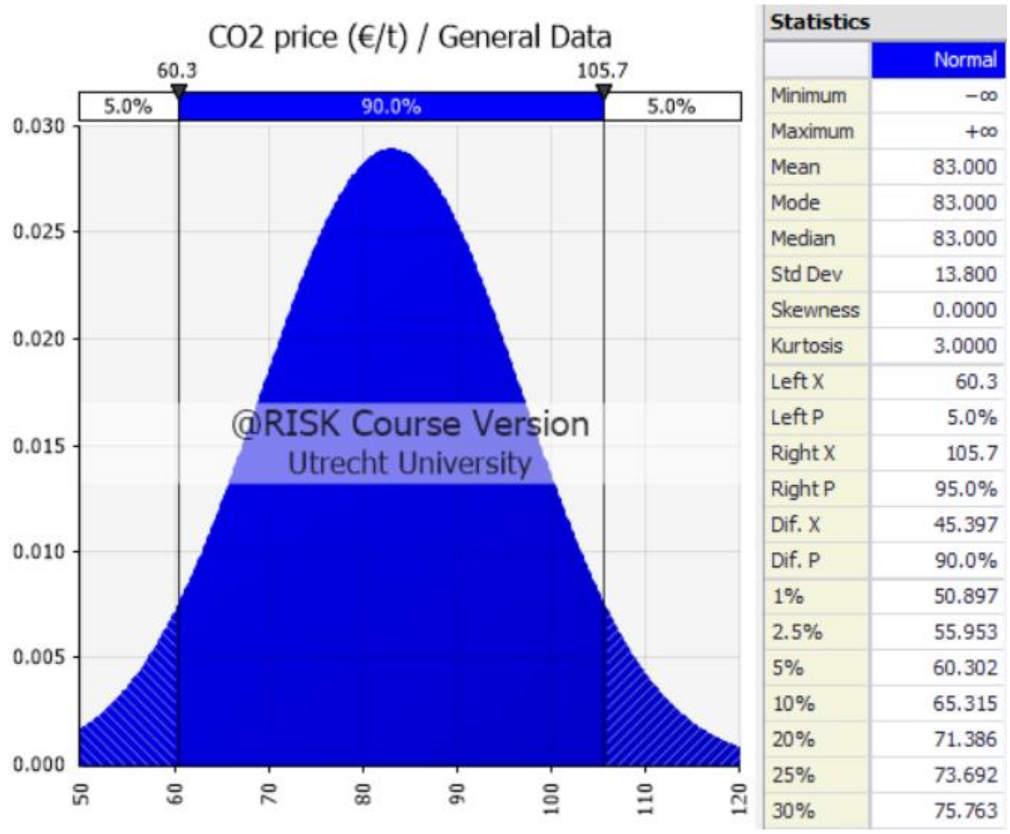


Figure 48 Normal distribution of CO_2 based on historic price fluctuations