INTERNATIONAL MASTER OF SCIENCE IN ADVANCED MINERAL RESOURCES DEVELOPMENT

&

MÁSTER UNIVERSITARIO EN MINERÍA SOSTENIBLE

MASTER'S THESIS

DEPARTMENT OF GEOLOGIC AND MINING ENGENEERING

ETSI MINAS Y ENERGÍA

PROGNOSIS OF CARBON DIOXIDE SAVINGS FROM THE USE OF BIOMASS IN THE CEMENT INDUSTRY IN THE IBERIAN PENINSULA

MARIA HELENA JESUS

SUPERVISORS:

MIGUEL ÁNGEL SANJUÁN BARBUDO
AND
PEDRO MORA PERÍS

Date (July of 2023)

Escuela Técnica Superior de Ingenieros de Minas y Energía
Universidad Politécnica de Madrid

Acknowledgments

Words can't express how grateful I am to my supervisors and Master coordinators for their time and feedback.

Furthermore, this project would not have been possible without the wonderful assistance of Oficemen and SECIL, who generously offered their expertise and information.

I am also eternally thankful to my classmates, particularly my office mates, for providing feedback and moral support.

Finally, I would be negligent if I did not mention my family, particularly my parents and sisters. Their confidence in me has maintained my spirits and motivation strong throughout the process.

Table of Contents

Abstract VI

1. Introduction .... - 1 -

1.1 Global Initiatives .... - 3 -
1.2 Secondary Fuels Alternatives .... - 5 -
1.2.1 Use of Biomass .... - 6 -
1.3 Objective .... - 8 -

2. Cement Industry background .... - 9 -

2.1 Cement Process .... - 9 -
2.2 Environmental Impact of Cement Industry .... - 10 -
2.3 International Cement Industry Roadmap 2050 .... - 12 -

3. Methodology: Alternative Fuels in the Iberian Peninsula Analysis .... - 15 -

3.1 Iberian Peninsula Cement Industry Background Analysis .... - 16 -
3.1.1 Spanish Roadmap 2050 .... - 16 -
3.1.2 Portuguese Roadmap 2050 .... - 17 -
3.2 Determination of the Biomass Factor .... - 18 -
3.2.1 Laboratory Analyses .... - 19 -
3.2.2 Estimation Methods .... - 21 -

4. Results .... - 21 -

4.1 Alternative Fuels used in the Iberian Peninsula .... - 21 -
4.2 Biomass Factor .... - 24 -

5. Discussion of Results .... - 26 -

5.1 Biomass Flow .... - 26 -
5.2 Alternative Biomass Fuels and Biomass Factor Analysis .... - 29 -
5.3 Economic Analysis .... - 32 -

6. Conclusion .... - 36 -

7. References .... - 37 -

Table of Contents: Figures

Figure 1- Temperature anomaly relative to 1961 – 1990 (IPPC, 2013)...................- 1 -

Figure 2- Main carbon dioxide emitters (IPPC, 2014). ....- 2 -

Figure 3- World emissions of Greenhouse Gases (GHG) by sectors (in gigatons of CO_2equivalent) (IPPC, 2014). ....- 3 -

Figure 4- SDG's (United Nations, 2015). ....- 4 -

Figure 6-General cement manufacturing process (IEA, 2018). ....- 9 -

Figure 7- Global cement production in 2016 (CEMBUREAU's, 2020)...................- 10 -

Figure 8- Gross $CO2$ emissions for grey clinker (Andrade & Sanjuán, 2018). ....- 11 -

Figure 9- CEMBUREAU's 2050 Roadmap (CEMBUREAU's, 2020). ....- 14 -

Figure 10- Spanish Cement Roadmap (Sanjuán et al., 2020)...............................- 16 -

Figure 11- Portuguese cement roadmap 2050: Reduction potential per element of the 5C chain (ATIC, 2021a). ....- 17 -

Figure 12- Distribution of the Biomass Fuels Rate (TBC) in the CIMPOR Portuguese cement plants(CIMPOR, 2021). ....- 23 -

Figure 13- Evolution of the consumption of alternative fuels in the Outão Cement Plant (Secil & EMAS, 2021). ....- 24 -

Figure 14- Portuguese Biomass Flow (after 2019) (European Comission, 2019). .- 27 -

Figure 15- Type of biomass flow going into Biomass for energy, in Portuga l(European Comission, 2019)...- 27 -

Figure 16 - Spanish Biomass Flow (after 2019) (European Comission, 2019).......- 28 -

Figure 17- Type of biomass flow going into Biomass for energy, in Spain (European Comission, 2019)...- 28 -

Figure 18- EU27 Biomass Flow (after 2019) (European Comission, 2019)............- 29 -

Figure 19- Avoided emissions by the use of biomass in the Spanish Cement Industry (CEMA, 2021)..- 31 -

Figure 20- Prognosis for the CO_2 emissions savings by the use of biomass fuel in the clinker production, in the Iberian Peninsula. ....- 31 -

Figure 21- Emissions Trading System Graphic (EEA, 2022). ....- 33 -

Figure 22- EU Carbon Permits prices (Trading Economy, 2023). ....- 34 -

Figure 23- Cost saved by the cement industry due to decarbonization levers (Renewable Energy Agency, 2012). ....- 35 -

Abstract

Climate change is a serious global problem caused mostly by the rise amounts of greenhouse gas emissions, particularly carbon dioxide (CO_2), in the Earth's atmosphere. Because cement production is highly energy-intensive and heavily reliant on fossil fuels, the cement sector contributes significantly to CO_2 emissions. As a result, alternative, more sustainable fuel sources in the cement making process are required.

The use of biomass as an alternative fuel in the cement industry has attracted attention in the Iberian Peninsula as an effective way to minimize CO_2 emissions. Biomass energy, which is obtained from organic materials such as agricultural wastes, wood waste, or specific energy crops, is renewable and carbon neutral. However, comprehensive biomass incorporation in the cement sector demands a thorough analysis of technological, logistical, and regulatory concerns.

The use of biomass as an alternative fuel in the Iberian Peninsula cement industry has enormous promise for lowering CO_2 emissions and addressing climate change. To overcome problems and effectively adopt sustainable practices, corporations, governments, and researchers must work together.

When comparing the roadmaps developed and implemented in Iberian Peninsula, to the European version, it is feasible to conclude that they all follow a very similar path towards achieving carbon neutrality by 2050. In 2050, it is expected to reach 70 kg CO_2/t cement as average (about 80 kg CO_2 /t cement and 60 kg CO_2 /t cement). Three times more than the current value in 2023 (around 22 kg CO_2 /t cement).

1. Introduction

Climate change is one of the most pressing issues facing society today. It can be measured through statistics such as average temperature, rainfall, and drought frequency at various geographic scales, including cities, nations, and the global level. Changes in these statistics over long periods of time indicate climate change (Harmeling, 2018).

Our knowledge of climate change and its causes has substantially increased, and a clearer picture of its current and future implications is developing. Research is also shedding light on potential strategies for easing the effects of climate change and becoming ready for them. The main consequence of climate change is the global warming (Figure 1), which is the gradual increase of temperatures due to the rise of Greenhouse Gases (GHG) emissions, such as Carbon Dioxide, Methane, Water Vapor, Ozone and Nitrous Oxide, to the atmosphere (Harmeling, 2018).

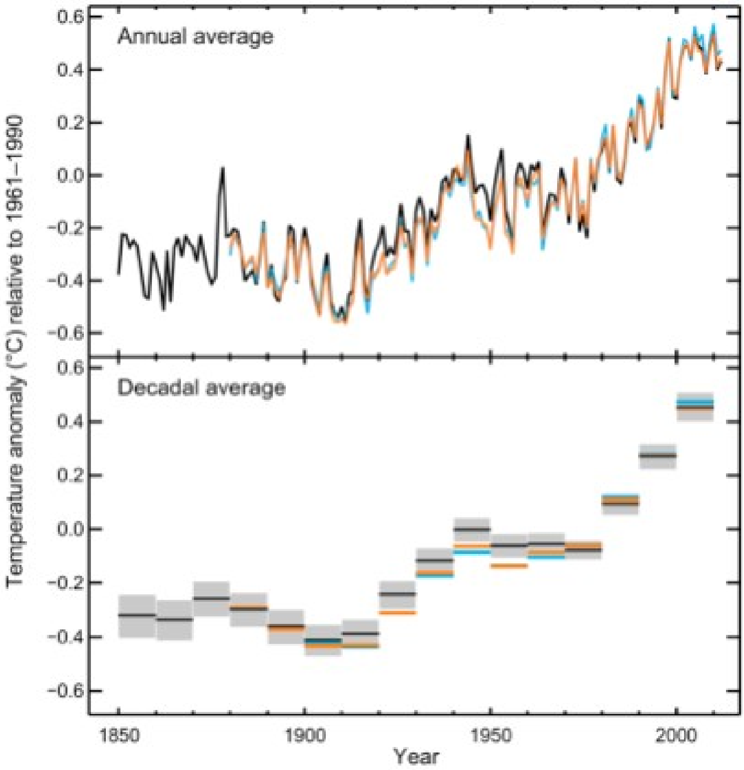


Figure 1- Temperature anomaly relative to 1961 – 1990 (IPPC, 2013).

It must be noted that human-caused greenhouse gas emissions have nearly doubled during the previous 50 years (Sanjuán et al., 2020a). These emissions come from various sources, being the sectors shown in Figure 2 the main contributors.

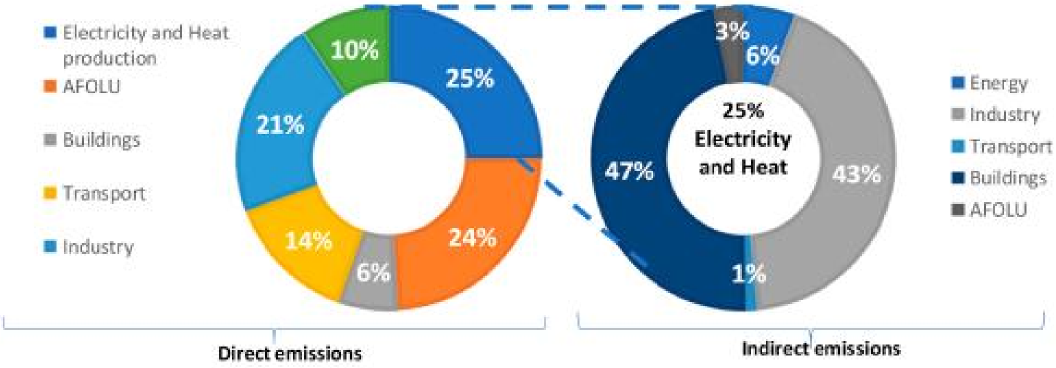


Figure 2- Main carbon dioxide emitters (IPPC, 2014).

The electricity and heat production sector, the industry sector, and the transport sector are responsible for 60% of the global direct emissions of greenhouse gases (GHG), with 25%, 21%, and 14% respectively (Figure 2). Technologies, such as better thermal insulation, hydrogen power, fuel cells, and electric engines are the best options when it comes to reduce the emissions of the aforementioned emitters. As a result, a decrease in GHG emissions is expected in the near future (Sanjuán et al., 2020a). However, reducing emissions in the industrial sector is a complex issue.

Furthermore, Figure 3 depicts the development of global greenhouse gas (GHG) emissions by economic sectors from 1970 to 2010. The rise in emissions between 2000 and 2010 was more than three quarters (+81%) attributable to industry (+45%) and energy (+36%). These findings imply the requirement for putting technical measures in place to lessen the aforementioned emissions (Sanjuán et al., 2020a).

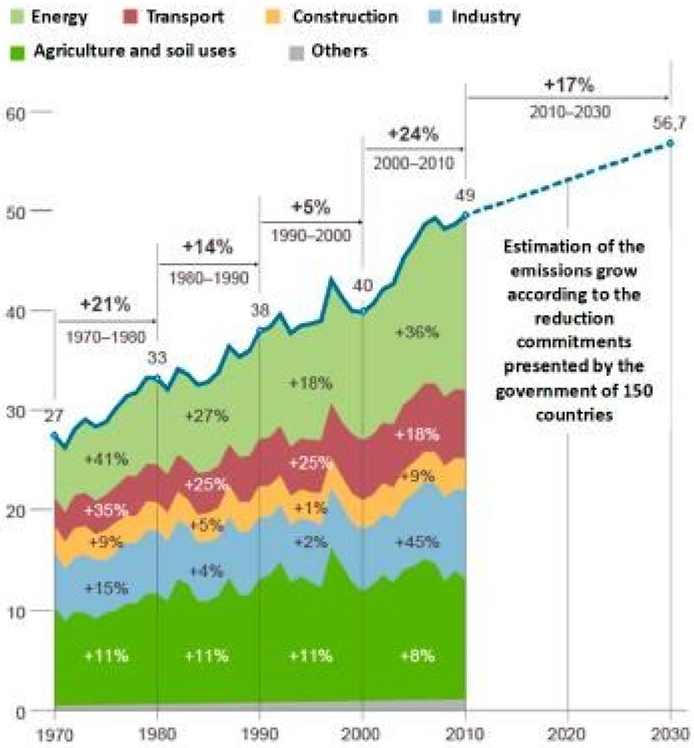


Figure 3- World emissions of Greenhouse Gases (GHG) by sectors (in gigatons of CO_2equivalent) (IPPC, 2014).

1.1 Global Initiatives

Consequently, global measures have been taken in order to prevent these events from happening.

The first international conference to discuss the environment took place in Stockholm, Sweden in 1972 (Sanjuán et al., 2022). The United Nations Conference on the Human Environment adopted a series of principles for sound management of the environment, resulting in the creation of the United Nations Environment Programme (UNEP) (United Nations, 2023). Twenty years later, in 1992, the “Earth Summit” conference took place in Rio de Janeiro, Brazil. This conference acknowledged the need for an integrated approach to balancing economic, social, and environmental considerations (Sanjuán et al., 2022). Moreover, the Kyoto Protocol was signed in 1997 and came into effect in 2005, with 126 countries committing to limit and reduce greenhouse gas emissions (United Nations, 2023). In 2000, the Millennium Summit set 8 Millennium Development Goals and in 2012, the United Nations Conference on Sustainable Development focused on the green economy and poverty eradication (United Nations, 2023). On 25 September 2015, at the United

Nations Summit on Sustainable Development, global goals to protect the planet, ensure prosperity and eradicate poverty were adopted in the “Agenda 2030” and its seventeen Sustainable Development Goals. In short, the 2030 Agenda for Sustainable Development is a plan of action focused on the well-being of people and the planet. The Agenda includes 17 Goals with 169 targets in economic, social, and environmental aspects (Sanjuán et al., 2022).

Figure 4- SDG's (United Nations, 2015).

In addition, at COP 21 in Paris (21st Conference of the Parties to the United Nations Framework Convention on Climate Change, UNFCCC) in December 2015, 195 nations reached a historic agreement to combat climate change and take the necessary actions to achieve a sustainable, low-carbon future (Sanjuán et al., 2022). The overarching objective of the Paris Agreement was a global response to climate change by setting a global warming limit below 2°C and preferably below 1.5°C compared to pre-industrial levels (United Nations, 2023).

Four years later, in Madrid, took place the United Nations Climate Change conference which consisted in setting up bases for the compromised countries present their commitments in 2022, related to the GHG emissions. Lastly, in 2021, COP26 focused on financing actions to increase climate ambition and the principles of international solidarity and urgency (United Nations, 2023).

Although, while the climate change was in the origin of innumerous movements and projects around the world in order to mitigate its existence, European Union also took some specific measures.

Consequently, in 2019, the European Union publishes “The European Green Deal”, which presents a strategy to achieve the European Union's goal to be the first climate-neutral continent by 2050 (Sanjuán et al., 2022). This is to be achieved by making efficient use of resources and boosting a competitive European economy. Accordingly, the European Commission drafted the European Climate Act as an institutional framework for achieving climate neutrality by 2050, which entered into force on 29 July 2021. This Act also sets the objective of reducing net greenhouse gas (GHG) emissions by more than 55% below 1990 levels by 2030 (United Nations, 2023).

The European Commission has analyzed the impacts of climate change in Europe and the adaptation pathways to be pursued to achieve a resilient Europe. The JRC PESETA IV report concludes that EU ecosystems, people and economies will face major impacts from climate change if GHG emissions are not urgently mitigated or the necessary actions for adaptation to climate change are not taken. The intensity of the impact of climate change will be very different between northern and southern Europe, with southern regions being hit hardest by the effects of extreme heat, water scarcity, drought, forest fires and agricultural losses. As a result, Spain, Portugal, Italy, and Greece must fight even harder to limit global warming to below the 2°C pledged at COP21 in Paris (United Nations, 2023).

1.2 Secondary Fuels Alternatives

The world currently relies heavily on fossil fuels such as coal, petroleum, and natural gas to meet its energy needs. These fuels, however, are finite in supply and have negative effects on the environment, being major emitter of GHG. To address these issues, alternative fuels have been developed as a replacement for conventional fossil fuels.

The eight major categories that are typically used to classify alternative fuels and energy sources are: biomass, natural gas, waste-derived fuels, renewable energy, and nuclear energy. Out of these categories, biomass has an extremely important role in the global CO_2 emissions reduction in the cement industry (EU Comission, 2022).

Biomass refers, according with the Renewable Energy directive II (RED II), to the biodegradable fraction of products, waste, and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin (Oficemen, 2022).

In accordance with the Monitoring and Reporting Regulations (MRR), Article 3, several other concepts must also be defined (EU Comission, 2022):

- *"Biomass fuels"* refer to gaseous and solid fuels made from biomass.
- *"Biogas"* refers to gaseous fuels produced from biomass.
- *"Waste"* refers to waste as defined in point 1 of Article 3 of Directive 2008/98/EC but does not include substances intentionally modified or contaminated to meet this definition.
- *"Residue"* refers to a substance that is not the end product directly sought after by a production process, and which is not a primary aim of the process, having not been deliberately modified to produce it.
- *"Agricultural, aquaculture, fisheries, and forestry residues"* refer to residues directly generated by agriculture, aquaculture, fisheries, and forestry, but not those from related industries or processing.
- *"Bioliquids"* refer to liquid fuel produced from biomass for non-transport energy purposes, such as for electricity and heating and cooling.
- *"Biofuels"* refer to liquid fuels for transport produced from biomass.

1.2.1 Use of Biomass

According to European regulations, the emission factor for biomass is zero if it meets the sustainability and greenhouse gas emission reduction criteria outlined in the Renewable Energy Sources Directive (RED II). This is stated in both Article 38 of Implementing Regulation 2018/2066 and Annex IV of Directive 2003/87/EC.

However, biofuels, bioliquids and biomass fuels made from non-agricultural, aquaculture, fisheries, or forestry waste, must only comply with the greenhouse gas emission reduction criteria set out in Directive (EU) 2018/2001. This also applies to residues and waste that are first transformed into a product before being transformed into biofuels, bioliquids and biomass fuels (EU Comission, 2022).

When the RED II requires GHG savings to be proved, this means that biomass energy must result in lower life cycle emissions than comparable fossil fuels. In section C of Annex V to the RED II, the technique for estimating GHG savings from biofuels and bioliquids is described. Section B of Annex VI to the RED II contains the technique for biomass fuels (biogas and solid biomass). Here is a brief summary of the methodology:

First, the formula for calculating emissions from the use of biomass is applied (EU Comission, 2022):

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{cus} - e_{ccr} \qquad (1)$$

Where:

e_{ec}: Emissions from the extraction or cultivation of raw materials;

e_l : Annualized emissions from carbon stock changes caused by land-use change;

e_p : Emissions from processing;

e_{td} : Emissions from transport and distribution;

e_u : Emissions from the fuel in use;

e_{sca} : Emission savings from soil carbon accumulation via improved agricultural management;

e_{cus} : Emission savings from CO_2 capture and geological storage;

e_{ccr} : Emission savings from CO_2 capture and replacement.

As a second step, the GHG savings are calculated as follows (EU Comission, 2022):

$$REDUCTION = (EC_{F(h\&c,el)} - EC_{B(h\&c,el)})/EC_{F\,(h\&c,el)} \qquad (2)$$

Where:

$EC_{B(h\&c,el)}$: Total emissions from the biomass fuel or bioliquid;

$EC_{F(h\&c,el)}$: Total emissions from the fossil fuel comparator for heating, cooling, or electricity.

The GHG savings must, afterwards, be evaluated against the standards outlined in RED II Article 29. Therefore, for biomass to be considered emission neutral, it is necessary to demonstrate compliance or non-applicability with the RED II criteria (Oficemen, 2022).

Consequently, considering biomass is carbon neutral, meaning that the carbon dioxide emitted when it is burned is equal to the carbon dioxide absorbed by it, will be an essential factor when it comes to the reduction of CO_2 emissions and leading to the achievement of the targets set by the European Union. For that reason, it’s a method that is exponentially being used all around the world in the cement industry.

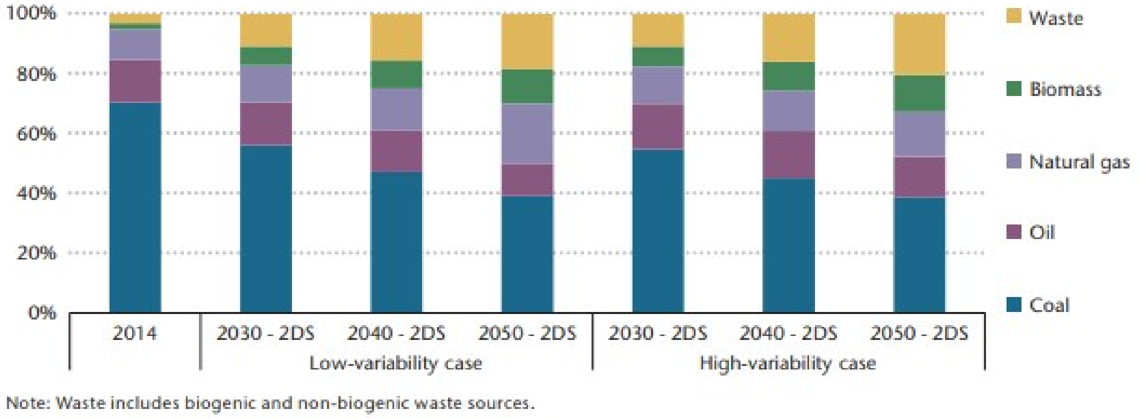


Figure 5- Global thermal energy mix in cement in the 2DS[1] (IEA, 2018).

1.3 Objective

The cement sector is currently deploying significant investments with clear focus to reach carbon neutrality in 2050. To achieve carbon neutrality down the cement and concrete value chain, the cement industry is utilizing some levers. One of them is the replacement of fossil fuels by non-recyclable waste and biomass waste. A realistic pathway is critical to decarbonize energy-intensive sectors like Portland cement.

The central aim of this Master Thesis was to analyze the technical issues regarding the use of biomass in the cement industry in Portugal and Spain and to perform a prognosis of carbon dioxide savings from the use of biomass in the cement industry in the Iberian Peninsula. The present state of knowledge could allow us to foresee the future carbon dioxide savings from the use of biomass in the cement industry in the Iberian Peninsula.

---

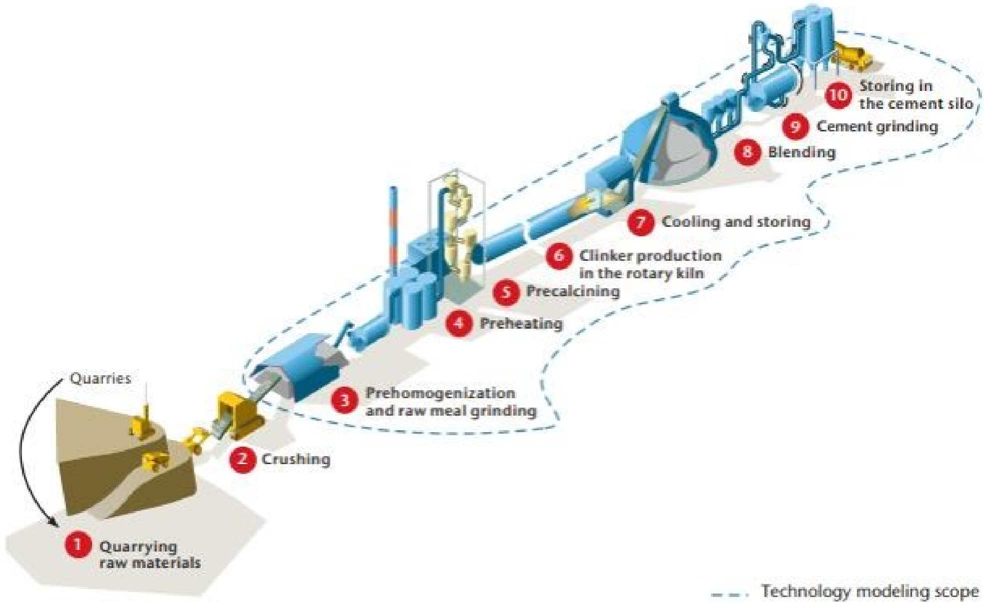
[1] 2DS- Describes an energy system consistent with the emissions trajectory that recent climate science research indicates. It would give an 80 per cent chance of limiting global temperature increase to 2°C(United Nations, 2023).

2. Cement Industry background

Cement is a vital building material, and its production is energy intensive. Historically, coal has been the primary fuel used in the cement industry, but other fuels such as gas, oil, waste materials, and petroleum coke have also been used. The cement industry is also facing pressure to reduce emissions, such as $\mathrm{CO_2}$ and $\mathrm{NO_x}$, as was already pointed before (IEA, 2018). Alternative fuels, in cement manufacturing not only can reduce energy costs, but also have environmental benefits such as conserving non-renewable resources, reducing waste disposal, and decreasing emissions. The use of low-grade alternative fuels in some kiln systems can also reduce $\mathrm{NO_X}$ emissions. Overall, using alternative fuels in cement production can lead to a net reduction in global $\mathrm{CO_2}$ emissions (Chinyama, 2016).

2.1 Cement Process

Cement manufacture is a three-stage process: raw materials preparation, clinker production and clinker grinding with other components to produce cement.



Note: A dry-process kiln is shown with a precalciner and multistage cyclone preheater, which is considered state-of-the-art technology. The modelling results used for the analysis in this roadmap include steps 3-10 of the above figure.

Figure 6-General cement manufacturing process (IEA, 2018).

Firstly, different raw materials are mixed and milled into a homogeneous powder, which is then heated to a sintering temperature as high as 1450 °C in a cement kiln where direct emissions of CO_2 occur (Step 6- Figure 6). In this process, the chemical bonds of the raw materials are broken down and then they are recombined into new compounds. The result is called clinker. Typically, 30-40% of direct CO_2 emissions comes from the combustion of fuels in this process, as was already mentioned; the remaining 60-70% comes from the chemical reactions involved in converting limestone to calcium oxide, a precursor to the formation of calcium silicates, which gives cement its strength (Leetham, 2015).
Clinker is then inter-ground with gypsum to produce cement. Other components, including fly ash, ground granulated blast furnace slag (GGBFS) and fine limestone, can be inter-ground or blended, depending on the required technical properties of the finished cement. Cement can be produced at the kiln site, or at separate grinding or blending plants. Blended cements or "combinations" can also be produced at the concrete plant. There are two basic types of clinker production – "wet" or "dry" – depending on the moisture content of raw materials, and there are also different kiln designs. The wet process consumes more energy than the dry process, as the moisture needs to evaporate (Aragaw, 2016).

2.2 Environmental Impact of Cement Industry

According to Rob Jackson, a climate scientist at Stanford University and leader of the Global Carbon Project, "Cement emissions have grown faster than most other carbon sources", attributing this largely to an increase in manufacturing in China (Tigue, 2022).

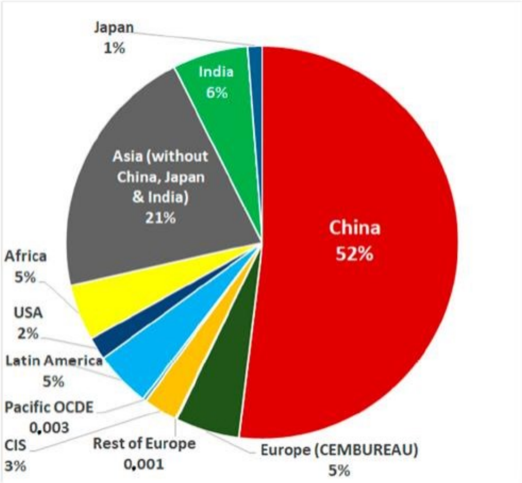


Figure 7- Global cement production in 2016 (CEMBUREAU's, 2020).

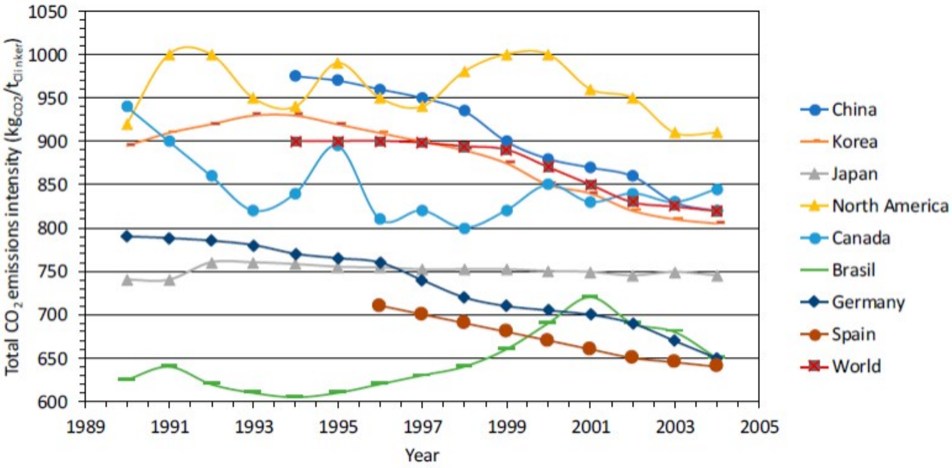


Figure 8- Gross CO_2 emissions for grey clinker (Andrade & Sanjuán, 2018).

Calcination of raw materials, mostly limestone calcination, is responsible for around 65% of the carbon dioxide emissions of the cement industry. The combustion of fuel produces the final 35% of emissions. As a result, the calcination of the raw materials created in clinker kilns is responsible for around 3% of the world's anthropogenic CO_2 emissions (Sanjuán et al., 2020b).

Currently, the production of cement is responsible for, approximately, 7.4 % of global CO_2 emissions. However, it must be considered that concrete carbonates, which means that it can uptake CO_2 across time. This phenomenon it’s still being study, but it’s believed that it could compensate for around 5% of the calcination emissions (Andrade & Sanjuán, 2018).

According to the International Energy Agency's (IEA) worldwide cement sector data for 2014, the cement industry was the second-largest industrial carbon dioxide emitter overall and the largest industrial process emitter (63% CO_2 process and 37% energy-related carbon dioxide). The cement industry was the third-largest industrial energy user in terms of energy consumption, using 61% coal, 13% electricity, 13% oil, 9% gas, 3% wastes, and 2% biomass (Andrade & Sanjuán, 2018). As a result, the cement sector may contribute significantly to reducing carbon dioxide emissions.

The usage of cement-based products like mortars and concretes has improved infrastructures like transportation, water supply, and energy in general (Blair et al., 2021). Therefore, cement manufacturing has a significant impact on both economic growth and human well-being (society), which are two of the three pillars of sustainable development (Sanjuán et al., 2020b). Moreover, the use of alternative fuels, with a percentage of biomass will contribute to affordable and clean energy, which is directly related to the effort of environmental preservation (Blair et al., 2021).

Additionally, the cement industry has made enormous efforts to support sustainable development, which have been recognized. Sanitation, infrastructure, sustainable cities, and climate action all depend on cement-based materials (Andrade & Sanjuán, 2018).

2.3 International Cement Industry Roadmap 2050

The European Green Deal and its initiatives made quick and significant decisions that have long and short-term effects on the European cement industry. Therefore, new measures should be implemented in order to effectively reduce the negative effects this industry has on global warming and climate change.

Thus, the Cement Sustainability Initiative (CSI) created a plan in order to achieve climate neutrality by 2050, as well as having into account the human well-being.

The Cement Sustainability Initiative (CSI) is a global effort by 24 major cement producers with operations in more than 100 countries. Members of CSI think that pursuing sustainable development makes the business stronger. These businesses, which range in size from extremely large multinationals to smaller local producers, produce about 30% of the cement consumed worldwide (IEA, 2018).

The "Vision 2050: Time to Transform" outlines a plan for change in systems and provides a framework for businesses to follow in the next decade. The framework is comprised of nine transformation pathways in critical areas such as energy, transportation, housing, health, financial, food, water and sanitation and material and products. These pathways align with the Sustainable Development Goals and the Paris Agreement. Each pathway includes concrete action to assist companies in making transformative changes in their practices and their impact on society (World Business Council for Sustainable Development, 2021). Moreover, was also developed a “Technology Roadmap” by partners and collaborators with specialized expertise from around the world in collaboration with the International Energy Agency (IEA), with the goal of achieving the 2050 carbon neutrality (IEA, 2018).

The “Technology Roadmap” concentrates on energy efficiency and carbon reduction strategies in the cement production process, but also acknowledges the importance of reducing CO_2 emissions in the entire life cycle of cement, concrete, and construction. The roadmap examines how the cement industry fits into the wider energy system, as well as potential limitations in sourcing raw materials for blended cements and alternative binding materials. It also explores the process requirements for curing alternative binding materials, as this has the potential to significantly decrease the overall carbon footprint (World

Business Council for Sustainable Development, 2021). The cement sector is committed to reducing emissions not just during production but throughout the entire construction process. By taking a holistic approach and collaborating with all stakeholders in the construction value chain, further emissions reductions can be achieved (IEA, 2018).
The main actions proposed are (IEA, 2018):

- Optimizing the use of concrete in construction. Lean design and efficient concrete specification can reduce waste by balancing the lowest carbon alternative with the best technical performance needed for a given application.
- Maximizing design life of buildings and infrastructure. Concrete's strength allows for extended design lives with little maintenance, and a purposeful design can guarantee that the built application is resilient to change and remains useful.
- Reducing operational energy. Utilizing concrete's intrinsic thermal mass characteristics to their fullest potential can cut down on a building's lifetime operational carbon emissions.
- Contributing to the albedo effect. For example, since concrete surfaces are bright in color and reflect light, this can lower city air temperatures and lessen the requirement for tunnel lighting.
- Encouraging reuse and recycling. Reusing concrete structures and infrastructure parts and recycling concrete can lessen the impact of new construction by reducing the need for primary concrete and preventing the production-related carbon emissions.
- Optimizing recarbonation. Over their lifetime, items made of cement absorb and chemically fix CO_2. Recarbonation is a slow process that can be sped up, particularly at the end of its useful life, by increasing the exposed surface area with the surroundings.

In parallel, the European Cement Association (CEMBUREAU’s) also develop a “Roadmap 2050”, with the same goals and principles as the plans described before. In order to achieve carbon neutrality along the cement and concrete value chain by 2050, as stated in the Carbon Neutrality Roadmap, significant CO_2 reductions must be made between now and 2030. Its main finding is that, in order to attain zero net emissions by 2050, CO_2 emissions can be decreased by taking action at each stage of the value chain, including clinker, cement, concrete, construction, and (re)carbonation (5C’s) (CEMBUREAU’s, 2020).

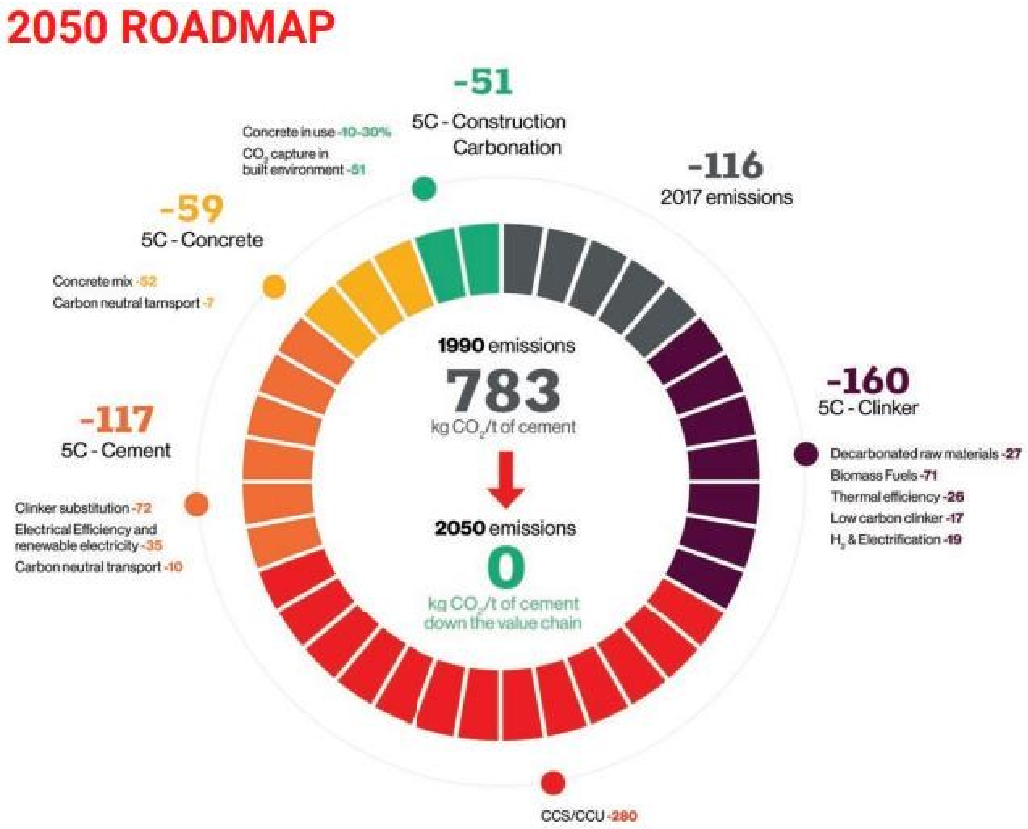


Figure 9- CEMBUREAU’s 2050 Roadmap (CEMBUREAU’s, 2020).

While some of these emission reductions will be made possible by the adoption of ground-breaking technologies, it is vital to note that CO_2 savings can also be made with modest technology investments. From the creation of clinker to the recarbonation and recycling of concrete, a variety of technologies, regulations, and production adjustments will be required. For instance, replacing fossil fuels with non-recyclable and biomass waste; developing novel low-clinker cements; implementing cutting-edge carbon capture and storage/use technologies (CCUS); and optimizing concrete mixtures and construction methods (CEMBUREAU’s, 2020).

In that way, one of the most important strategies or levers for reducing the CO_2 emissions footprint of cement production and for supporting the global cement industry in achieving the roadmap vision pathway is “Switching to alternative fuels (fuels that are less carbon intensive than conventional fuels)”. This methodology should be adopted, promoting the substitution of carbon-intensive fossil fuels with biomass and waste resources as fuels in cement kilns.

The European Roadmap sets as a goal, for biomass fuel switch (clinker), a potential reduction of 30 kg CO_2 /t cement in 2030 and 71 kg CO_2 /t cement in 2050 (Oficemen, 2021).

This study will focus on this strategy of the roadmap, applied in the clinker process, and specifically examine the use of alternative fuels with biomass, as means of achieving the targets outlined in The European Green Deal.

3. Methodology: Alternative Fuels in the Iberian Peninsula Analysis

The Iberian Peninsula is located in southwestern Europe, with Spain occupying the majority (85%) of its land and Portugal (15%) located in the far southwestern corner. Other small areas are occupied by Andorra, France, and Gibraltar (UK). Spain is the most populous, economically significant, and largest cement producer in the region, while Portugal has a much smaller cement industry (Edwards, 2017). Similar to many other EU nations, huge multinational cement makers control and dominate Iberian Peninsula's cement production base.

In Spain, the combined capacity of Cemex, LafargeHolcim, HeidelbergCement, CRH, and Votorantim is 24.4Mt/yr., or about 58%. Locally owned manufacturers, most notably Grupo Cementos Portland Valderrivas (CPV), which was largest producer in Spain in 2017, accounts for 17.6Mt/yr. (42%) of the integrated capacity. Cementos Molins and SA Tudela Veguín are examples of more regional manufacturers (Edwards, 2017).

According to The Spanish Cement Association (Oficemen) data, pet coke was the primary fuel used by the Spanish cement industry in 2015, accounting for almost two-thirds of all fuel consumed. However, the industry also utilized a variety of alternative fuels, accounting for 33% by weight (the relationship between these percentages and thermal contribution is not direct because different fuels have different heat values). The most commonly used alternative fuel was refuse-derived fuel (RDF), which made up about 38% of the alternative fuels and about 13% of all fuels used. Other alternative fuels utilized include tires, waste wood, and animal meal (Oficemen, 2022).

On the other hand, Portugal has only six cement plants which combined have an integrated capacity of 12.4Mt/yr., with an additional 0.9Mt/yr. of grinding capacity (International Cement Review, 2022).

Only two companies operate these sites. By installed capacity, Cimpor - Industria de Cimentos is the biggest. Three facilities totaling 8.2Mt/yr. of combined cement capacity are operated by Cimpor. SECIL, which has 4.2Mt/yr. over three units, is the other competitor in the Portuguese market with integrated capacity (Edwards, 2017).

When it comes to alternative fuels, according to the Portuguese Technik Association of the Cement Industry (ATIC) in 2016, around 2.4 kt were used, corresponding to around 40% of the total energy (ATIC, 2019).

3.1 Iberian Peninsula Cement Industry Background Analysis

3.1.1 Spanish Roadmap 2050

The Spanish cement industry has increased energy efficiency over the years and is committed to reducing emissions. This commitment has been set out in the roadmap to achieve climate neutrality by 2050, presented on 21 December 2020 by the Spanish Cement Manufacturers' Association, Oficemen (Sanjuán et al., 2020).

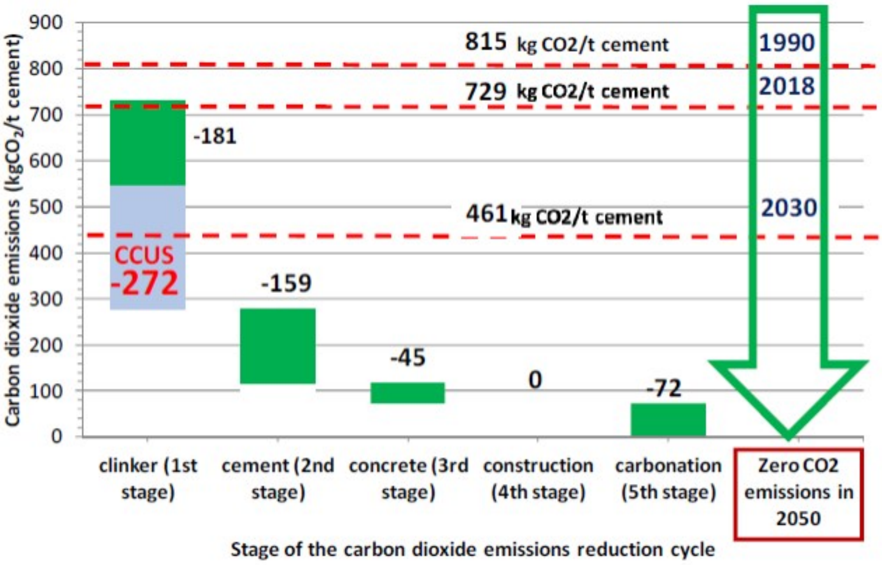


Figure 10- Spanish Cement Roadmap (Sanjuán et al., 2020).

In accordance with the Spanish roadmap, by switching fuels to biomass in the 1st stage (Clinker production) there's a potential reduction of 48 kg CO_2 /t cement in 2030 and 79 kg CO_2 /t cement in 2050 (Oficemen, 2021).

3.1.2 Portuguese Roadmap 2050

The Portuguese cement sector is determined to support the objectives of the European Green Pact and to contribute to the European Union's vision of a carbon-neutral society in 2050. For that reason, based in the CSI Roadmap, the Portuguese Technik Association of the Cement Industry (ATIC) published a plan, including direct measures and solutions in order to achieve the goals proposed by the European Union related to GHG gases (ATIC, 2019).

Consequently, as well as in the spanish case, it was used the system of the 5C’s, more concretly, five stages where measures to reduct emissions can be applied. The measures sugested are similar to the ones mentioned in the “Technology Roadmap”.

Firstly, a roadmap until 2030 was created and subsequently was added a plan until 2050, as we can see bellow:

Figure 11- Portuguese cement roadmap 2050: Reduction potential per element of the 5C chain (ATIC, 2021a).

Finally, according to the Portuguese roadmap, by switching fuels in the 1st stage (Clinker production) there’s a potential reduction of 27 kg CO_2 /t cement in 2030 and 60 kg CO_2 /t cement in 2050 (ATIC, 2021a).

3.2 Determination of the Biomass Factor

According to the EU ETS Directive[2], it is permitted biomass emissions to be set to zero if RED II conditions are met. Only for accounting purposes, the installation is still emitting CO_2 on a physical level (EU Comission, 2022).

As a result, and for the sake of transparency, the emission factor where biomass is concerned must be ascertained from the preliminary emission factor and the fuel's biomass fraction (Oficemen, 2022):

$$EF = EF_{pre} \times (1 - BF) \qquad (3)$$

Where:

EF - Emission factor;

EF pre - Preliminary emission factor (i.e., according to Article 3(36) of the MRR, the "*assumed total emission factor of a fuel or material based on the carbon content of its biomass fraction and its fossil fraction before multiplying it by the fossil fraction to produce the emission factor*");

BF - biomass fraction that complies with the RED II criteria [dimensionless].

Calculation factors may be established by applying default values for the purposes of emission control using a calculation method or by laboratory analyses. There are three ways in which the calculation of the biomass or fossil fraction of combined fuels or materials differs from the calculation of other calculation factors (EU Comission, 2022):

1. When the biomass/fossil fraction cannot be determined due to a mixture of biomass and fossil in the source stream, or if there's doubt or a very small biomass fraction, the operator may assume the fossil fraction to be 100% without further analysis (per MRR Article 39(1)).
2. There is no list of default values in Annex VI of the MRR.
3. Laboratory analyses may be unreliable or difficult due to technical or sampling issues.

---

[2] Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a system for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC, amended several times.

Regardless these variations, the MRR 2018 added the following tier definitions for calculating the biomass fraction in Annex II, section 2.4 (EU Comission, 2022):

> Tier 1: Values published by the competent authority or the Commission, or values in accordance with Article 31, i.e., “Type I and Type II default values”.
> Tier 2: Estimation method approved by the competent authority.
> Tier 3: Laboratory analyses.

3.2.1 Laboratory Analyses

For solid materials (usually waste), the relevant standard, according to the MRR 2018, is EN 15440 (“Solid recovered fuels – Methods for the determination of biomass content”). However, when more specific national or international standards are available, they may be applied as well (Oficemen, 2022).

EN 15440 offers three methods for determining the biomass fraction of a mixed material:

1. The selective dissolution method;
2. The manual sorting method;
3. The ^{14}C method.

The ^{14}C Method

For a complete overview of the carbon-14 method, its necessary to refer to the Annex C of EN 21644:2022 ("Solid recovered fuels - Methods for the determination of the biomass content"). The principle of the method is based on the fact that the amount of biomass in a sample is proportional to the carbon 14 content of the sample (Beta Analytic, 2017).

The method consists of combustion of the sample in such a way that the measurement of ^{14}C by one of the following (equivalent) methods is applicable (EU Comission, 2022):

- Scintillation proportional method
- Beta-ionization
- Accelerated mass spectrometry

The Selective dissolution method

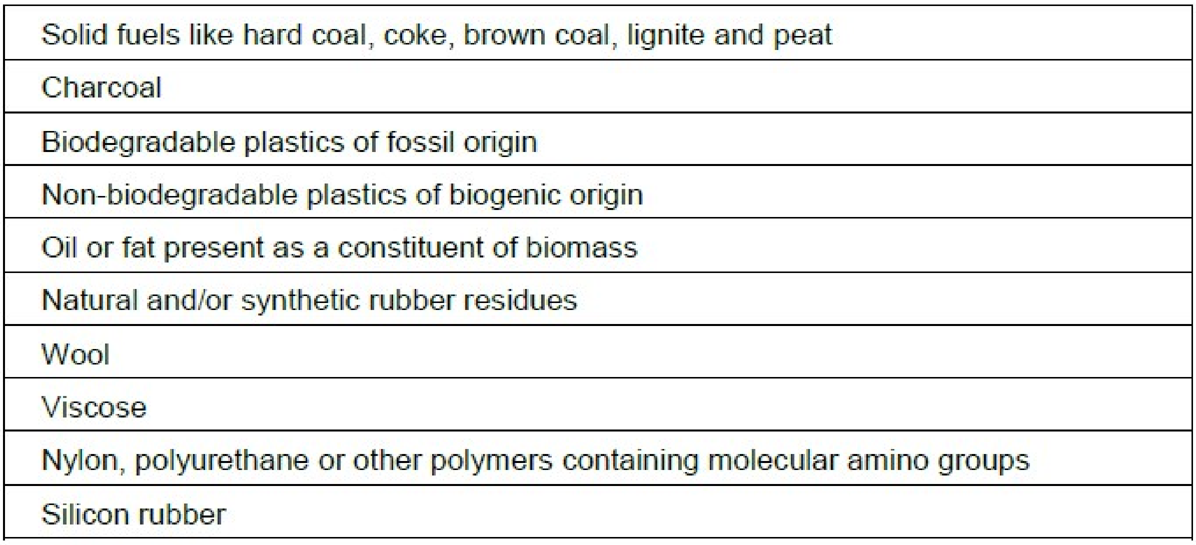
This can be considered as a variant of the second method listed in the variable discount criteria with the difference that the selection (classification of the fuel) is not done at source by the supplier but is done by the operator himself according to sampling criteria to be defined for this purpose (Beta Analytic, 2017).

The manual sorting method

The manual selection test method can be found in Annex B of EN 21.644:2022. The manual sorting method may be particularized to the number of fractions held at the plant provided that the general methodology laid down in the plant is respected (EU Comission, 2022).

For solid fuels produced from waste, the reference method of analysis is ^{14}C. Selective dilution is also feasible, but only if the material/waste (Table 1) does not contain more than 5% of biodegradable non-biomass components (EU Comission, 2022).

However, it is foreseen that under a justification of unreasonable costs or if it is not technically feasible, instead of the ^{14}C method, selective dilution, or an estimation method (mass balance) can be applied, which must first be authorized by the competent authority.



Solid fuels like hard coal, coke, brown coal, lignite and peat
Charcoal
Biodegradable plastics of fossil origin
Non-biodegradable plastics of biogenic origin
Oil or fat present as a constituent of biomass
Natural and/or synthetic rubber residues
Wool
Viscose
Nylon, polyurethane or other polymers containing molecular amino groups
Silicon rubber

Table 1- Materials for which the selective dissolution method is considered inappropriate according to EN 15440:2011(EU Comission, 2022).

3.2.2 Estimation Methods

Because there is a lot of flexibility in the estimation techniques, an operator may suggest as tier 2 for determining the biomass fraction. The assessment of the total biomass load of an emission source or source stream should be investigated in addition to the estimation of the biomass fraction as a distinct factor for a single source stream, such as the “Balance Method” (EU Comission, 2022).

However, the operator should also include a technique for validating the findings in cases where the method's dependability is uncertain.

4. Results

4.1 Alternative Fuels used in the Iberian Peninsula

The Cement Industry in Spain employed roughly 12% alternative fuels during clinker production in 2020, indicating a rise from the previous year's figure of 9.9%.

It was feasible to analyze the types of alternative fuels employed in all Spanish cement plants between 2019 and 2021. The gathered data (Table 2), made available by Oficemen, provides precise quantities for each material utilized.

Taking these three years into consideration, notable changes can be observed (Table 2). Firstly, the percentage of alternative fuels derived from fossil sources has decreased from 16% in 2019 to 14% in 2020, ultimately representing only 8% in 2021. The proportion of fuels partially composed of biomass has remained relatively constant over the same period. Lastly, the fraction of entirely biomass-based products has slightly increased over the years, with a difference of 8% between the data from 2019 and 2021.

	Fuels	**2019**	**2020**	**2021**
Fossil Origin	Used mineral oils and emulsions	35.269	52.321	-
	Solvents, varnishes, paints and blends	28.680	22.773	19.780
	Industrial sludge	140	-	---
	Other non-biomass alternative liquids	16.722	27.649	1.261
	Other non-biomass alternative solids	4.218	1.459	5.940
	Plastics	9.740	1.611	34.309
	Liquid hydrocarbon wastes	20.306	808	2.942
	Wastes from end-of-life vehicles	28,587	31.148	**64,232**
	Solid hydrocarbon wastes	4.912	383	275.979
	Total of Alternative fuels of fossil origin	**148,573**	**138,15**	168.104
Parcially biomass	RDF - MSW	279.165	304.720	---
	Tyres	178.439	146.825	**444,083**
	Waste from the paper industry	-30.774	-34.581	-
	Treated sawdust or treated wood	4.345	56	135.544
	Textile	**492,723**	**486,183**	76.887
	Total of Alternative fuels with partially biomass	-97.946	-	10.201
100% biomass	Vegetable oils and glycerine	105.270	107.357	42.222
	Vegetable biomass	12.953	96.247	63.228
	Animal meal	15.116	14.182	--
	Urban sewage sludge	62.725	22.164	**328,081**
	Wood	--	100.940	
	Other alternative solid biomass fuels	**294,01**	10.933	
	Other alternative liquids biomass		-	
	Paper, cardboard or cellulose		**351,823**	
	Total of Alternative fuels with 100% biomass			

Table 2 - Alternative Fuels, in tonnes, used in Spanish Cement Industry(Oficemen, 2022).

Unfortunately, there is an absence of comprehensive and recent data on the use of alternative fuels in Portugal's cement industry's clinker manufacturing. Such information is not as prominent or detailed as in the Spanish case. Therefore were analyzed the Sustainability Reports of both companies responsible for all the Cement Industry in Portugal.

Regarding Cimpor, a rough figure of 9.7% for the Biomass Fuel Rate (TCB) in 2021 has been measured (Figure 12). Over 1.5 million tonnes of non-recyclable waste, including textiles, plastics, used tyres, and oily waste, have been effectively co-processed by Cimpor since 2007. This accomplishment is equal to the total amount of municipal solid waste that is disposed of annually in landfills across Portugal (CIMPOR, 2021).

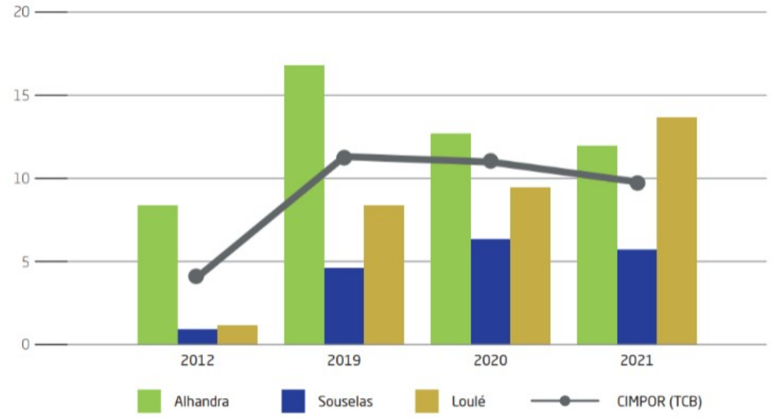


Figure 12- Distribution of the Biomass Fuels Rate (TBC) in the CIMPOR Portuguese cement plants(CIMPOR, 2021).

In the case of Secil, due to its vast international operations, it was extremely difficult to get particular data that was only connected to Portuguese cement factories. However, Secil provided detailed information (Table 3) describing precise amounts of alternative fuels used throughout all of the countries where it operates, providing valuable reference information for further analysis (Secil, 2021).

		SECIL GROUP (PT, TN, LB, BR)		
Kiln Fuel Consumption (tonnes per year)		**2019**	**2020**	**2021**
Conventional fossil fuels	Coal + anthracite	40,916	58,407	92,976
	Petrol coke	355,137	308,467	270,592
	(ultra) heavy fuel	1,871	1,823	1,764
	Diesel oil	173	320	466
	Natural gas [1'000 Nm3/yr]	426	489	381
	Shale	--	--	--
	Lignite	**996,924**	**1177,697**	**1212,332**
	Total of Conventional Fossil Fuels	5,06	5,728	5,621
Alternative fossil and mixed fuels	Waste oil	36,382	38,536	39,7
	Tyres	21,45	32,275	41,646
	RDF including plastics	--	1,643	1,261
	Solvents	95,066	-99,007	-98,451
	Impregnated saw dust	6,997	8,017	9,47
	Mixed industrial waste	**164,955**	**185,206**	**196,149**
	Other fossil based wastes and mixed fuels	-27,198	-7,025	-519
	Total of Alternative fuels of fossil origin and with partially biomass	-421	-1,107	-
Biomass fuels	Dried sewage sludge	--	--	1,698
	Wood, non impregnated saw dust	16,867	3,97	--
	Paper, carton	-	-	14,748
	Animal meal	**465,065**	**12,102**	-
	Animal bone meal			**535,446**
	Animal fat			
	Agricultural, organic, diaper waste, charcoal			
	Other biomass			
	Total of Biomass Fuels			

Table 3-Alternative Fuels, in tonnes, used in Secil Group Cement Plants (Secil, 2021)

When focusing specifically on the Portuguese context, data was found for only a single plant, Outão. Despite the rising mass consumption, the Outão plant's average annual replacement rate of fossil fuels with alternative fuels in 2021 was 47%, matching the value seen in 2020 but falling short of the budgeted target of 54%. It is noteworthy that animal biomass consumption has increased while vegetable biomass consumption has decreased noticeably, helping to keep the total CO_2 emissions from combustion steady. Common industrial waste continues to be the primary source of alternative fuels in terms of both biomass content and heat production (Secil & EMAS, 2021).

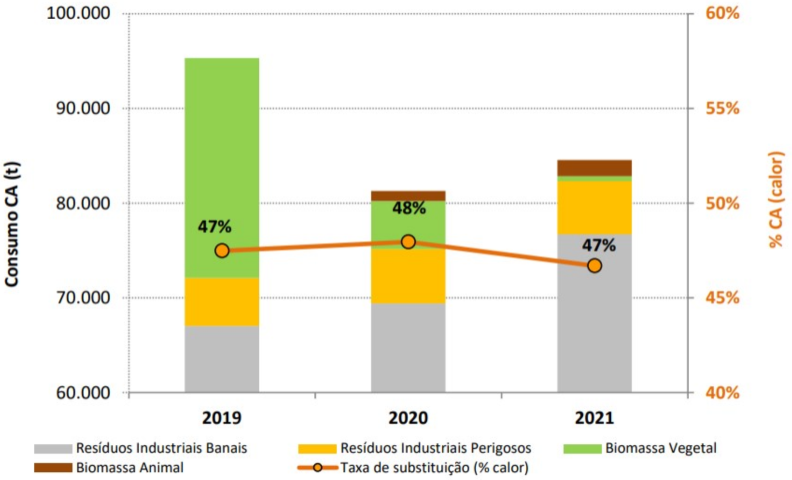


Figure 13- Evolution of the consumption of alternative fuels in the Outão Cement Plant (Secil & EMAS, 2021).

4.2 Biomass Factor

Following the normative given by the EU, by research was possible to assess the following values for the content of biomass in different type of alternative fuel used in the Cement Industry in Iberian Peninsula.

Alternative fuels for cement production typically need to have a high energy content, low ash content, low sulfur content, and low moisture content. Some of the best alternative fuels for cement production based on biomass fraction include, based on the table below (Table 4), biomass pellets, waste wood, agriculture waste and Municipal solid waste (MSW).

		2019-2021		
Type of Fuel	**Fuel**	**Weighted mean of BIOMASS (%)**	**Max. BIOMASS (%)**	**Min. BIOMASS (%)**
Alternative fuels with partially biomass	Total RDF - MSW	44,11	100	12,84
	Total TYRES	28,09	43,06	24,5
	Total TREATED SAWDUST OR TREATED WOOD	67,99	100	40,65
	Total TEXTILES	32,19	32,19	32,19
		40,26	**100**	**12,84**
Alternative fuels with 100% biomass	Total VEGETABLE BIOMASS	100	100	100
	Total ANIMAL MEAL FLOUR	100	100	100
	Total URBAN SEWAGE TREATMENT SLUDGE	100	100	100
	Total WOOD	100	100	100
	Total OTHER SOLID SOLID ALTERNATIVE FUELS BIOMASS	83,38	100	16,5
	Total OTHER ALTERNATIVE LIQUIDS BIOMASS	100,00	100	100
		95,96	**100**	**16,5**
Total		**62,65**	**100**	**12,84**

Table 4 - Biomass average percentage in different types of fuels(Oficemen, 2022).

Biomass pellets made from wood, agricultural waste, or other plant materials are a popular alternative fuel for cement kilns. They have a high energy content, low moisture content, low ash content and they have an almost 100% biomass fraction. Waste wood (treated wood) from construction sites, demolition projects, or other sources is also a very popular alternative, having a biomass factor around 40%, however it can in some cases reach the 100% content. Agricultural waste such as rice husks, straw, or corn stover can be burned to generate heat. This waste material has a high energy and biomass content and low ash content, making it a suitable alternative fuel for cement production. Finally, Municipal solid waste (MSW) can be processed to remove non-combustible materials and then burned to generate heat. This waste material has a high energy content but must be carefully screened to ensure it meets the industry's specifications and the range of biomass fraction is very big, from 12 to 100%.

5. Discussion of Results

5.1 Biomass Flow

The European Commission has issued several initiatives over the past few years that continue to mark out specific goals for distancing economic growth from resource use (The European Green Deal; European Commission, 2019), protecting biodiversity, mitigating climate change and, generally, enhancing the economy's sustainability and circular use of resources. Biomass is a crucial element in all these projects, as already highlighted.

In this context, were created the “The EU biomass Flows” tool, which presents the flows of biomass for all European Union (EU) Member States (MS), as well as for the EU27 for a period that varies depending on the source of biomass. The three major use categories of biomass—for food and feed, materials, and energy production—can be analyzed using the diagrams that are displayed (Gurría et al., 2022).

As a result, the biomass flows from the two countries of interest were examined to contrast them with data from across the EU (Avitabile et al., 2023). The biomass used for energy production was the target of the analysis as it falls under the use category that is intended to be implemented in the cement industry. However, this evaluation only provides a broad overview of how biomass is utilized throughout the chosen regions, and it has no direct bearing on the cement industry.

Firstly, according to Figure 14, approximately 28.5% of biomass supply in Portugal is allocated to the energy creation sector, making it the second largest sector of biomass utilization. This percentage also enables us to determine the specific type of biomass utilized for energy creation, which was limited to forestry biomass up until 2017, Figure 15 (European Comission, 2019).

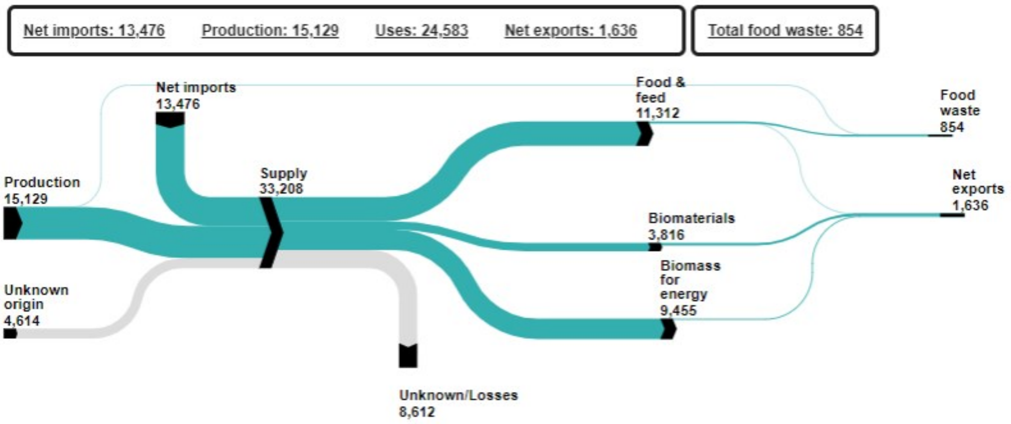


Figure 14- Portuguese Biomass Flow (after 2019) (European Comission, 2019).

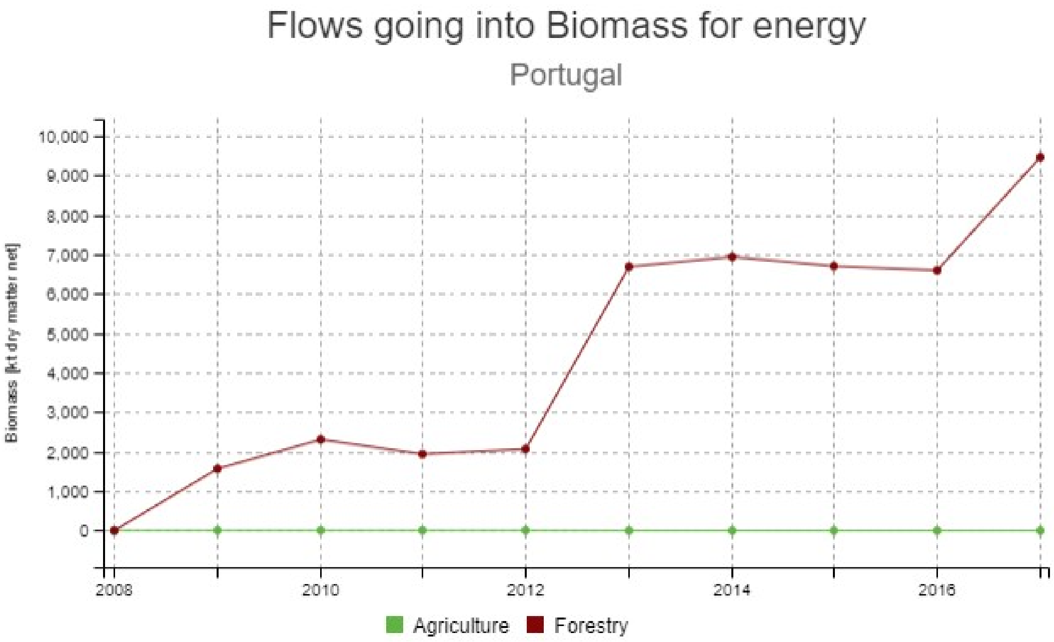


Figure 15- Type of biomass flow going into Biomass for energy, in Portugal (European Comission, 2019).

In contrast, in Spain, only 6% of the total biomass supply is utilized for energy production, and in 2017, this biomass consisted solely of forestry resources. By comparing these percentages, one can discern notable differences between the two countries, Figure 16. Moreover, if we examine the absolute figures, Portugal employs 9,455 Kt of biomass, whereas Spain utilizes 5,614 Kt.

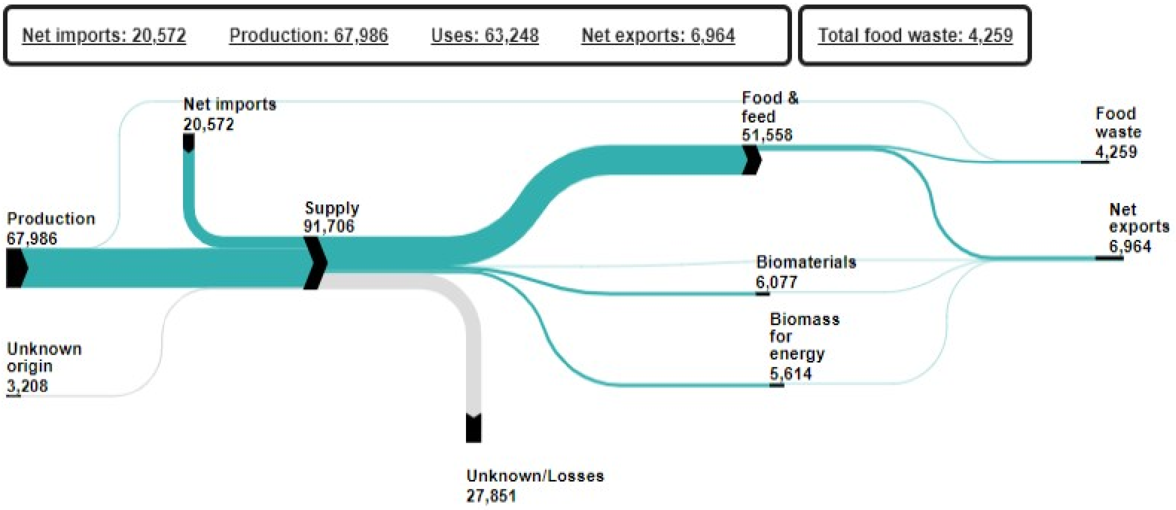


Figure 16 - Spanish Biomass Flow (after 2019) (European Comission, 2019).

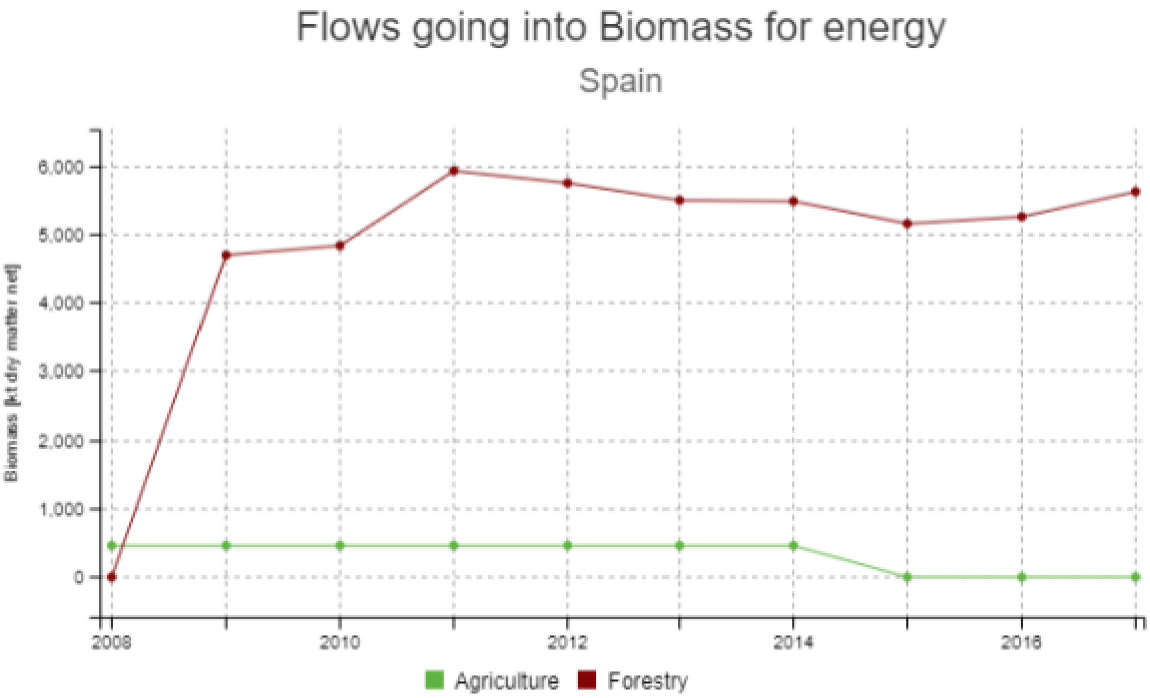


Figure 17- Type of biomass flow going into Biomass for energy, in Spain (European Comission, 2019).

Based on the information analyzed above and the overall EU results, which indicate that 19.3% of biomass (207,292 Kt) is allocated for energy production as shown in Figure 18, it is possible to draw some conclusions. Specifically, when considering the 27 countries included in the analysis, it is noteworthy that Spain contributes only 2.7% of the biomass used for energy, while Portugal's contribution is slightly higher at 4.6%. This data suggests that, as of 2019, Portugal relied significantly more on biomass as a source of energy, accounting for nearly 5% of all the biomass used for energy in Europe. This is a positive outcome.

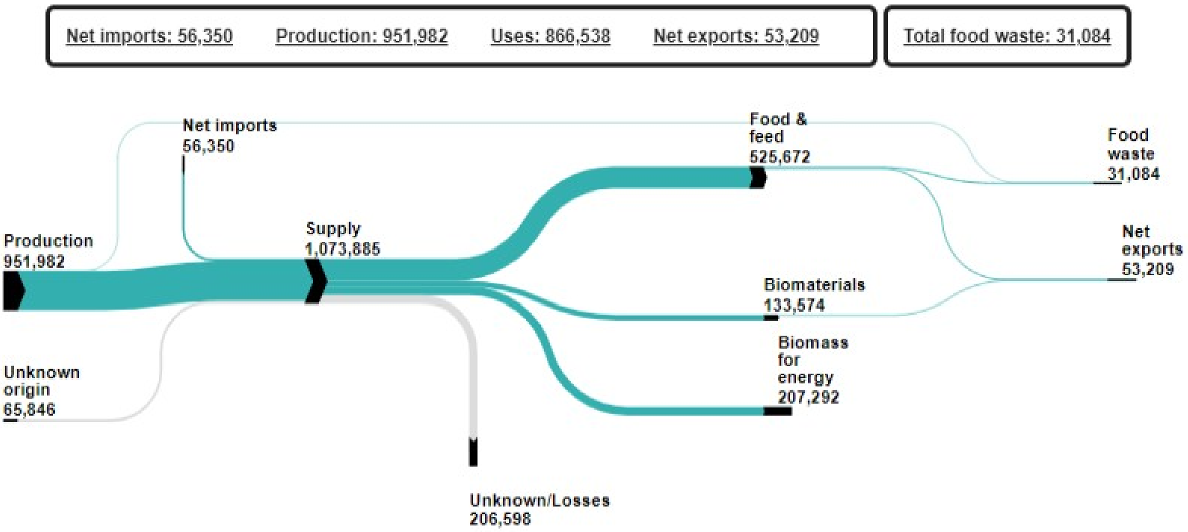


Figure 18- EU27 Biomass Flow (after 2019) (European Comission, 2019).

5.2 Alternative Biomass Fuels and Biomass Factor Analysis

Based on the data collected, it’s possible to develop some assumptions about the types of biomass fuels used and their progression in the cement industries in the Iberian Peninsula. Firstly, despite the fact that the two countries' information formats differ, there are certain analogies that may be drawn. The types of biomass and other fuels used in cement plants in Portugal and Spain are comparable, with Municipal Solid Waste (MSW) being the most prevalent alternative fuel. This decision is mostly motivated by the many benefits it offers. Municipal solid waste has a significant energy content, and in some situations allows for a biomass fraction of up to 100%. In line with biomass net zero emission legislation, this contributes to minimize the industry's carbon footprint. Additionally, by lowering landfill quantities and fostering a circular economy, the usage this alternative fuel contributes greatly to the national waste management sector. Furthermore, using MSW as an alternative fuel in the cement business can create jobs in the area, promoting a more effective and sustainable industry.

Secondly, there are distinctions between the two states when examining biomass fuels. While Portugal shows an increase in the use of animal biomass sources, Spain shows a growth in the use of vegetable biomass fuels. This choice of biomass fuel is influenced by a number of variables, including national policies, infrastructure, and the requirements of each country's cement industry. Despite the general tendency favoring plant-based biomass in Spain and animal-based biomass in Portugal, there may still be differences and overlaps in the ways that the various forms of biomass fuels are used in these two countries.

In light of the analysis of the Spanish situation, it is clear that Spain gains from a broad agricultural sector and an extensive production of vegetable biomass resources. As evidenced by the biomass flows aforementioned, crop residues, energy crops, and forestry residues are easily accessible in Spain (Avitabile et al., 2023). This is consistent with the nation's agricultural practices, the availability of crop wastes, and energy-specific crops like switchgrass and miscanthus. As a result, the cement industry may successfully use these resources as biomass fuel for energy generation.

On the other hand, Portugal has a long history of animal husbandry and cattle farming, which creates a sizable quantity of animal biomass resources (Avitabile et al., 2023). The accessibility of these resources as a result of Portugal's agricultural practices and the need to properly utilize organic waste streams may have an impact on the preference for animal biomass in the country's cement sector.

In terms of evolution, both countries saw an increase in the use of biomass fuel from 2019 to 2020. Portugal's growth was about 2%, whereas Spain's rate of growth was around 5%. However, a slight decline was seen between 2020 and 2021, which was probably brought on by the COVID-19 pandemic's effects on the cement sector. Despite the fact that this decrease was very minimal in both instances, it is important to recognize how the pandemic affected cement production.

Despite these fluctuations it is clear that the cement industry in the two countries are working actively to switch to alternative fuels, especially biomass fuels, in order to lower greenhouse gas emissions. Positive outcomes from these efforts have already been shown. According to data from the CIMPOR cement plants, the use of alternative fuels, such as biomass fuels, helped Portugal avoid releasing 900,000 tonnes of CO_2 into the atmosphere in 2020, which is equal to two months' worth of nationwide car emissions (CIMPOR, 2021). Similar to this, Figure 19 shows that in Spain, emissions savings exceeded 1,000,000 tonnes in 2021 (CEMA, 2021).

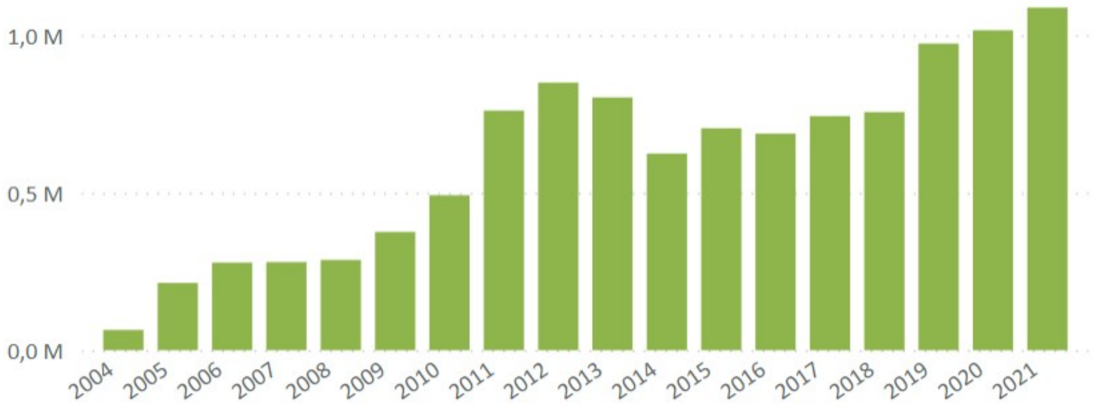


Figure 19- Avoided emissions by the use of biomass in the Spanish Cement Industry (CEMA, 2021).

Overall, it is admirable that the cement industry in Portugal and Spain are working to switch to renewable fuels and lessen their environmental impact. These initiatives show a dedication to sustainability and aid in the worldwide shift to a low-carbon economy.

Based on that, the prognosis for the CO_2 emissions savings is very promising, being safe to predict that the increased technology evolution with a much considerate attitude towards the climate change ideology collaborate greatly to a consistent increasing of the emissions savings, Figure 20.

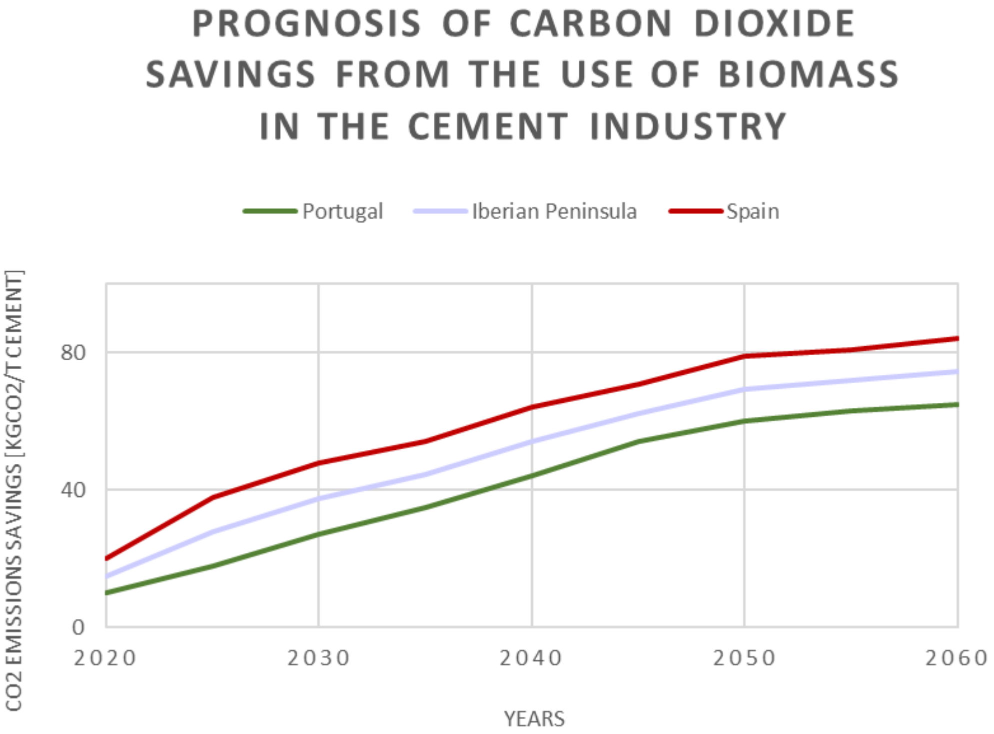


Figure 20- Prognosis for the CO_2 emissions savings by the use of biomass fuel in the clinker production, in the Iberian Peninsula.

It is noteworthy to emphasize the three distinct phases depicted in the aforementioned diagram, Figure 20. From the present until 2025, carbon dioxide emissions are expected to fall steadily and abruptly, due to the adoption of several European policies. As a result, the amount of CO_2 saved will gradually grow over time, creating a slope of 2.6 kg CO_2 /t cement saved per year.

Following that, a steady increase in CO_2 savings is expected between 2025 and 2050, but on a less steep trajectory (gradient of 1.6 kg CO_2 /t cement per year), eventually reaching an average of around 70 kg of CO_2 saved per tonne of cement produced by 2050.

Nevertheless, by the year 2050, the circumstances may have changed slightly. The rate of reduction in emissions will no longer be able to increase at the same rate as before. This is related mostly to the European Union's goal of reaching carbon neutrality by the same year. As a result, a much smaller slope (around 0.5 kg CO_2 /t cement) is anticipated in this scenario.

5.3 Economic Analysis

The European Emissions Trading System (EU ETS) is a cornerstone of the EU's policy to address climate change and its primary mechanism for cutting greenhouse gas emissions in an efficient and cost-effective manner. It was the first major carbon market (2005) in the world and continues to be the most significant. In addition to operating in all EU nations, it also covers Iceland, Liechtenstein, and Norway and, since 2017, has connections with the Swiss Trading System as well. Furthermore, it restricts emissions from roughly 10,000 manufacturing and energy-related installations as well as air carriers that fly between these nations, accounting for about 40% of the EU's total greenhouse gas emissions (EU Comission, 2021).

The EU ETS includes the following industries, concentrating on emissions that can be precisely measured, reported, and verified (EU Comission, 2021):

- Electricity and heat production;
- Energy-intensive industry sectors like cement production;
- Aviation within the European Economic Area.

The "cap and trade" theory underlies how the EU ETS operates. The overall amount of particular greenhouse gases that the operators covered by the system may emit is limited. Over time, the cap is lowered to reduce overall emissions (European Comission, 2022).

Operators purchase or receive emissions allowances within the cap, which they can exchange with one another as necessary. The restriction on the overall amount of available allowances makes sure that they have a purpose. While trading offers flexibility that ensures emissions are reduced where it is least expensive to do so, the price signal encourages emission reductions and investment in cutting-edge, low-carbon technologies (EEA, 2022).

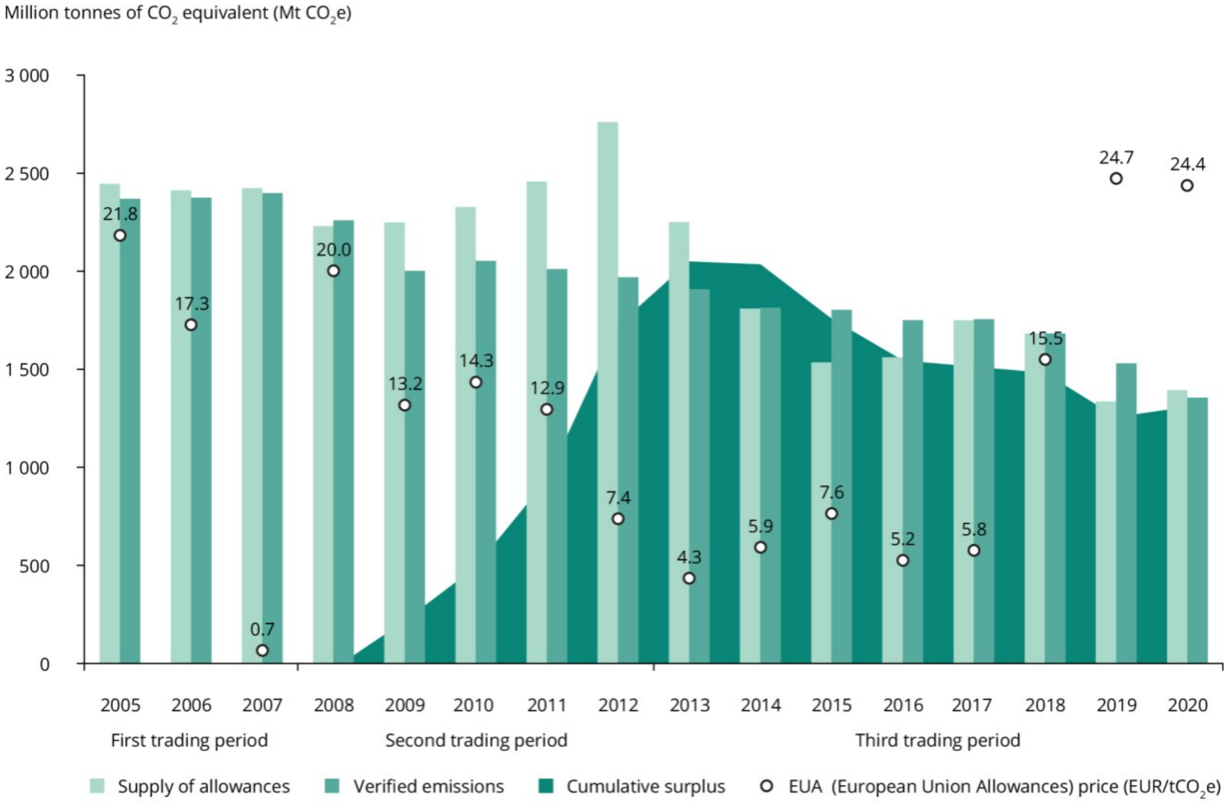


Figure 21- Emissions Trading System Graphic (EEA, 2022).

Presently, the system is in its fourth trading phase (2021-2030), and the Emissions Trading System (ETS) framework has undergone various revisions to ensure its continued alignment with the broader climate policy objectives of the European Union to lessen the effects of carbon pricing on disadvantaged communities, the EU Commission suggested strengthening the EU ETS framework, adding new industries to emissions trading, and creating a new Social Climate Fund on July 14, 2021. The proposal was duly evaluated and approved by the European Parliament and the Council of the EU in December 2022 (EU Comission, 2021).

Over the years, the price of CO_2 in the EU ETS has fluctuated as a result of a number of factors, including shifts in market supply and demand, regulatory changes, prevailing economic conditions, and international events that have an impact on the energy and carbon markets, Figure 22.

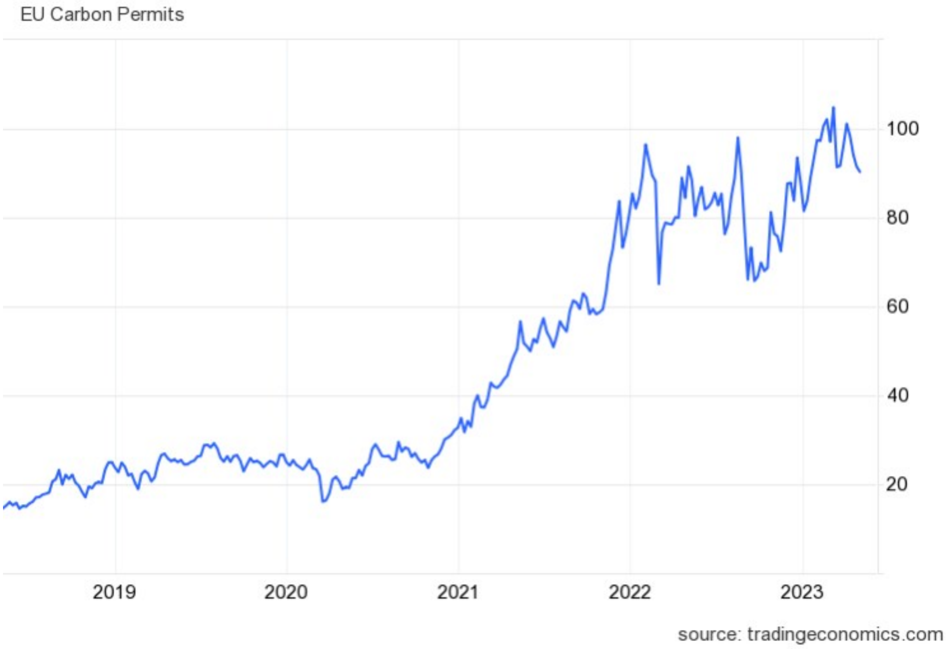


Figure 22- EU Carbon Permits prices (Trading Economy, 2023).

For instance, in the early years, the EU ETS had relatively low carbon prices as a result of an excess of carbon permits and a lackluster market for emissions trading. However, costs started to increase in the middle of the 2010s as a result of a mix of market interventions, policy changes, and growing demand for low-carbon technologies, as can be seen at Figure 22.

Since then, there has been a noticeable increase in the price of CO_2 under the EU ETS, with prices reaching record highs in the early February of this year, of around 100 €/ton reflecting the increasing ambition for emissions reduction targets (Trading Economy, 2023).

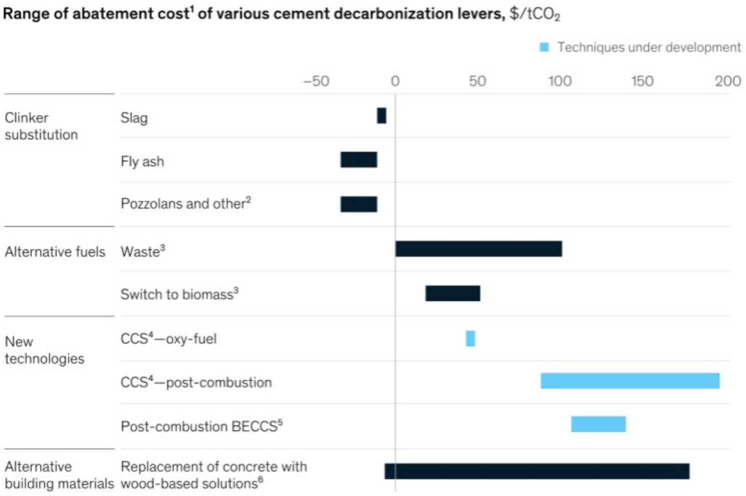
When it comes to biomass for the cement industry in Europe, its prices are determined by a variety of factors, including market supply and demand, production costs, regulatory developments, and competition with other industries and applications of biomass (Material Economics, 2021).

The use of biomass as a fuel in the cement industry has garnered more attention recently as a means of lowering greenhouse gas emissions and enhancing sustainability. However, depending on variables like the type of feedstock, the distance from the source to the cement plant, and the expense of processing and transporting the biomass, the availability and cost of biomass can vary dramatically (Material Economics, 2021).

In addition, legislative changes like the EU Renewable Energy Directive (RED) and the EU Emissions Trading System (ETS) may have an impact on the cost of biomass for the European cement sector, as previously stated.

As an instance, within the context of the EU Renewable Energy Directive (RED), biomass utilization in the cement industry can be considered as a source of renewable energy, which can stimulate the demand for biomass-based fuels, leading to a potential increase in prices. This is the current scenario that is being observed (Renewable Energy Agency, 2012).

In conclusion, accounting for both the CO_2 emission market price and the price of biomass, based on the reduction of emissions generated, it’s possible to assess major savings accomplished (Material Economics, 2021).



[1] Globally assumed cost, can vary locally.
[2] Limestone, kaoline, and other.
[3] Depending on availability, quality of material, and cost to dispose.
[4] Carbon capture and storage.
[5] Bioenergy with carbon capture and storage.
[6] Includes abatement coming from displacement from steel.

Figure 23- Cost saved by the cement industry due to decarbonization levers (Renewable Energy Agency, 2012).

6. Conclusion

Various outcomes can be drawn from this study as regards to the prognosis of carbon dioxide savings from the use of biomass in the cement industry in the Iberian Peninsula:

- Both Portugal and Spain have embraced biomass fuels and set ambitious targets for their application.
- When comparing the roadmaps developed and implemented in both countries to the European version, it is feasible to conclude that they all follow a very similar path towards achieving carbon neutrality by 2050.
- In 2050, it is expected to reach carbon dioxide savings of 70 kg $\mathrm{CO_2}$ /t cement as average (Upper and lower limits 80 kg $\mathrm{CO_2}$ /t cement and 60 kg $\mathrm{CO_2}$ /t cement, respectively). Three times more than the current value in 2023 (around 22 kg $\mathrm{CO_2}$ /t cement).
- The use of biomass fuels in the Iberian Peninsula cement sector has proven to be an effective method for reducing emissions and promoting sustainable development. This transformation demonstrates the region's commitment to climate change mitigation and serves as a model for other businesses and governments to emulate. A reduction of almost 32% can be assessed to 2050.
- The Iberian Peninsula's cement sector can continue to lead the way in attaining a more sustainable and environmentally conscious future by harnessing existing biomass resources and promoting cooperation.
- This master thesis supports the significance of proceeding to updating the biomass resources and usage data at least annually, within the current management procedures, if the cement sector wish to get good levels of biomass use to reach carbon neutrality in 2050.

In conclusion, the prognosis for the $\mathrm{CO_2}$ emissions savings is very promising, being safe to predict that the increased technology evolution with a much considerate attitude towards the climate change ideology collaborate greatly to a constant increasing of the emissions savings.

7. References

Andrade, C., & Sanjuán, M. A. (2018). Updating Carbon Storage Capacity of Spanish Cements. *Sustainabitlity*.

Aragaw, T. A. (2016). Cement Manufacturing and Use of Biomass Energy: energy option for Greenhouse Gas Reduction. *Research Journal of Chemical and Environmental Sciences*, *4*(3), 1–7.

ATIC. (2019). Roteiro nacional para a descarbonização da industria cimenteira. In *Roteiro nacional para a descarbonização da industria cimenteira* (Vol. 53, Issue 3).

ATIC. (2021). *ROTEIRO PARA A NEUTRALIDADE CARBÓNICA 2050*.

Avitabile, V., Baldoni, E., Baruth, B., Bausano, G., Boysen-Urban, K., Caldeira, C., Camia, A., Cazzaniga, N., Ceccherini, G., De Laurentiis, V., Doerner, H., Giuntoli, J., Gras, M., Guillen Garcia, J., Gurria, P., Hassegawa, M., Jasinevič ius, G., Jonsson, R., Konrad, C., … European Commission. Joint Research Centre. (2023). *Biomass production, supply, uses and flows in the European Union : integrated assessment.*

Beta Analytic. (2017). *Carbon-14 Analysis vs. Selective Dissolution Method*. https://www.betalabservices.com/renewable-carbon/carbon-credits-sdm.html

Blair, M. J., Gagnon, B., Klain, A., & Kulišić, B. (2021). *Contribution of Biomass Supply Chains to the Sustainable Development Goals When Implemented for Bioenergy Production*. https://www.ieabioenergy.com/blog/publications/contribution-of-biomass-supply-chains-to-the-sustainable-development-goals-when-implemented-for-bioenergy-production/

CEMA. (2021). *Ahorro de emisiones de CO2*. https://www.recuperaresiduosencementeras.org/ahorro-de-emisiones-de-co2/

CEMBUREAU's. (2020). *Activity report*.

Chinyama, M. P. M. (2016). Alternative Fuels in Cement Manufacturing. In *Intech* (Vol. 11). https://www.intechopen.com/books/advanced-biometric-technologies/liveness-detection-in-biometrics

CIMPOR. (2021). *Sustainability Report*.

Edwards, P. (2017). The cement industries of the Iberian Peninsula. *Global Cement Magazine*. https://www.globalcement.com/magazine/articles/1015-the-cement-industries-of-the-iberian-peninsula

EEA. (2022, January 12). *The EU Emissions Trading System in 2021: trends and projections*. https://www.eea.europa.eu/publications/the-eu-emissions-trading-system-2

EU Comission. (2021). *EU Emissions Trading System (EU ETS)*. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

EU Comission. (2022). *Guidance Document- Biomass Issues in the EU ETS*. https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-

European Comission. (2019). *Biomass Flows*. Data-Modelling Platform of Resource Economics. https://datam.jrc.ec.europa.eu/datam/mashup/BIOMASS_FLOWS/index.html

European Comission. (2022). *REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL on the Functioning of the European carbon market in 2021*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2022:516:FIN

Gurría, P., González Hermoso, H., Cazzaniga, N., Jasinevicius, G., Mubareka, S., De Laurentiis, V., Caldeira, C., Sala, S., Ronchetti, G., Guillén, J., Ronzon, T., M'barek, R., & European Commission. Joint Research Centre. (2022). *EU biomass flows : update 2022.*

Harmeling, S. (2018). Climate change impacts. *Routledge Handbook of Human Rights and Climate Governance*, 90–109. https://doi.org/10.4324/9781315312576-7

IEA. (2018). Technology roadmap for cement. *Low-Carbon Transition in the Cement Industry*, 66.

International Cement Review. (2022). *The Global Cement Report^{TM}, 14th Edition*. https://www.cemnet.com/global-cement-report/country/portugal

IPPC. (2013). *Climate change 2013 : the physical science basis* (T. F. Stocker, D. Qin, G. K. Plattner, M. M. B. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley, Eds.; 1st ed.).

IPPC. (2014). *Climate change 2014 : mitigation of climate change* (R. Edenhofer, Y. Pichs-Madruga, E. Sokona, S. Farahani, K. Kadner, A. Seyboth, I. Adler, S. Baum, P. Brunner, B. Eickemeier, J. Kriemann, S. Savolainen, C. Schlömer, T. von Stechow, & C. Zwickel, Eds.; 1s ed.).

Leetham, D. (2015). *The Cement Manufacturing Process*. ThermoFisher Scientific. https://www.thermofisher.com/blog/mining/the-cement-manufacturing-process/#:~:text=In this process%2C the chemical,with gypsum to create cement.

Material Economics. (2021). *EU Biomass Use in a Net-Zero Economy*.

Oficemen. (2021). *Hoja de ruta de la industria cementera española para alcanzar la neutralidad climática en 2050*.

Oficemen. (2022). *GUIA SECTORIAL MONITORIZACION GEI* (p. Biomass Chapter).

Renewable Energy Agency, I. (2012). *RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES Biomass for Power Generation Acknowledgement*. www.irena.org/Publications

Sanjuán, M. , Morales, A. , & Zaragoza, A. (2022). *La optimización del efecto albedo de los hormigones utilizados en pavimentación en respuesta a la mitigación del cambio climático*.

Sanjuán, M. Á., Andrade, C., Mora, P., & Zaragoza, A. (2020a). Carbon dioxide uptake by cement-based materials: A spanish case study. *Applied Sciences (Switzerland)*, *10*(1). https://doi.org/10.3390/app10010339

Sanjuán, M. Á., Andrade, C., Mora, P., & Zaragoza, A. (2020b). Carbon dioxide uptake by mortars and concretes made with Portuguese cements. *Applied Sciences (Switzerland)*, *10*(2). https://doi.org/10.3390/app10020646

Sanjuán, M. A., Argiz, C., Mora, P., & Zaragoza, A. (2020). Carbon dioxide uptake in the roadmap 2050 of the Spanish cement industry. *Energies*, *13*(13). https://doi.org/10.3390/en13133452

Secil. (2021). *Sustainability Report*.

Secil, & EMAS. (2021). *Declaração Ambiental*.

Tigue, K. (2022). Concrete is Worse for the Climate Than Flying. Why Aren't More People Talking About It? *Inside Climate News*. https://insideclimatenews.org/todaysclimate/concrete-is-worse-for-the-climate-than-flying-why-arent-more-people-talking-about-it/#:~:text=Cement manufacturing now accounts for,from the International Energy Agency.

Trading Economy. (2023, May 5). *EU Carbon Permits*. https://tradingeconomics.com/commodity/carbon

United Nations. (2015). *Sustainable Development Goals*.

United Nations. (2023). *Conferences | Environment and sustainable development*. https://www.un.org/en/conferences/environment

World Business Council for Sustainable Development. (2021). *Time to Transform: Vision 2050*. 1–118. https://timetotransform.biz/wp-content/uploads/2021/03/WBCSD_Vision_2050_Time-To-Transform.pdf