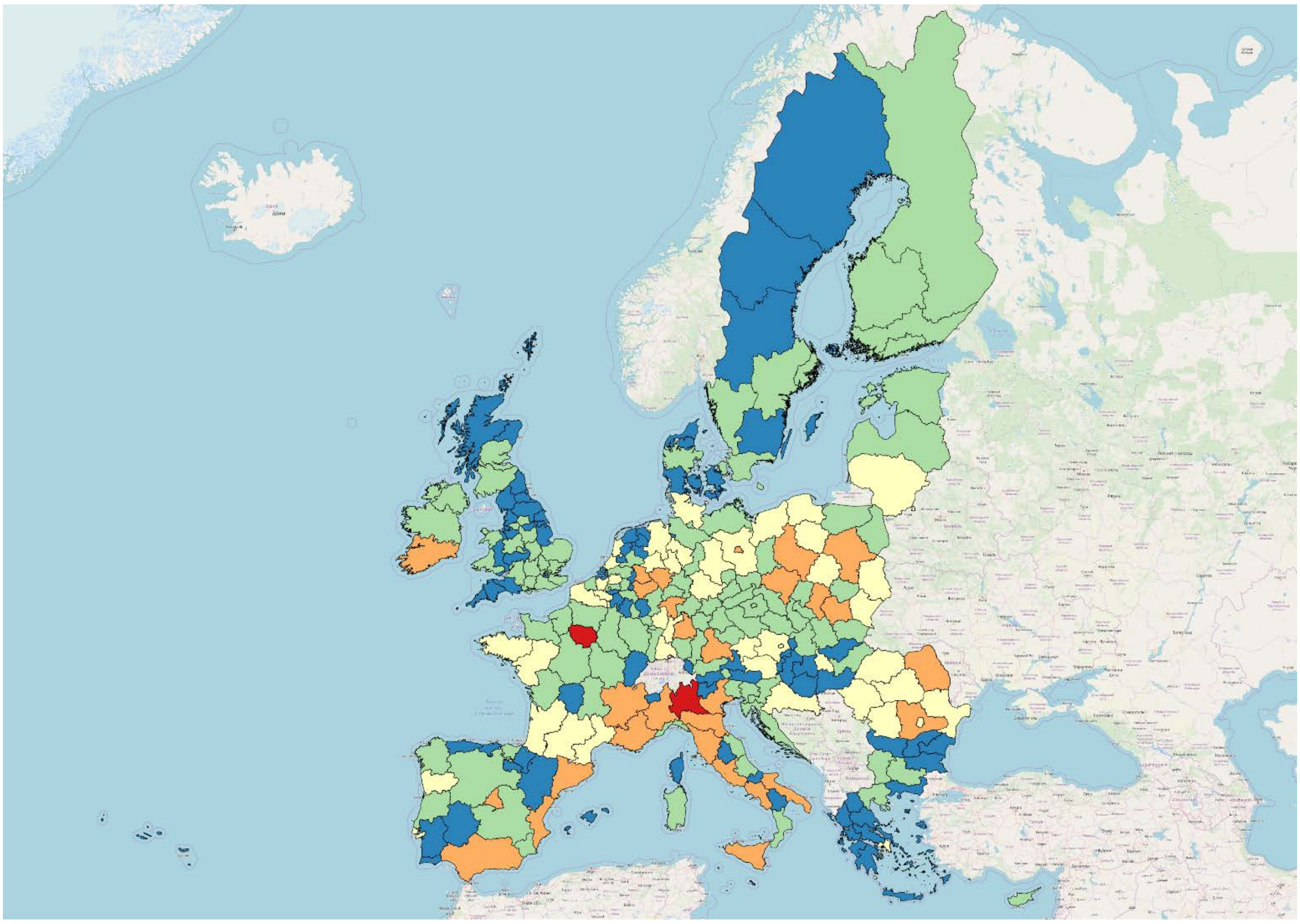


Concrete Change

Exploring the effects of scaling up the use of alternative binders to reduce the climate impact from concrete

Master's thesis in Industrial Engineering

SANTIAGO ESCUDERO CARMONA

Department of Energy Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

Concrete change: Exploring the effects of scaling up the use of alternative binders

to reduce the climate impact from concrete

SANTIAGO ESCUDERO CARMONA

Department of Energy Technology

CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2019

Concrete change: Exploring the effects of scaling up the use of alternative binders to reduce the climate impact from concrete

SANTIAGO ESCUDERO CARMONA

Department of Energy Technology
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone + 46 (0)31-772 1000

Cover:

[Cement consumption heatmap in EU NUTS, Figure 27, page 46]

[Chalmers Reproservice]
Göteborg, Sweden 2019

Concrete Change: Exploring the effects of scaling up the use of alternative binders

To reduce the climate impact from concrete

SANTIAGO ESCUDERO CARMONA

Department of Energy Technology

Chalmers University of Technology

ABSTRACT

This thesis explores the potential of using alternative binders to replace cement clinker on a European scale in order to reduce the carbon dioxide emissions associated with concrete/ cement. Numerous studies highlight the importance of increasing the replacement ratio to meet international environmental goals [1]. However, little advancement has been made with respect to describing how to achieve these replacement goals.

This thesis work is focused on estimating the resource base, and the regional availability, of two conventional alternative binders, fly ash and blast furnace slag, in the EU. The availability of fly ash was estimated based on existing coal-fired power plants block net capacity. The blast furnace slag resource base estimated based on the existing and projected capacity of EU blast furnaces.

Further, the thesis, through scenario analysis, explore how the availability of alternative binders may change over time as existing capital stock in the power and steel industries are phased out. The scenarios were assessed using simulations from Matlab and further analysed with a software for spatial analysis. The results show that in the short term (5-10 years) it is possible, in most EU regions, to meet the demand for conventional alternate binders. In the long term (10-30 years), however, it will not be possible to fulfil a sufficient replacement in all European regions using only these two alternative binders. These finding confirms the importance of increasing the efforts to develop other measures to reduce the climate impact from concrete and cement, including increased use of lesser-known binders.

This study can hopefully encourage further researcher aimed at developing: a better understanding of the availability of other alternative binders, of processing techniques and of means to distribute them, so that the environmental goals in the concrete and cement industries may be achieved.

Keywords: fly ash, blast furnace slag, concrete, cement, clinker, scenario, mapping, QGIS

1 CONTENTS

2 SUMMARY OF FIGURES

3 SUMMARY OF TABLES

1. Introduction

1.1. Objective

The aim of this master's thesis is to analyse the potential for and effects of increasing the replacement ratio of clinker content in cement through the introduction of alternative binders. The study explores the limitations and possible benefits of using alternative binders as to reduce the climate impact from concrete in Europe and Sweden. These limitations are subjected to two sub-goals: linking the resource base of conventional alternative binders with cement demand across Europe regions while existing coal-fired power plants and blast furnaces are phased out and future cement demand estimates and maximizing clinker replacement.

1.2. Background

Throughout the last two millennia, humans have been using concrete in a wide range of applications. In modern society, concrete is next to water the most consumed material in the world. Over time, concrete has become one of the most important materials for human beings thanks to its many applications in structures and buildings, which provide shelter, transportation and mobility for people.

However, concrete has not always been made in the same way. In the beginning, roman engineers tailored concrete with volcanic rocks. Over the last two centuries, however, cement clinker has replaced all other binders, thus capturing almost all market shares. Figure 1 provides an overview of the cement making process.

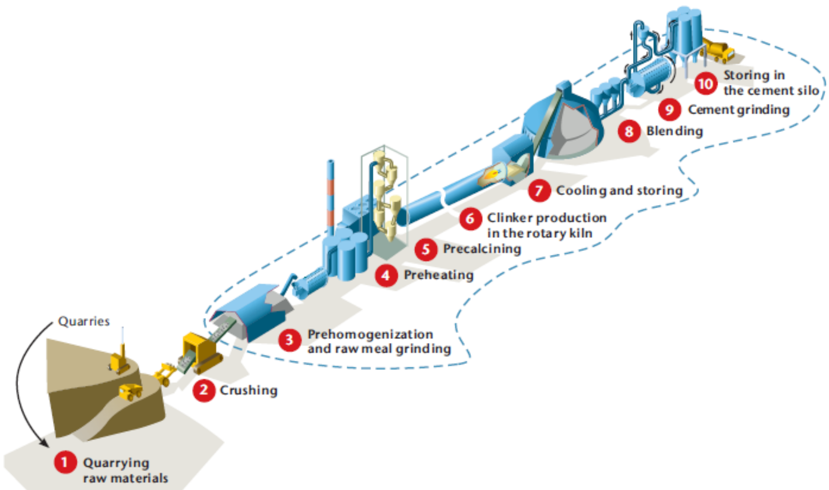


Figure 1 Overview of a cement plant. Source: IEA Technology Roadmap [1]

First, raw materials are quarried (1) from calcareous deposits such as limestone, marl or chalk. Then, they are crushed and milled (2) until it is obtained a fine powder called "raw meal". Later, this fine powder enters the cyclonic preheater (3) of multiple stages rising its temperature to over 900ºC by coming into contact with exhausted gases. At the end of this stage, the preheated material starts to calcine (5) as long as it approaches to the bottom of the preheater above the kiln and starts entering inside the combustion chamber. Once inside the rotary kiln, precalcined meal gradually becomes clinker (6) by constantly falling to hotter zones towards the flame, where fuel is fired directly. After that, clinker is cooled (7) from over 1000ºC to 100ºC on a grate cooler, where combustion air is blown onto the clinker. Once cooled, clinker is blended (8) and grinded

(9) with other mineral components to craft perfect cement mixture or is stored directly in silos (10). [1]

The cement manufacturing process accounts for the vast majority of the carbon footprint of concrete. These carbon dioxide emissions arise mainly from two sources: approximately 40% from fuel combustion in the cement kiln and approximately 60% from the calcination of limestone [1]. Hence, it is clear that those emissions are lately accounted in buildings and infrastructures, increasing their carbon footprint. Then, it becomes a major priority to reduce cement production emissions' to lower the whole carbon footprint of all concrete-made infrastructures.

There are in general three overarching options, to reduce climate impact associated with the use of concrete. To use alternative construction materials such as wood or metals instead of concrete to optimise designs, i.e., to use less concrete for the same function; and to reduce the cement clinker content in concrete by replacing the clinker with alternative binders.

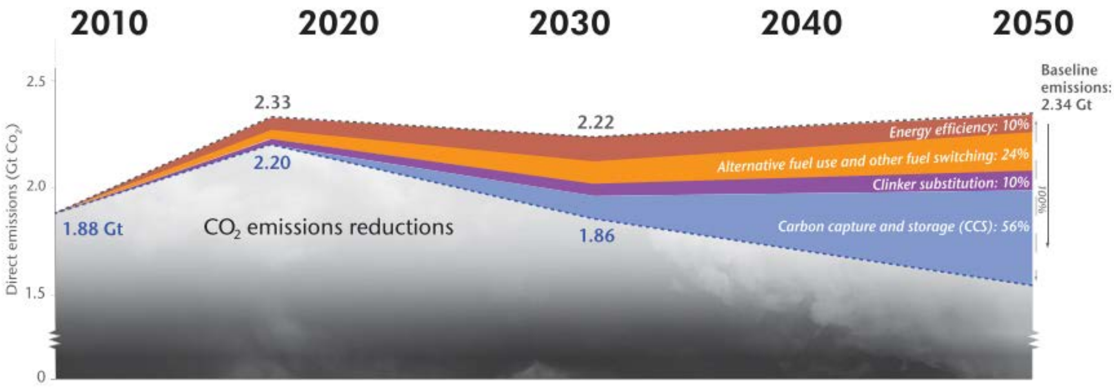


Figure 2 Cement sector CO2 emissions reduction 2010-2050. Source: IEA Cement Roadmap Keyfindings.[2]

In addition, there are four main areas of improvement that could contribute to lowering emissions from cement production [1] to 2050. As seen from a systems perspective, it is clear that achieving the maximum energy efficiency of the systems becomes the first step. Using the best available techniques (BAT) to produce cement helps reducing the amount of emissions around a 10%. Next focus of improvement are the fuel usage in the cement plant. As said before, inside the rotary kiln fuel, today often fossil fuels, is combusted to produce heat. Turning towards alternative fuels becomes another source of improvement that adds around a 24% of emissions reduction. Later, the clinker substitution for alternative binders represents a 10% emission reduction potential. Finally yet importantly, introduction of carbon capture and storage (CCS) technologies in the cement industry could potentially reduce emissions to zero. Latest advances on CCS may have opened a door to possible business opportunities because of future policies on emission reductions across the EU [1].

Instead of achieving a rather less than a 50% emission reduction, Sweden ambitions go far more away from those figures. There are three cement facilities in Sweden located in the south region of the country. All three plants are owned by the same company, Cementa (a subsidiary to Heidelberg Cement) and have a collective production capacity of 2-3 Mtonnes of cement per year. However, one of the plants, located in Degerhamn is predicted to be decommissioned by 2019 in order to meet environmental goals [3]. As illustrated by Figure 3, Cementa has been working on a complete decarbonisation of its production processes, with the ambition to become carbon neutral by the year 2030.

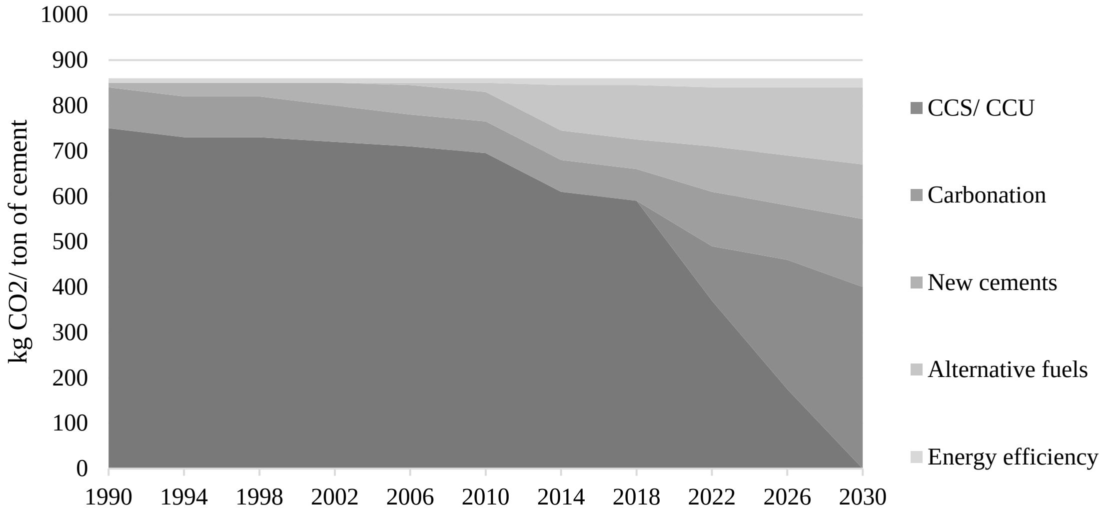


Figure 3 Cement sector CO2 emissions reductions 1990-2030. Source: Swedish cement industry Roadmap [4].

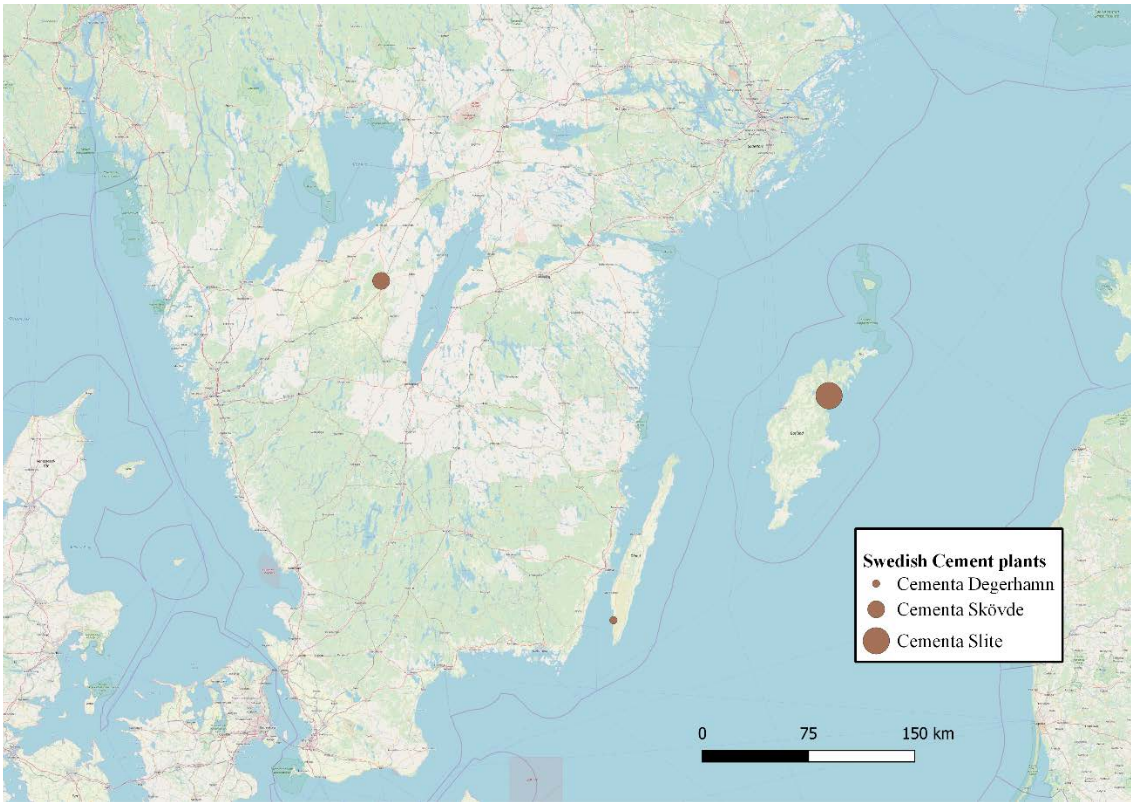


Figure 4 Swedish cement production facilities. Source: Cemnet – QGIS mapping..[5]

In order to achieve a lower clinker to cement ratio reduction, it has been proposed the use of alternative binders. These are materials that show hydraulic or pozzolanic behaviour, which means that is a material that can set and harden submerged in water by forming cementitious products in a hydration reaction. Some of the most common and widely used alternative binders are fly ash from coal-fired power plants and ground granulated blast furnace slag from integrated steel plants.

Most alternative binders share nearly all properties with ordinary cement clinker. But, many times its utilization is linked to external factors such as local availability, economical feasibility or the final design expected for the concrete.

Many countries around the world have been exploring the use of alternative binders in the cement industry and it is common practice to use both fly ash and blast furnace slag in many cement and concrete applications. Figure 5 shows the share (vol. %) of alternative binders used in the production of clinker-based Portland cement in the EU28 in the period from 1990 to 2016.

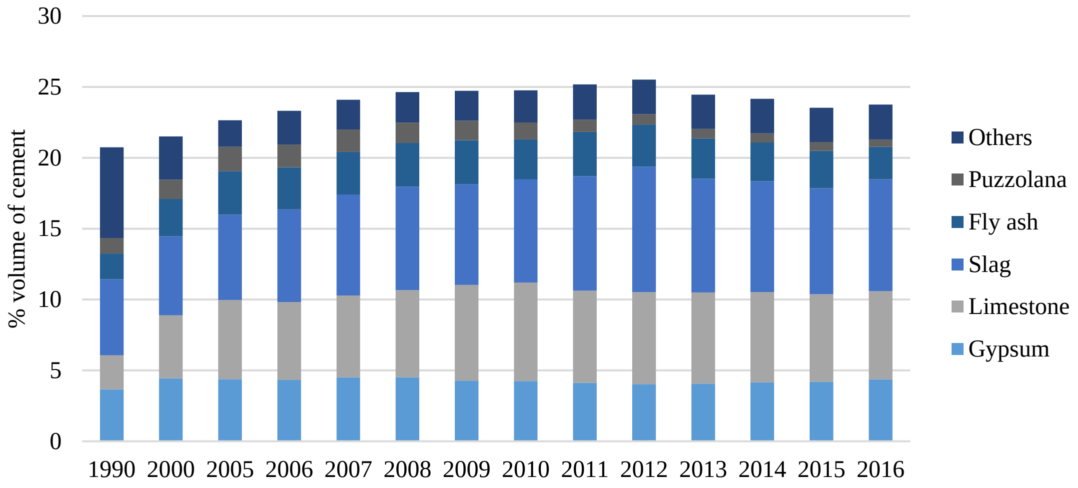


Figure 5 Mineral components used to produce clinker-based Portland cement, weighted average, EU-28. Source:[6]

However, in a European and Swedish context, there have been some limitations of their application due to a lack of testable data and regulative directives. Therefore, it becomes a big opportunity of improvement to explore the alternative binders' application.

1.3.Problem statement

Concrete is, as mentioned above, next to water the most consumed material in the world, being the cause of 5-8% of all global anthropogenic greenhouse gas emissions. Carbon dioxide emissions from the cement production account for the vast majority of these emissions.

A key option to decrease these emissions is via replacement of clinker for alternative binders. In Europe, the average clinker to cement ratio of 74.2% [3], which is slightly under the average world ratio replacement of 75% [3]. However, previous work suggests that there is a considerable potential to both lower the clinker to cement ratio and to reduce the cement content in many concrete applications. Therefore, it is clear that there is a huge opportunity of improvement towards a less carbon intensive industry.

Moreover, all countries that signed the Paris agreement in 2015 attempted to limit the rise in global temperature this century to less than two degree above preindustrial levels. As a result of this premise, the project is presented as part of the solution in order to achieve that goal with realistic changes.

1.4.Methodology

The methodology used in order to develop this thesis was conducted through quantitative research and literature review. In a quantitative research, any data analysed is in numerical form such as, e.g., statistics, figures or tables.

The literature review conducted in the thesis included a wide spectrum of categories. The most important category were reports from well-known international organisations, e.g., “Technology Roadmap, Low-Carbon Transition in the Cement Industry” from International Energy Agency (IEA) [1] or “A Sustainable Future for the European Cement and Concrete Industry: Technology assessment for full decarbonisation of the industry by 2050” by Faviere et al. [7]. Other important sources of knowledge were scientific articles and papers related to alternative binders and their utilization in cement industry.

After the literature review, it was developed a short overview of the most relevant alternative binders known today. This overview included a short description of these alternative binders’ origin and other data like, e.g., estimated use, estimated availability or rival uses. It was decided that fly ash and blast furnace were the two alternative binders chosen to conduct the estimates. This decision was influenced by the fact that these two alternative binders are widely used and because there is larger information available compared with the other alternative binders.

Later, there were developed two sections in order to estimate the alternative binders’ resource base chosen. In the first section (see Section 3), it was conducted an estimation of the availability of fly ash and its future estimates for the period 2017-2050. In the second section (see Section 4), it was conducted an estimation of the availability of the blast furnace slag and its future estimates for the period 2017-2050. The fly ash estimates were calculated based on existing coal-fired power plants block net capacity, and the blast furnace slag estimates were calculated based on the existing and projected capacity of EU blast furnaces.

In addition, it was developed a section in which is discussed first from a global point of view (world basis), and later more specifically (Western Europe), the cement demand evolution occurred in the last decades. Inside this section, it was included a sub-section describing estimated future cement demand and the scenario basis in which the following section will oscillate.

In the last stage of the thesis, it was developed a scenario analysis using spatial GIS analysis and Matlab programming. Three scenarios were considered: a business as usual (BAU) scenario (constant demand), a Low-demand scenario (20% reduction of cement demand over the studied period) and a High-demand scenario (20% increase of cement demand over the studied period). In every scenario, conventional alternative binders (fly ash and blast furnace slag) and cement demand are tied in to achieve a certain clinker replacement ratio.

Within the following subsections it is described in more detail the process used to estimate the availability of conventional alternative binders (fly ash and blast furnace slag) and the background of the spatial GIS analysis.

1.4.1. Data sources

Using reliable and trustable data sources is crucial for the project credibility. As one of the end objectives of the project is creating a set of scenarios in order to evaluate how alternative binders can scale up, high priority have been given to finding, using and producing as relevant and as accurate data as possible. Table 1 presents briefly the main data sources used in this work.

The coming section provides a more thorough description and discussion of the method to estimate every magnitude used in the study.

Table 1 Main data sources of the project.

Data source	Description
Chalmers PP db [8]	It consists on a set of data about all coal-fired power plants existing on Europe. It includes data describing, e.g., geo-referenced location and country, block net capacity, type of coal used, year of construction.

Chalmers IND db [4]	It consists on a set of data about all blast furnaces existing on Europe. It contains a huge amount of parameters and data, from which there will be used: geo-referenced location and location, operational status, production and capacity as a whole and for each furnace, year of construction as a whole and for each furnace …
Plantfacts [9]	It consists on a set of data about existing blast furnaces in Europe. It contains detailed data and parameters of the blast furnaces, as well as basic information, e.g., steel production, location, status or daily hot metal production.
Eurostat [10]	From this website it will be used many indicators, ratios and overall GIS data. They offer geo-referenced data about statistical regions of Europe, being the most crucial for the project population figures.
Cemnet [11]	This association also provides useful indicators and figures for cement all across the world. However, as the project scope is limited to Europe, only EU28 countries data will be considered. Besides, they also produce useful reports about every country cement facilities.
Cembureau [12]	It is another European cement association which produces reports about cement consumption and production evolution in all Europe countries. Moreover, they also provide statistical figures about these and other parameters.
GNR [13]	It is a European project that provides many statistical data about cement for every EU28 country. Their data are presented both for one year or on a time evolution since they began to document it.

1.4.2. Geographical scope

The study covers all EU-28 member states. Table 2 shows the countries included in the study and the number of blast furnaces (steel industry column) and operating units (coal-fired power plants column):

Table 2 Geographical scope of Europe, steel industry and coal-fired power plants.

EU-28	Steel industry (number of blast furnaces)	Coal-fired power plants (number of operating units)
Austria	2	5
Belgium	2	3
Bulgaria	-	27
Croatia	-	2
Cyprus	-	-
Czech Republic	2	94
Denmark	-	9
Estonia	-	12
Finland	2	14
France	4	7
Germany	7	149
Greece	-	18
Hungary	1	10
Ireland	-	3
Italy	4	27
Latvia	-	-
Lithuania	-	-
Luxembourg	-	-
Malta	-	-
Netherlands	1	7
Poland	3	318
Portugal	-	6
Romania	-	35
Slovenia	1	14

Slovakia	-	5
Spain	1	34
Sweden	2	9
United Kingdom	1	30
TOTAL	33	838

1.4.3. Estimation of FA

Fly ash (FA) is a by-product that belongs to the family of the coal combustion products (CCPs). CCPs are produced during the combustion of pulverized coal in the furnace of a power station boiler, resulting in the production of a number of solid products, traditionally regarded as residues [14]. The majority of the CCPs (80-85%) remain in the furnace gases, which are usually captured in an electrostatic precipitator at the boiler outlet [14]. Traditionally, this fraction is known as fly ash (FA).

The estimates of the production of fly ash from coal-fired power plants in Europe are based on the following assumption.

i. Capacity factor:

Determining an average capacity factor is a key point to develop a realistic power output studio. However, capacity factors are a source of uncertainty because they are strongly linked to the energy need of the society which may vary from one year to another. Values near one means that a power plant is being nearly fully used at their maximum capacity.

Data from different organisations provide different points of view on how capacity factor should be consider. U.S. Energy Information Administration (EIA) considers acceptable a 53,5% capacity factor [15]. A working paper from the University of Oxford considers a more conservative point of view stating a 20% capacity factor according to last years' figures [16]. International Energy Agency (IEA) provides a range of values from 80 to 85% in which plants can be more efficient [17].

Here, an average capacity factor for EU coal-fired power plants was calculated by comparing the known gross electricity generated from coal technology in EU-28 in 2017 (data extracted from International Energy Agency) [13] with the potential output from the current fleet of coal-fired power plants in the EU (Chalmers PP db in 2017) [8].

$$\frac{E_{coal}}{P_e \cdot 24 \cdot 365} \quad (1)$$

Where P_e is the block net capacity of all coal-fired power plants and E_{coal} is the electricity generated by coal in EU-28. Table 3 shows the block net capacity of all coal-fired power plants from Chalmers PP db, the gross electricity generated by coal and the capacity factor:

Table 3 Coal-fired power plants capacity factor calculi.

Total block net capacity (GW)	**Potential electricity supplied (GWh**	**Electricity generated by coal (GWh)** [18]	**Capacity factor**
163	1 421 300	669 000	0.47

ii. Coal lower heating value (LHV):

Table 4 Net calorific value of fossil fuels. Source: UPC "Energy Technology Course".

Fuel		**Net calorific value**	
Oil Products		10 000 kcal/kg	41 900 kJ/kg
Coal	Anthracite	7 000 kcal/kg	29 300 kJ/kg

	Bituminous	6 000 kcal/ kg	25 000 kJ/kg
	Lignite	4 500 kcal/kg	18 800 kJ/kg
Natural gas		9 000 kcal/m^3	36 000 kJ/m^3

iii. Coal chemical composition:

According to Table 5, for anthracite coal (hard coal) ashes and water represent a 2% of total coal. Then, a 10% of the 90% are volatile compounds. In summary, if we sum 2% from water and ashes and the 8% from volatile compounds it is obtained a 10% of non-combustible products.

Similar as anthracite, lignite has a percentage of water and ashes. However, the water and ash content in lignite is significantly as larger than in hard coal, approximately 40%. The remaining 60% is weighted among a 55% of fixed carbon and a 45 of volatile compounds. Through some calculus, all non-combustible products represent a 67% in lignite coal.

Table 5 Coal chemical composition. Source: UPC "Energy Technology Course".

Type of coal	**Fixed carbon**	**Volatile compounds**	**H_2O and Ashes**
Anthracite	>90%	<10%	2%
Bituminous	~70%	~30%	8%
Lignite	~55%	~45%	40%
Peat	~50%	~50%	75%

Table 6 summarizes the calculi previously described:

Table 6 Coal chemical composition calculi summary.

Coal	**Non-combustible products (%)**	**Fixed carbon (%)**
Anthracite	10	90
Lignite	67	33

Based on these estimates, an average quantity of coal combustion products (CCPs) is possible to calculate. They can be calculated using the following relation:

$$P_{TH} = \dot{m} \cdot LHV \tag{2}$$

Where P_{TH} is the thermal power of the facility, $\dot{m}$ is the coal mass flow per time unit and LHV is the lower heating value of the coal type used. Note that thermal power (P_{TH}) needs to be obtained from block net capacity (P_e) since is the only data given. Also, in order to match with the lower heating value their units need to be transformed.

$$\boldsymbol{P_{TH}} = \frac{\boldsymbol{P_e}}{\boldsymbol{\mu}} \textbf{ x LCP} \tag{3}$$

$\boldsymbol{\mu}$	0.36
LCP	0.8

Where μ is the coal-fired power plant efficiency and LCP is the load capacity factor.

Besides, not all coal combustion products are suitable for binders application. According to some studies and regulations [14], about 85% of all CCPs are possible to use as fly ash. The 15% not used, it is meant to be bottom ash, which later is converted into conditioned ash through a water cooling stream.

Table 7 Coal profitable fly ash content calculi.

Coal	Non-combustible products (%)	Profitable Fly Ash (%)
Anthracite	10	8.5
Lignite	67	56.95

1.4.4. Estimation of BFS

Blast furnace slag (BFS) is formed during processing of pig iron in a blast furnace. Iron ore is melted to over 1350 ºC, when slag is formed at the surface and is decanted by gravity. Later, that slag is rapidly cooled to below 800ºC to prevent crystallization of other compounds and finely ground. Depending on how is it cooled, air-cooled blast furnace slag is obtained (crushed stone look) or ground granulated blast furnace slag (water-cooled, looks like sand).[19]

About 300 kg of slag are obtained per ton of pig iron produced. [20] Then, thanks to this assumption, it is possible to obtain an approximation of the blast furnace slag produced in Europe blast furnaces. Converting that information into a ratio [21]:

$$\frac{M_{slag}}{M_{pig\ iron}} x \frac{M_{pig\ iron}}{M_{iron\ ore}} x \frac{M_{iron\ ore}}{M_{steel}} = \frac{M_{slag}}{M_{steel}} \tag{4}$$

Table 8 Steel to slag ratio summary.

Ratio	
$\boldsymbol{M_{slag}/M_{pig\ iron}}$	300/1 000
$\boldsymbol{M_{pig\ iron}/M_{iron\ ore}}$	1 000/1 600
$\boldsymbol{M_{iron\ ore}/M_{steel}}$	1 400/1 000
$\boldsymbol{M_{slag}/M_{steel}}$	0.2625

Data extracted from the European Steel Association [22] provides a useful view about the steel industry distribution across Europe. Data acquired thanks to information gathering and organisation collaboration shows million tons of steel produced in each country from Europe from 2011 to August 2017. In order to achieve a wider perspective, data from 2017 will be ignored. It will be taken into account data from year 2016 as long as it can provide whole year variability.

1.4.5. Estimation of cement demand

Regional cement demand for each European region was estimated based on the population and per capita consumption of cement in each country. Data extracted from Eurostat [10] provides exact population figures for every NUTS region level 2 (see Section 1.4.6 for an extended description) in Europe. In addition, there were extracted data from NUTS region 0 (country level) for future calculi. Moreover, hypothesis regarding future population were required in the study. According to Eurostat projections [23], the population of EU28 countries will experience an increase. Table 9 shows the population rising compared to population in 2015 by the years 2030 and 2050.

Table 9 Population increase in EU28 countries in years 2030 and 2050.

Year	Population increase compared to 2015
2030	2.3%
2050	2.5%

Data extracted from Cemnet [24] provides different information related to cement, e.g., consumption, production or capacity. However, consumption figures for year 2017 were the data used to conduct the cement estimates. Later, a cement consumption per capita ratio for year 2017 was calculated by dividing cement consumption in each country by their population. Next, this ratio was used to estimate the cement demand in each NUTS region level 2 by multiplying it with their correspondent population. Further information about cement estimates can be found in Section 5.4.

However, using this method to estimate cement demand in each NUTS region level 2 is not perfect. This method assumes all cement demand is concentrated in the NUTS region centroid. In order to develop a more accurate estimation it would be required the centroid of every city or town of EU-28 countries. If this data had been available, the distance matrix used in the GIS spatial analysis (see Section 1.4.6) would have been different.

1.4.6. GIS – Spatial Analysis

To link the resource base of conventional alternative binders (fly ash and blast furnace slag) with cement demand across Europe regions requires spatial GIS analysis. In addition, scenario analysis was required to conduct future estimates. Future estimates were subjected to phased out of existing capital stock (coal-fired power plants and blast furnaces) and future cement demand estimates.

The spatial analysis has been performed using QGIS, an open source Geographic Information System (GIS) [25] Nowadays, there are plenty of convenient mapping resources for spatial analysis and scenario analysis. However, for this case, it was chosen the QGIS 3.4.1 since it is a widely used open source tool that is able to provide the desired results.

In spatial analysis, Europe was subdivided in hierarchical statistical regions, referred to as NUTS regions. NUTS, which means “Nomenclature of Territorial Units for Statistics”, is a geocode standard for referencing EU countries subdivisions for statistical purposes. There are three levels of NUTS defined, but in this case, it will be considered the level 2 only. This decision was motivated due to the easy availability to trustable data.

Therefore, the first step was to introduce data related to countries shape and their own subdivions. This information about NUTS shape files and population numbers for each NUT were obtained from Eurostat [26]. Thanks to this, was possible to provide accurate data about more populated zones and how they are divided.

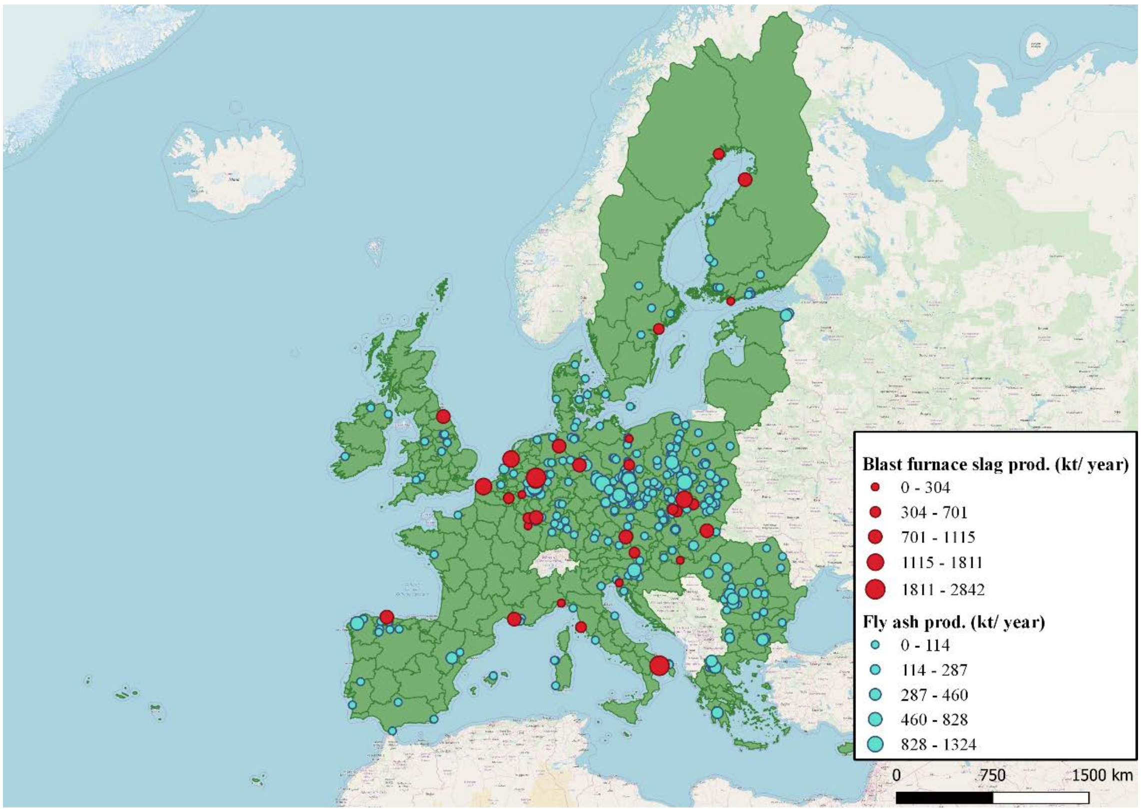


Figure 6 EU NUTS and Coal fired power plants (blue dots) and Blast Furnaces locations (red dots)

The next step was describing the per capita production and consumption for each subdivision. Estimates of annual production and consumption of cement comes from Cemnet, which provides a vast amount of information including, e.g., cement consumption, production and capacity for every country of the world [24]. EU coal fired power plants and blast furnaces were mapped based on data from Chalmers PP db (power plants) and Chalmers IND db and Plantfacts (blast furnaces) (see Table 1 for references and a description of the databases). Figure 6 shows the map shape after introducing all mentioned data.

Since the goal is to maximize clinker replacement throughout Europe, one sub task was to estimate how the availability of these by-products are distributed. Thus to find out whether it is possible or not to send these fly ash and blast furnace slag from their production sites to each NUTS region it is required to solve a transportation problem.

A transportation problem is the abstraction of the following statement: given a certain number of production sites with a certain production (A, B, C); a set of demand centres with a given demand (D, E, F); and a cost matrix (in this case a distance matrix between each production site and storage), find how to distribute all the production among storages with the smallest cost possible. Figure 7 illustrates the transportation problem.

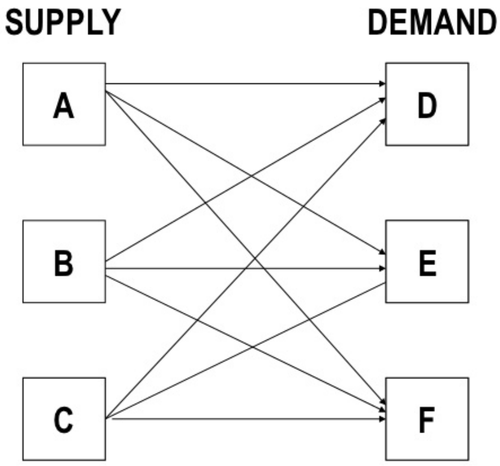


Figure 7 Transportation problem scheme.

For the project objective, it can be a close approach to solve how to distribute the alternative binders among all regions in EU. In the analysis, the following correlations were made according to the transportation problem abstraction:

- Production sites (A, B, C) were coal-fired power plants and blast furnaces location. Their production was fly ash and blast furnace slag estimates calculated in Sections 3 and 4.
- Demand centres (D, E, F) were NUTS regions centroids. Their demand was cement demand estimates calculated in Section 5.
- The cost matrix was the distance between each NUTS region centroid and each coal-fired power plant and blast furnace.

The transportation problem was solved using Matlab. The following inputs were used:

- Production supplies of by-products (fly ash and blast furnace slags) for every facility.
- Demand of by-products for every region (NUT level 2). There were to possibilities to fulfil the demand of by-products for every region. The first possibility was to assign the maximum quantity of by-products to the nearest regions surrounding coal-fired power plants and blast furnaces. The second and finally used possibility was to maximize the clinker replacement in all NUTS regions, assigning the same replacement to all zones.
- Distance matrixes from production facilities to region centroids.

After, it was designed a code that was able to assign the maximum quantity of by-products to the closest region. Given the inputs listed above, it replied with the quantities of by-products that was available for every region included in the simulation. Once obtained this extremely valuable information, it was finally uploaded to the QGIS map. Changing the colour of every NUTS region using a comparison formulation in the QGIS program, allowed to create a map that could show with an easy-to-interpret code of colours, which regions are covered the assigned replacement and which are not.

2. Alternative binders' overview

2.1.Description

Concrete industry utilizes a large variety of cements depending on their final application. Each one of these cements has a different composition that makes it unique for a specific design, which means that each one has different properties and features. Today, the most commonly used cement is ordinary Portland cement (OPC), which account for the largest share of the climate impact of concrete [1]. To reduce climate impact, parts of the cement content can be substituted with alternative binders.

Many alternative binders possess very similar properties to cement clinker that make them suitable for construction purposes in buildings and infrastructures. However, it is not always possible to add these alternative binders under uncontrolled conditions and without pre-treatment in many cases. Moreover, as mentioned before, many alternative binders require some kind of physical pre-treatment as, for instance, grinding or impurity extraction [27]. Chemical pre-treatments which may require significant investments and can be limited by external factors like environmental taxes.

Even though alternative binders differ significantly depending on their physical and chemical properties, it is a widely spread practice to classify them according to their origin, in other words, if they have been extracted from the earth directly or if they are by-products from another industry.

So on, a first layout of alternative binders classified according to their origin [19].

- **Natural origin**: tipically need little or no preparation, e.g. separation and grinding.
  i. Volcanic origin
    - Unaltered pyroclastic material (vitreous pumices and ashes)
    - Altered pyroclastic material (zeolitised tuffs)
  ii. Sedimentary origin
    - Chemical sediments (diatomaceous earths, hydrothermal siliceous sinters)
    - Materials of mixed origin
    - Detrital sediments (naturally burned clays, burned clays/ shales –artificial-)
- **Natural thermally activated**: natural materials activated by temperature (calcined).
    - Kaolinite
    - Illite
    - Montmorillonite
- Man-made or **artificial origin**: these materials have undergone structural modifications due to manufacturing or production processes.
    - Blast-furnace slag
    - Fly ash
    - Silica fume
    - Burned organic matter residues
    - Steel/ non-ferro industry slags
    - Bottom ash
    - Municipal solid waste ash
    - Waste glass
    - Fluid cracking catalyst residues

The following section provides a description of the most well-known alternative binders and their main properties and features useful for construction purposes.

2.2.Natural origin

Volcanic rocks represent the large majority of natural pozzolans and are relatively widely spread and available in many countries [19].

But, not all volcanic rocks can be used as pozzolanic materials. Pyroclastic materials are the most suitable. They originate from volcanic eruptions, specifically, ashes and pumice. The larger the silica content is in the magma the more explosive will be the volcanic eruption and the better the pozzolanic

A second group of alternative binders of are sedimentary materials, which use is scarcer [19]. Their use is only considered under specific conditions, when sediments are rich in pozzolanic active components formed by deposition or alteration, for instance, naturally burned clays.

Table 10 Cathegorization and description of alternative binders of natural origin.

Material	Volume	In use	Description
Unaltered pyroclastic rocks (UPR)	Plentiful*	Y	UPR result from rapid energy changes whereby magma moves and is violently erupted from a deep higher temperature and higher pressure environment to earth surface. [28] The gases originally dissolved in the liquid magma are then released.[19] They consist on quenched microporous structure particles in a glassy state. Those rocks can be deposited whether on ground or in water. The ones deposited on the ground are mixed with ashes from the volcanic eruption.[29] When the eruption is not enough explosive, the quenching process is not enough fast and creates ashes, which are not suitable for pozzolanic purposes. [19]
Altered pyroclastic rocks (zeolites)	Plentiful*	Y	Zeolites are formed where pyroclastic rocks and ash layers react with alkaline groundwater, controlled by pH and temperature too [30]. They are characterized by a high content of water adsorbed by the material, which produces a high loss on ignition. [19] However, zeolites can also be produced synthetically heating aqueous solutions of alumina and silica with sodium hydroxide. Since the main raw materials to produce and manufacture zeolites are alumina and silica, which are the most abundant components on earth, the potential supply of zeolites is almost unlimited. [31]
Biochemical sediments	N/A	Y	Biochemical sediments comprises sediments from the deposition of organism skeletons, as well as chemical precipitates resulting from the circulation of hydrothermal waters. Diatomaceous earths, also called diatomites, are the principal biogenic materials that show pozzolanic activity inside biochemical sediments. They consists of siliceous fossilized remains of diatoms, a type of hard-shelled protist.[32] The deposits result from an accumulation in oceans or fresh waters of the amorphous silica cell walls of dead diatoms that are microscopic single-cell aquatic plants (algae). It is very finely porous, very low in density and essentially chemically inert in most liquids and gases. Low thermal conductivity and a rather high fusion point.[32]
Detrital and mixed origin rocks	N/A	Y	Detrital and mixed origin rocks. These sediments are usually composed of stable mineral compounds derived from the erosion and weathering of other rocks. It is quite uncommon to find pozzolanic behaviour in sufficient quantities to consider them suitable for cement applications. [19]

*Plentiful but localized

2.3.Natural thermally activated

Natural thermally activated alternative binders refer to a category of materials, of natural origin, that are tailored made for specific applications. These group of alternative binders comprise for instance streams of waste from clay pottery, bricks or tiles that can be recycled as a pozzolanic material in cement production. Thermally activated SCMs are traditionally blends of thermally activated clays or soils and lime [19].

Natural thermally activated alternative binders are in use in many countries due to their excellent pozzolanic properties. These properties are a result of kaolinite-rich materials burned under controlled conditions, better known as metakaolin. The overall resource base, however, tends to be limited.

Those materials can be obtained above from burned clays, also from shales, soils and burned agricultural residues. As a consequence, they are receiving considerable attention in rural areas with no possibility of obtaining more modern alternative binders [19].

Table 11 Cathegorization and description of alternative binders of natural thermally activated origin.

Material	Volume	In use	Description
Kaolinite	Limited*	Y	Kaolinite is obtained from clay deposits all over the worlds. However, there are only a few high purity deposits. Moreover, the industrial process to obtain them by removing mineral impurities is too expensive and complex. Once burned and grounded, this material becomes metakaolin, which has its pozzolanic properties enhanced. [33]
Illite	Limited*	N/A	Illite clay is usually found in deep oceans containing micaceous minerals. It can also be found underground but only in calcareous clays. [33] According to some studies, illite has a low-moderate pozzolanic activity. No treated illite is a practically inert component in cement and concrete chemistry. Only at certain ranges of calcination, 790-930 ºC, it is possible to obtain a decent compressive strength compared to OPC. [34]
Montmorillonite	Limited*	N/A	Montmorillonite clay is a type of smectite clay that tends to expand with water. It is formed through alteration of silicate minerals in alkaline conditions, such as pyroclastic rocks (e.g. volcanic ashes), that can be deposited in oceans. [35] Montmorillonite comprises many industrial applications such as oil decolourants, pesticide or heavy metal adsorbent in wastewater, and catalyst for certain chemical reactions. Their catalytic properties are enhanced when treated with acids.[34]

*Clays are widely available, but supply of calcined clays, which requires process facilities allowing their calcination, is more limited

2.4. Artificial origin

The vast majority of the alternative binders of artificial origin are by-products and come from societal waste and valorization of industrial residues.

Table 12 Cathegorization and description of alternative binders of artificial origin.

Material	Volume	In use	Description
Blast furnace slags	480-560 Mt/year [1]	Y	The most widely used SCM. By-product obtained in the extraction of pig iron in blast furnaces. They present a latent hydraulic behaviour. [19] Depending on how slag is cooled, it is possible to obtain air-cooled GBFS (crystalline structured mass, more suitable as construction aggregate) or granulated GBFS (rapidly cooled with large amounts of water, which forms a glassy/ amorphous granulated GBFS. It can be mixed with cement clinker to use it as a binder for cement). [36] Nowadays is mostly combined with OPC to constitute a large fraction of blended cements. Their cementitious properties are properly activated in combination with lime, alkali hydroxides, sodium carbonates or sodium silicates and calcium or magnesium sulphates.
Fly ash	780 Mt/year [14]	Y	Fly ash are a big part of the over one billion tons of the coal combustion products (CCP) generated from the coal combustion [19]. It is usually captured with electrostatic precipitators or bag filters before the flue gases are emitted. [36] They also include municipal solid waste incineration fly ash. After being appropriately treated and dried, it can be used as clinker addition, cement addition or other industrial applications such as soil amelioration. [36]

			Nature and properties of fly ash dependent on a variety of factors that include: coal's mineral composition; furnace/boiler temperature; type and fineness of the coal; length of time the minerals are retained in the furnace/boiler. [14]
Silica fume	0,9 Mt/year [37]	Y	By-product of the silicon metal and ferro-silicon alloy industries. Silica fume is produced during the reduction of quartz at high temperatures in electric arc furnaces. Silica fume has nearly no variation in chemical composition over time.[19] Silica fume remains initially inert when is added to concrete. Once OPC and water start to mix with each other and hydrates, two chemical compounds are produced that produce strength with their crystallization. [38] It has a high pozzolanic activity due to its high content of SiO2 in amorphous form and a very fine particle size distribution, 0.1-0.2 um on average diameter.
Burned organic matter residues	N/A	N	They consist on burned agricultural remains such as rice husk or wood ashes, which can be used as OPC replacement. Once fired under controlled conditions, silica is concentrated in the residue enhancing pozzolanic properties. [19] The characteristics of the ash depend upon biomass characteristics, combustion technology and the location where ash is collected. Burned ashes present pozzolanic properties that makes them suitable for cement binders. Their strength decrease slightly with increase in ash content in the concrete. [39]
Non-ferro industry slags	N/A	Y	It comes from the steel manufacture process, when main raw materials (liquid iron and scrap steel), auxiliary raw materials (lime, ore, dolomite and fluorspar) and ferroalloys melt into two incompatible parts under high temperature. Cements blended with steel slag show higher later period strength, better frost resistance, good wear resistance and lower hydration heat. [40]
Waste glass	130 Mt/yr [41]	N	Once the glass purpose ends, it becomes a waste and usually disposed as landfills. However, it can also be used as a potential supplementary cementitious material as long as it has a chemical composition and phase compared to traditional binders. When milled, reactions between glass and cement hydrates are enhanced. [41] Very finely ground glass has been shown to be excellent filler and may have sufficient pozzolanic properties to be utilized as a cement replacement. [42]
Fluid catalytic cracking catalyst (FC3R) residues	0,4 Mt/yr [43]	N	Fluid catalytic cracking catalyst residues (FC3R) are collected from petrol refineries. Even though the sources (refineries) are different, the catalyst residues do not produce different behaviour. [44] FC3R is formed by particles of spherical shape, highly porous and chemically composed by alumina, which provides its greats pozzolanic properties. [43]

2.5.Key features

Table 13 presents a summary of some important features related to the alternative binders reviewed above in a global context. As a matter to simplify the table, sources from natural origin will be displayed as "natural pozzolans" and natural but thermally activated as "activated clays".

Regarding only on estimated use figures, artificial origin alternative binders are the dominating sources. Fly ash and blast furnace slag provide approximately 600 Mtonnes of by-products to the cement industry globally. Although natural sources claim to provide a substantial amount of alternative binders, their availability is regionally limited and still requires larger research.

Other promising alternative binders are activated clays and burned organic matter residues. As mentioned below in the table, clays are widely available in many world regions. However, taking maximum profit of their features requires calcination processes, which can only be conducted in specific facilities. Moreover, burned organic matter residues includes different sources, e.g., biomass ash or rice husk ash. Some studies claim that the available biomass ash is estimated in 100-140 Mtonnes [45].

Conventional alternative binders (fly ash and blast furnaces slag) are widely used in cement industry. In particular, blast furnace slag is nearly fully used in many countries, being especially difficult to increase their utilisation. However, fly ash utilisation can still be largely improved. It is estimated that only 30-50 % of the total resources of fly ash are currently being used.

Non-ferro industry slags is another portion of alternative binders that can help reduce cement emissions. These kind of slags are estimated in a maximum quantity of 205 Mtonnes. However, cement industry is not the only interested manufacturer for these by-products. Inside non-ferro industry slags are included by-products, e.g. bauxite, copper and other minor residues. Aluminium industry is actually using nearly the whole quantity of these bauxites residues for their manufacturing processes.

Other minor sources of alternative binders from artificial origin are silica fume and FC3R (fluid catalytic cracking catalyst residue). Their potential contribution pales in comparison with the sources commented before. However, these alternative binders may have a niche of utilisation due to regional availability.

Table 13 Alternative binders' key features.

Material	Geographical spread	Treatment requirement	Price range ($/ tonne)	Estimated use (MT/y)	Estimated availability	Rival uses
Natural pozzolans	Widely	Crushing, drying	35-90 [45]	75 [45]	Plentiful but localized. [27]	No
Activated clays	Widely, but require process facilities allowing their calcination.	High water demand, crushing, drying and calcining	13 (common) 150 (kaolin) 600-700 (metakaolin) [45]	2-3 [45]	Clays are widely available, but supply of calcined clays, which require process facilities allowing their calcination, is more limited. [27]	Yes
Blast furnace slag	Blast furnaces	Grounding	1-110 [45]	290 [45]	480-560 variable quality and availability. [45]	Yes
Fly Ash	Coal-fired power plants	Separation	35-110 [45]	300 [45]	600-900 variable quality and availability. [45]	Yes
Silica Fume	Silica industries	Superplasticiers-none	300-1100 [45]	>1 [45]	1-2.5 [27]	No
Burned organic matter residues (biomass ash, rice husk ash)	Agricultural zones	Grinding, selective removal	N/A	N/A	100-140 (Biomass ash) [45] 22 (rice husk ash) [27]	Yes
Non-ferro industry slags/ residues	Non-ferro industry industries	Grinding, thermal activation	29-180 [45]	5-205	30-40(Copper slag) 5-15 (other) 100-150 (Bauxite residue) [27]	No
Waste glass	Recycling glass facilities	Chemical pre-treatment	53 €/ tonne [46]	N/A	130 [41]	Yes
Fluid catalytic cracking catalyst (FC3R) residues	Petrol refineries	Thermal activation [43]	N/A	N/A	0.4 [43]	Yes

3. Estimation of Fly Ash availability

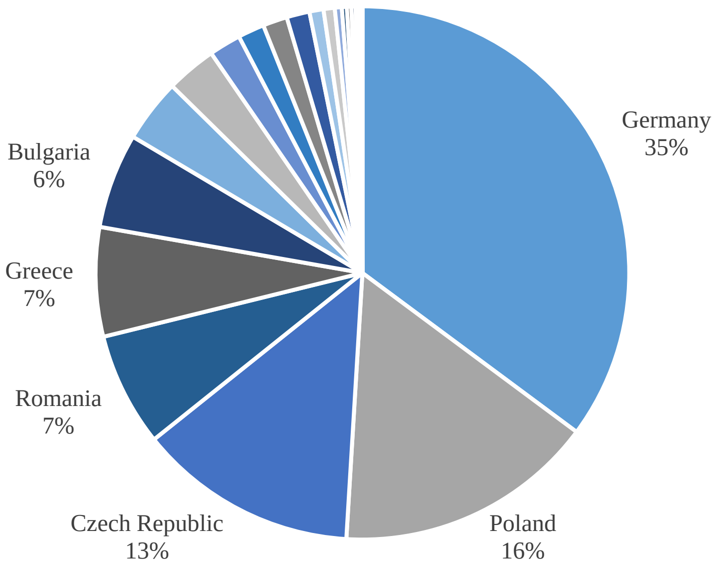
3.1. Current supply

As described in Section 1.4.2 Estimation of FA the availability of fly ash in Europe were estimated based on detailed data describing European coal-fired power plant fleets. Table 14 shows a summary of the estimates obtained:

Table 14 Amount of fly ash per region.

Region	Estimates of Fly Ash (kt FA/ year)
EU-28	84 000
SWEDEN	51

The data clearly shows how, compared to a European level, Sweden has a little amount of locally sourced fly ash. Representing less than 1% of total fly ash produced in Europe. Figure 8 shows the countries with the most production of fly ash residues:



*Note that all countries with less than a 5% have been erased from the labels.

Figure 8 Fly ash per country in Europe in 2017.

Three countries, Germany, Poland and the Czech Republic, which are the most production-intensive on fly ash as by-products for cement industries, account for significantly more than half of the production.

Summing the amount of fly ash of Sweden, Finland, Estonia and Denmark, a potential of less than a 4% is obtained. Taking into consideration this, it is clearly unproductive to focus efforts towards fly ash production in Sweden. This would signify that only when obtaining FA from countries like Poland or Germany at an economic price, can fly ash be a real opportunity as an alternative binder for Swedish cement production.

Section 6 further describes how the future potential for meeting the EU and Sweden demand for alternative binders were explored by combining scenario analysis with geospatial analysis.

3.2.Estimates of future supply of fly ash

Estimating future scenarios is a useful tool to decide in which direction current decisions should be driven. Scenarios are not projections of the future, that is to say, they may be thought more like the answer to “what if” than to attempt to depict the actual future development [47]. Exploring a range of future possibilities helps decision making decide on which policies to drive future developments, for example, when it comes to combating climate change. However, each future is “path-dependant”, which means it results from a large series of conditionalities [47].

To sum up, forecasting is, in most cases, very difficult and its outcome influenced by human judgement. Here, two of the key assumptions when estimating the future supply of fly ash were:

- Lifespan of coal power plants of 40 years.
- Study horizon until 2050.

It may be overconfident to assume that all coal power plants with more than 40 years will shut down from one day to another. Despite of having plants with more than 100 years of operation, it is common sense that no plant will close if they are allowed to operate. In addition, firms may have little economic incentive to retire existing plants [48]. It is often assumed that equipment lifetime is an important determinant on timing the capital investment/ retirement, while it is not always the case. Plant lifetime is usually extended thanks to investment in maintenance and equipment enhancement to meet market and policy emission goals. Even a high performance improvement of an exceptional magnitude on a new technology may not make a firm retire existing equipment whose capital costs have been paid [47]. In other words, even if a plant is inefficient compared to what modern technology can offer, this inefficiency must be very large in order to outweigh the costs of building a new and more efficient plant [47].

Nevertheless, for the case of study, it will help to answer to “what if” all coal power plants with more than 40 years of lifetime automatically shut down and which are the consequences to fly ash used for blended cements production.

Currently there are 418 coal power plants operating in Europe. Of these, around 70% are using anthracite as primary fuel. Assuming that lifespan of coal power plant is about 40 years of operation, it can be expected, according to year of construction, the yearly distribution and number of coal power plants operating. Table 15 shows the existing coal-fired power plants sorted by age and by their primary fuel.

Table 15 Existing coal-fired power plants sorted by age.

Type of coal	X>40	40>X>30	30>X>20	20>X>10	X<10
H (n)	292	115	79	25	0
B (n)	126	62	24	14	0
ALL (n)	418	177	103	39	0

* Where X means lifetime of the coal-fired power plant.

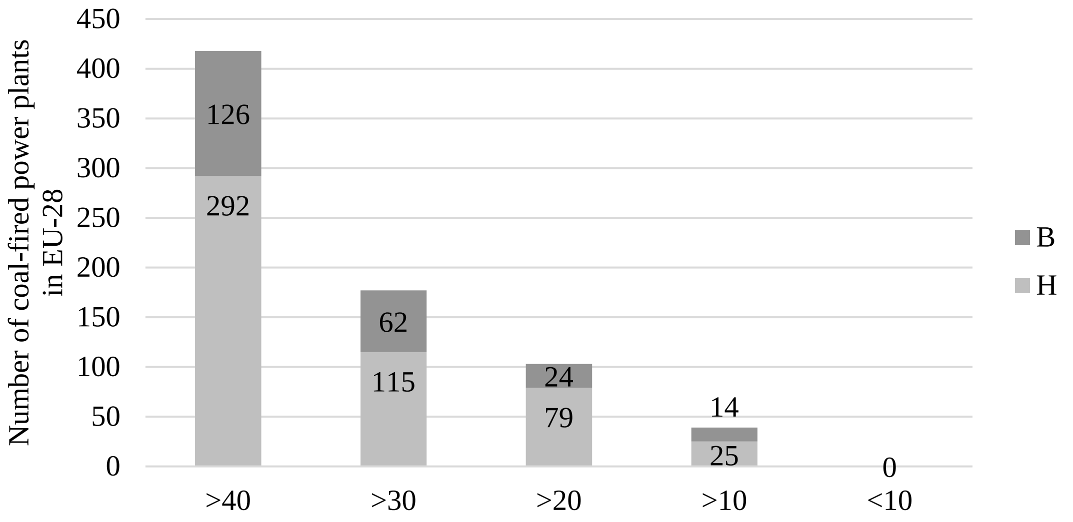


Figure 9 Coal power plants sorted per age.

Figure 9 shows how most of the coal power plants currently in operation in Europe are quite old with a lifetime of more than 40 years. The European Central Bank, which is a major investor in power plants, recently announced that it will no longer invest in coal plants [49]. Thus, can be assumed that no more coal power plants will appear in the future.

Thus based on the age structure of existing coal-fired power plants (Figure 9) and the assumed average technical life time of 40 years the fly ash resource base for the period 2017-2050 could be estimated.

Table 16 Fly ash resource base estimation up until 2050 calculi summary.

Type of coal	2017	2025	2030	2035	2040	2045	2050
H (Mt/y)	12.6	4.6	3.4	2.2	1.6	1.5	1.3
B (Mt/y)	71.4	27.4	21.6	19.9	11.6	9.1	7.9
ALL (Mt/r)	84.0	32.0	25.0	22.1	13.2	10.6	9.2

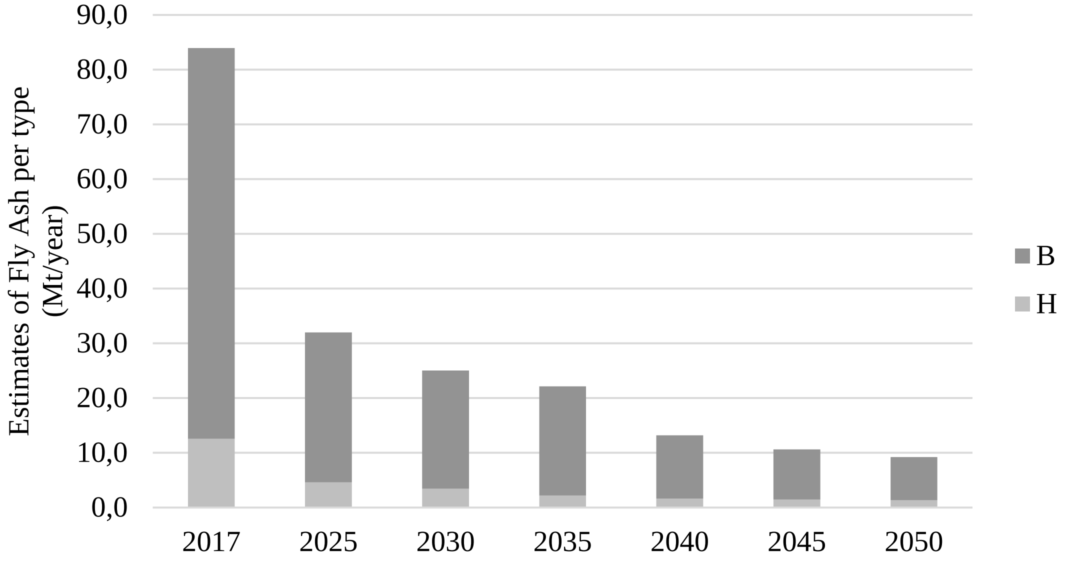
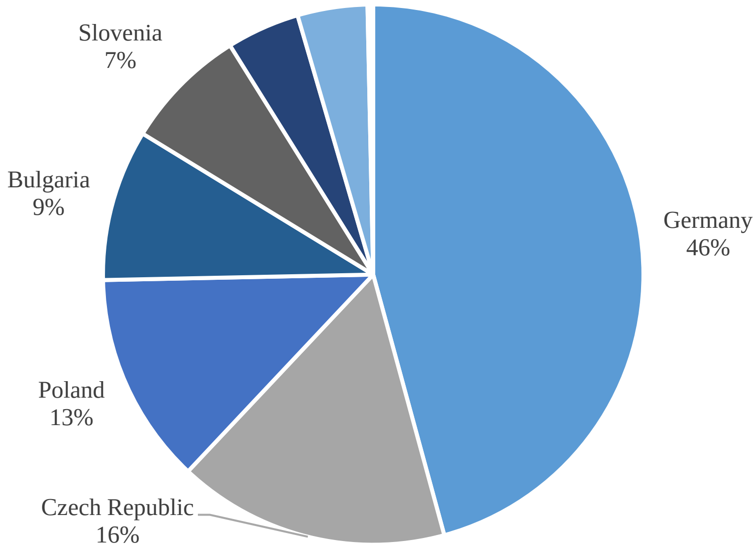


Figure 10 Fly ash resource base estimation up until 2050.

Clearly, after first five years a large share of the existing of coal-fired power plants should be dismantled as they reach the end of their technical life time. Installed coal capacity is reduced from 162 to 60 GW. This decrease obviously affects directly the amount of fly ash available, being reduced more than a 60%. After this point, the number of power plants decrease in a slower rate than before. In exception of years 2035 to 2040 where there is a significant reduction of almost a 50% from the previous year.

Moreover, it is important to note that the biggest contributor to the fly ash resource base is lignite plants. Based on the data and assumptions used here, the general distribution is 85% lignite fly ash and 15% anthracite fly ash. This distribution is a result of the high amount of non-combustible products contained in lignite coal, accounting for approximately 67% of the original coal mass. *Note *that all countries with less than a 5% have been erased from the labels.*

Figure 11 shows the estimated per country fly ash resource base in the year 2050.



*Note that all countries with less than a 5% have been erased from the labels.

Figure 11 Fly ash per country in 2050.

Again, Germany account for the largest part of the overall resource base, this since a significant number of their coal power plants still are relatively “young”. This is mainly due to the recent construction of 13 power plants (in the last 6 years), the majority of them with a huge block net capacity.

Sweden stops producing fly ash at some point between 2025 and 2030. If Sweden in the future wants to utilize fly ash as an alternative binder, it should use resources from other countries such as Germany or Poland.

4. Estimation of blast furnace slag availability

4.1. Current supply

Whether air cooled blast furnace slag (ABS) or ground granulated blast furnace slag (GGBS), all blast furnace slag can be used for construction purposes [50] (a more thorough description is provided in Section 2.4). The main difference arises from the granules measure, being far tinier when cooling slag with water. In case of ABS, its utilization is mostly linked to be used as a concrete aggregate. GGBS is finely grounded until obtaining a fine powder for blended cements [51].

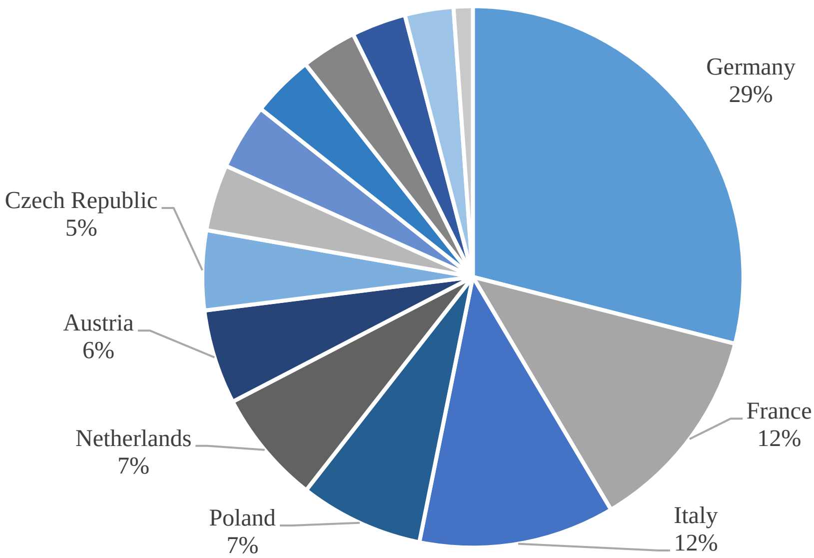
In the following estimation, as a simplification, it will be assumed that whole BFS resource base is transformed into GGBS for cement industry.

As described in Section 1.4.3. the availability of blast furnace slag in Europe were estimated based on detailed data describing European blast furnaces. Table 13 shows a summary of the calculi:

Table 17 Estimation of blast furnace slag availability in Europe and Sweden.

Region	kTones of slag/ year
EUROPE	26 600
SWEDEN	989

As seen in Table 17, compared to a European level, Sweden has a little amount of slag. Specifically it represents less than a 3% of total blast furnace slag use in Europe. Figure 12 shows the most important countries that can have a high potential of taking profit of their blast furnace slag.



*Note that all countries with less than a 5% have been erased from the labels.

Figure 12 Blast furnace slag per country in Europe.

Clearly, countries with the highest potential of taking real profit of their BFS as by-products for cement industry are Germany, France and Italy.

Currently, it does not seem that Sweden can take a real profit from BFS as a reliable source of alternative binders. In order to achieve higher ratings of utilisation it will be required to import part of that resource base from other countries with larger production, i.e. Germany.

4.2. Estimates of future supply of blast furnace slag

Actual steel production can be divided into two main categories: primary steel (produced in blast furnaces) and secondary steel (produced in electric arc furnaces). The latter dominate in regions such as the US and Western Europe, while the former arises stronger in emerging economies like India and China. Electric arc furnace technology accounts for a 75% of total steel production in Western Europe [52]. By 2050 that share is projected to decrease to a 66% because of reduced scrap availability.

From a waste utility point of view, blast furnaces will need to account for a larger share in order to meet steel commodities. Thus, the availability of blast furnace slag resources are expected to increase in Western Europe and the US. Therefore, steel consumption is forecasted to decrease in these regions in China steadily from 66% share in 2010 to a 52% by 2050 [52].

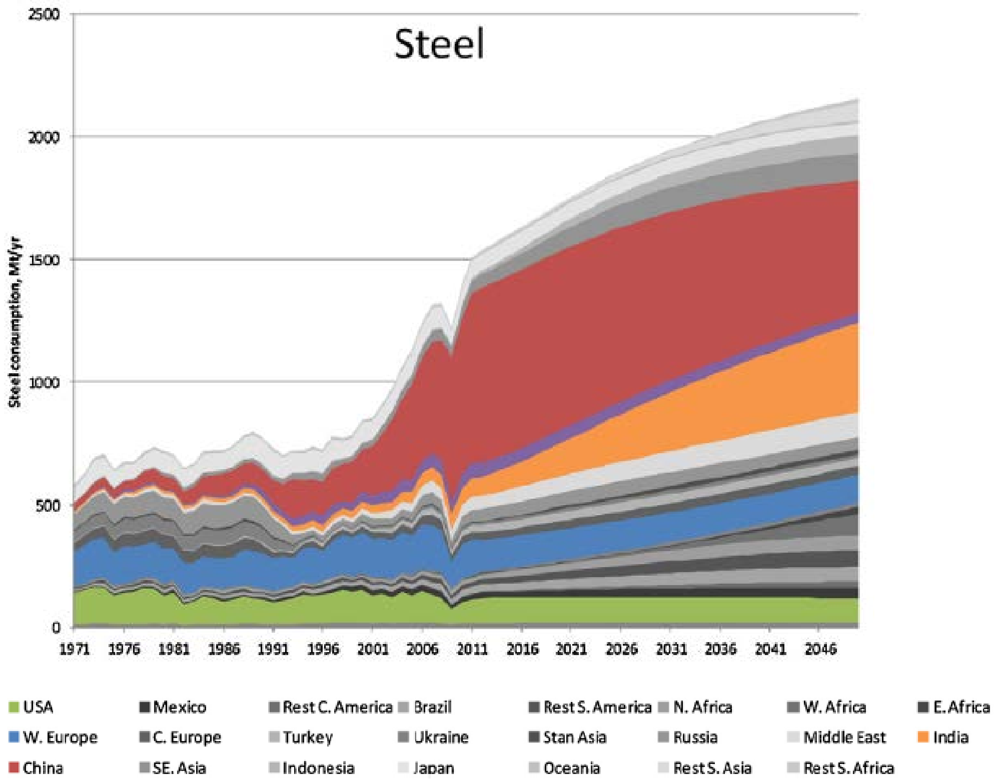


Figure 13 Steel consumption 1971-2050. Source: " Long-term model-based projections of energy use and CO 2 emissions from the global steel and cement industries" [52]

Besides, in countries such as China and India they see increased share for EAF from 13% and 18% to 30% and 50% respectively. Energy efficiency measures and upgrades are forecasted to strongly reduce energy use per tonne of steel in regions such as Western Europe and the US. Also, emissions will decline slowly too from 150 Mt/yr to 100 Mt/yr in the US and 300 Mt/yr to around 170 Mt/yr for Europe by 2050 [52].

The OECD in a recent report, “Global Material Resources Outlook to 2060” [53] adds another point of view on how materials use will rise in coming decades. The assumptions used in this outlook will be presented and discussed later in the Cement Demand expectations section (Section 5.2.). But, as a starting point, it may be useful to have a perspective on how steel consumption, or specifically iron ores consumption, will evolve by 2060.

As the figure show, iron ores use may be doubled by 2060 worldwide. However, materials intensity is predicted to decrease in all regions. As global GDP and materials use are forecasted to grow with different growth rates, finally results in a general decrease of materials intensity per unit of GDP. In the case of OECD Europe, this rate goes from 0,4 to 0,3 [53].

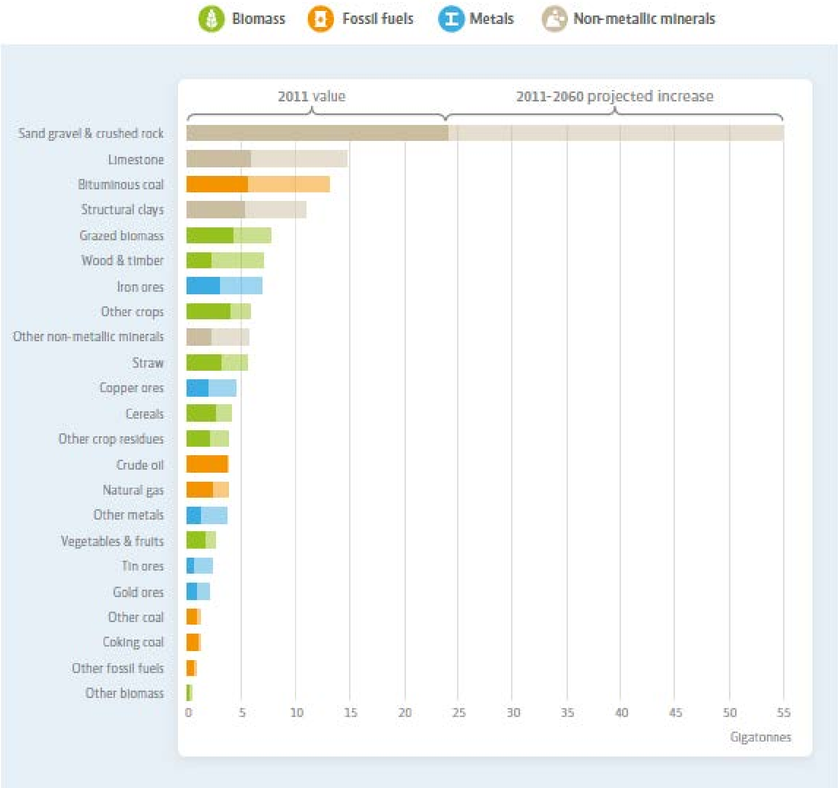


Figure 14 Growth in materials use expected to 2060. Source: Global Material Resources Outlook to 2060. [53]

Other analysts, like McKinsey&Company suggest a more specific point of view for the steel sector. As said before, the steel demand growth globally over the last decade was mostly driven by the industrialization and urbanization of China [54].

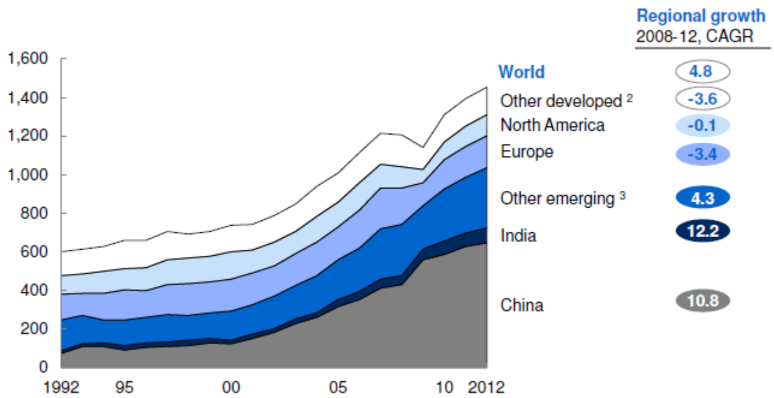


Figure 15 Apparent demand for finished steel, million tons. Source: McKinsey&Company [54].

Figure 15 clearly describes this trend. While steel production in regions such as North America and Europe have remained steady and even declined, China and India has experienced an enormous growth. Therefore, the overall global steel industry capacity has been growing. The largest growth in crude steel making have occured in China and other emerging economies. If, as expected, these capacities continue increasing in the next decades, creating an overcapacity effect in regions where demand has remained impassive such as Western Europe as North America.

There are a number of key trends that are expected to have important implications for the future development of global steel demand. Some of the most important drivers and trends are summarized in Table 18:

Table 18 Trends with significant impact on steel demand by user segment. Soure: McKinsey&Company.

Industry sector	**Overall industry trends**
Transport	• Growth of lightweight materials • Penetration of electrical vehicles (lower steel intensity)
Construction	• Shift towards higher buildings (increased steel intensity) • Increased mechanization to reduce steel wastage • Higher buildings and more prefabrications require more structural steel.
Oil & gas	• Unconventional technologies and deep-water drilling is increasing (more steel intensity) • Increased need for new distribution pipelines
Shipbuilding	• Larger vessels can imply less total material (decrease steel intensity)

Whereas future car production is likely to grow in the coming years, steel consumption will remain flat due to their lower steel intensity. The current trend of using more lightweight materials in cars can be expected to significantly reduce the amount of steel consumed per car [54]. Thus, both trends will compensate their effects, expecting steel consumption to be stay on a constant level.

4.3.Study scenarios

With these future trends for the steel sector as a background, it is clear that some tools are required to estimate future slag production. In the GIS analysis that will be described in Section 6.1., two scenarios are explored. As have been clearly stated above, the scenarios used in this work can be characterized as a explorative (i.e.-“what if” type scenarios), and are not intended to predict future developments. They become a tool to explain what would happen if different policies were applied. In this case, one of the key assumptions on the key drivers in the scenarios is the technical lifetime of blast furnaces, which here has been assumed to be 40 years. But, the main distinction between both suggested scenarios is going to be the year in which the lifetimes is counted from. Date of construction and an average technical lifetime to describe how existing blast furnaces can be expected to be decommissioned may have limitations (see e.g. [55]) but it gives a reasonably good indication of coming trends.

- **Case A**: In this Case, existing blast furnaces are assumed to be decommissioned as they reach the end of their technical lifetime, i.e. 40 year after construction.

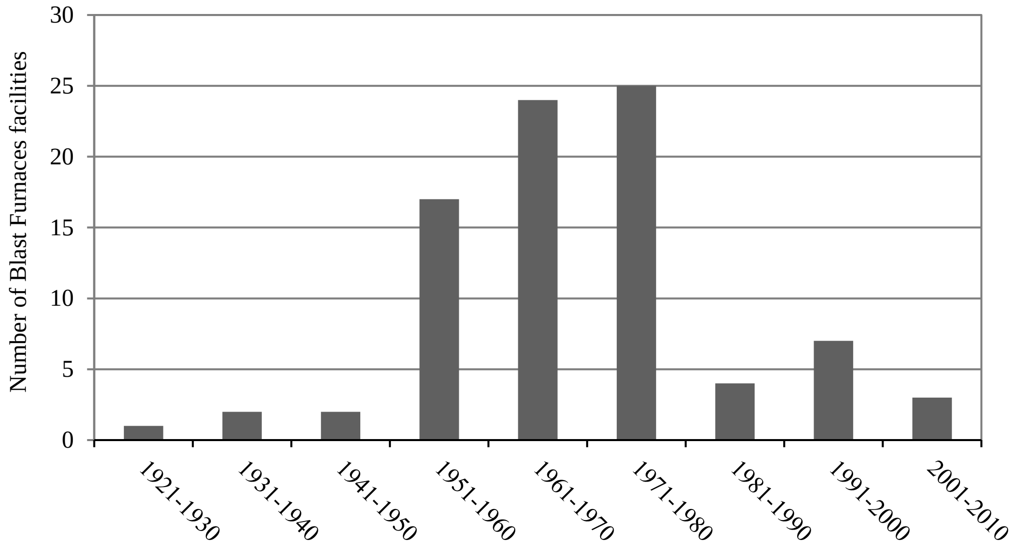


Figure 16 Blast furnaces separated according to their year of commissioning. Source: [9]

Figure 16 shows the year of commissioning of all blast furnaces in Western Europe. The vast majority of the BF's were commissioned during the period 1950-1980. This means that more than 80% of all blast furnaces have already 40 years or more. It is thus clear that most European BF's will be decommissioned in the coming years.

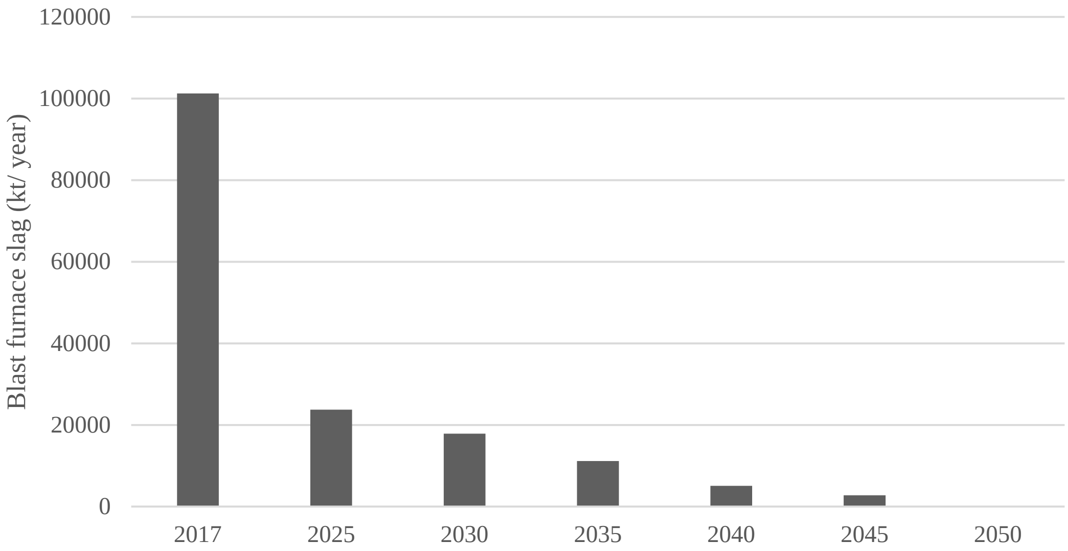


Figure 17 Amount of slag capacity production forecast until 2050, Case A.

Figure 17 shows the development of slag production in Europe in Scenario 1. The amount of slag obtained from steel blast furnaces decreases dramatically in the first years after applying the restriction of 40 years lifetime. Table 19 presents the estimated steel production capacity and slag production, 2017-2050, in Scenario 1.

Table 19 Steel and slag forecast until 2050, Case A.

	2017	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Steel capacity (kT/y)	101 200	24 000	18 000	11 200	5 000	2 800	0

Slag production (kT/y)	26 600	6 200	4 700	3 000	1 300	700	0

Most of the plant closures occur in the beginning of the studied period, closures then gradually slow down until the end of the period, when BF's finally remaining are decommissioned.

- **Case B**: year of last relining. This scenario takes into account the last year in which the blast furnace was relined or refurbished. It means, that in this scenario the lifetime of all kilns will significantly increase compared with the Case A. This assumption limits all existing BF's to be relined just one more time their existing parts.

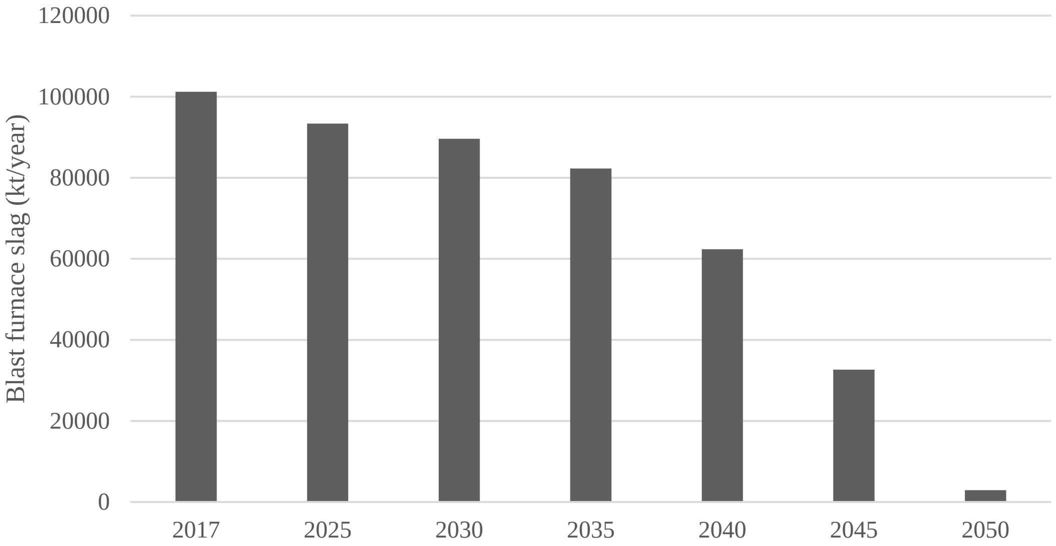


Figure 18 Amount of slag capacity production forecast until 2050, Case B.

Clearly, the amount of slag available is higher than in Case A. As a result of prolonged blast furnaces lifetime, the decommissioning occurs at a slower rate, allowing for a softer decrease of the amount of slag available. However, towards the end of the studied period, from 2040, many of the recently nowadays (2017 surroundings) relined furnaces face their end. Table 20 presents the estimated steel production capacity and slag production, 2017-2050, in Case B.

Table 20 Steel and slag forecast until 2050, Case B.

	2017	2025	2030	2035	2040	2045	2050
Steel capacity (kT/y)	101 200	93 300	90 000	82 300	62 300	32 700	3 000
Slag production (kT/y)	26 600	24 500	23 500	21 600	16 400	8 600	800

As said before, the major reduction occurs in the period from 2040 to 2050. This means that many of the existing furnaces have been recently relined during 2000-2010 period.

5. Cement demand

5.1. Historic development in cement demand

For decades, cement and concrete have been a cornerstone in modern construction and an important part of societal development. Cement consumption is strongly correlated with economic activity [56] and all phenomena involved in how fast it increases. From first data collected, European cement production and demand has been increasing steady up until today. Despite decreasing after the economic crisis occurred in 2008, cement consumption continued increasing again to levels of 2000 [57]. Figure 19 shows the cement production during the period 2001-2011 in EU-28 countries.

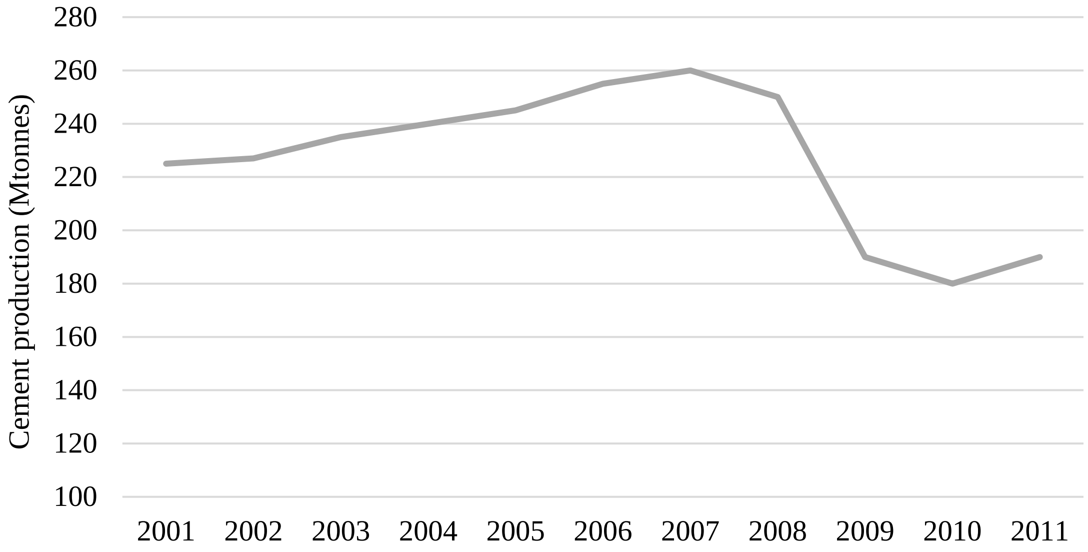


Figure 19 Cement production in EU-28 countries. Source: CEMBUREAU [57].

Some of the main indicators associated to cement industry on a country are GDP and cement consumption, both on a per capita basis [58]. As common understanding has become, those two variables are highly correlated among them, creating an inverted U curve when describing the evolution in any developed country.

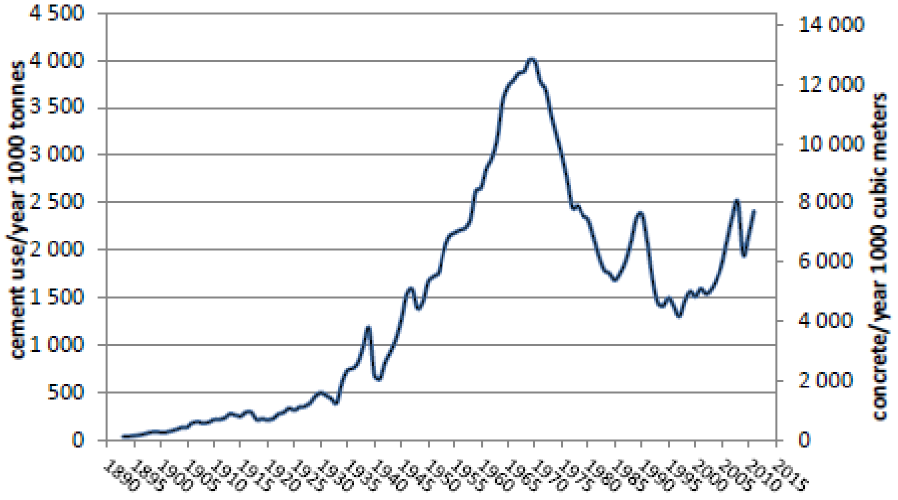


Figure 20 Total annual cement use in Sweden for the years 1893 to 2011. Source: [59]

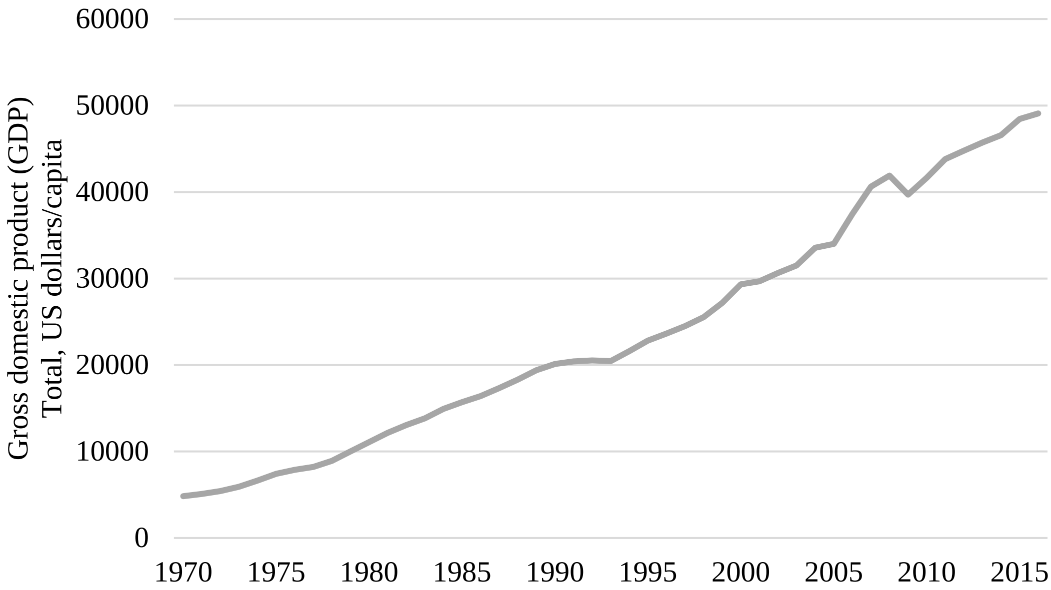


Figure 21 Gross domestic product for Sweden, 1970-2016 period. Source: OECD Economic Outlook. [60]

As an example, Figure 20 and Figure 21, show the evolution of these two variables in Sweden. As it can be deduced, the higher the GDP the higher the cement consumption until a peak point, when it starts decreasing even if GDP keeps increasing. Features behind this shape are:

- Countries with low GDP have low cement consumption being only at the starting point economical development.
- Emerging economies have an economic development requiring heavy investment in manufacturing facilities, machinery and transportation, which pulls cement consumption in all kinds of buildings and infrastructures, resulting in massive cement needs and fast peaks of cement consumption [58].
- Mature economies, once having reached a certain point of economic development, consumption rate decreases since much of the infrastructure have already been built. From here on, the cement consumed in maintenance gains a stronger position. This does not mean that the country can continue growing, but in a slower rate. Moreover, technological progress may also bring new materials to substitute cement, reducing the cement intensity.

An study conducted by van Ruijvena et al [52] describes how cement consumption per capita evolved for the period 1970-2012. In order to represent this evolution over 42 years they used a linearized regression model that relates economic activity with cement consumption. Figure 22 shows cement consumption per capita for each region according to its GDP per capita in the period specified previously.

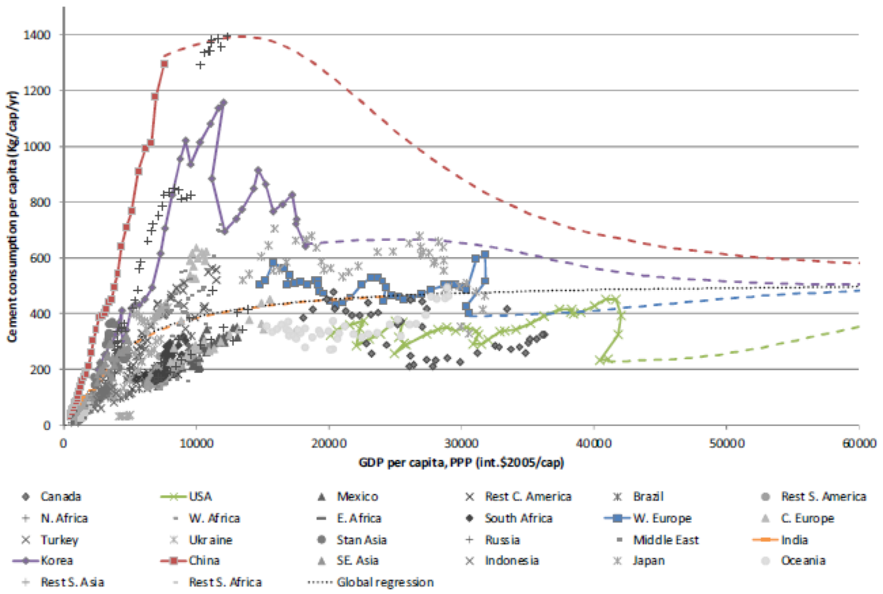


Figure 22 Per capita consumption of cement vs. GDP per capita. Source: [52]

Just like in the case of Sweden, developed economies describe an inverted U pattern, whereas emerging countries keep growing their cement consumption per capita.

Generally, cement consumption is split into three categories depending on the final purpose in which is going to be used: civil engineering and commercial and residential building construction. The first end-use category refers to all infrastructure needed for transport (bridges, railways, ports …) and facilities that cannot be included in other sections (e.g. water and sewage infrastructures). The second category, commercial buildings refer to both stores and offices for companies or administration. The final category, as the name indicates, residential buildings includes houses, hotels, flats and all kinds of construction for people to leave.

Simultaneously, the cement consumption distribution has also been changing over the years. As discussed above, the more GDP grows the more the cement consumption increases until a peak point. At higher rates of economic development, investment in infrastructures and commercial tends to be relatively higher.

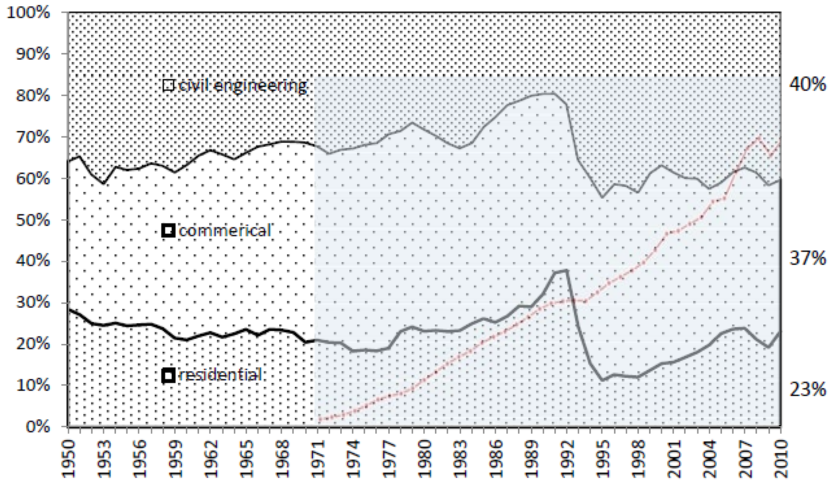


Figure 23 Relative variation of the cement used per "civil engineering", "commercial" and "residential" for Sweden. Source:[59]

A comparison between the GDP evolution graphic and the relative variation of cement end-uses in Sweden tend to support the theories stated above (see Figure 23). Moreover, on the description of cement consumption in Figure 21 and Figure 23, the following trend can be traced: when reaching the peak point of cement consumption, commercial and residential share increased, losing market shares to civil engineering after that. A few years later, cement consumption experienced a moderated expansion, which is likely linked to the fact of enlarged share of civil engineering again after the residential peak point. In recent years, the evolution reflects a pretty stable and steady fluctuation between three cement purpose sections.

Cement can also be divided depending on the end-use. The European Cement Association (Cembureau) classifies cement consumption and domestic deliveries into three types: ready-mixed concrete, precast concrete and others. Ready-mixed concrete refers to concrete that is mixed and prepared of site but cast on site. Precast concrete include reinforced and pre-stressed concrete structural elements and frames manufactured [61] under specific conditions, which are cast offsite and directly delivered to the construction site. Generally, precast concrete parts present enhanced strength properties. The last category includes a wide variety of concrete components containing cement that may not be included in neither of the previous categories, including, e.g., tiles, bricks, blocks or pipes.

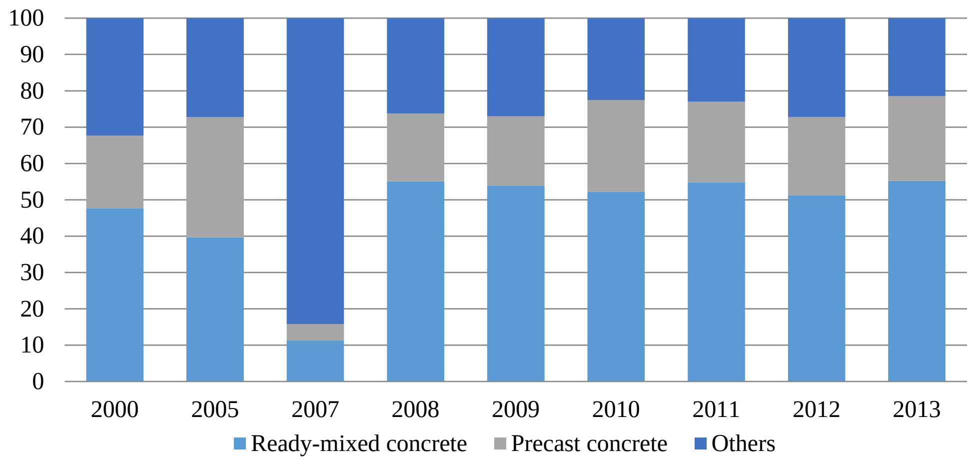


Figure 24 Evolution of cement consumption by end users (%) in EU 28. Source: CEMBUREAU. [62]

From data provided by CEMBUREAU [62], the evolution of cement consumption by users in EU 28 countries in the period from 2000 to 2013 can be deduced.

As a general trend, ready-mixed concrete dominate concrete and cement consumption [62] accounting for approximately 50-60% of the total. The remaining part is divided between precast concrete and other cement containing concrete products. Apart from 2007 (when the last recession started), the graphical data exhibit a quite steady and constant fluctuation of the three sections in a short range.

5.2.Describing cement demand

To analyse and match cement demand with supply of cement and alternative binders it is necessary to describe current consumption in EU, and in Sweden. The data presented in Table 21 Cement consumption in EU and Sweden.Table 21 and Table 22 shows amount of cement consumed annualy in the EU and Sweden.

Table 21 Cement consumption in EU and Sweden.

Region/ country	Cement consumption 2017 (kt/yr)
EU 28 [63]	160 760
Sweden [61]	2 400

Table 22 Population and consumption/ capita in EU and Sweden.

Region/ country	Population (Million people)	Consumption/ capita (kg/capita)
EU 28 [64]	511.8	315
Sweden [64]	9,99	240

Swedish cement consumption per capita is well under the EU 28 average.But, it may be noted that Swedish cement consumption may be slightly different. Some studies offer a wider point of view using all Nordic countries data when calculating production/ consumption figures. For instance, Rootzén and Johnsson, 2016 [61] use data from cement facilities in Norway, Finland, Denmark and Sweden to describe production and consumption figures.

5.3.Estimates of future demand for cement

To assess the overall climate impact from cement production it is important to try to estimate the future evolution of demand. Many studies have discussed the evolution of cement consumption intensity and production in the coming years, usually with a time horizon until 2050-2060. The disparity among the studies may explained by many factors, e.g., assumed relationship between economic development and cement consumption or on how they expect future climate policies will evolve.

Van Ruijven et al [52] assumes that no climate policies will be applied to future cement industry. Figure 25 shows the resulting projection, suggests that cement consumption will continue to increase in the coming years. But, not all countries/ regions experience the same growth. Emerging economies such as India or Latin America will keep on increasing their consumption continuously. Other regions such as China will increase their consumption until a peak point where at this point will start to decrease steadily (in line with the hypothesis of inverted U) [56]. Cement consumption in developed regions such as Europe, USA and Canada will keep stagnated with tiny fluctuations.

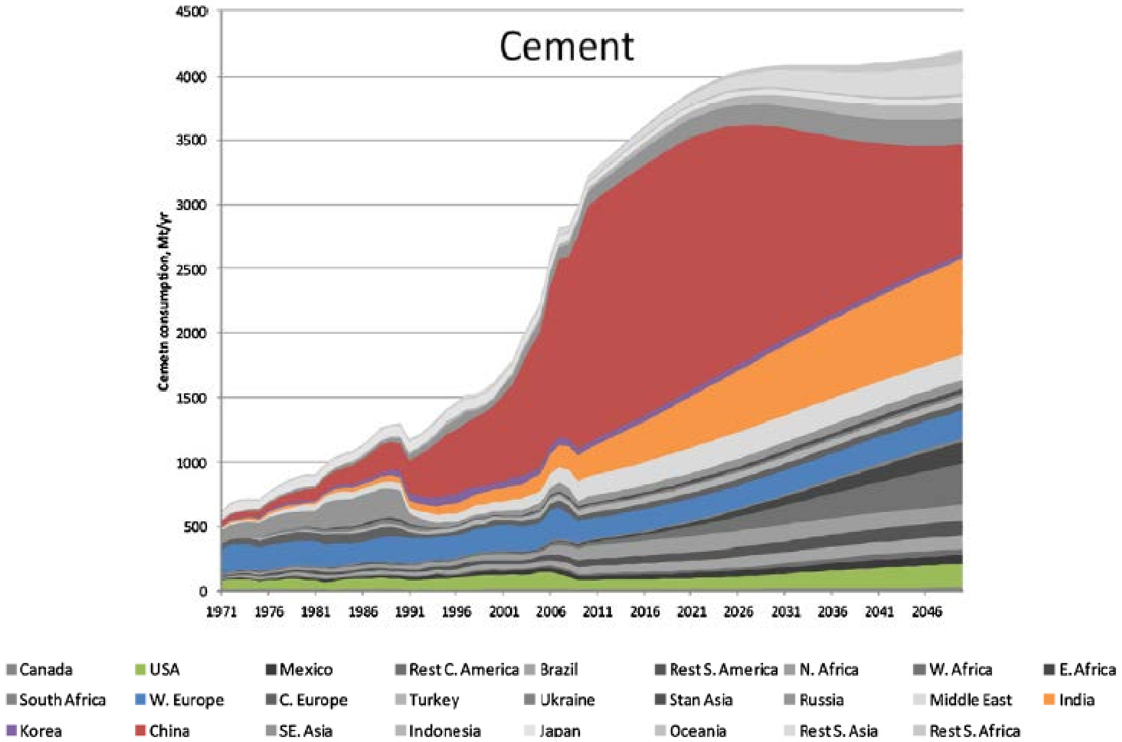


Figure 25 Cement consumption 1971-2050. Source: [52]

Despite of an increasing share of efficient cement production technologies, it will not be sufficient to negate the effects of consumption growth. However, energy use per tonne clinker is expected to decrease in all regions thanks to production technology improvements. As is well known, cement kilns often strive to use the cheapest and most available fuel. In the near future, it is assumed the depletion of relatively low cost natural gas, triggering a switch towards cheap coal and bioenergy. Regarding carbon dioxide emissions, they increase until a peak point somewhere between 2020-2030 and start decrease steadily until 2050.

Other studies suggest even worse future expectations with regards to the climate impact from cement manufacturing. In a study carried out by EU Joint Research Centre (EU JRC) [56] compares development relative a business as usual (BAU), reference scenario. In addition to parameters such as GDP and primary fuel prices this analysis assumes conservative features for the near future such as:

- Trend for shaft kilns
- No fluidised cement technology, no alternative cement product penetration
- No change in clinker/cement ratio in cement production

The BAU scenario predicts high cement consumption in the near future (time horizon until 2030). The cement consumption will increase on a global level to 2880 Mt/yr 2030 at an annual 2% growth rate. Generally, the study by EU JRC does not differ from the previous studies in different global regions. The biggest difference appears in Western Europe, where its consumption is assumed to reach a peak point somewhere between 2010-2020 and start to decrease thereafter.

OECD in their report, “Global Material Resources Outlook to 2060” [53] adds another perspective on how materials use will rise in coming decades. Figure 26 show how a number of key-materials are expected to increase to 2060 (cement may be included in non-metallic minerals section).

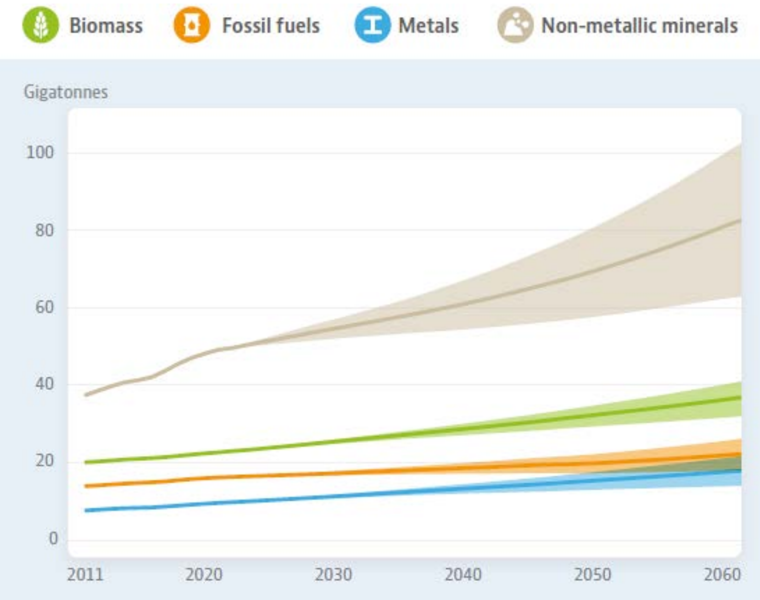


Figure 26 Growth in materials use expected to 2060. Source: Global Material Resources Outlook to 2060, OECD.[53]

Population growth and the rate at which countries catch up in income levels are assumptions introduced in the study that introduce a range of uncertainty of around 20% on either side of the central baseline scenario. However, in all cases, global materials are expected to grow over time to 2060.

At the same time, materials intensity is predicted to decrease in all regions. As global GDP and materials use are forecasted to grow with different growth rates, finally results in a general decrease of materials intensity per unit of GDP. To support this assumption, the authors point to the ongoing shift towards more services globally and the expected end of the construction boom in emerging economies, especially in China.

In summary, the vast majority of studies conclude that cement consumption and production will increase in the coming decades. There will be differences in how consumption and production evolves and differences in growth rates between regions. Emerging economies are expected to increase their consumption and production constantly, while a stable or in some cases stagnating demand is expected in developed regions and countries.

5.4.Study scenarios: Cement demand

In this section will be discussed the study scenarios that will provide the basis for the spatial GIS analysis. Based on the varying expectation with regards to supply and demand for cementitious material (as described in Sections 3-4), it is clear that relying on just a single prediction of the future development of supply and demand will not cover the rage of possible outcomes. Thus, here, three different scenarios were assessed to cover a wider range of possibilities:

- **Scenario 1**: Business as Usual. In this scenario, in line with other work [52][56], cement demand in Europe is assumed to remain relatively stable through the studied period. Cement consumption is assumed to increase up until 2020, later it will start to decrease and stay constant for EU-28 countries. Cement consumption and production are here assumed to remain at current (2017) levels throughout the studied period.

Table 23 Scenario 1 cement consumption in EU28 and Sweden.

Region/ country	Cement consumption 2017 (kt/yr)
EU 28 [63]	160 760
Sweden [65], [61]	2 400

- **Scenario 2**: Decreasing demand. In this scenario, thanks to conscious actions to improve material efficiency, predicted cement demand can slowly decrease from current levels. Actions like: optimisation of the quantity of cement needed in a specific concrete recipe [3], increase of concrete waste recycling, efficiency of cement production or better packing and selection of concrete aggregates are here assumed to a reduction in the amount of cement needed in concrete, contributing to lowering of overall cement demand [7]. Overall a 20% reduction of cement demand is assumed between 2017 and 2050.

Table 24 Scenario 2 cement consumption in EU28 and Sweden, 2017-2050 period.

Region/ country	Cement consumption 2030 (kt/yr)	Cement consumption 2050 (kt/yr)
EU 28	131 600	131 800
Sweden	1 960	1 970

- **Scenario 3**: Increasing demand. In contrast to the previous scenario, in this one is highlighted an increase on the cement consumption and production capacity. Without climate policy, future projections for cement consumption show a fast increase over the next few decades [52]. This growth is typically assumed to be smaller for EU-28, where cement consumption, both in absolute and relative terms, are expected to be low. Here, in the High-demand scenario, a 20% increase between 2017 and 2050 is considered.

Table 25 Scenario 3 cement consumption in EU28 and Sweden, 2017-2050 period.

Region/ country	Cement consumption 2030 (kt/yr)	Cement consumption 2050 (kt/yr)
EU 28	197 400	197 700
Sweden	2 940	2 950

6. GIS analysis

6.1. Scenarios design

To cover a range of possible outcomes, three scenarios of the future development of cement demand were explored (see Section 5.3). A BAU scenario (constant demand), a Low-demand scenario (20% reduction of cement demand over the studied period) and a High-demand scenario (20% increase of cement demand over the studied period). In addition, two cases, (Steel slag Case A and B), describing different future development of the availability of blast furnace slag were included in the scenario analysis. Table 26 summarizes the scenario layout:

Table 26 Scenarios design

Scenario 1 (BAU)	**2017**	**2030**	**2050**
Cement demand (Mt/year)	160		
Fly ash (Mt/year)	84		
Blast furnace slag Case A (Mt/year) Blast furnace slag Case B (Mt/year)	26.6		
Scenario 2 (Low-demand)			
Cement demand (Mt/year)		131	132
Fly ash (Mt/year)		25	9.2
Blast furnace slag Case A (Mt/year)		4.7	0
Blast furnace slag Case B (Mt/year)		23.5	0.8
Scenario 3 (High-demand)			
Cement demand (Mt/year)		197	198
Fly ash (Mt/year)		25	9.2
Blast furnace slag Case A (Mt/year)		4.7	0
Blast furnace slag Case B (Mt/year)		23.5	0.8
Bonus scenario 1 (Low-demand) [1]			
Cement demand (Mt/year)		131	132
Fly ash (Mt/year)		25	9.2
Blast furnace slag Case A (Mt/year)		4.7	0
Blast furnace slag Case B (Mt/year)		23.5	0.8
Bonus scenario 1 (High-demand) [1]			
Cement demand (Mt/year)		197	198
Fly ash (Mt/year)		25	9.2
Blast furnace slag Case A (Mt/year)		4.7	0
Blast furnace slag Case B (Mt/year)		23.5	0.8
Bonus scenario 2 (Case 1)[7]			
Cement demand (Mt/year)		160	160
Fly ash (Mt/year)		25	9.2
Blast furnace slag Case A (Mt/year)		4.7	0
Blast furnace slag Case B (Mt/year)		23.5	0.8
Bonus scenario 2 (Cases 2 and 3)[7]			
Cement demand (Mt/year)		131	132
Fly ash (Mt/year)		25	9.2
Blast furnace slag Case A (Mt/year)		4.7	0
Blast furnace slag Case B (Mt/year)		23.5	0.8

In addition, two bonus scenarios where explored. The first bonus scenario explores development based on the levels of cement clinker replacement suggested by the IEA Technology Roadmap [1], and the second bonus scenario explore developments based on inputs from the study "A Sustainable Future for the European Cement and Concrete Industry: Technology assessment for full decarbonisation of the industry by 2050" by Faviere et al. [7].

6.2. Business as usual (Scenario 1)

As a first step the current situation, with respect cement demand the availability of fly ash and blast furnace, were explored.

Approximately, all countries and their foreign regions such as French islands are consuming an average of 161 Mt of cement per year [11]. It is clear, however, that not all regions are consuming at the same rate. The most populated regions tend to be the regions with highest consumption. As shown in Figure 27, the most red/orange-coloured regions are the ones with a bigger cement consumption.

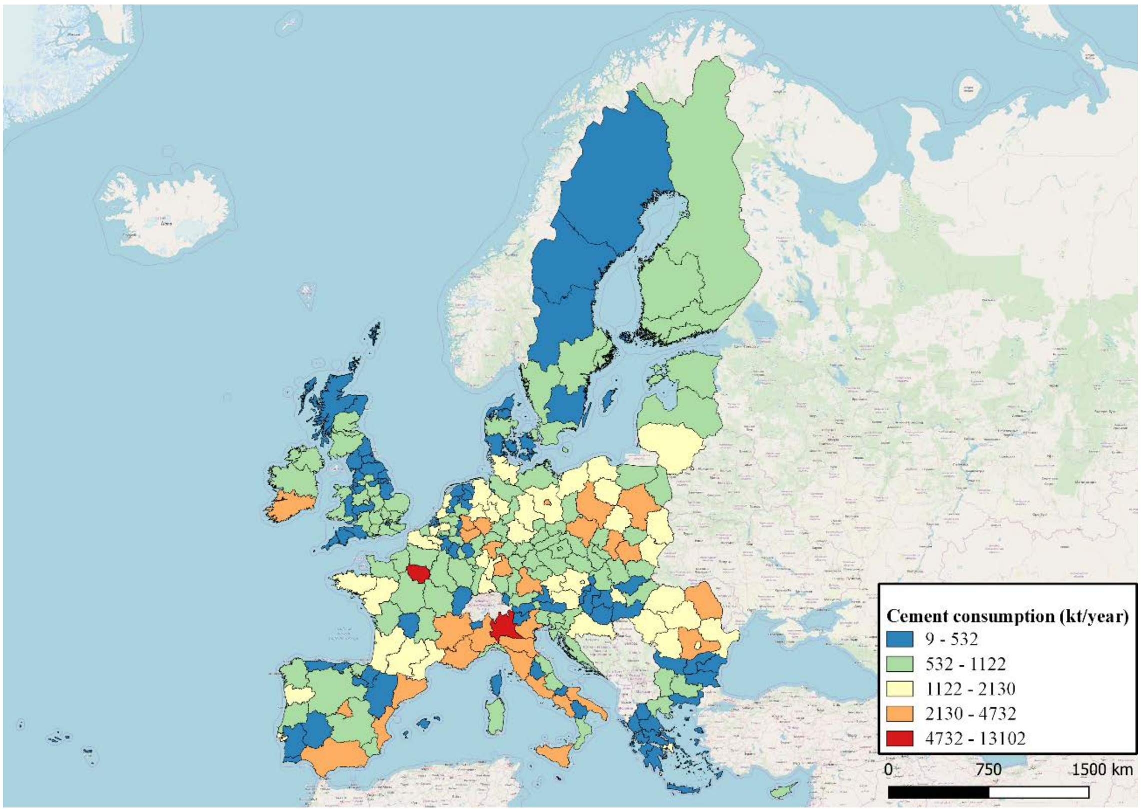


Figure 27 Cement consumption heatmap in EU NUTS.

Italian regions like, e.g., Lombardia or Toscana stand out with high cement demand, followed by Mediterranean regions of Spain, central France, Romania and Poland. Sweden and the Nordic countries, on the other hand, have few or no regions where cement consumption excess 680 kt per year.

Just as cement consumption is unevenly distributed, coal-fired power plants and blast furnaces, which are the sources of alternative binders considered here, are not evenly located across Europe. There is a clear unbalance between the central regions of Europe and the more external regions. Figure 28 and Figure 29 show the location of European blast furnaces and coal-fired power plants, estimated production of blast furnace slag and fly ash at each location, as well as heatmaps giving an indication of the geographical spread of the availability of blast furnace slag and fly ash respectively.

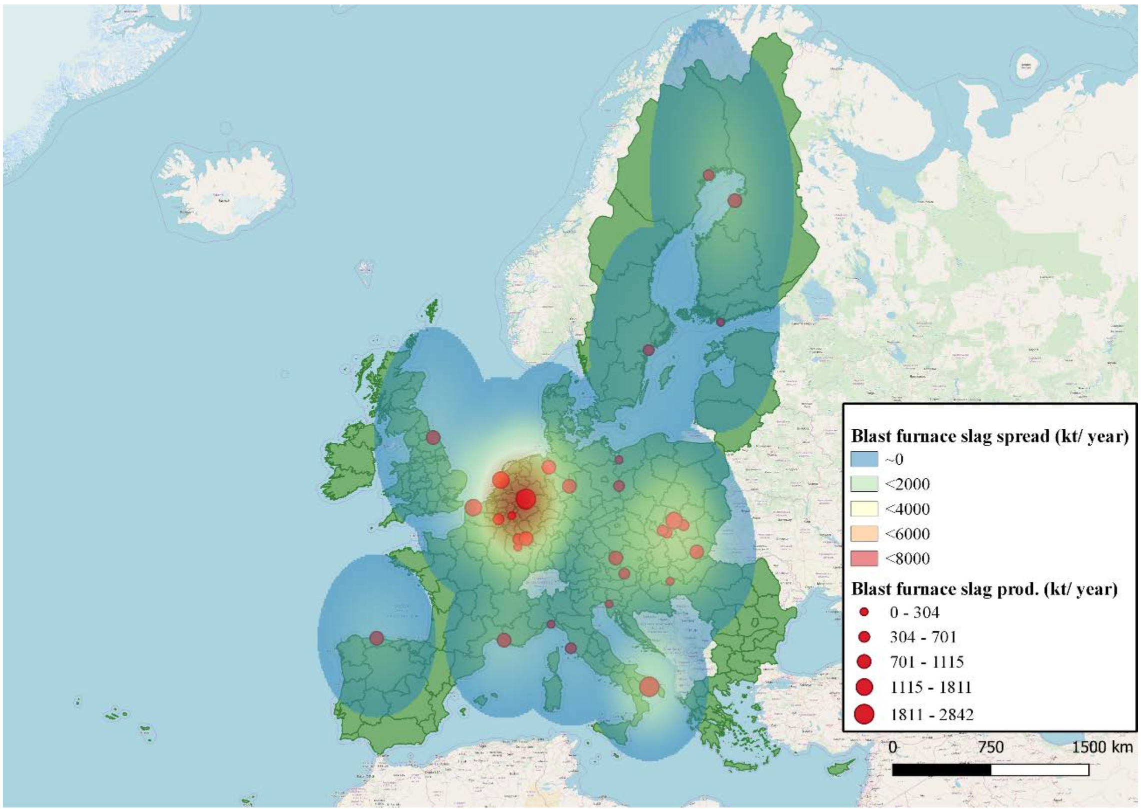


Figure 28 Blast furnaces slag 2017 heatmap.

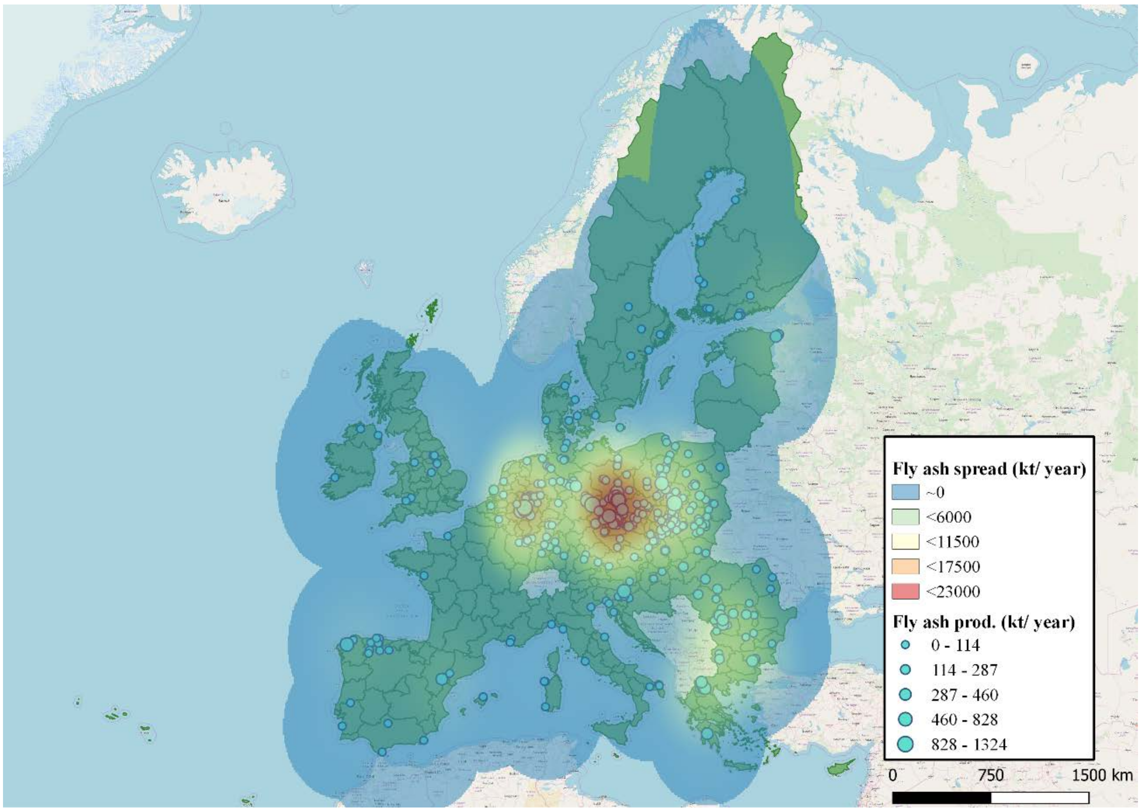


Figure 29 Coal-fired power plants heatmap.

The heatmaps represent with a colour gradient the availability of blast furnace slag and fly ash which depend on the distance to the nearest blast furnace and/or coal-fired power plant steel and power. The size of the round markers indicates the scale of the production of blast furnace slag(red markers) and fly ash (blue markers). Centrally located regions like Germany, Poland, The Netherlands, Belgium and the Czech Republic have a superior production of alternative binders compared to other regions. In many other regions, Sweden included, production is almost negligible.

Table 27 presents a summary of the results of the analysis of the current situation including an estimate of the maximum average clinker cement replacement in all possible regions. Comparing all possible supply with all cement demand, it results in the following calculi.

Table 27 Scenario results.

Supply alternative binders (kt/yr)	Cement demand (kt/yr)	Max. average substitution (%)
110 500	160 760	70

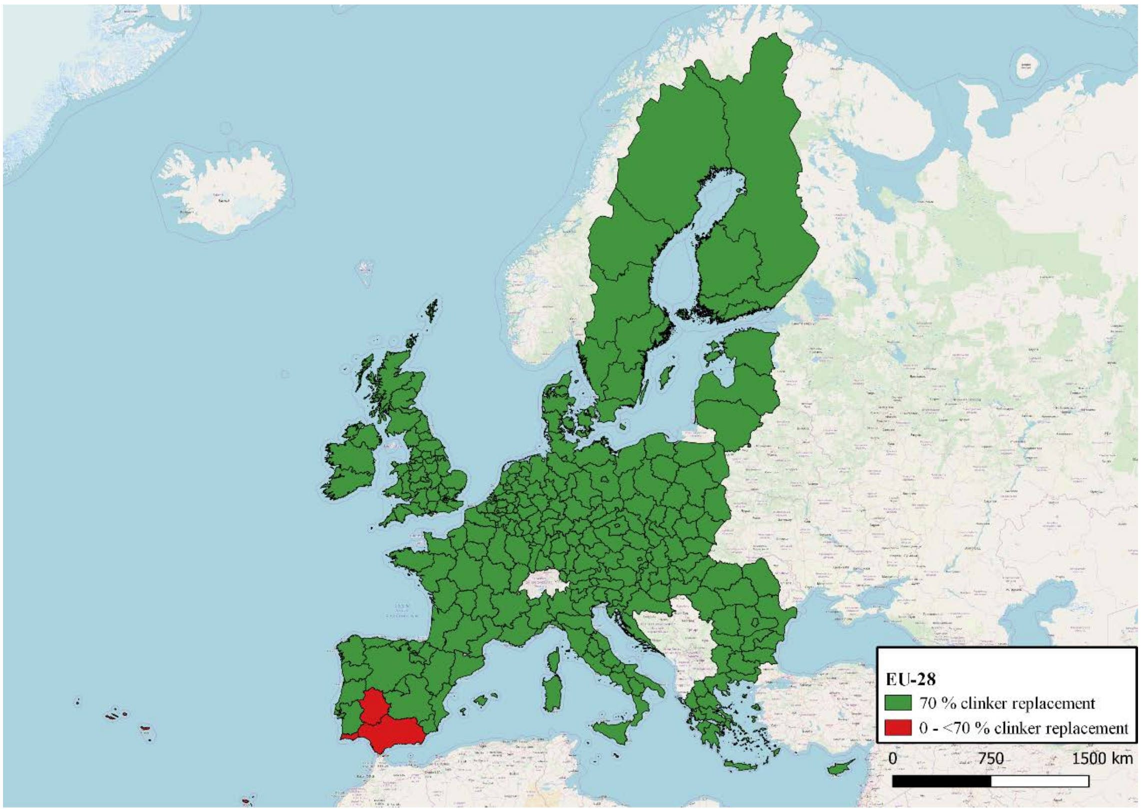


Figure 30 Scenario 2017 mapping results.

Figure 30 presents all the regions in which it is possible to substitute at least a 70% of their cement demand by conventional alternative binders, i.e., fly ash and blast furnace slags. For sure, as long as it has been calculated a 70% and not an exact 68,7%, not all regions are fully covered. This difference was taken in order to meet the demand of actual Europe regions without taking into consideration overseas regions outside of the European continent. In addition, some of the southern regions of Spain and Portugal are also uncovered.

6.3. Low-demand scenario (Scenario 2)

The development of cement demand is the key driver in all of the scenarios assessed here. In the coming decades, many changes in policies related to construction and GHG emissions are likely to occur. The Low-demand scenario (Scenario 2) explores a development where cement demand is reduced by 20% over the studied period at the same time as the supply of conventional alternative binders gradually decline.

In the scenario runs the goal of the GIS analysis was to maximise average cement clinker replacement in a maximum number of regions across Europe. The basic assumptions were (see also section 3, 4 and 5):

- 20% reduction in cement demand 2017-2050.
- Existing coal-fired power plants decommissioned as they reach the end of their technical life (40 years).
- Existing blast furnaces:
    - Decommissioned as they reach the end of their technical life (40 years) (Case A).
    - Are relined once (to extend their lifetime) and decommissioned after 40 years (Case B).

Before keeping up with the study, it requires adding another hypothesis regarding future population. According to section 1.4.5., the population across Europe would have increase a 2.3% compared to current population by 2030. Thus, in order to progress with the study and offer a trustable result, population in all NUT regions must be increased this percentage when estimating cement demand.

On the one hand, the consumption map does not offer any changes in respect to the actual one. There is simply an increase of 2.3% due to the population projections and a reduction of 20%, as the scenario tells.

On the other hand, there is a huge change in the number of plants that could supply alternative binders available. From the initial 840 facilities, there only remain around 200. In the figures below can be deduced a reduction in the number of markers of every map. Also, the reddest regions before have partially lost some of their original intensity.

In the Figure 32, it is shown the second way to estimate, since the last year the facility was relined (Case B). Unlike their counterpart, this method allows for a more conservative perspective, allowing actual blast furnaces a longer lifetime. Later on, it will be shown the facilities mapping using the other assumption (Case A), knowing in advance that the amount of blast furnaces will be considerably lower.

6.3.1. Scenario 2 – 2030

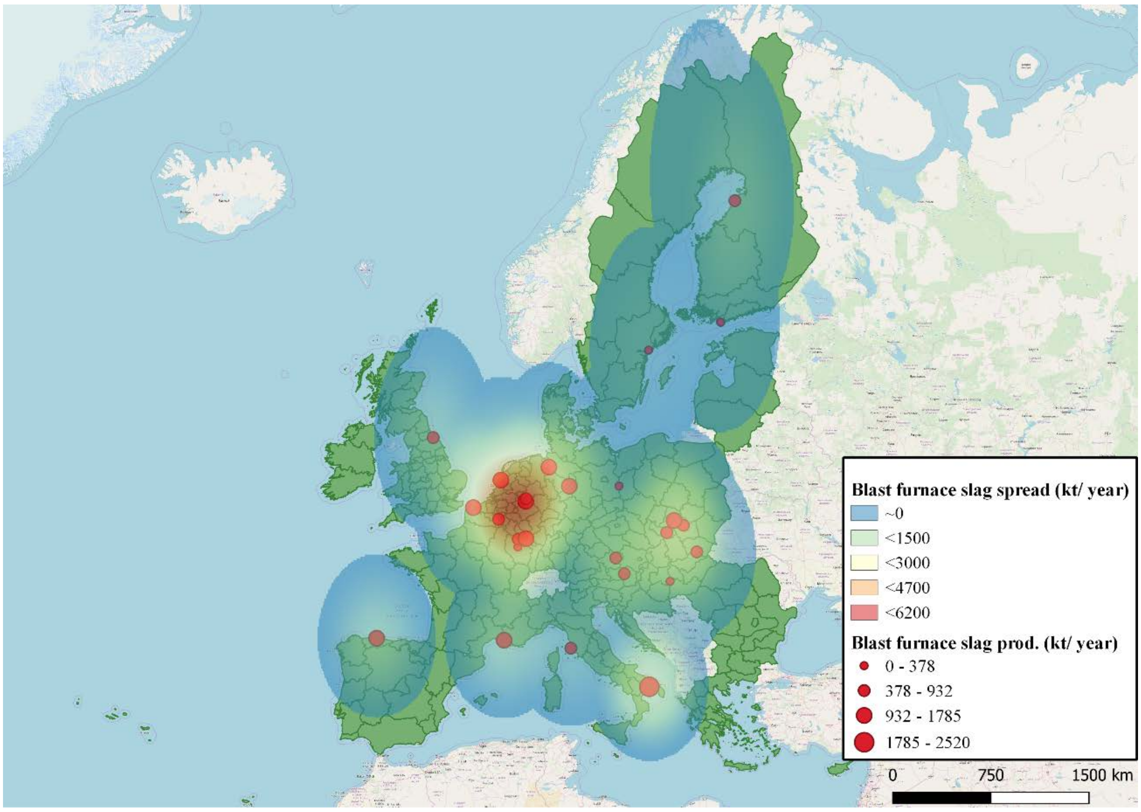


Figure 31 Blast furnace slag (relining (Case B)) heatmap 2030.

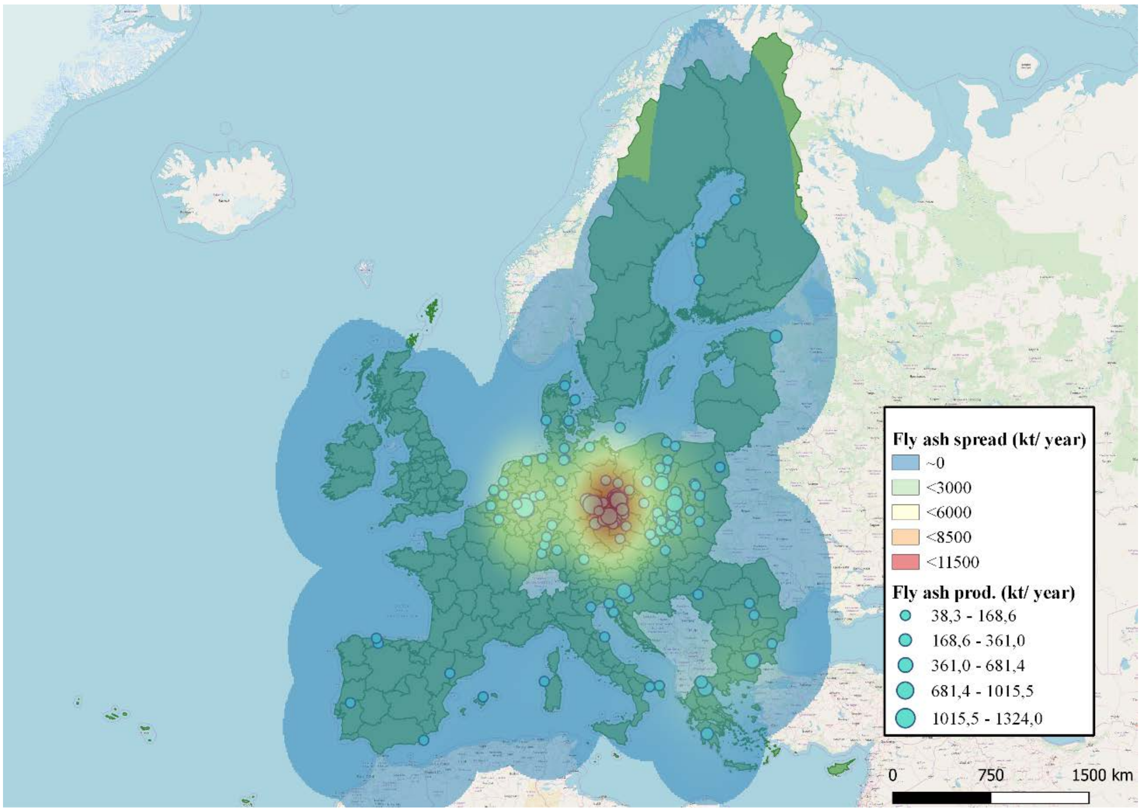


Figure 32 Coal-fired power plants heatmap 2030.

Figure 29Figure 31 and Figure 32 shows how the achievable clinker replacement in 2030 will be considerably lower than the one found for the BAU scenario. Table 28 shows for the Low-demand scenario (Scenario 2) in the year 2030 the estimated supply of alternative binders, the cement demand and an estimate of the maximum average percentage of clinker cement replacement in all possible regions.

Table 28 Scenario low cement demand 2030 (relining (Case B)) results.

Supply alternative binders (Relining (Case B)) (kt/yr)	Cement demand (kt/yr)	Max. average substitution (%)
48 600	131 600	40

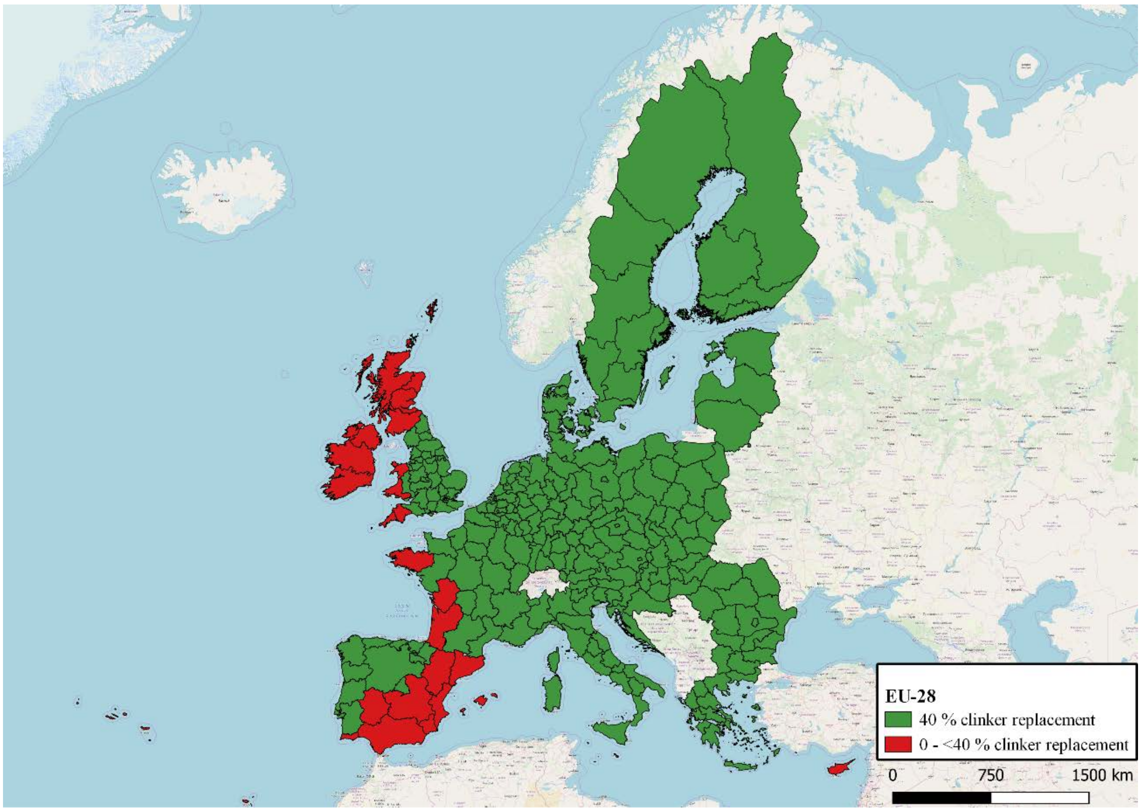


Figure 33 Scenario 2030 Low Demand (relining (Case B)) mapping results.

Figure 33 shows how in 2030 in the Low-demand scenario it would be possible to achieve a 40% substitution rate in most European regions. However, there are a number of Spanish and UK regions that will not be able to fulfil their by-products demand. This difference is due to estimating using a 40% substitution rate instead of a 36.9%. Another thing to note is that the transportation costs are likely to increase since fewer facilities are available to supply alternative binders. By 2030 the number of production facilities with by-product that are suitable as alternative binders (blast furnaces and coal-fired power plants) have been reduced considerably. This means that the remaining facilities with a larger production need to supply to more regions, causing increased transportation costs.

In the other case considered, Case A, the existing blast furnaces will be decommissioned at a faster rate. The primary iron-making facilities are assumed to decommission blast furnaces as they reach the end of their technical life (40 years). Since many European blast furnaces are already old, by 2030, a significant share of these will have been decommissioned. The estimates presented in Table 29 show how this would lower the supply of alternative binders even further and consequently lower the maximum achievable average substitution rate.

Table 29 Decrease in supply of alternative binders since no relining is assumed to take place (Case A) 2030 Low demand scenario.

Supply alternative binders (Relining (Case B)) (kt/yr)	Supply alternative binders (No relining (Case A)) (kt/yr)	Reduction in supply of alternative binders (%)
48 600	29 800	40

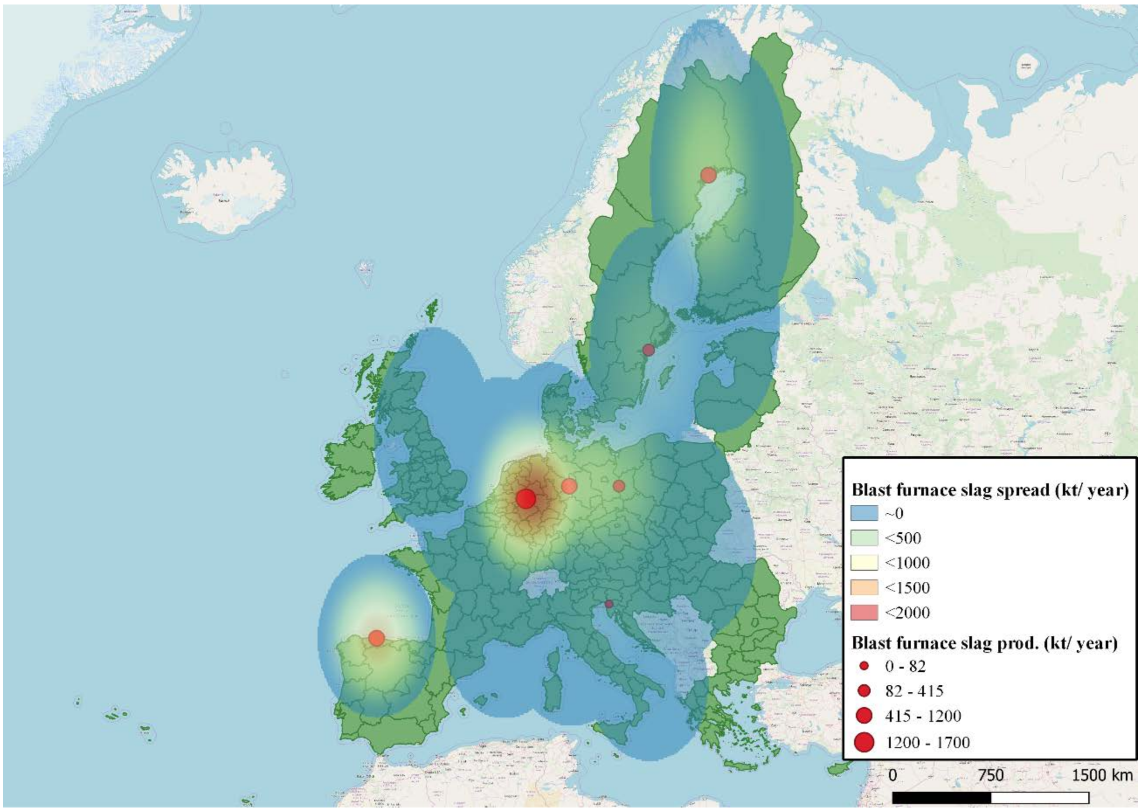


Figure 34 Blast furnace slag Heatmap (No relining (Case A)).

Figure 34 has far less facilities than Figure 31, creating a situation in which the remaining facilities will need to spread their by-products even more in order to meet the maximum demand. Clearly, under these circumstances, the availability of clinker replacement will be lower than in Case B, where blast furnaces were assumed to be decommissioned at a slower rate. Table 30 summarize for the Low-demand scenario (Scenario 2) in the year 2030, with no relining of blast furnace (Case A) the estimated supply of alternative binders, the cement demand and an estimate of the maximum average percentage of clinker cement replacement in all possible regions.

Table 30 Scenario low demand 2030 (no relining (Case A)) results.

Supply alternative binders (No relining (Case A)) (kt/yr)	Cement demand (kt/yr)	Max. average substitution (%)
29 800	131 600	25

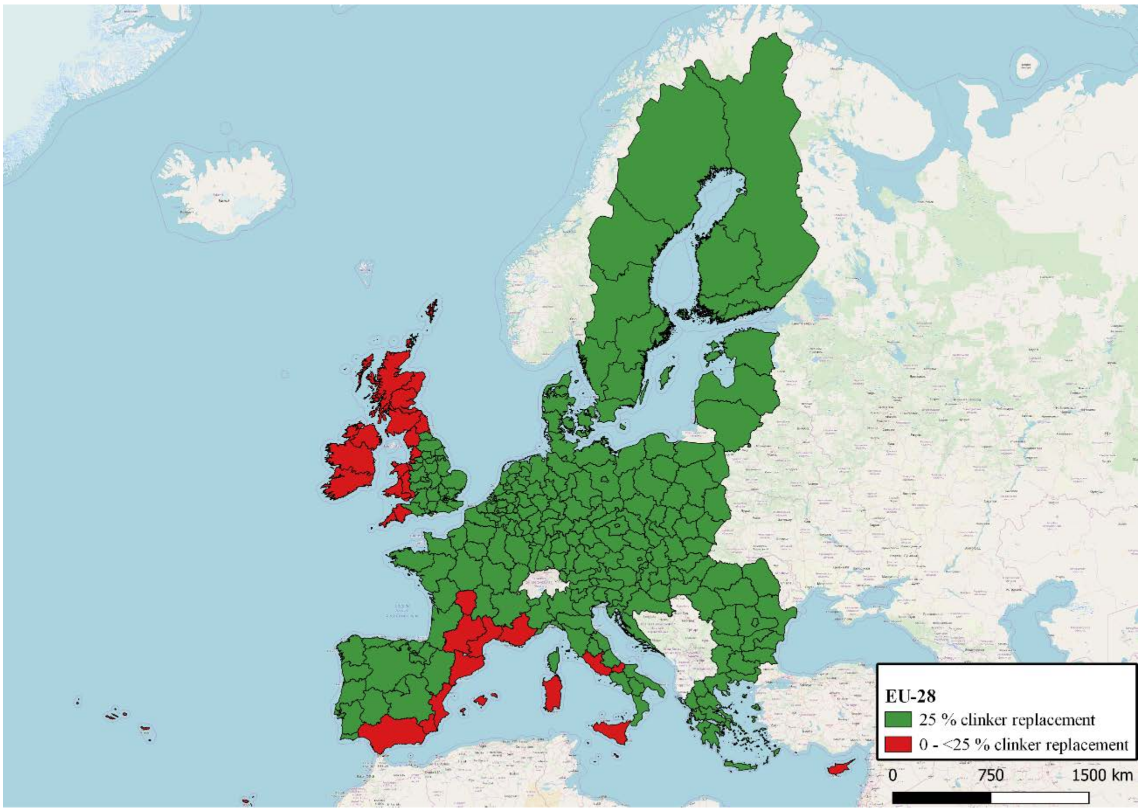


Figure 35 Scenario 2030 Low Demand (no relining (Case A)) mapping results.

At a first sight, apart from the lower average substitution rate, there are not big changes with respect to regions provisioning. Although reducing the achievable replacement ratio, there are still some Spanish and UK regions with very low or no by-products supply.

6.3.2. Scenario 2 - 2050

In the year 2050, the end of the studied period, all remaining blast furnaces will have been decommissioned in Case A, and only 35 coal-fired power plants are still in operation (see Figure 36A)

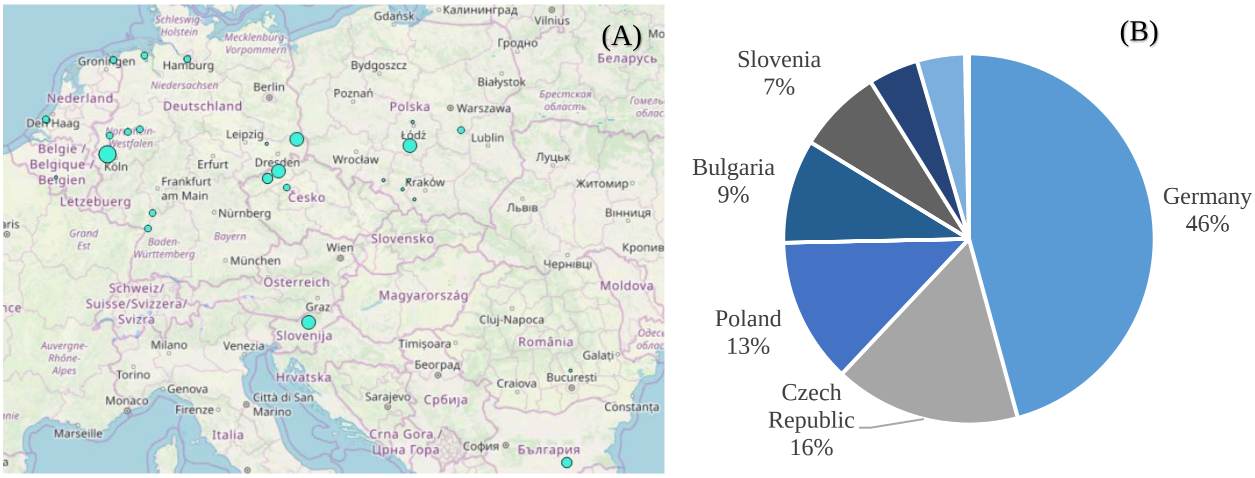


Figure 36A: Coal-fired power plants in 2050. Figure 35B: pie chart showing biggest fly ash producers in 2050.

As can be seen in the pie chart (Figure 36B), Germany, in 2050, continues to be the biggest fly ash producer. A majority of the remaining coal-fired power plants are located in Germany (see

Figure 36A). The following two major producers keep on the same ratings just like 2017 scenario: Czech Republic and Poland.

Consequently, clinker replacement in 2050 in Scenario 2 is predicted to be significantly lower compared to the 2017 and 2030. The maximum average percentage of clinker cement replacement across all region is in this Scenario estimated to be less than 10% (Table 31).

Table 31 Scenario Low-demand 2050 (Case B) results.

Supply alternative binders (kt/yr)	Cement demand (kt/yr)	Max. average substitution (%)
10 000	131 800	10

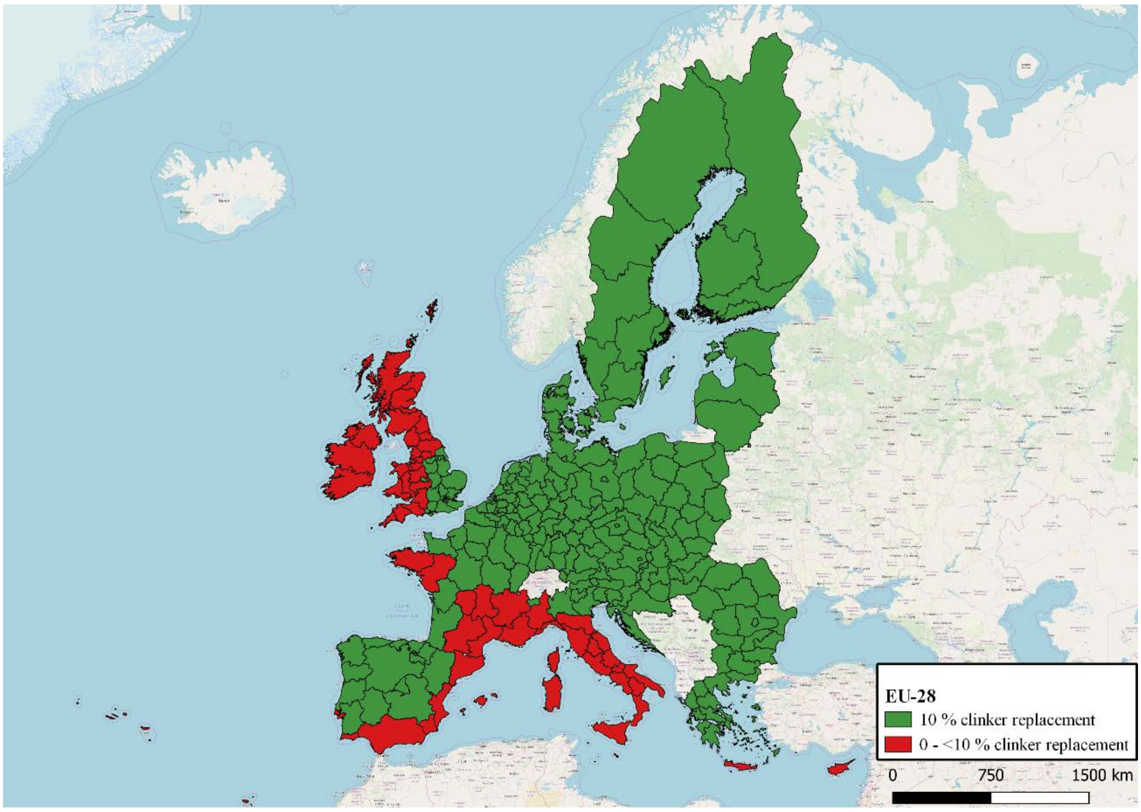


Figure 37 Scenario 2050 Low-Demand (Scenario 2) mapping results.

Unlike most all other scenarios, in this one there are more regions without a minimum by-products supply being covered. The recent additions to the list of regions without coverage are southern France, whole Italy, Cyprus and Greece Islands. Clearly, the new additions obtain their red colour because of being the furthest ones in relation to the remaining coal-fired power plants.

6.4.High-demand scenario (Scenario 3)

The High-demand scenario (Scenario 3 explores a situation where cement demand increases over the studied period. This may represent a development where few or no policies or measures aimed at lowering the climate impact of cement and concrete are enforced. This would also be representative for emerging economy, since larger amounts of cement are required in developing economies in order to build new infrastructure.

Logically, a higher demand will results in less by-products, in relative terms, to each region and thus lower replacement ratios. Since assumptions with respect to the decommissioning of blast furnaces and coal-fired power plants are the same in Scenario 2 and 3, the development of the supply of alternative binder will be the same. Thus, the main focus will be to check differences in respect to the alternative binders coverage.

The basic assumptions were (see also section 3, 4 and 5):

- 20% increase in cement demand 2017-2050.
- Existing coal-fired power plants decommissioned as they reach the end of their technical life (40 years).
- Existing blast furnaces:
    - Decommissioned as they reach the end of their technical life (40 years) (Case A).
    - Are relined once (to extend their lifetime) and decommissioned after 40 years (Case B).

6.4.1. Scenario 3 - 2030

Table 32 presents, for the High-demand scenario (Scenario 3 Case B (with relining of blast furnaces)) in the year 2030 the estimated supply of alternative binders, the cement demand and an estimate of the maximum average percentage of clinker cement replacement in all possible regions.

Table 32 Scenario high demand 2030 (relining (Case B)) results.

Supply alternative binders (kt/yr)	Cement demand (kt/yr)	Max. average substitution (%)
48 600	197 400	25

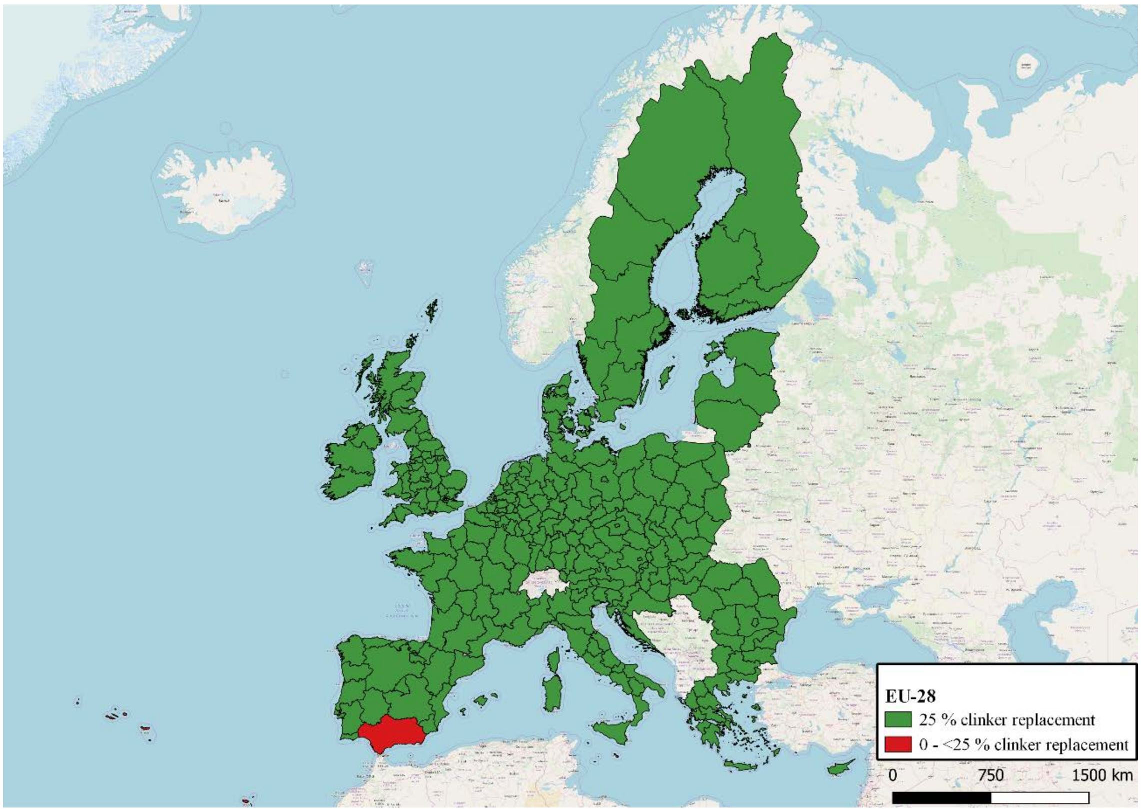


Figure 38 Scenario 2030 High Demand (relining (Case B)) mapping results.

The results do not show huge differences compared to the low demand scenario. Only one Spanish region (Andalusia) is not being covered at least a 25%. Therefore, instead of a 35% achievable substitution it descends to a 25%. In the case where no relining of blast furnaces are assumed to take place (Case A) supply of alternative binders are even lower. As presented in Table 33, maximum average percentage of clinker cement replacement across the studied regions in the High-demand scenario with no relining of blast furnaces is estimated to be less than 20%.

Table 33 Scenario high demand 2030 (no relining (Case A)) results.

Supply alternative binders (kt/yr)	Cement demand (kt/yr)	Max. average substitution (%)
29 800	197 400	20

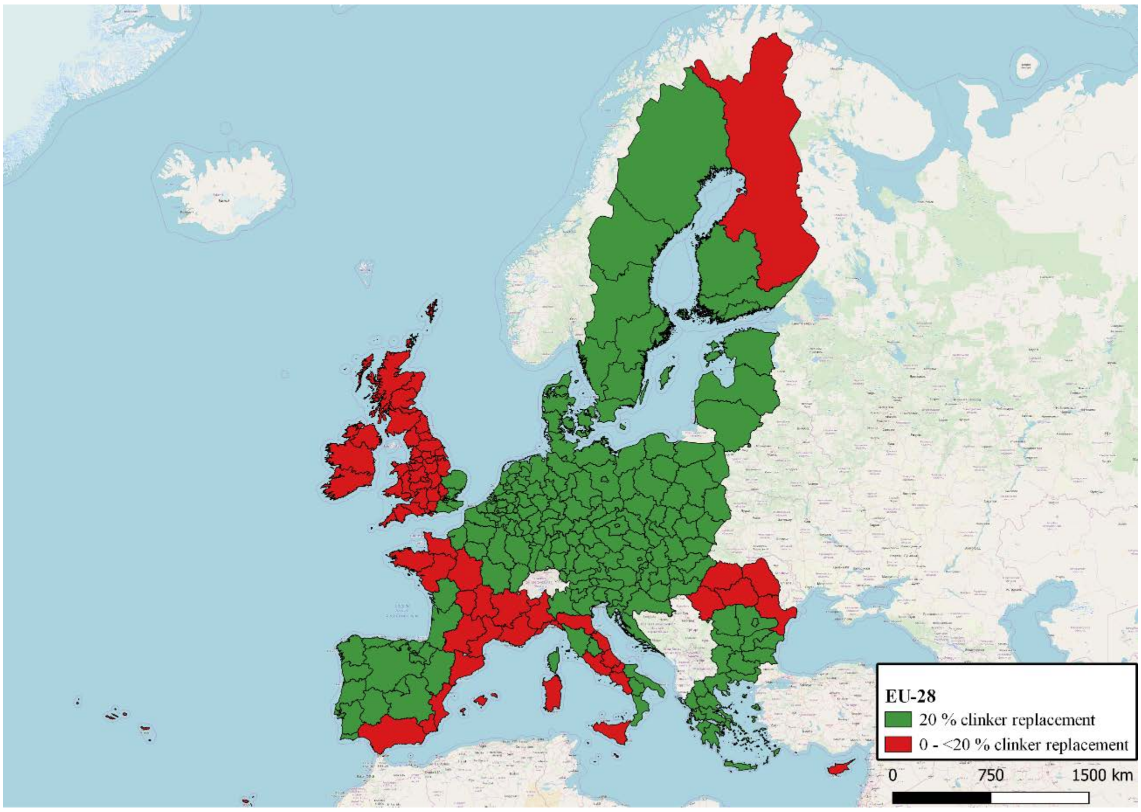


Figure 39 Scenario 2030 High-demand (no relining (Case A)) mapping results.

As predicted, the number of uncovered regions increases. Apart from being almost whole Ireland and UK uncovered, there are also several Mediterranian regions from Spain, France and Italy. In addition, north of Finland, Cyprus and almost all Romanian regions are also uncovered.

6.4.2. Scenario 3 - 2050

In the year 2050, the end of the studied period, with a high cement demand and all remaining blast furnaces decommissioned (in Case A) and only 35 coal-fired power plants still in operation, the supply of alternative binders and consequently the achievable substitution rate will have been considerable lowered.

Table 34 Scenario High-demand (Case B) 2050 results.

Supply alternative binders (kt/yr)	Cement demand (kt/yr)	Max. average substitution (%)
10 000	197 700	10

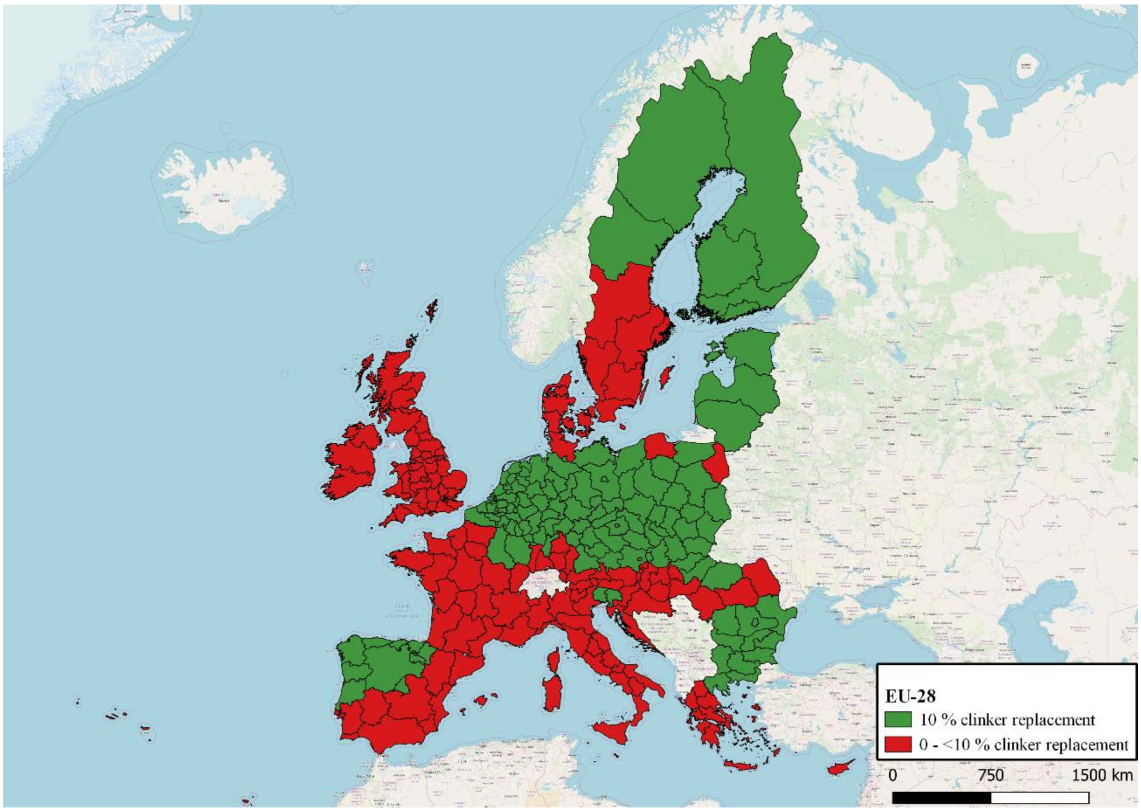


Figure 40 Scenario 2050 High-demand mapping results.

Figure 40 reflects this situation mentioned. With only a few remaining facilities suppling alternative binders and with an increased demand, the ability to replace cement clinker will be very limited. The situation will be worst in the regions furthest away from central Europe (i.e. Germany, Czech Republic and Poland were the remaining coal-fired power plants are located).

Also, note that some regions outside Central Europe, e.g., Sweden and Finland still cover their by-products demand despite being further away from supply. The main reason for this is the transportation cost considered (see section 1.4.6). Central Europe is not considered an intensive cement zone, so supply easily satisfy demand.

6.5.Bonus Scenarios

6.5.1. Scenario base on the IEA cement roadmap

The first "bonus" scenario was based on input from the Cement Industry Technology Roadmap developed by the IEA [1]. Here, instead of seeking to achieve the maximum replacement rate in the largest number of regions, a fixed replacement ratio was assigned. Once introduced the data, the program will state which regions can be covered that ratio in which not.

The IEA Cement Industry Roadmap considers two main scenarios:

- The Reference Technology Scenario (RTS), considered a "business as usual scenario", in which temperature will rise up to 2,7ºC to 2100 [1], and
- The 2ºC Scenario (2DS), in which temperature will not rise up to 2ºC to 2100 [1].

Besides, it considers two cases. A Low-variability case, which is considered the most likely future and thus the reference scenario and a High-variability case, in which is the relative variation of cement demand is scaled over time in the different regions.

Table 35 presents some of the main results from the IEA study:

Table 35 IEA Technology Roadmap scenario results.

		RTS Low-variability case			Roadmap vision (2DS) Low-variability case		
	2014	2030	2040	2050	2030	2040	2050
Cement production (Mt/yr)	4 171	4 250	4 429	4 682	4 250	4 429	4 682
Clinker to cement ratio	0.65	0.66	0.67	0.66	0.64	0.63	0.60
Thermal energy intensity of clinker (GJ/t clinker)	3.5	3.4	3.3	3.2	3.3	3.2	3.1
Electricity intensity of cement (kWh/t cement)	91	89	86	82	87	83	79

The analysis presented here was based on IEA's 2DS scenario and the Low-variability case (see Table 36)

Table 36 2DS ratios used for the study (world basis).

2DS			
2030		2050	
Clinker ratio	Substitution ratio	Clinker ratio	Substitution ratio
0,64	0,36	0,6	0,4

However, these numbers are suited for a world basis scenario. It is clear that they must be adjusted to a Europe level. The IEA study also provides a handful of figures in which are represented the evolution of the clinker to cement ratio in different regions. Figure 41 shows the Europe clinker to cement ratio evolution in the 2DS:

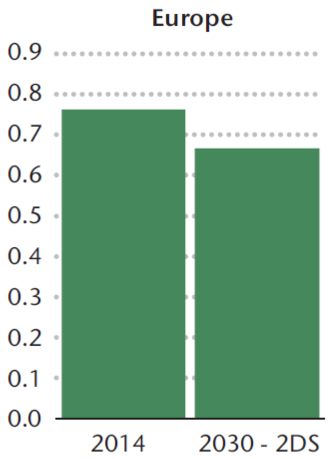


Figure 41 Clinker to cement ratio evolution in Europe, 2DS.

The figure states that Europe evolves from an estimate 0,75 clinker to cement ratio in 2014 to an also estimated 0,65 in 2030. Since the IEA study does not provide any specific data for the EU in 2050 the following analysis was based on the world basis result for 2050 in order to conduct the simulation.

The method applied to estimate the development of cement demand and the supply of alternative binders were the same as in Scenario 1-3 above (see Sections 6.1, 6.3 and 6.4 for extended description of the method)

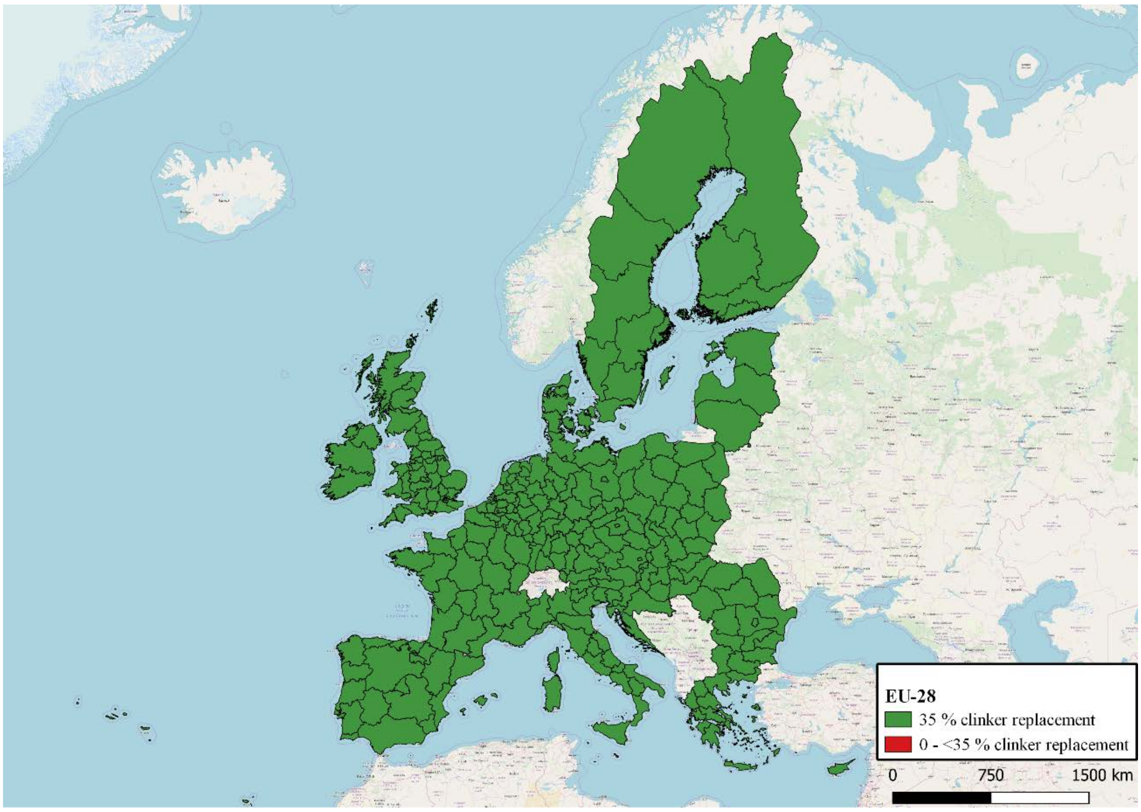


Figure 42 Scenario 2030 IEA 35% substitution Low-demand relining (Case B) mapping results.

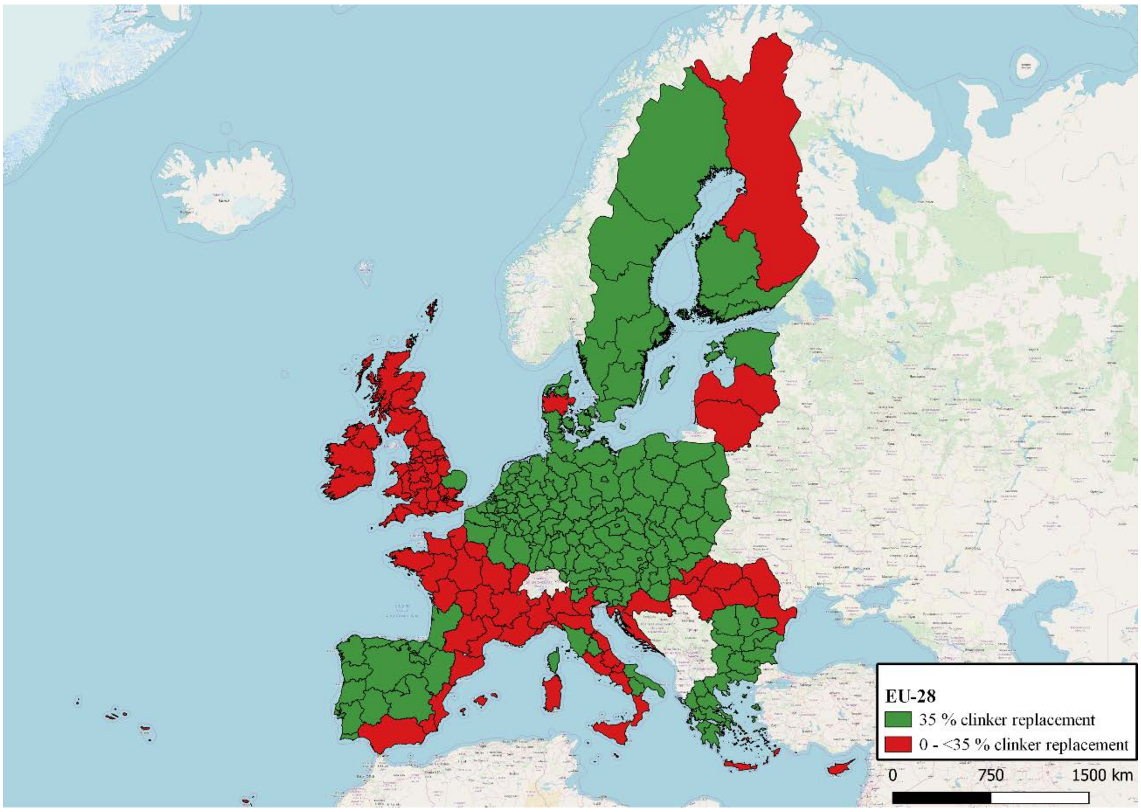


Figure 43 Scenario 2030 IEA 35% substitution Low-demand no relining (Case A) mapping results.

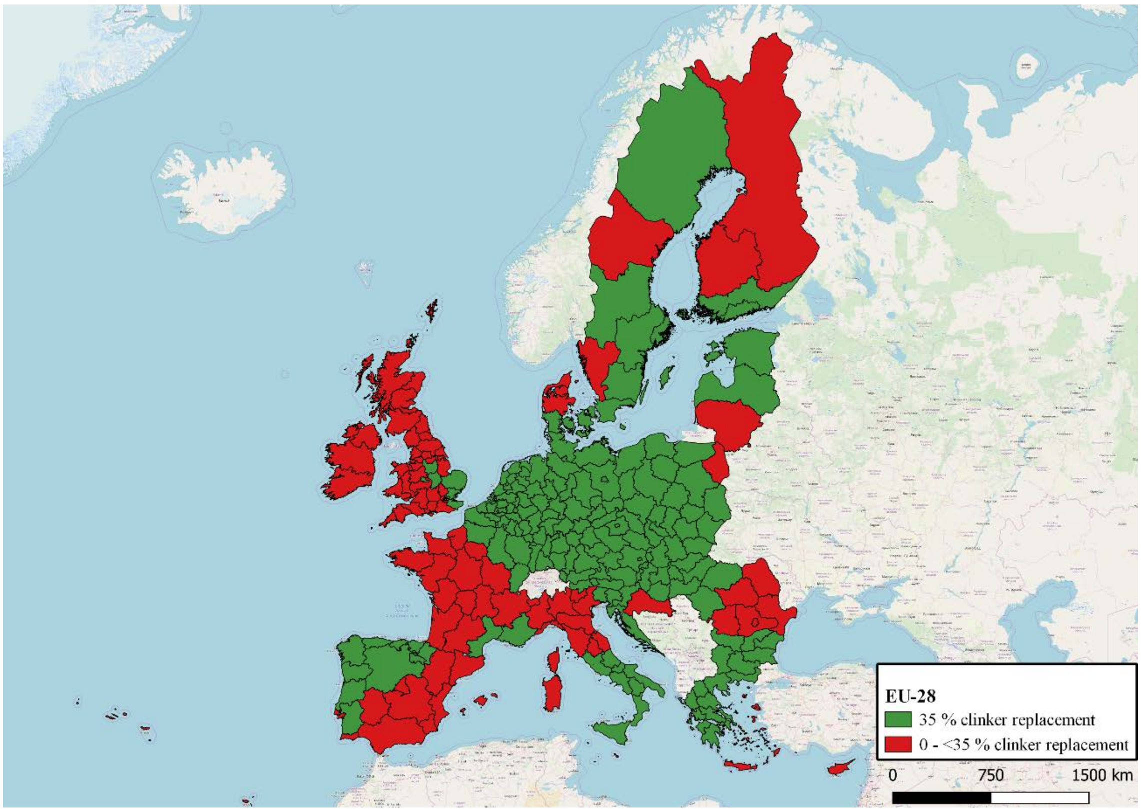


Figure 44 Scenario 2030 IEA 35% Substitution High-demand relining (Case B) mapping results.

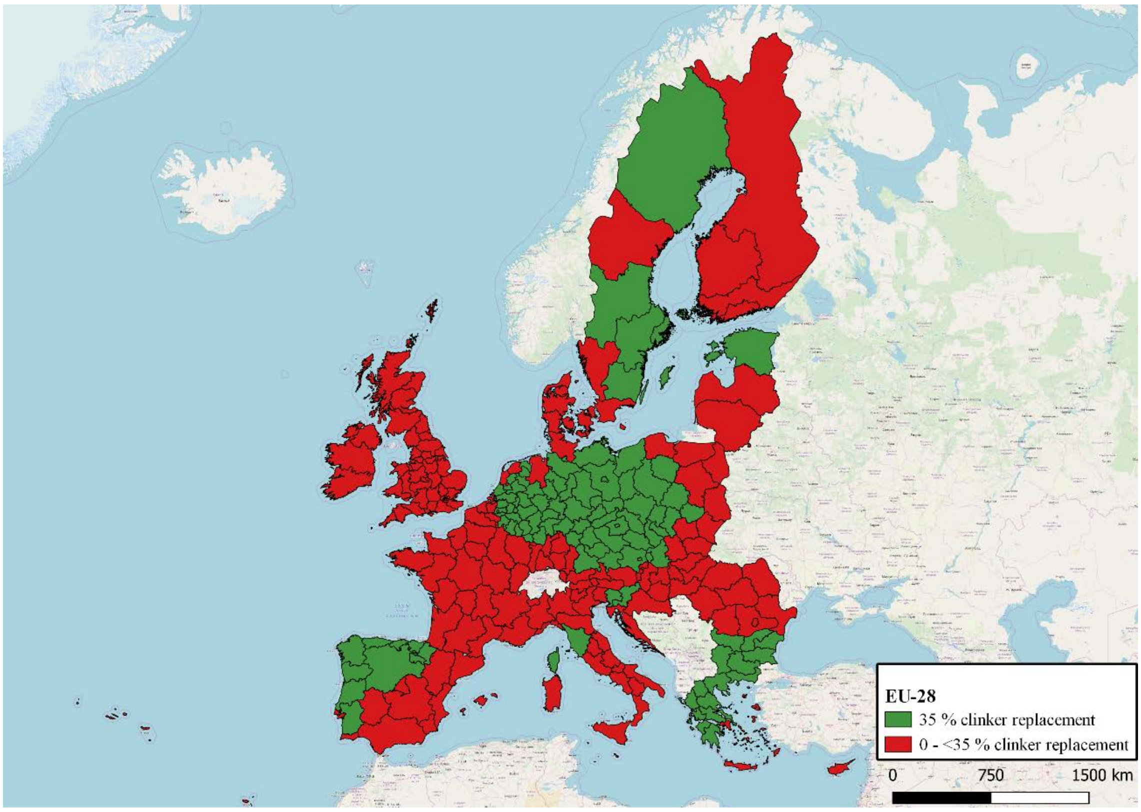


Figure 45 Scenario 2030 IEA 35% Substitution High-demand no relining (Case A) mapping results.

Figure 42 and Figure 43, represent the low demand scenario in 2030. Figure 42 does not show any difference with their previously done homologue, Figure 33, as long as the substitution rate assumed was the same. However, the following figures show a phenomenon that was expected to happen: the more the demand grows or the supply declines, the less regions fully covered their by-products supply. When this happens, the most external regions of Europe stop receiving their by-products quantity. This trend is enforced and strenghted towards the end of the studied period as more and more blast furnaces and coal-power plants are closed.

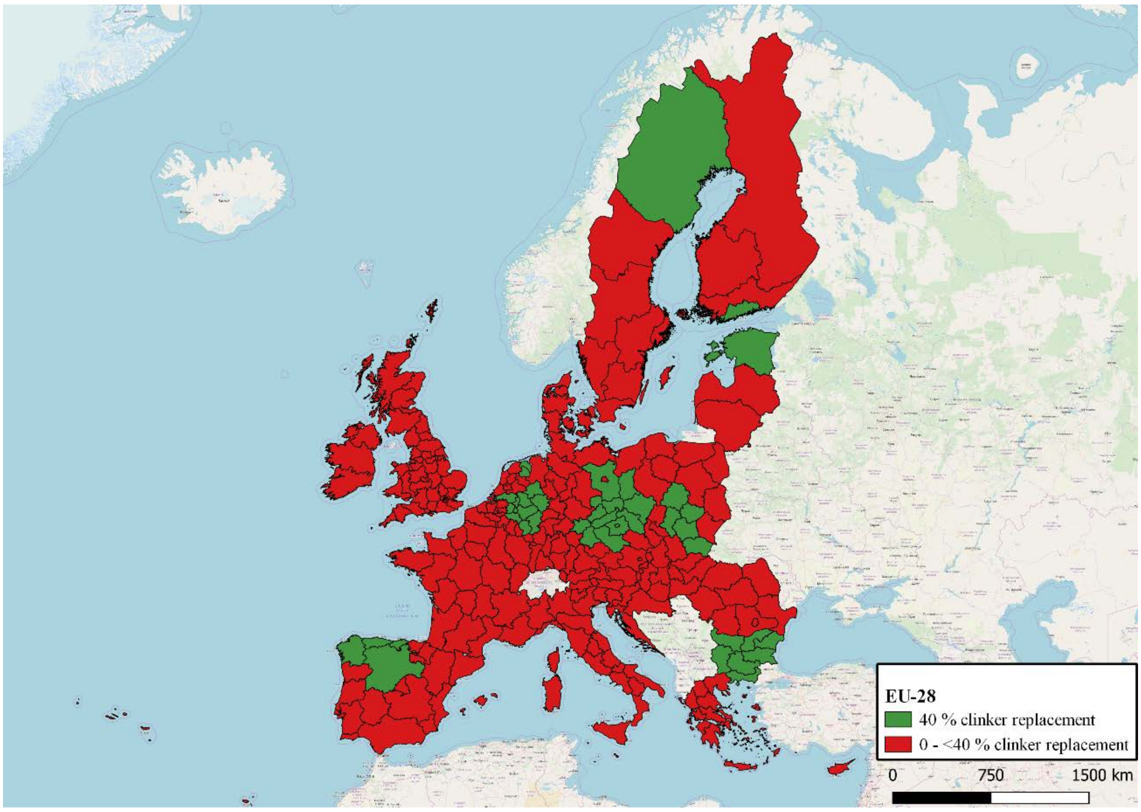


Figure 46 Scenario 2050 IEA 40% Substitution Low-demand (Case B) mapping results.

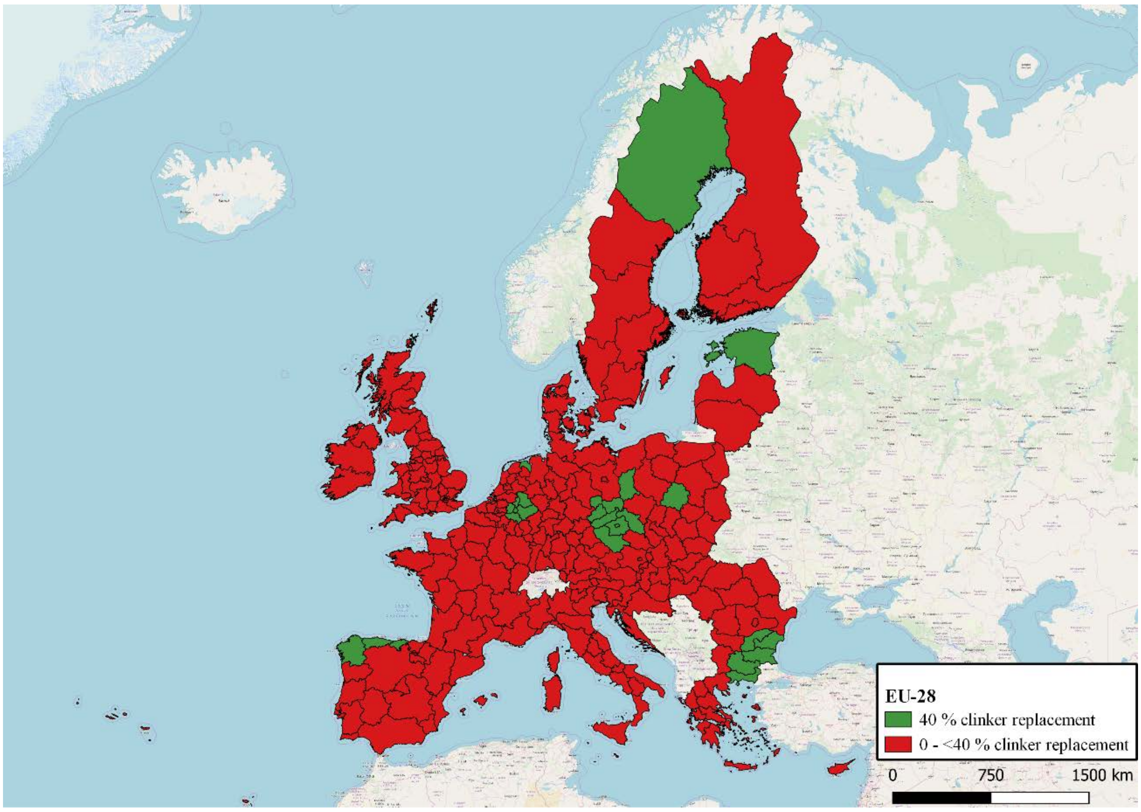


Figure 47 Scenario 2050 IEA 40% Substitution High demand (Case B) mapping results.

As the figures above state, a 40% substitution rate is quite difficult to achieve in all Europe regions using the hypothesis of this study. Only the surrounding regions to the remaining coal-fired power plants in 2050 will be able to meet the by-products demand.

These results build on the assumption that existing blast furnaces and coal-fired power plants are phased out at the end of their technical lifetime. Resulting a radical decline in the supply of conventional alternative binders. While this development would be in line with EU climate goals, it is by no means certain. If this relatively rapid phased out of blast furnaces and coal-fired power plants would be realised there are, as discussed above, a number of non-conventional alternative binders could potentially fill the gap. However, more research and quantifiable data need to be conducted in order to create predictions that are more accurate.

6.5.2. Scenario from ETHZ cement roadmap

The second "bonus" scenario was based on the Technology assessment for full decarbonisation of the cement and concrete industry by 2050 undertaken by the Swiss Federal Institute of Technology (ETHZ), Zürich, and the Swiss Federal Institute of Technology (EPFL), Lausanne, and commissioned by the European Climate Foundation. The objective of the ETHZ/EPFL was to assess the potential of technologies to reduce CO2 emissions from the cement and concrete industry [7]. The mitigation options reviewed in the report are:

- Reduce CO_2 emissions from clinker production by improving the energy efficiency of cement plants.
- Reduce CO2 emissions from cement by reducing the clinker content.
- Reduce CO2 emissions from concrete by reducing the cement content.
- Reduce CO2 emissions from concrete structures by adapting the concrete mix design and the element shape to the final application.

Some of the key assumptions used from an economic activity point of view in the roadmap scenarios that should be reflected in the simulation are:

- Cement demand projected to remain stable for the coming decades.
- Stable population
- Existing production capacity
- No investment in new cement infrastructure will occur in Europe

There are three scenarios considered with a handful of strategies for CO_2 reduction in the cementitious value chain. Not all scenarios make use of all the potential technologies to achieve that emissions reduction. Table 37 presents the clinker substitution ratios stated in the ETHZ/EPFL report which were used in this assessment:

Table 37 ETHZ clinker substitution ratios for each scenario.

Scenario	**2015**	**2030**	**2050**
Reference scenario	23	30	35
Scenario 1	23	30	35
Scenario 2	23	30	40
Scenario 3	23	30	40
Extreme scenario 3	23	30	50

The reference scenario is pretended to be an extension of the RTS in the IEA technology roadmap (see Section 6.5.1). Scenario 1 uses the same cement demand as the reference scenario, but cement producers must do the investment of all new technologies. Both scenarios 2 and 3 use reduced cement demand as long as the amount of cement required for concrete is considered to be reduced. Besides, the scenario 3 considers higher use of prefabrication. Also, there exists an extreme scenario 3 in which the required clinker substitution must be over 50%.

At the time to simulate, the inputs used are the cement demand assumptions from the report next to the clinker substitution ratios and the project-calculated by-products supplied by the coal-fired power plants and the blast furnaces. Below are presented the results of the simulations driven. The figures show some disparities compared with the project scenarios. First of all, the results for the 2030 time frame.

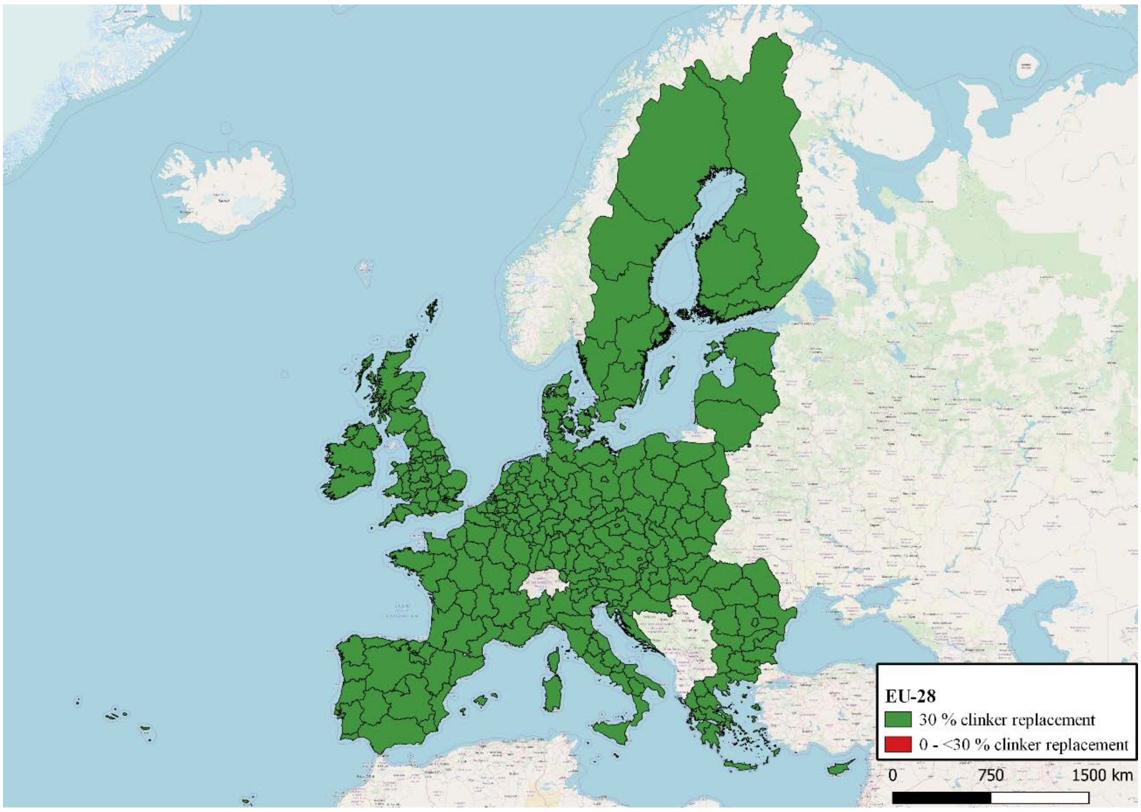


Figure 48 Scenario 1, 2030 30% substitution relining (Case B) mapping results.

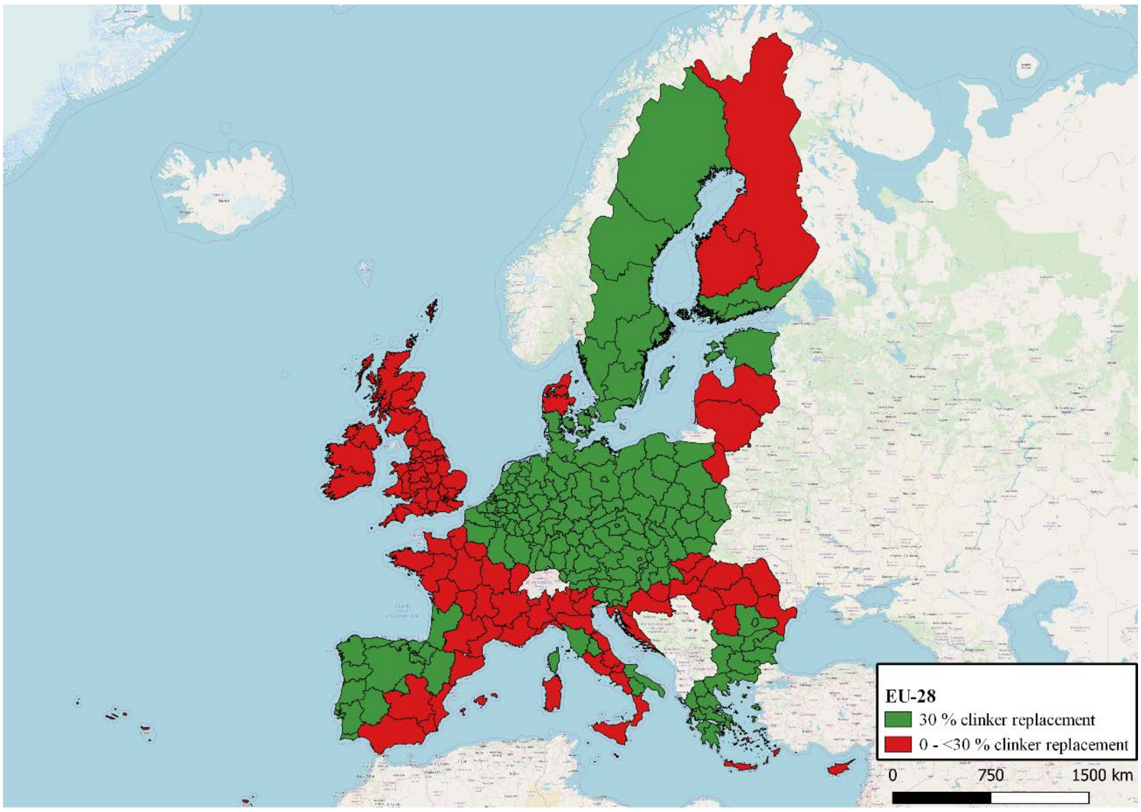


Figure 49 Scenario 1, 2030 30% substitution no relining (Case A) mapping results.

Relining or not, the vast majority of the Europe regions are within the coverage rates of substitution and so they are able to achieve the percentage goal for the scenario 1. However, for the right figure, it is clear that a big part of France, Spain, Romania, Finland and whole UK decay their by-products supply to levels that do not allow them to achieve that 30% clinker substitution.

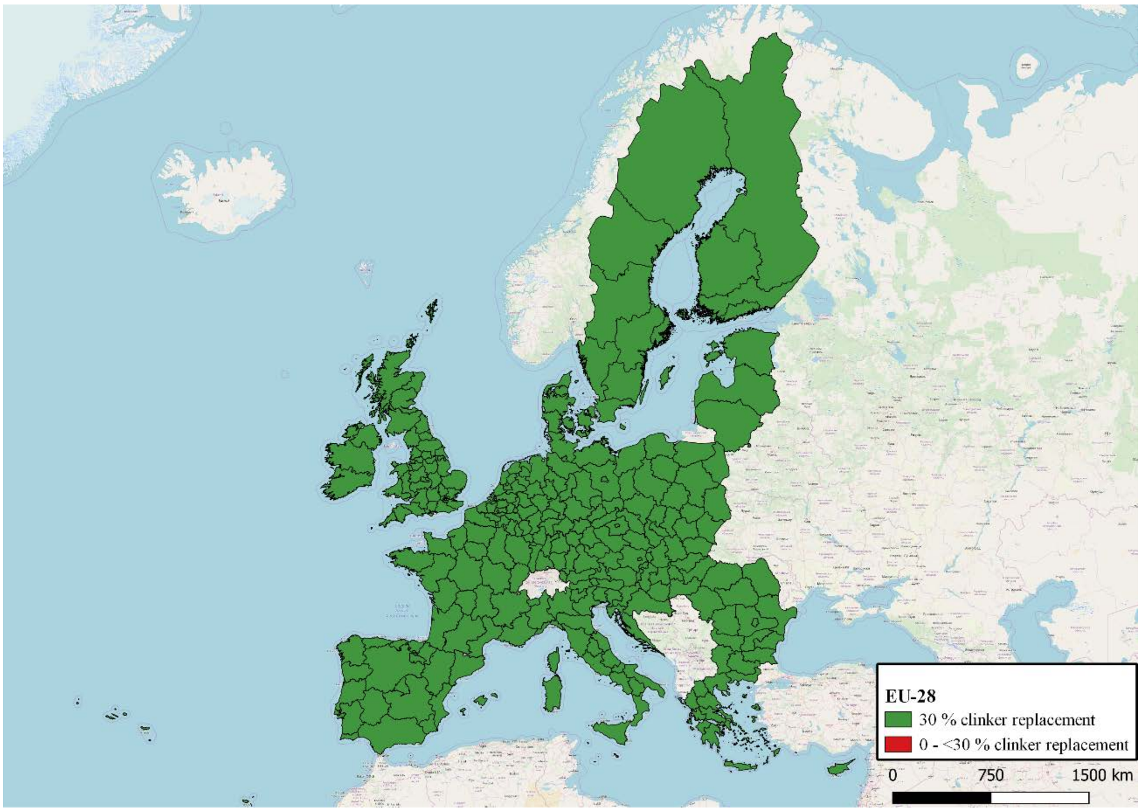


Figure 50 Scenario 2&3, 2030 30% substitution relining (Case B) mapping results.

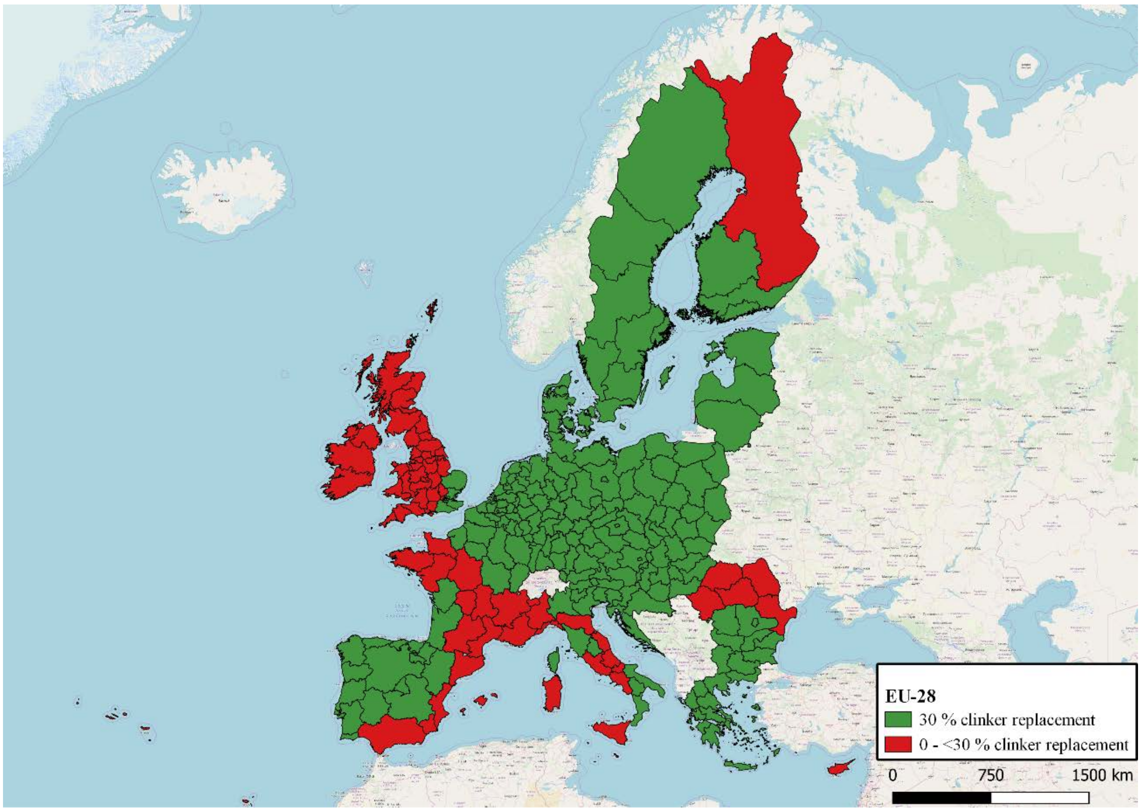


Figure 51 Scenario 2&3, 2030 30% substitution no relining (Case A) mapping results.

This is not the case for the scenario 2&3, in which the cement demand is an 80% of the scenario 1 demand. Considering relining, allows supplying all regions of Europe all their by-products demand.

Therefore, the 2050 scenarios present similarities with their homologues from the IEA technology roadmap, in which the substitution ratio was a 40% too (as it is the case for scenarios 2 and 3).

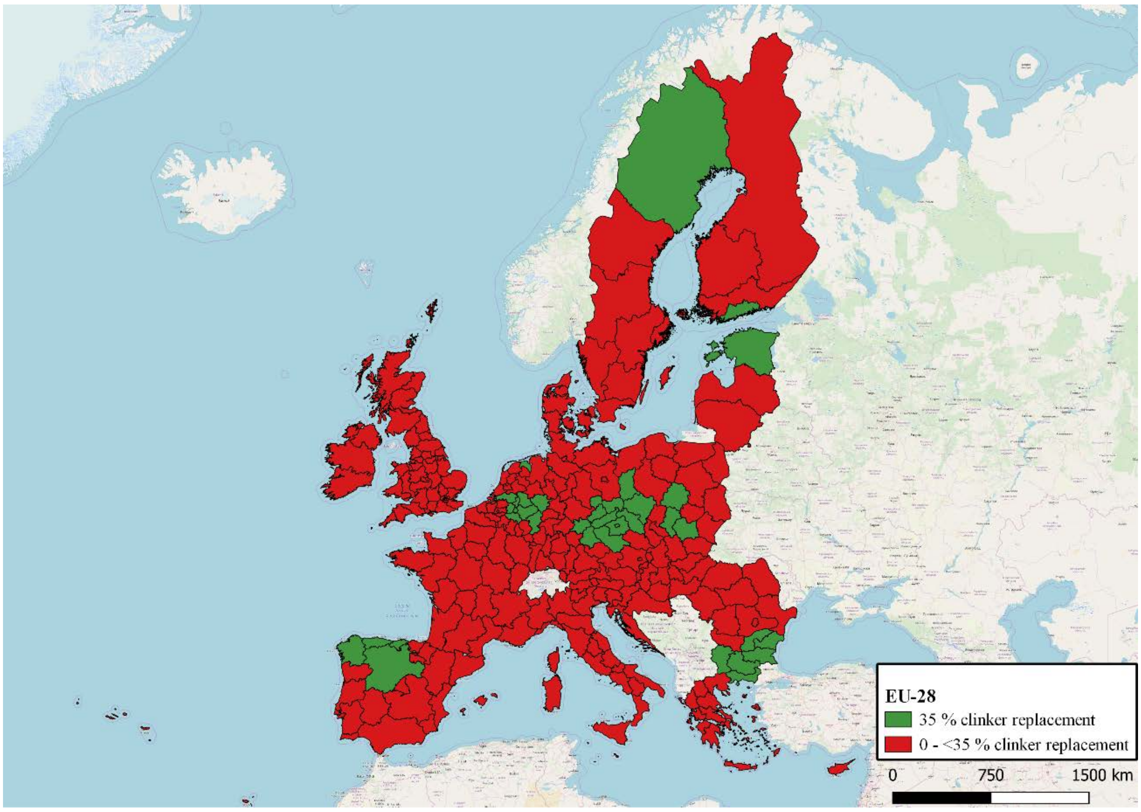


Figure 52 Scenario 1, 2050 35% substitution (Case B) mapping results.

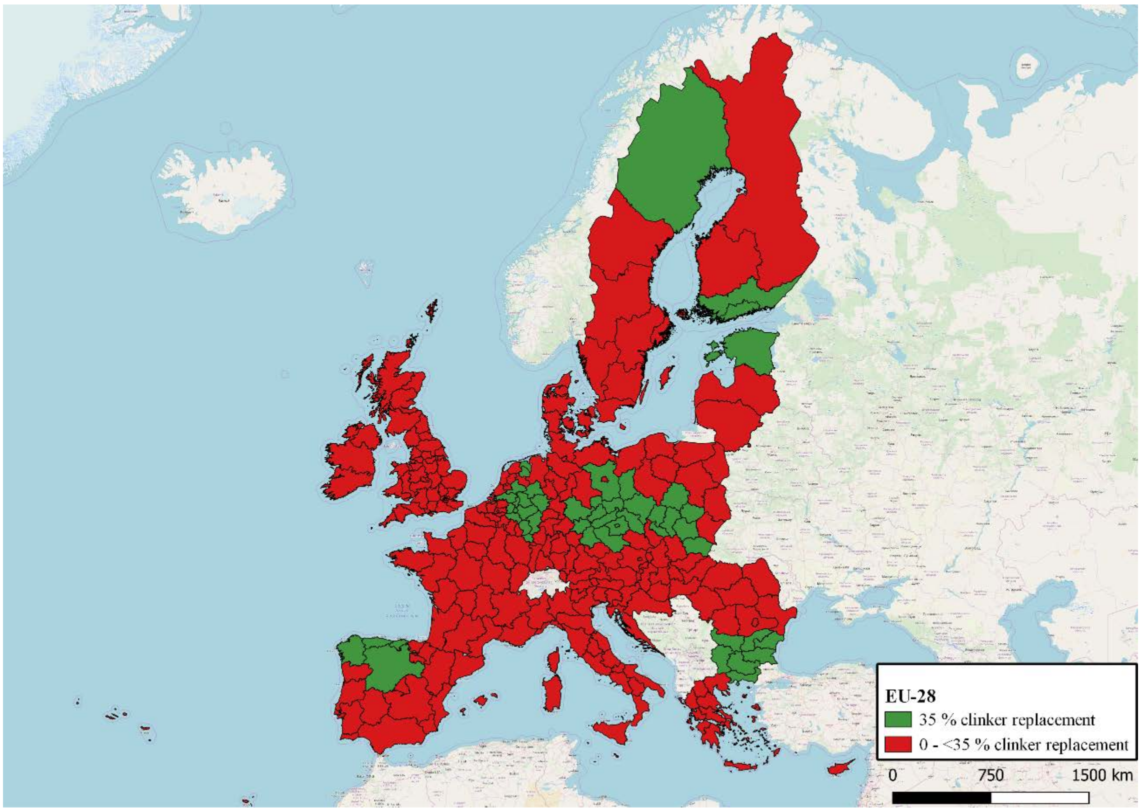


Figure 53 Scenario 2&3, 2050 40% substitution (Case B) mapping results.

Again, only the regions surrounding the remaining coal-fired power plants receive their by-products demand. As seen in the figures, regions from Belgium, central Germany, Bulgaria, Latvia, Estonia and southern Finland would be covered. Although being a discrete number of regions, achieving a 40% substitution can be considered an impressive goal taking into consideration the reduced supply considered of these two sources by 2050, in means of the project.

6.6. Summary of results

Table 38 shows the results obtained from the spatial GIS analysis conducted through all the thesis scenarios. For the BAU, Low-demand and High-demand scenarios the table gives the maximum average clinker replacement ratios achieved in each time period. For the IEA and ETHZ/EPFL scenarios the table gives the number of regions from the total (276) in which the targeted clinker replacement ratio was achieved. The results from every scenario are divided according to the case they belong to: Case A (no relining) and Case B (relining).

Table 38 Summary of GIS analysis results.

		2017	2030		2050	
BAU scenario (%)		70	-		-	
Low-demand scenario (%)	Case A	-	25		10	
	Case B	-	40		10	
High-demand scenario (%)	Case A	-	20		10	
	Case B	-	25		10	
			Low	**High**	**Low**	**High**
IEA scenario (number of regions) (replacement ratio: 35% in 2030, 40% in 2050)	Case A	-	174	105	0	0
	Case B	-	276	175	45	26
			S1	**S2&3**	**S1**	**S2&3**
ETHZ/ EPFL scenario (number of regions) (replacement ratio: 30% in 2030, 35% in 2050)	Case A	-	165	198	37	47
	Case B	-	276	276	38	51

7. Concluding discussions

In modern society, concrete is next to water the most consumed material in the world thanks to its many applications in structures and buildings, which provide shelter, transportation and mobility for people. Concrete has become one of the most GHG emission-intensive activities in the world because of clinker usage for its cement. CO_2 emission from cement clinker production account the vast majority of concrete emissions, approximately 60-70%. Countries that are more environmentally concerned have started to work on reducing cement emissions by implementing new measures and techniques in different stages of its production.

One of the most promising options is the application of alternative binders to substitute part of the Clinker content of cement. During the last decades, much research has been in devoted to studying the suitability and the effects of different alternative binders in the final applications of concrete. These alternative binders are usually classified by their origin, being from natural sources or a by-product (residue) from other industries. The most well-known and most widely used alternative binders are fly ash from coal-fired power plants and blast furnace slag from steel industry blast furnaces. These two by-products are currently being used, however not at their maximum potential for the case of the fly ashes. This and other reasons such as the availability of information and well-known effects of the final concrete mixture make them the most suitable for this project study. In this study, thorough analysis have been carried out to estimate an approximate quantity for both fly ash and blast furnace slag produced in Europe countries for three periods: current, 2030 and 2050. The analysis is based on explorative scenarios ("what if" type scenarios) which, in turn, build on a number of simplifications and assumptions. One of the key assumptions relates to capital stock turnover. Here, key capital, coal-fired power plants and blast furnaces, are assumed to be decommissioned as they reach the end of their technical lifetime. While actual life times tends to vary considerably, a lifespan of 40 years was used as the basic assumption for both power plants and blast furnaces. The assumption goes in line with the Paris Agreement goals, which means that all OECD countries should phase out coal power generation by 2030 [66]. However, coal power generation in Germany may continue up to 2038 as a result of slower decommissioning [67].

Nevertheless, for blast furnaces two different possibilities were considered. The basic assumption was exactly the same one as the coal-fired power plants lifespan hypothesis, when they reach 40 years they are phased out in means of estimating future supply of slag. However, since approximately 80% of the existing furnaces are already that old (>40 years), and thanks of having data about the year in which they were last relined, a second possibility arose. This second one considered counting 40 years of operation since the beginning of the year in which they were lastly relined, as long as their machine parts would have been replaced by new ones.

Based on these assumptions and data provided it was possible to estimate an approximate quantity of both by-products. On the one hand, it was estimated 143 megatons of profitable fly ash currently available to use. The estimate includes fly ash produced from lignite and anthracite coal in 840 power plants. The estimates of fly ash developed are correlated with the capacity factor used. However, a fixed capacity factor was used to conduct the estimation. The difference between using a slightly higher or lower capacity factor do not significantly affected the final clinker replacement ratios achieved. As a result of using an average replacement ratios, the possible differences between different capacity factors were not relevant enough to split the fly ash estimates into two additional cases. The most production-intensive zones are Germany that accounts a 35 % of total FA produced, followed by Poland and the Czech Republic with a 16 and 13 % respectively. For its part, Sweden produces a modest amount of 51 kt/ year, which is equivalent to 1 % of the total fly ash production in the EU. For both 2030 and 2050 estimations, the amount of fly ash available would be dramatically reduced to 25 and 9.2 Mt/ year respectively. As discussed above, many of the existing facilities already surpass the 40 years lifespan, which conditions the future possibilities of massively exploiting that resource.

The amount of blast furnace slag, on the other hand, were estimated to be an approximate of 26.6 Mt/ year from 33 facilities. Again, Germany is the country with the highest production of slag accounting for 29 %, followed by France and Italy with both a 12 %. Just as was the case with fly ash, Sweden contributes with a low quantity, approximately 989 kt of slag per year, or 3 % from total. Whereas using the year in which the furnace was first constructed results in a shorter lifespan, using the year in which the furnace was last relined allows for prolonged operational life. In the later case, blast furnace slag can contribute to a greater extent to the total resource base of by-products. From the current 26.6 Mt, it drops to 4.7 for the first case (no relining) an to 23.5 for the second case (relining) in 2030. In 2050, Case A estimates lead to a null production while Case B estimates are 0.8 Mt/year.

These estimated supply of conventional alternative binders need to fulfil part of the expected cement demand. Many studies try to predict how cement consumption will evolve in the near decades. Currently, EU-28 regions consume 160 million ton of cement each year. Two different scenario for the future development of cement consumption were explore: a Low-demand and a High-demand scenario. Each will take into consideration population growth projections made by Eurostat with a tolerance of ± 20 % from the initial demand.

- The low demand scenario may be caused by features like: optimisation of the quantity of cement needed in concrete [3], increase of concrete waste recycling, efficiency of cement production or better packing and selection of concrete aggregates can allow to a reduction of the cement needed in concrete.
- The high demand scenario may be a consequence of no climate policies and increased investments in new building and infrastructure over the next few decades.

Combining the estimates of supply of alternative binders with the cement demand scenarios allow to simulate and calculate which are the possible clinker replacement ratios across EU-28 regions under the studied period. The results show how as supply of conventional alternative binders decreases, the maximum average substitution rate achievable across EU-28 regions decreases as well. The current maximum average substitution rate was estimated to be approximately 70%. However, the results also show the potential for replacing cement clinker with conventional alternative binders will considerably lower in the coming decades:

- In the Low-demand scenario a 40/ 25 % (relining/ no relining case) replacement ratio was achieved in 2030.
- In the High-demand scenario, a 25/ 20 % (relining/ no relining case) replacement ratio was achieved in 2030.
- In 2050 in both scenarios, with the exceptions of a few external regions (where the remaining coal-fired power plants are not located) it was possible to achieve a 10% replacement ratio in most regions of EU-28.

The simulation results show how, given the assumptions and limitations applied in the study, if the limited to only these two conventional alternative binders it will not be possible to achieve higher replacement ratios. Thus, one recommendation would be to dedicate more work to increase the knowledge about and the use of other alternative binders. Increased use of non-conventional binders like, e.g., calcined clays, natural pozzolans, and organic ashes could potentially help meeting the relatively ambitious cement clinker replacement goals proposed in previous studies by IEA and ETHZ/ EPLF (see [1] and [7]). They state an approximate goal of replacing 35 % of cement clinker with alternative binders by 2030 and 40 % by 2050. It is clear that these goals will be very challenging to meet under the project hypothesis, at least in the EU-28. It is worth noting that some of the scenarios suggested by IEA and ETHZ/ EPFL, use different cement demand evolution compared to the ones used in this work. The substitution ratios achieved in 2030 in the scenarios explored in this work are quite near the ones suggested by IEA and ETHZ/ EPFL. However, in 2050 period the supply remaining cannot fulfil a 40 % replacement ratio demand. Only regions located close to the remaining coal-fired power plants would see their demand covered, at the cost of creating a large amount of regions with no possible supply of fly ash or blast furnace slag.

In summary, this work raises the concern that, despite all efforts done towards analysing the potential for increasing the cement clinker substitution rates, the resource base of conventional alternative binders in the EU-28 in the coming decades may be significantly lower than previously expected. It may be possible to substitute large amounts of clinker by conventional alternative binders such as fly ash and blast furnace slag, in the short term (5-10 years). However, longer term (10-30 years), the need to phase out an ageing fossil capital stock, included coal-fired power plants and blast furnace, to meet climate targets will rapidly and significantly reduce the resource base of conventional alternative binders. Even though there is already a relatively large body of literature analysing the potential for and effects of an increased use of unconventional alternative binders in concrete, this study highlights the importance of stepping up efforts to analysing their availability and how to distribute them all across Europe regions. With an increased use of unconventional alternative binders in combination with several other measures to reduce the climate impacts of cement and concrete, it would still be possible to allow continued use of concrete without jeopardising the climate goals.

8. References

[1] International Energy Agency IEA, “Technology Roadmap,” *SpringerReference*, p. 60, 2014.

[2] OECD/ IEA and The World Business Council for Suistanable Development, “CEMENT ROADMAP Key findings,” 2009.

[3] Cementa HeidelbergCement Group, “Cementa está considerando eliminar la producción de cemento en Degerhamn | Cementa AB,” *2018 oktober 16*, 2018. [Online]. Available: https://www.cementa.se/sv/cementa-overvager-avveckla-degerhamn. [Accessed: 05-Jan-2019].

[4] J. Rootzén, “Pathways to deep decarbonisation of carbon-intensive industry in the European Union,” Chalmers University of Technology, Gothenburg, Sweden.

[5] Cemnet, “Cement Plants located in Sweden,” *Global Cement Report: Sweden*, 2018. [Online]. Available: https://www.cemnet.com/global-cement-report/country/sweden. [Accessed: 15-Oct-2018].

[6] GNR, “Mineral components used to produce clinker-based Portlande cement - Weighted average, EU-28,” *2016*. [Online]. Available: https://www.wbcsdcement.org/GNR-2016/EU28/GNR-Indicator_12AG-EU28.html.

[7] A. Favier, C. De Wolf, K. Schrivener, and G. Habert, “A Sustainable Future for the European Cement and Croncrete Industry: Technology assessment for full decarbonisation of the industry by 2050 The authors,” p. 96, 2018.

[8] F. Kjarstad, J., & Johnsson, “The European power plant infrastructure.” 2007.

[9] Steel Institute VDEh, “Plantfacts database.” 2018.

[10] Eurostat, “Population on 1 January by NUTS 2 region,” *24-10-2018*. [Online]. Available: https://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tgs00096%0A. [Accessed: 02-Dec-2018].

[11] Tradeship Publications Ltd (UK), “The Global Cement Report,” 2017.

[12] CEMBUREAU, “Activity report 2016,” p. 36, 2016.

[13] WBCSD/CSI GNR, “GNR Project,” *Emissions Report 2016*, 2015. [Online]. Available: https://www.wbcsdcement.org/GNR-2016/. [Accessed: 05-Jan-2019].

[14] C. Heidrich, H. Feuerborn, and A. Weir, “Coal Combustion Products : a Global Perspective,” *World Coal Ash*, p. 17, 2013.

[15] U.S. Energy Information Administration, “Monthly Electric Power Industry Report,” 2018.

[16] B. Caldecott *et al.*, “The fate of European coal-fired power stations planned in the mid-2000s,” *Sustain. Financ. Program.*, no. August, p. 86, 2017.

[17] International Energy Agency, *Energy Technology Perspectives 2012*, Second edi. Paris, France: IEA PUBLICATIONS, 2012.

[18] International Energy Agency, “European Union - 28 - Electricity generation by fuel.” [Online]. Available: https://www.iea.org/statistics/?country=EU28&year=2016&category=Electricity&indicator=ElecGenByFuel&mode=chart&dataTable=ELECTRICITYANDHEAT. [Accessed:

24-Jan-2019].

[19] R. Snellings, G. Mertens, and J. Elsen, “Supplementary Cementitious Materials,” *Rev. Mineral. Geochemistry*, vol. 74, no. 1, pp. 211–278, 2012.

[20] T. Miyamoto, K. Torii, K. Akahane, and S. Hayashiguchi, “Production and Use of Blast Furnace Slag Aggregate for Concrete,” no. 109, pp. 102–108, 2015.

[21] World Steel, “Fact sheet Raw materials Steel and raw materials.” pp. 1–2, 2018.

[22] World Steel Association, “Crude steel production,” 2015. [Online]. Available: http://www.eurofer.org/Facts%26Figures/Crude Steel Production/All Qualities.fhtml. [Accessed: 22-Oct-2018].

[23] E.-S. O. of the E. U. European Commission, “Eurostat Population projections 2015 based,” *24-10-2018*, 2018. [Online]. Available: https://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tps00002%0A.

[24] Tradeship Publications Ltd (UK), “The Global Cement Report,” 2018. [Online]. Available: https://www.cemnet.com/global-cement-report/statistics/Export/%0A.

[25] QGIS, “Welcome to the QGIS project!” [Online]. Available: https://qgis.org/en/site/index.html. [Accessed: 21-Jan-2019].

[26] E.-S. O. of the E. U. European Commission, “NUTS - Eurostat,” 2016. [Online]. Available: https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/nuts. [Accessed: 21-Jan-2019].

[27] R. Snellings, “Assessing, Understanding and Unlocking Supplementary Cementitious Materials,” *RILEM Tech. Lett.*, vol. 1, p. 50, 2016.

[28] R. V. Fisher and H.-U. Schminke, “Pyroclastic rocks: New York,” *Springer-Verlag*, p. 472, 1984.

[29] J. Bensted, “Special Cements,” in *Lea’s Chemistry of Cement and Concrete*, Elservier Butterworth- Heinemann, 2003, pp. 783–840.

[30] I. Marantos, T. Markopoulos, G. E. Christidis, and V. Perdikatsis, “Geochemical characteristics of the alteration of volcanic and volcaniclastic rocks in the Feres Basin, Thrace, NE Greece,” *Clay Miner.*, vol. 43, no. 4, pp. 575–595, 2008.

[31] L. D. Rollmann, E. W. Valyocsik, and R. D. Shannon, “Zeolite Molecular Sieves,” in *Inorganic Syntheses*, vol. 22, Wiley-Blackwell, 2006, pp. 61–68.

[32] L. E. Antonides, “DIATOMITE,” p. 6.

[33] A. Tironi, M. A. Trezza, A. N. Scian, and E. F. Irassar, “Incorporation of Calcined Clays in Mortars: Porous Structure and Compressive Strength,” *Procedia Mater. Sci.*, vol. 1, pp. 366–373, Jan. 2012.

[34] Y. M. Vargas-Rodríguez *et al.*, “Caracterización espectroscópica de una montmorillonita mexicana,” *Rev. Mex. Cienc. Geol.*, vol. 25, no. 1, pp. 135–144, 2008.

[35] Oilfield Glossary, “Montmorillonite - Schlumberger Oilfield Glossary,” *2018*. [Online]. Available: https://www.glossary.oilfield.slb.com/es/Terms/m/montmorillonite.aspx. [Accessed: 04-Oct-2018].

[36] S. Alberici, J. De Beer, I. Van Der Hoorn, and M. Staats, “Fly ash and blast furnace slag for cement manufacturing: BEIS research paper no. 19,” 2017.

[37] B. L. Damineli, R. G. Pileggi, and V. M. John, “Lower binder intensity eco-efficient

concretes," in *Eco-Efficient Concrete*, Woodhead Publishing, 2013, pp. 26–44.

[38] I. Norchem, "How Does Silica Fume Work in Concrete?," 2011. [Online]. Available: http://www.norchem.com/silica-fume-concrete.html. [Accessed: 03-Oct-2018].

[39] S. Chowdhury, A. Maniar, and O. M. Suganya, "Strength development in concrete with wood ash blended cement and use of soft computing models to predict strength parameters," *J. Adv. Res.*, vol. 6, no. 6, pp. 907–913, Nov. 2014.

[40] G. Zhu, Y. Hao, C. Xia, Y. Zhang, T. Hu, and S. Sun, "Study on cementitious properties of steel slag," *J. Min. Metall. Sect. B Metall.*, vol. 49, no. 2, pp. 217–224, 2013.

[41] G. M. S. Islam, M. H. Rahman, and N. Kazi, "Waste glass powder as partial replacement of cement for sustainable concrete practice," *Int. J. Sustain. Built Environ.*, vol. 6, no. 1, pp. 37–44, 2017.

[42] H. Vishaliny, D. Govindarajulu, G.Vijayakumar, G. Vijayakumar, M. H. Vishaliny, and D. Govindarajulu, "Studies on Glass Powder as Partial Replacement of Cement in Concrete Production," *Int. J. Emerg. Technol. Adv. Eng.*, vol. 3, no. 2, pp. 153–157, 2013.

[43] S. Izquierdo, J. Diaz, R. Mejía, and J. Torres, "Blended cement containing fluid catalytic cracking catalyst residue (FCC): hydration and paste microstructure," *Rev. Ing. Construcción*, vol. 28, no. 2, pp. 141–154, 2013.

[44] P. Garcés, F. P. Glasser, D. R. M. Brew, E. Zornoza, and J. Payá, "Pozzolanic activity of a spent fluid catalytic cracking catalyst residue," *Adv. Cem. Res.*, vol. 23, no. 3, pp. 105–111, 2011.

[45] J. Lehne and F. Preston, "Making Concrete Change: Innovation in Low-carbon Cement and Concrete," *Chatham House Rep.*, pp. 1–122, 2018.

[46] E.-S. O. of the E. U. European Commission, "Eurostat - Material prices for recyclates," 2018. [Online]. Available: https://ec.europa.eu/eurostat/web/waste/prices-for-recyclates. [Accessed: 05-Jan-2019].

[47] M. G. Morgan and D. W. Keith, "Improving the way we think about projecting future energy use and emissions of carbon dioxide," *Clim. Change*, vol. 90, no. 3, pp. 189–215, 2008.

[48] R. J. Lempert, S. W. Popper, S. Resetar, and S. Hart, "Capital Cycles and the Timing of Climate Change Mitigation Policy," *Pew Cent. Glob. Clim. Chang.*, p. 60 pp., 2002.

[49] Bankwatch Network, "European Investment Bank to stop financing coal-fired power plants - Bankwatch." [Online]. Available: https://bankwatch.org/bw_in_media/european-investment-bank-to-stop-financing-coal-fired-power-plants. [Accessed: 22-Jan-2019].

[50] D. Suresh and K. Nagaraju, "Ground Granulated Blast Slag (GGBS) In Concrete – A Review "," *IOSR J. Mech. Civ. Eng.*, vol. 12, no. 4, pp. 2278–1684, 2015.

[51] T. E. A. representing metallurgical slag producers and preocessors Euroslag, "Blast Furnace Slag," no. 10. Euroslag, p. 2613, 2012.

[52] B. J. Van Ruijven, D. P. Van Vuuren, W. Boskaljon, M. L. Neelis, D. Saygin, and M. K. Patel, "Long-term model-based projections of energy use and CO 2 emissions from the global steel and cement industries," vol. 112, pp. 15–36, 2016.

[53] OECD, "Global Material Resources Outlook to 2060," Paris, France, 2018.

[54] McKinsey & Company, "Overcapacities in the steel industry." p. 19, 2013.

[55] V. Smil, “Perils of Long-Range Energy Forecasting,” *Technol. Forecast. Soc. Change*, vol. 65, no. 3, pp. 251–264, 2000.

[56] L. Szabó, I. Hidalgo, J. C. Císcar, A. Soria, and P. Russ, “Energy consumption and CO2 emissions from the world iron and steel industry - EUR 20686 EN,” Spain, 2003.

[57] CEMBUREAU, “Cement production in CEMBUREAU and EU28 countries,” *Cembureau*, p. 2011, 2015.

[58] C. Consumption and S. C. Picking, “CEMENT CONSUMPTION vs GDP PER CAPITA : A REVIEW,” Global Bulk Technologies S.L., Madrid, Spain, 2018.

[59] R. Andersson, K. Fridh, H. Stripple, and M. Häglund, “Calculating CO2 uptake for existing concrete structures during and after service life,” *Environ. Sci. Technol.*, vol. 47, no. 20, pp. 11625–11633, 2013.

[60] *OECD Economic Outlook, Volume 2018 Issue 2*. OECD, 2018.

[61] J. Rootzén and F. Johnsson, “Managing the costs of CO2abatement in the cement industry,” *Clim. Policy*, vol. 17, no. 6, pp. 781–800, 2017.

[62] CEMBUREAU, “End_Users_Cement.” 2013.

[63] KGF, “2017 Activity Report,” Brussels, 2018.

[64] Eurostat, “Demographic_balance,_2016_(thousands).png (1103×843),” 2017. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/images/6/6d/Demographic_balance%2C_2016_%28thousands%29.png. [Accessed: 02-Nov-2018].

[65] E. Adriansson *et al.*, “National Inventory Report Sweden 2017 - Greenhouse Gas Emission Inventories 1990-2015,” Stockholm, Sweden, 2017.

[66] *OECD Companion to the Inventory of Support Measures for Fossil Fuels 2015*. OECD Publishing, 2015.

[67] “Science based coal phase-out pathway for Germany in line with the Paris Agreement 1.5°C warming limit Opportunities and benefits of an accelerated energy transition,” 2018.

9. Acknowledgments

Thanks to my colleagues Sergi Ponsà, Rut Guijarro and her brother Albert for their incalculable help and advice in the most difficult moments of the project. Thanks for helping with your valuable knowledge and patience.

Thanks to my department colleagues Irene and Ana for your precious help. You were there when I most needed it.

Thanks to my family and friends for your patience and extraordinary support and encouragement throughout this thesis process.

Special thanks to my supervisors for understanding all situations arose during the project. Thanks for helping with your valuable knowledge in the project scope and for providing such useful tools to develop it.