# DECARBONISATION PATHWAYS FOR THE CEMENT INDUSTRY

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# Decarbonisation pathways for the cement industry

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# Executive summary

Cement is one of the most consumed substances on the planet, and its use is expected to increase with an increase in urbanisation and infrastructure development needs. There is a challenge of meeting this increased demand while reducing emissions from cement production. The global cement industry contributes to around 8 % of global $CO_2$ emissions. However, mitigating emissions from the cement sector is challenging due to the reliance on fossil for its high temperature requirement of cement production and emissions released from the calcination process in its production.

To reach the "well below 2 degrees" target of the Paris Agreement, it is essential that the cement sector reaches net-zero target by 2050. There are many mitigation options to reduce emissions from the cement sector. Some measures include energy efficiency, hydrogen and biomass usage, electrification of heat, carbon capture technology, demand side measures such as material efficiency and material substitution. However, it is not unclear how the cement sector could decarbonise. Therefore, this study intends to model the energy demand of the cement sector to achieve net-zero emissions by 2050. In addition, the geographical scope of this thesis is limited to China, India, Italy, Spain, and Germany. Based on this, the main research question is formulated as follows:

*"What is the role of different energy supply-side options for the cement industry to transition towards net-zero emissions by 2050?"*

In addition, the sub research questions are stated below.

*SQ1: "What are the characteristics of the cement sector in terms of the sector's energy use, its decarbonisation options, cement manufacturers' commitments and relevant government policies?"*

*SQ2: "How will the demand for cement develop?"*

*SQ3:" How would the energy demand for the cement industry develop?"*

*SQ4: "What are the implications of this energy transition in terms of cumulative emissions?"*

The first step of research is to get an overview of country's energy use and different decarbonisation options implemented in different countries. This is provided in answer to *SQ1.* The next step is to model the future cement demand of the countries till 2050 to obtain future energy demand. The analysis of cement demand projections is done for *SQ2.* Results show that cement demand for European countries decreases while for India, the cement demand increases. China's demand increases, with peak demand reaching till 2040.

After the cement demand modelling, the next step is to model the energy demand of the cement sector. Different mitigation scenarios are developed based on different combinations of decarbonisation options stated above. Three mitigation scenarios are considered (M1, M2 and M3), with M1 being the least ambitious and M3 being the most ambitious with all decarbonisation options implemented in that scenario. In all mitigation scenarios, CCS technology is adopted. In addition, in the M1 scenario, energy efficiency and reduction of clinker to cement ratio are adopted. In the M2 scenario, in addition to the mitigation options adopted in M1, electric and hydrogen kilns and material efficiency are

also implemented. In the M3 scenario, in addition to the mitigation options adopted in M2, the use of novel cement is also included. Furthermore, the uptake of electric and hydrogen kiln and material efficiency is assumed to be higher in M3 than in the M2 scenario.

Results of energy modelling provide an answer to *SQ3*. It is found that fossil fuel demand decreases in all countries. The uptake of alternative fuels (biomass and waste) increases in all scenarios with a proportional decrease of fossil fuels. Biomass and electricity use also increases in all mitigation scenarios as it is used to operate CCS technology. In addition, the year in which fossil fuels get phased out is also analysed. In the M1 pathway, there is no phase out of fossil fuel as alternative fuels have only a 90 % share in the thermal energy mix. Results show that in European countries, fossil fuel gets phased out in M2 and M3 pathways. In the case of China, only coal is not phased out, whereas, in India, none of the fossil fuel is phased out.

The final step of the modelling is calculating CO2 cumulative emissions in different scenarios. Results of the M1 scenario show that energy efficiency measures and reduction in clinker factor bring minor emission reduction compared to the BAU scenario. Only with the implementation of CCS higher emission reduction is seen. In the M2 scenario, emissions reduce further with electric and hydrogen kiln and material efficiency. Finally, in the M3 scenario, emissions reduce further with faster electric and hydrogen kiln and CCS deployment. Among all the mitigation options adopted, the role of CCS is found to be crucial in reducing emissions in all scenarios.

Cumulative emissions are also analysed in terms of their implication for net-zero transition. It is found that pursuing the M1 pathway puts significantly higher emissions as compared to the M1 pathway. Hence, pursuing a pathway with the lowest cumulative emissions is beneficial as cumulative emissions harm the climate. Furthermore, the residual emissions that remain in 2050 are analysed; the share of process emissions in the residual emission is high.

Once the energy and emissions modelling is done, the main research question is answered. Results show that the role of different energy carriers in different mitigation pathways depends on the assumptions taken for decarbonisation. In the short term, fossil fuels have an important role in the transition to alternative fuels. In the medium to long term, the role of alternative fuels is high as fossil fuels begin to phase out. The role of electricity and hydrogen is moderate as electric, and hydrogen kilns are introduced later and do not take a high share in clinker production.

In conclusion, alternative fuels and CCS technologies are crucial for countries to pursue low carbon pathways. There is also a necessity to pursue deeper decarbonisation, with higher adoption of mitigation options than considered in this study, as there are some residual emissions in all pathways. Furthermore, cement manufacturing in developing countries would occupy high carbon space in the future. Hence, cement companies in developed countries must decarbonise faster.

# Acknowledgements

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# 1. Introduction

## 1.1 Problem context

***Role of industry in climate change mitigation***

The Paris Agreement sets global mean temperature limit increase well below 2°C as compared to pre-industrial levels. Meeting the climate targets set by the Paris Agreement will require deep emissions reductions in the next few decades. For all sectors, emissions will have to be reduced to zero by 2050. However, the global mean surface temperature is already 1.1°C as compared to the pre-industrial baseline. The UNEP's 2020 *Emissions Gap Report* estimated that if current national policies persist, global mean temperature will exceed 3°C by the end of this century (UNEP, 2020). This implies that immediate rapid emissions reduction needs to be achieved from all sectors of the economy.

In 2017, the industrial sector accounts for close to 40 % (157 EJ) of global final energy consumption and 23 % of direct $CO_2$ emissions. Figure 1.1, taken from (IEA, 2019b), shows global final energy consumption and direct $CO_2$ emissions of iron and steel, chemicals, aluminium, cement, paper and pulp and other industries over the years. This thesis will focus on mitigating emissions from only the cement sector.

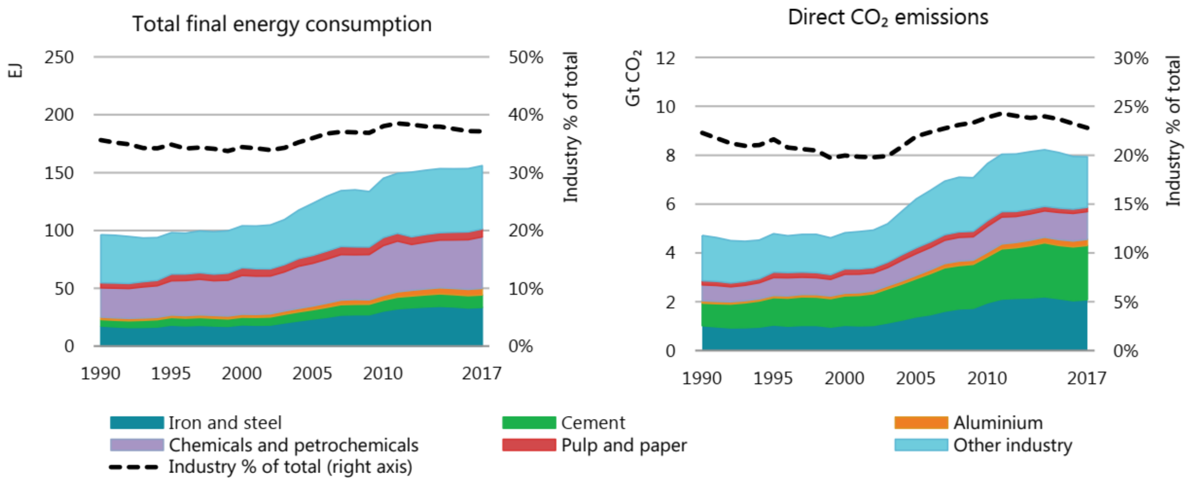


**Figure 1.1 Final energy consumption and direct $CO_2$ emissions for global industry (IEA, 2019b)**

***Overview of cement industry***

Concrete is an important structural component of buildings and infrastructure. It is made up of cement, water, and aggregates. Cement acts as glue and helps to bind fine sand and coarse aggregates together. In addition, it acts as a hydraulic binder; that is, it hardens after water is added (IEA, 2018b). Cement content in concrete varies between 7 to 20 % depending on the compressive strength required. Even though cement content isn't a significant fraction of concrete, cement accounts for 95 % of concrete's carbon footprint from a climate perspective (Material Economics, 2020).

Cement is a basic ingredient used in concrete and widely used as construction material. Its use is projected to increase with increasing economic development and infrastructural demand. Global production of cement was over 4 billion tonnes in 2019 (Cembureau, 2020). Out of this total production, more than half of the production is in China, and India is the second largest producer. In Europe, Italy has the highest cement production, followed by Germany and Poland (Wojtacha-Rychter et al., 2021).

As per the IEA's Reference Technology Scenario, global cement demand is forecasted to grow to 4.7 billion tonnes by 2050 (IEA, 2018b). The demand is expected to rise in rapidly growing and urbanising economies in Asia and Africa. On the other hand, China is expected to see a drop in demand in the next few decades as the Chinese construction activities are expected to slow down (Lehne & Preston, 2018).

Ordinary Portland cement is the most manufactured cement in the world. The production process of clinker, which acts as a binder in cement, involves the calcination of limestone at high temperatures in cement kilns. This process releases a large amount of waste $CO_2$ and constitutes half of the emissions from the cement industry. The next 40 percent of the emissions come from burning fossil fuels to provide high temperature heat for clinker production (IEA, 2020a). On a global level, the cement sector contributes to around 8 % of global GHG emissions. The process emissions from the cement sector contribute to 5 % of total anthropogenic emissions, excluding land use change (Boden et al., 2017).

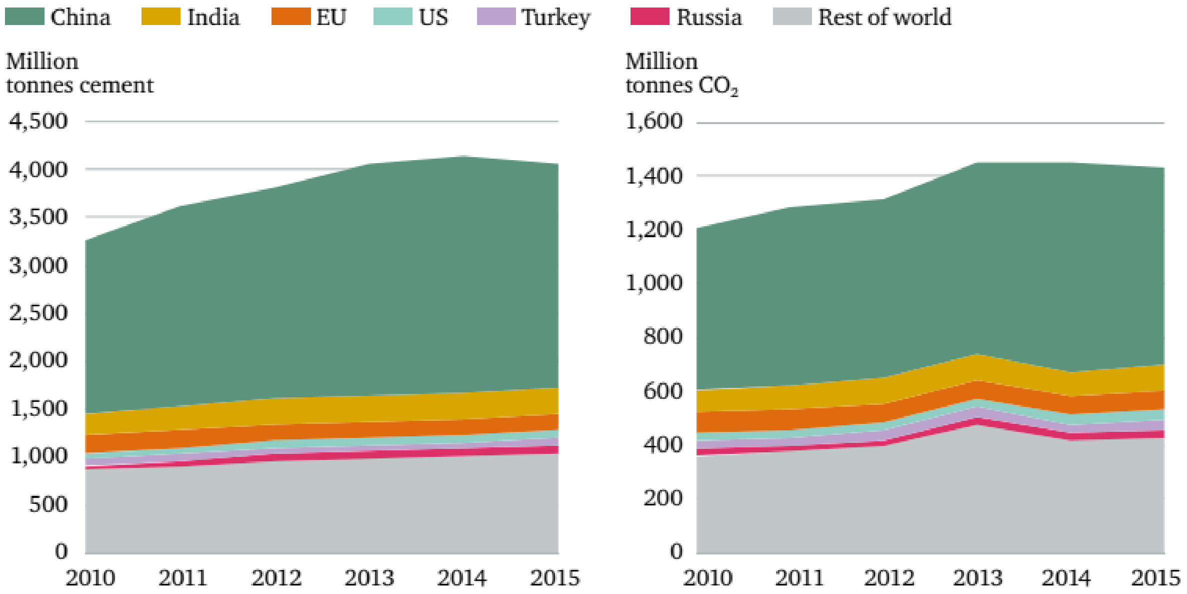


**Figure 1.2 Cement production and emissions (Chatham, 2018)**

## 1.2 Problem statement

There are many ways to lower emissions from the cement sector. Some measures include improving energy efficiency, hydrogen and biomass usage, electrification of heat, carbon capture technology, demand side measures such as material efficiency and material substitution and other innovations (IEA, 2020). However, despite the wide range of mitigation options, the cement sector is considered hard to abate due to several technical and economic factors.

Production of cement involves calcination of limestone, which requires high temperature heat obtained through fossil fuel combustion. Decarbonising the high temperature heat required remains a major challenge and would require fuel switching to low carbon hydrogen or zero carbon electricity. Currently, the use of hydrogen and electricity as fuel is at the development stage and deployment at a large scale is highly uncertain. For the use of these technologies, production facilities would be required to modify. These technologies could also lead to prohibitively high electricity demand (IEA, 2019). In addition, the chemical reaction involved in the calcination process itself leads to $CO_2$ emissions, known as process emissions. These process emissions cannot be eliminated by just switching to low carbon fuel as they are inherent to the process.

Another challenge to decarbonising of cement sector is the lock-in of emission from existing production facilities of cement plants. The average lifetime of cement plants is 30 to 50 years with regular maintenance (Chan et al., 2019). However, since 2000, the global production capacity of clinker (main cement component) has almost doubled. This implies production facilities is relatively young. According to IEA analysis, existing industrial infrastructure and facilities currently under construction would lock in around one-quarter of the total emissions allowable in the IEA Sustainable Development Scenario (IEA, 2018).

## 1.3 Research gap

Several studies model the emissions and energy of the cement sector, as shown in table 1.1. The various decarbonisation options and the research method used in these studies is stated. In all the studies, the main mitigation options are energy efficiency options and clinker to cement ratio reduction. More recent studies (Cao et al., 2021; IEA, 2021b; Material Economics, 2020; NewClimate, 2020) have also included low carbon heat options such as electrification and hydrogen kilns. The role of electric and hydrogen kiln and novel cement is seen to be moderate in all studies. Only a few studies (Cao et al., 2021; Favier et al., 2018; Miller et al., 2018; NewClimate, 2020) include novel cement as a mitigation option. Furthermore, the role of carbon capture technologies is seen to be high for achieving net-zero emissions in various studies (Cao et al., 2021; Favier et al., 2018; IEA, 2018a, 2021b; Material Economics, 2020; NewClimate, 2020).

Besides the various combinations of mitigation options, the evaluated studies also differ on the geographical scope and the research approach used. For example, the use of life cycle analysis is only done by Miller et al. (2018) to examine the role of new Portland clinker-based cement alternatives and alkali-activated materials for reducing $CO_2$ emissions from the global cement industry by 2050. On the other hand, while Miller et al. (2018) focus only on material-based solutions, Cao et al. (2021) developed a stock flow-based model to project future cement demand and create a nexus between material flows and energy and $CO_2$ emissions for different scenarios.

Except for Miller et al. (2018) and Cao et al. (2021), the energy models used in these studies can be categorised into optimisation and simulation models. In an optimisation model, an objective function is defined, for example, to minimise $CO_2$ emissions or maximise social welfare. These models also include secondary objectives such as to achieve the above conditions keeping cost minimum. For example, TIMES based linear optimisation model developed by the IEA minimises total energy system cost while meeting final energy demand and additional constraints.

| Study | Region | Method | Energy efficiency | Clinker to cement ratio reduction | Electrification of heat | Hydrogen based heat | CCS | Novel cement | Material efficiency |
|---|---|---|---|---|---|---|---|---|---|
| **IEA Net - zero (2021)** | Global | TIMES model | ✓ | ✓ | ✓ | ✓ | ✓ |  |  |
| **Cao et al. (2021)** | USA<br>China<br>India | Stock-flow model | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **New Climate Institute (2020)** | Europe | Bottom-up Simulation model | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Material Economics (2020)** | Europe | Simulation model | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Miller et al. (2020)** | Global | LCA |  | ✓ |  |  |  | ✓ |  |
| **Dhar et al. (2020)** | India | ANSWER MARKAL | ✓ | ✓ |  |  |  |  | ✓ |
| **Wei et al. (2019)** | China | Scenario Analysis | ✓ | ✓ | ✓ | ✓ | ✓ |  |  |
| **IEA cement roadmap (2018)** | Global | TIMES model | ✓ | ✓ |  |  | ✓ |  |  |
| **Favier et al. (2018)** | Europe | Scenario Analysis | ✓ | ✓ |  |  | ✓ | ✓ | ✓ |
| **Van ruijven et al. (2016)** | Global | IMAGE model | ✓ | ✓ |  |  |  |  | ✓ |

**Table 1.1 Relevant literature related to the decarbonisation of the cement industry**

Note: ✓ indicates which decarbonisation options are included in the study

Another important set of energy models based on cost optimisation are the Integrated Assessment Models (IAMs), used by the IPCC. IAMs are designed to find the most cost-effective emission reduction pathways. They prioritise between different mitigation technologies primarily based on economic and technological criteria (Carton, 2020). In the IAMs, the cement sector is commonly modelled as a part of the non-metallic sector except for IMAGE and DNE 21+, which models the cement sector explicitly (Kermeli et al., 2019).

The other approach for energy system modelling is a simulation based or alternatives assessment. In simulation models, different scenarios are compared concerning factors such as cost, emissions, and energy supply. These models have several alternative solutions rather than one optimal solution (Lund et al., 2017). Some studies reviewed (Favier et al., 2018; NewClimate, 2020) use bottom-up simulation model. For example, NewCimate (2020) analysis uses four different scenarios – first with business-as-usual trends and second with accelerated conventional options, and the other two with ambitious and innovative mitigation scenarios. One of the mitigation scenarios has a very high focus on carbon capture technologies and electrification of the kiln, while the other mitigation scenario has a very high penetration of novel cement.

In many of these studies conducted for Europe as a whole or at a global scale, country specific technological details are missing. Thus, the role of different decarbonisation options for individual European countries is unknown. Furthermore, in some simulation model scenarios, a very high share is given to specific technologies. However, this share is often not representative of the current TRL level and mitigation potential of the technology. For example, New Climate (2020) gives a very high share to novel cement, contrary to GCCA (2020) projections of novel cement.

In addition, in energy optimisation models, technology share is obtained by minimising the economic costs of achieving mitigation outcomes. However, a risk of focusing on costs alone is that underestimation or overestimation of technology costs can impact the scenario's outcome.

This thesis approaches the problem of decarbonisation of the cement industry, knowing this research gap. Decarbonisation pathways are developed for European countries, India, and China. The share of emerging technologies is taken based on their current TRL levels and mitigation potential. Furthermore, in this thesis, scenarios do not give prominence to any single emerging technology. Instead, all emerging technologies are included based on the narrative of the scenario. In addition, this thesis does not carry out any economic analysis.

### 1.4.1 Research questions

Based on the stated research gap, a simulation model is developed for the cement industry on a country level. The model determines the energy demand of the cement sector to achieve net-zero emissions by 2050, using a combination of mitigation options. The main research question in this study is:

***“What is the role of different energy supply-side options for the cement industry for transitioning towards net-zero emissions by 2050?”***

Based on the energy backcasting technique and different steps in the simulation model developed, the following sub research questions are formulated:

*SQ1: What are the characteristics of the cement sector in terms of the sector’s energy use, its decarbonisation options, cement manufacturers’ commitments and relevant government policies?*

This question assesses the current situation of the cement sector in terms of their energy use and decarbonisation options adopted by the cement industry so far.

*SQ2: How will the demand for cement develop?*

For this question, cement demand is modelled using population and GDP assumptions. In addition, assumptions about material efficiency are taken in decarbonisation pathways.

*SQ3: How would the energy demand for the cement industry develop?*

This research question analyses future energy demand in different decarbonisation pathways. The role of different decarbonisation options and different demand side interventions is analysed. Furthermore, how many years it will take to phase out fossil fuel is looked at.

*SQ4: What are the implications of this energy transition in terms of cumulative emissions?*

For this question, decarbonisation pathways are analysed in terms of cumulative emissions as compared to the baseline. In addition, the implications of this energy transition for net-zero are also discussed.

### 1.4.2 Research scope

The geographical scope of the thesis is limited to the top three cement producing regions– China, India, and Europe. These three regions are chosen as they represent diverse trends of cement consumption. Europe has a mature cement market, whereas China represents a transitioning market and India an emerging one. Further characteristics of the cement market in these regions are described below.

*China*

China has the highest cement production globally, accounting for about 60 % of the global cement production (Zhang et al., 2021). One of the main reasons for very high cement consumption is China's rapid urbanisation (Woodward & Duffy, 2011). In 1980, 20 % of China's population lived in cities. This figure has risen to 60 %, with over 800 million people living in cities and more than 100 cities with over one million inhabitants. Another reason for China's construction boom is the very high investment in real estate. For starters, homeownership in China is among the highest in the world at around 90%.

Moreover, 87% of new homeowners already owned at least one property (The Wall Street Journal, 2020). However, over 65 million of them still remain vacant in 2021 (Kubota, 2021). There has also been a rise in speculative demand as housing is seen as a safer asset than stock markets (The Wall Street Journal, 2020).

*India*

India is the second largest cement producer globally, accounting for 8 % of total global installed capacity (CMA India, n.d.). In the financial year 2019, cement was majorly consumed in the housing and real estate sectors due to affordable housing schemes. The per capita cement consumption is less than half of the world's average, implying increasing cement demand as the country develops (TERI, 2021). Cement consumption is expected to rise due to rapid urbanisation and infrastructure needs. Thus, many new cement plants are expected to be built (Lehne & Preston, 2018). Moreover, as a country with a high vulnerability to climate impacts, India has an essential role in developing climate resilient infrastructure.

*Europe*

Many studies show that for Europe, cement production is likely to remain stable in the near future. Europe has a long record of cement sustainability policies and reduced its emission to 15 % relative to the 1990 level (Cembureau, 2020). In addition, several research projects are being carried out in Europe to reduce emissions, e.g., electrification of kiln (CemZero project) and carbon capture technologies (Leilac project, Cleanker, Catch4climate).

In this thesis, energy modelling is done for all European -28 countries, but the focus is only on three European countries – Germany, Italy, and Spain. Although these three countries represent a mature market, they differ based on their decarbonisation efforts so far. Germany and Italy are top cement producers within Europe. Germany is also advanced with regards to the use of alternative fuel. On the other hand, Spain lacks behind in terms of alternative fuel use and reducing clinker use.

## 1.5 Relevance to Industrial Ecology

The research objectives of this thesis meet Industrial Ecology program requirements. This research focuses on a sustainability problem, i.e., mitigating emissions from the cement industry by 2050. The thesis is interdisciplinary in nature as it uses theories from engineering and social science fields. To address the research problem, a backcasting method will be used which is relevant to the Industrial Ecology. This thesis integrates circular economy principles which has roots in Industrial Ecology. Circular economy principles are adopted by implementing options such as use of waste as fuel and substituting the clinker in cement with by-products from other industries.

## 1.6 Outline of thesis

The general structure of the thesis is as follows. In chapter 2, a literature review is done regarding the cement manufacturing process and decarbonisation options for the cement industry. The aim is to provide an overview of different decarbonisation options used in the simulation model. Chapter 3 answers sub research question 1 by providing an overview of the current situation of the cement industry in terms of its energy, emissions, and climate targets. Chapter 4 provides the methodology of this thesis which describes the framework of the simulation model and how different decarbonisation options are incorporated in the model. Next, chapter 5 answers sub-research question 2 by analysing how cement activity is modelled for different countries.

Further, in chapters 6 and 7 sub research questions 3 and 4 are answered. Next, in chapter 8, there is a discussion about uncertainty in assumptions taken for modelling and the study's limitations. Finally, in chapter 9, conclusions from the research question are stated and recommendations to the cement industry and policy makers are given.

# 2. Literature review

The literature review consists of three parts. The first part discusses the cement production (section 2.1), followed by description of emissions from cement production (section 2.2). Finally, in section 2.3, different strategies to decarbonise the cement sector are described. First, the conventional decarbonisation options are described followed by the emerging options and challenges associated with their implementation.

## 2.1 Cement production process

Ordinary Portland cement (OPC) is the most common type of cement manufactured globally. The manufacturing process of OPC is very energy and emissions intensive and consists of the following steps:

1. **Raw material preparation:** This begins by extracting raw materials such as limestone, iron ore, bauxite, shale, clay, or sand. These raw materials are homogenised and pulverised into a thin powder known as raw meal (CEMBUREAU, n.d.).

2. **Preheating and precalcining:** Portland cement is manufactured in rotary kilns. There are both ‘wet’ and ‘dry’ production technologies for cement clinker and, semi-dry/semi-wet kilns. In wet kilns, wet raw meal is introduced in form a slurry which increases energy consumption for water evaporation. In most countries, wet kilns are being phased out and there is shift towards dry kiln production (CEMBUREAU, n.d.; IEA, 2018b).

3. **Clinker production:** In modern dry kilns, preheater and pre-calciner are present. The raw meal gets preheated as it is passed through a preheater tower which consists of series of cyclones. Hot exhaust gases from the kiln are used to preheat the raw meal. As heat from the hot gases is recovered, it helps in improving efficiency and reducing fuel requirements of the process. The raw meal gets further preheated and precalcined as it enters precalciner, an additional furnace, before entering the rotary kiln. During calcination, limestone gets decomposed into limestone ($CaCO_3$) into calcium oxide ($CaO$) and carbon dioxide ($CO_2$) as follows:

   $$CaCO_3 \rightarrow CaO + CO_2$$

   Further, the pre-calcined meal enters the rotary kiln and is heated up to around 1450 deg. C, most commonly using fossil fuels. As the meal enters the kiln, intermediate compounds start forming. The calcium oxide formed reacts with silica, alumina, and ferrous oxide to form the silicates, aluminates, and ferrites, respectively, forming the clinker (CEMBUREAU, n.d.; IEA, 2018b).

4. **Cement formation:** The clinker formed is rapidly cooled down using a grate cooler to about 100 C. It is then ground with gypsum (around 4-5 %) and other additives to form Portland cement. Blending with other cementitious material to replace clinker produces blended cement (CEMBUREAU, n.d.; IEA, 2018b).

## 2.2 Emissions

Direct and indirect $CO_2$ emissions are produced at different stages of cement production and can be classified as follows:

**Direct process emissions:** Calcination of limestone to form Portland clinker releases half of the cement sector's emissions. Emissions arising from this calcination process are known as process emissions. For every tonne of clinker produced, 0.5 tonne of $CO_2$ is produced (Chan et al., 2019). As these emissions are inherent to the process, they remain the same for any energy source used for the heat production unless the feedstock is changed.

**Direct thermal emissions**: Fossil fuels such as coal, coke or natural gas are fired into cement kiln to provide high temperature heat required for clinker production. Emissions from combustion of fossil fuels account for around 40 % of total emissions (Lehne & Preston, 2018). These emissions can vary depending on the fuel mix used and could be potentially reduced to zero in future.

**Indirect emissions:** Indirect emissions occur from generation of electricity used in quarrying of raw materials, grinding and preparation of raw meal, cooling of clinker and grinding of cement. These emissions account for around 10 percent of total emissions from the cement sector (Lehne & Preston, 2018).

## 2.3 Decarbonisation strategies

Current decarbonisation options for cement industry are based on best available technologies that reduce $CO_2$ emissions by switching from fossil fuels to low carbon fuels and improving energy efficiency of the production. Indirect $CO_2$ emissions are reduced by substituting clinker materials with fly ash, blast furnace slag (BFS) and limestone. However, these technologies have limited potential in the future given the urgent need to switch from fossil fuels and less availability of fly ash and BFS with ambitious climate policies. Different decarbonisation options which mitigate direct and indirect emissions are shown in figure 2.1.

Further emissions reduction in the cement industry is likely to come from technologies currently in the pilot or demonstration stage (ETP,2020). Several other decarbonisation options such as CCS, use of hydrogen, electrification of kiln are currently under development. The readiness level of these technologies varies widely with some technology being in prototype stage while some being at pilot stage. These low or zero emissions technologies are classified by commonly used NASA's technology readiness level (TRL) scale in literature. The TRL is a scale from 1 to 9, indicating technological maturity with one being the lowest level. Technologies that have TRL level above 6 aim for market entry in coming years. The table 2.1 below shows the technology maturity of different decarbonisation options (IEA, 2020).

| Decarbonisation option | TRL | Year available |
|---|---|---|
| **Thermal and energy efficiency improvements** | 9 | Today |
| **Alternative fuel** | 9 | Today |
| **Clinker substitution with blast furnace slag and fly ash** | 9 | Today |
| **Clinker substitution with calcined clays and limestone** | 9 | Today |
| **Biomass** | 9 | Today |
| **Direct electrification of heat** | 4 | Unknown |
| **Hydrogen for heat** | 4 | Unknown |
| **Carbon capture and storage (chemical absorption)** | 7 | 2024 |
| **Carbon capture and storage (Calcium looping)** | 7 | 2025 |
| **Carbon capture and storage (Oxy-fuel)** | 6 | 2030 |
| **Carbon capture and storage (Direct separation)** | 6 | 2030 |

**Table 2.1 Technology readiness level for different decarbonisation options (IEA, 2021)**

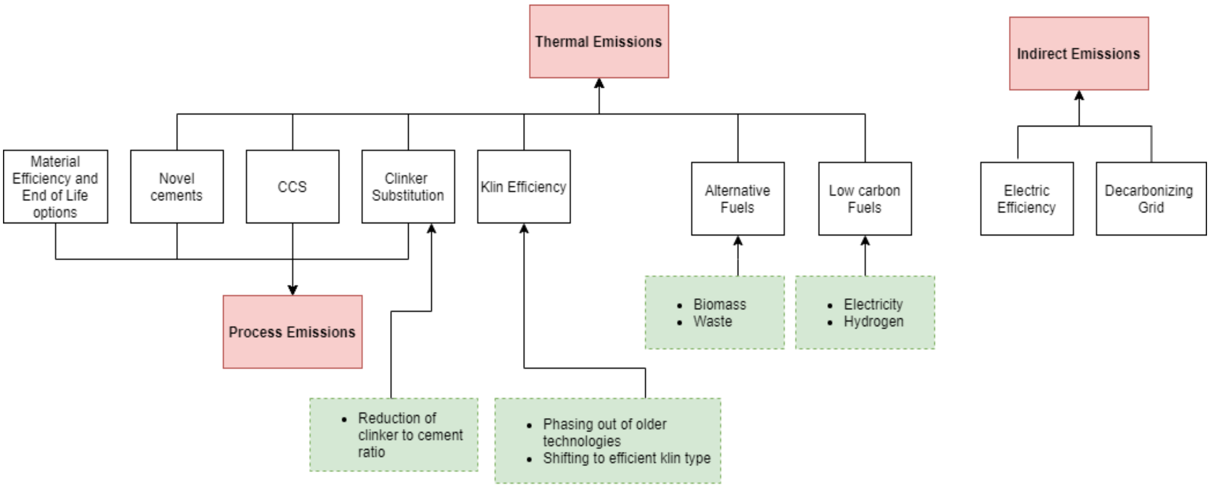


**Figure 2.1 Decarbonisation options for the cement industry**

### 2.3.1 Energy efficiency improvements

Retrofitting of the kilns allows extending the lifetime of industrial equipment and replacing inefficient and outdated equipment. However, the pace of phasing out of older and more emission intensive kilns is hindered due to long lives of cement kilns and its assets (*typically 30-40 years*). Old cement kilns are often upgraded by replacing preheater cyclones, clinker cooler, burner etc. New cement kilns are often only constructed in countries with high demand for cement (particularly in Asia and Eastern Europe) (Kermeli et al., 2019).

**Kiln thermal efficiency improvements:** Energy required for clinker production has declined over the years as there has been shift from wet to dry kiln process. Wet kilns use raw materials with high moisture content. Hence, more thermal energy is consumed due to drying requirement of raw material. The minimum theoretical energy for clinker production is 1.8 GJ/tonne for dry limestone feedstock. However, feedstocks have considerable moisture and hence, need higher thermal energy than the theoretical requirement. The current best available technology (BAT) for producing cement is dry kiln with six cyclone preheating and precalcination stages, with a thermal energy requirement of 3000 to 3400 MJ/tonne of clinker. Long dry process kiln can be retrofitted by adding a precalciner and preheater (Chan et al., 2019).

**Grinding electrical efficiency improvements:** Grinding is biggest source for electric energy consumption in a cement plant. Electricity demand depends on product quality requirement. In case of fine cement requirements, additional grinding increases electricity demand. As per the current best available technologies, electricity consumption in cement industry rages from 95 kWh/t to 100 kWh/t (Chan et al., 2019). However, with increased use of alternative fuels, electricity demand increases for pre-treatment of alternative fuels. Ball mills are commonly used as grinding technologies. High pressure grinding rolls and vertical roller mills are the current BAT for grinding and are replacing ball mills used. High pressure grinding rolls can reduce electricity consumption up to 50 % and vertical roller mills can reduce up to 70 % as compared to ball mills (CSI, 2017). However, retrofitting these mills requires very high investment and takes place only if market demand is promising or in the case of old equipment. Energy efficiency can also be improved by adding additives which can improve grindability.

Cement plants also implement many energy efficiency measures and technologies that lower energy consumption and $CO_2$ emissions. Some of the common energy efficiency measures include (IEA, 2018b) :

- increase burnability of raw materials by adding mineralisers which lower temperature of clinker melting
- using oxygen enriched air in kilns which can lower thermal energy consumption up to 5 %.
- Using grate clinker cooler enabling excess heat recovery (EHR)

### 2.3.2 Alternative fuels

Coal, oil, and natural gas have been traditionally used in cement kilns due to their low costs and high heating values. However, in recent years, fossil fuels are being substituted by alternative fuels such as waste derived fossil fuels and waste biomass for sustainability reasons (Cao et al., 2021). Alternative fuels include pre-treated industrial and municipal solid wastes, discarded tires, waste oil and solvents, plastics, textiles and paper residues, and biomass (e.g., animal meal, logs, wood chips and residues, recycled wood and paper, agricultural residues, sewage sludge, and biomass crops) (Obrist et al., 2021). In 2019, the use of alternative fuels on global level was 19 % of total fuel energy demand for cement manufacturing (GCCA,2020). The use of alternative fuels is particularly high in European countries. The average substitution rate for Europe is at about 60 % and for some individual plants, the substitution rate is as high as 95% (Ecofys, 2016).

The use of alternative fuels in cement kilns to provide thermal energy is referred to as co-processing of fuels. Co-processing helps recover the energy content of the waste and reduce the volume of landfilled waste. Besides improving waste management, it helps capture minerals in waste fuel which become part of clinker produced (CEMBUREAU, n.d.). If these wastes had been incinerated, additional $CO_2$ emissions would be produced as additional fossil fuels would be needed to burn them. It is also cheaper to adapt cement kiln to use alternative fuels than built a new incineration plant.

It is technically possible for cement kilns to use up to 100 % of alternative fuels. However, its usage has limitations, such as local availability and contamination of alternative fuels and heating requirements of kiln (Cao et al., 2021). The calorific value of most organic material is relatively low (10 - 18 GJ/tonne). An average calorific value of at least 20 to 22 GJ/tonne is required for the main firing of the cement kiln. It is possible to use low calorific fuel in precalciner of modern cement kiln as lower process temperature is required and hence, it is possible to use up to 60 % of low calorific fuel input in the precalciner (European Cement Research Academy, 2017). Another challenge with increasing use of biomass in future is that it may require increased use of virgin biomass. However, sustainable biomass resources are limited, and many other sectors and activities compete for biomass, such as power generation, building, and industrial heating. The cement sector is also not considered a priority sector for sustainable biomass use as there are many other sectors where fewer decarbonisation alternatives are present. However, the cement sector may be prioritised in certain regions with greater biomass supply (Energy Transition Commission, 2018; Mineral Products Association et al., 2019).

Fuels that are biomass based are considered carbon-neutral when sustainably harvested as the future regrowth of biomass can compensate for $CO_2$ emissions emitted from biomass combustion. However, there is ongoing debate regarding carbon neutrality of biomass (Cao et al., 2021). Another factor to consider for the use of alternative fuel is waste management legislation and emission control regulation in different countries. For example, waste legislation rules restricting landfilling can encourage waste collection and treatment and increase substitution rates (European Cement Research Academy, 2017).

### 2.3.3 Clinker to cement ratio

Reducing the clinker to cement ratio is one of the conventional ways of reducing $CO_2$ emissions. It reduces not only thermal related $CO_2$ emissions but also the process $CO_2$ emissions from the chemical transformation of limestone. It is estimated that around 3.7 GJ and 0.83 tonnes of $CO_2$ can be saved per tonne of clinker displaced (IEA, 2018b). Historically, clinker reduction has been done due to economic reasons since clinker substitutes cost less than clinker or can enhance concrete's properties. The share of clinker in cement on a mass basis is referred to as clinker-to-cement ratio. Cement with lower clinker to cement ratio containing supplementary cementitious material are called blended cements. Commonly used clinker substitutes include fly ash from coal fired power stations, blast furnace slag from steel industry, natural and artificial pozzolanas, and limestone and are described further (Lehne & Preston, 2018).

Ordinary Portland cement contains more than 90 % of clinker, and the remainder is gypsum. It is possible to reduce the clinker to cement ratio to 50 % without changing key cement or concrete properties. Cement with low clinker to cement ratios generate less $CO_2$ emissions when manufactured as $CO_2$ footprint of some clinker substitutes is low or even zero (IEA,2018).

**Granulated Blast furnace slag (GBFS):** Blast furnace slag (BFS) is by product of pig-iron (molten-iron) production process. For every tonne of pig-iron produced, 0.25-0.3 kg of BFS is produced (USGS, 2002). Several types of BFS exists such as granulated, air-cooled and pelletized. The global availability of BFS is expected to reduce in future as iron and steel industry may shift production from pig iron to secondary steel (Kermeli et al., 2019).

**Fly ash:** Fly ash is a fine powder formed by burning pulverised coal in power plants. It can be of siliceous (silica-rich) or calcareous (lime-rich) nature and has pozzolanic properties (European Cement Research Academy, 2009). Fly ash of calcareous nature has some hydraulic properties besides pozzolanic properties. For the use of both type of fly ash, certain criteria has to be meet (Kermeli et al., 2019). The availability of fly ash will reduce as the power sector gets decarbonised with ambitious climate policies in the future.

**Pozzolanas:** Pozzolans are of siliceous nature and are available either naturally or can be developed artificially. Natural pozzolanic materials are obtained from volcanic compounds or sedimentary rocks. Its use is common in some European countries such as Italy, Greece, and Slovenia. The use of volcanic rocks and ash is expected to rise in regions with plentiful of these materials (Favier et al., 2018). Calcined clays, an artificial pozzolan, will also become important alternative for clinker. Clay is widely available worldwide and is required to be calcined to 700-850 ˚C for clinker substitution. Calcined clay production is more energy intensive than traditional clinker substitutes; it is not used more commonly (Kermeli et al., 2019).

**Limestone:** Limestone can also be used as clinker substituting material apart from using it as main raw material used in cement. Cements containing limestone need to be finely ground to have same strength as Portland cement. The typical mass content of limestone in cements is up to 5 %. However, the limestone content could be as high as 25-35% and up to 50% is also possible (European Cement Research Academy, 2009).

### 2.3.4 Low carbon heat

Friedmann et al. (2019) discuss the following low carbon heat options for industrial processes which could substitute fossil fuels, keeping in mind the temperature requirements of different industrial processes:

- Biomass – It can replace some fuels and feedstocks and is already widely used to provide industrial heat.
- Electricity- Zero carbon electricity can be used for furnaces, boilers, and heat pumps to generate heat. Although the electrification of heat can be easily achieved, it has not been used widely so far as cost of electricity has been greater than conventionally used fuels.
- Hydrogen- Hydrogen can be produced without $CO_2$ emissions out of renewable electricity through electrolysis (green hydrogen) or natural gas through methane reforming with carbon capture and storage (blue hydrogen). It can be combusted to produce heat or used as feedstock. However, producing hydrogen without $CO_2$ emissions is very expensive as compared to other low carbon heat sources.
- Natural gas with CCS – Natural gas is already widely used for industrial heating in Europe and the USA. Using natural gas with carbon capture and storage (CSS) allows industry to continue using natural gas while reducing the $CO_2$ they emit. Currently, natural gas with CCS is a cheaper option than other low-carbon heating options for industrial processes.

Only biomass of all the above low carbon heat options is in use in the cement sector now. Electrification of the kiln and hydrogen-based kiln are in research phase and face many technical challenges. The challenges of burning hydrogen include the high combustion velocity and non-luminous flame of hydrogen, making it difficult to monitor optically. Hydrogen flame has low radiated heat, which requires mixing other materials to hydrogen to increase heat radiation. Clinker dust or calcined kiln inlet dust could be mixed which would require redesign of burner to deal with it. Another challenge is corrosiveness of hydrogen when in contact with some metals; hence, it would be necessary to have new coatings in the kilns. Due to these challenges, low TRL level and expected high cost of hydrogen in kilns, hydrogen is likely to play a small role in the cement sector (IEA, 2020b).

It is theoretically possible to use electricity for process heat and decarbonize the cement sector if the electricity came from renewable sources. There are several pilot projects testing electrification of kiln using plasma generators and microwave energy (Xavier & Oliveria, 2021). Plasma generators can generate a very high temperature required for cement production with an 85-90 % efficiency. These generators have been proven in industrial context and can provide more than 7MW output per generator. Moreover, it is possible to run several generators in parallel for higher power requirements (Material Economics, 2020). A study conducted by the CemZero pilot project in Sweden has shown that electrification of heat is technically possible using electric plasma kiln technology (Xavier & Oliveria, 2021).

### 2.3.5 Material efficiency and recirculation

Although options like hydrogen and CCS show significant potential to mitigate emissions, they are still at an early deployment stage. Given the urgency and challenges of mitigating industrial emissions, it is necessary that we not only look at ways of cleaner material production but also at how new material demand can be reduced (Material Economics, 2019). Reducing cement production is also one of the cheapest and most efficient ways to mitigate emissions (NewClimate, 2020). Analysis by Material economics (2019) shows that circular economy measures applied to material inputs- cement, aluminium, plastic, and steel in European construction can mitigate $CO_2$ emissions up to 34 % by 2050. Emissions from cement can be reduced up to 45 %. There are three ways to reduce cement consumption in buildings: material recirculation, material efficiency, and getting greater value out of each square meter of a building during its life (Energy Transition Commission, 2018).

***Material recirculation***

Material recirculation involves using end of life materials as an input to new production or using alternative low $CO_2$ emissions materials which provide the same function. The measures for material recirculation include cement recycling and recovering cement, substituting clinker with other cementitious materials, and substituting wood (Material economics, 2020).

It is not possible to recycle hydrated cement in the same way as plastics and steel scraps are recycled for reuse. However, it is still possible to reduce cement demand by adopting a circular approach for concrete recycling. Currently, demolition waste is either not recycled and sent to landfills or recycled to aggregates for low-value use such as road base. It is possible to replace sand in the concrete by recycled concrete to a certain level. However, this could be more energy and emissions intensive and need decontamination (Chan et al, 2019). New technologies to recycle demolition waste are developed which use electrodynamic fragmentation to separate gravel, sand, and lime (Chan et al, 2019). This would make possible recovery and separation of unhydrated cement for direct reuse.

Another strategy for material recirculation is increasing the use of timber and engineered wood products as a substitution for many structures that currently use cement and steel. This could provide significant emissions reduction as compared to the conventional use of concrete. For example, according to a study, using a wooden floor beam instead of concrete slab beam for supporting one square meter of floor space could reduce $CO_2$ emissions from 27 kg to 4 kg. The exact reduction of emissions will however vary in different buildings. Substitution with wood can be considered as low carbon only if the replacement material is genuinely zero emission. Hence, sourcing wood products through sustainable forestry is essential from emissions perspective (Material economics,2019).

***Material efficiency***

Material efficiency options include reduction of waste in construction, using less cement in concrete and less concrete per structure. There is enough research to show that even with lower use of cement in concrete it is possible to achieve the required strength, reliability, and durability. Reducing cement use can be achieved by reducing the overspecification of concrete compared with what is needed for intended application. By improved material management, waste of materials can be avoided (Material Economics,2019).

***Circular business model***

Emissions from construction sector and use of cement can be reduced considerably if buildings can be made to last longer. Buildings' lifetime can be prolonged by maintaining key components and adopting new modular approaches that can allow for periodic renovations of buildings. It is also possible to derive more value from each square metre by space sharing to reduce need for additional built area (Energy Transition Commission, 2018; Material Economics, 2020).

### 2.3.6 Carbon capture and storage

Carbon capture and storage (CCS) captures and permanently stores $CO_2$ emissions produced from fossil fuels and industrial processes. In carbon capture and utilisation (CCU), the $CO_2$ captured is utilised for other industrial processes. There are three types of carbon capture technologies: pre-combustion process, post-combustion process and oxyfuel combustion. Oxy-fuel firing and post-combustion are the most promising carbon capture technology for cement plants and are discussed further. In post-combustion, $CO_2$ is separated and captured from the exhaust gases of a combustion process by absorbing it in a suitable solvent. Chemical absorption using amines is the most mature technology used for a long time in different industries. As post-combustion technologies are “end of pipe” technologies, there is no need for a major change in the kiln firing process. In oxyfuel combustion, fuel is burned using oxygen rather air, resulting in a purer stream of $CO_2$ that is easier to capture. There are ongoing CCS pilot projects in the cement sector, such as 1) the amine-based absorption pilot project in Anhui Conch in China; 2) Brevik project in Norway that is testing different post-combustion technologies (Material Economics, 2020).

CCS can solve the problem of both fuel and process emissions in cement production. It could be therefore used as a single decarbonisation option for all cement plants. Thermal emissions are difficult to capture as it contains many other gasses than $CO_2$. Oxyfuel CCS is likely to be a long-term option to capture both thermal and process emissions. It could capture up to 95 % $CO_2$ when fully developed (Energy Transition Commission, 2018). Another way to capture $CO_2$ emissions is by using CCS direct separation technology which separates thermal and process emissions before $CO_2$ capturing. This results in pure stream of process $CO_2$ which could be easily captured. Another advantage, compared to oxy-fuel and post combustion, is that for direct separation CCS, a large amount of additional energy is not required for $CO_2$ capture (Chan et al, 2019). Direct separation CCS for cement production is being developed under EU Horizon 2020 project LEILAC in Belgium.

### 2.3.7 Novel cement

Many firms are developing clinker free cements known as novel cements, which could significantly reduce emissions. Some of these firms claim emissions reduction up to 90 % while others say that the cement could sequester carbon. However, none of these novel cements have reached extensive and have been used only in niche applications. Table 2.2 shows different novel cements and their potential to reduce process emissions and thermal energy and emissions associated with it.

| Cement type | Phase | Process CO2* | Thermal energy* |
|---|---|---|---|
| **Reactive belite** | Research | 3.1% | 8.2% |
| **Belite-ye'elimite-ferrite (BYF)** | Demonstration | 29.1% | 34.9% |
| **Carbonatable calcium silicate cement (CCSC)** | Pilot | 24.8% | 38.9% |
| **Calcium sulfoaluminate (CSA)** | Research | 42 % | 46.9 % |
| **Celitement** | Research | 33.2 % | 50.6 % |
| **Magnesium oxides derived from magnesium silicates (MOMS)** | Research | 100 % | 46.5 % |

**Table 2.2 Process $CO_2$ and energy savings of lower-carbon cement clinker compared to OPC clinker (Cao et al., 2021).**

# 3. Overview of the cement sector

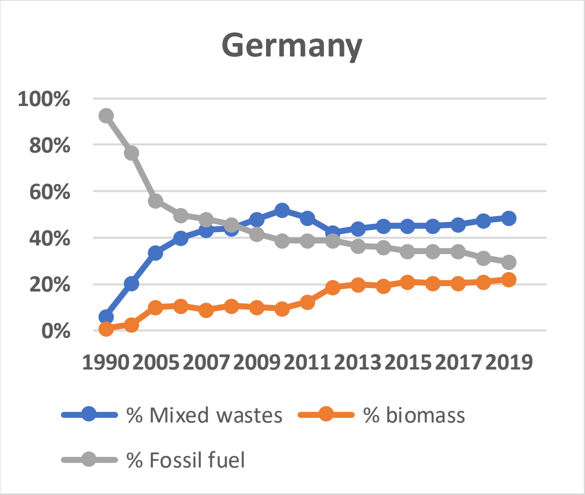
This chapter provides an overview of the cement sector in different countries. First, an overview of energy use in the past is given in section 3.1. Second, in section 3.2, thermal energy efficiency improvements by kiln technologies is described. Third, in section 3.3, an overview of clinker factor reduction is given in different countries. Finally, an overview of relevant government policies (section 3.4) and climate commitments made cement manufacturer companies (section 3.5).

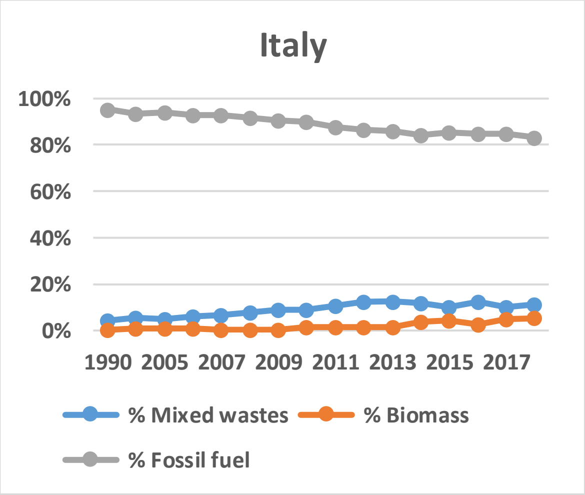
## 3.1 Energy use

### *Europe*

Alternative fuel use is very high in Europe and have replaced a part of traditional fossil fuel sources. In 2019, almost 50 % of thermal energy use of European cement industry was from alternative fuel. The use of alternative fuel is advanced in some cement firms using over 90% alternative (CEMBUREAU, 2020) . Examples of such cement plants are in Germany, Austria, and Norway.

Thermal substitution rates in Europe vary country to country due to different regulations and waste management practices. Figure 3.1 shows share of biomass and waste in total thermal energy demand of cement production for Germany, Italy, Spain, and India.





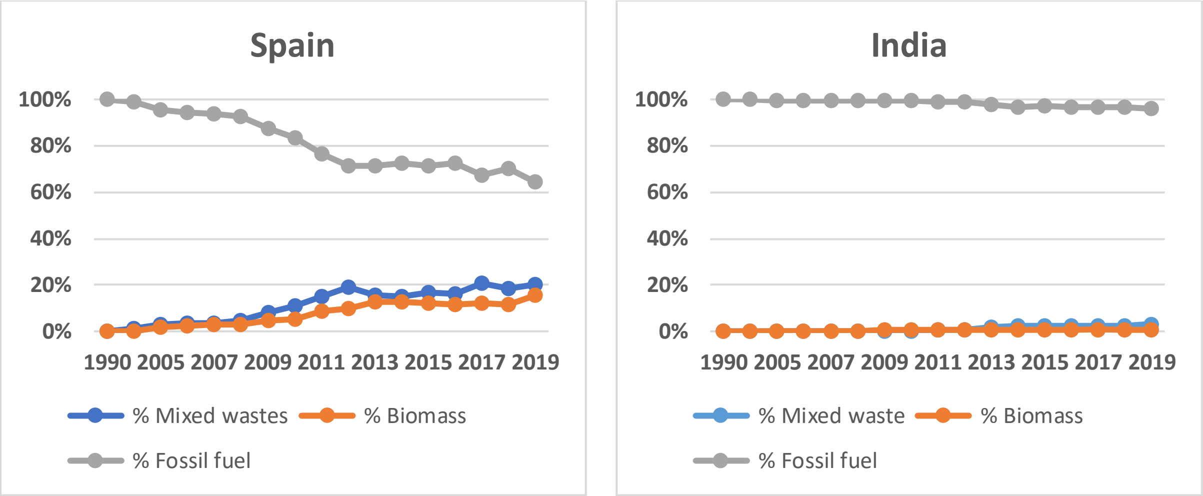


**Figure 3.1 Share of mixed waste, biomass, and fossil fuel in total thermal energy demand for Germany, Italy, Spain, and India (GCCA, 2021)**

### *India*

At present, the thermal energy demand for heating kilns is mainly provided by fossil fuels. However, among fossil fuel use, coal use has been declining, and the use of pet coke has increased over the years. One of the reasons for increased pet coke use in the Indian cement industry has been its high calorific value. In 2017, the use of pet coke was 56 %, while that of coal was 41 %, and alternative fuel was 3 % (WBSCD, 2018).

Although, as per the existing policy (PWM Rules 2016), the cement industry must use at least 5 % of its fuel using refuse-derived fuel, there has been limited uptake of alternative fuel. The reason for low uptake is due to the nature of solid waste management in India. Solid waste is not often segregated, which increases the cost of segregation of waste for cement manufacturers. In case the waste is segregated, it is often sent to informal recyclers. Another issue is the transportation of waste for its use for large distances, increasing cement plants' carbon footprint and operational costs (TERI, 2021).

### *China*

Coal accounts for 75 % of energy inputs for the Chinese cement production, with the remainder comprising electricity, natural gas, and small amounts of oil products, waste, and bioenergy (IEA, 2021). Like India, China also falls behind Europe on the use of alternative fuels. Biomass and waste accounts for 11.4 % of total thermal energy consumption (Cao et al., 2021).

## 3.2 Thermal Energy efficiency

There has been major improvement in European cement industry with almost complete phase out of wet kilns. In 2019, almost half of the European kilns were dry kilns of best available technology standard and only 2 % wet kilns. Dry kilns with preheaters and precalciner are considered best available technology standard and require 3000 MJ/tonne of clinker. The energy efficiency of European cement plant is around 3300 MJ/tonne of clinker (Favier et al., 2018).

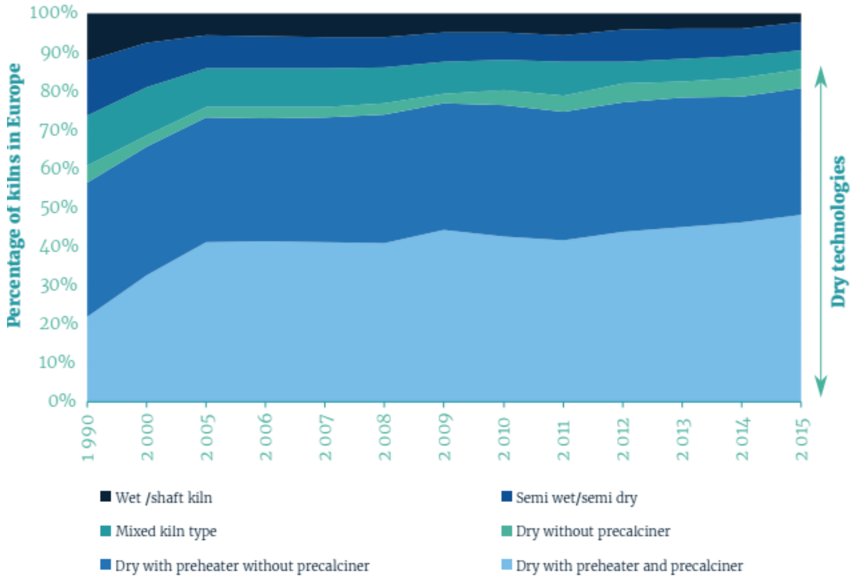


**Figure 3.2 Share of cement kilns in Europe (Favier et al., 2018)**

***India***

The Indian cement industry is considered as one of the most energy efficient industry in the world. One of the major reasons for being energy efficient is that new cement plants built in the last decade are equipped with the latest energy-efficient technologies. Almost 99 % of Indian cement plants are equipped with dry kilns (WBSCD, 2018).

The thermal specific energy consumption has increased in the last few years. The increase in thermal SEC has been due to increase in alternative fuel and pet coke use and frequent start and stop due to market circumstances (WBSCD, 2018).

***China***

Following cement kiln types exist in China: advanced new suspension pre-heater and pre-calciner (NSP) kiln, large NSP kiln, middle NSP kiln, small NSP kiln, and other kilns (mainly vertical shaft kilns). Currently, NSP kilns are dominant kiln type in China.

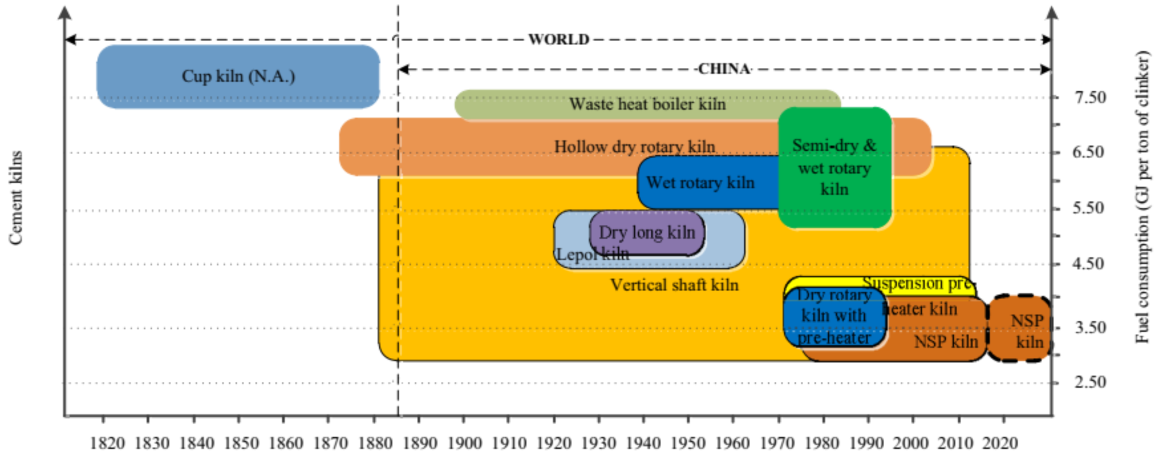


Figure 3.3 Cement kilns in China (Wei et al., 2019)

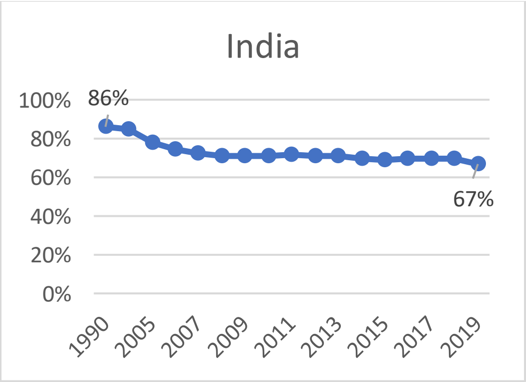
## 3.3 Clinker to cement ratio

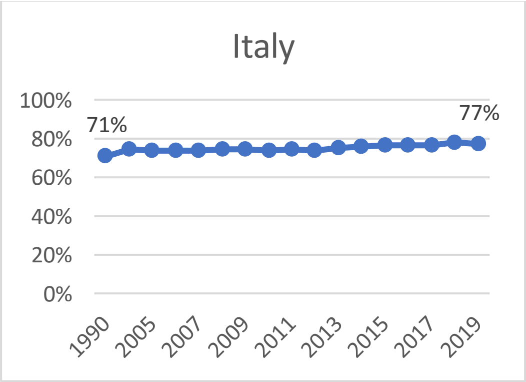
### *Europe*

In 2019, the clinker to cement ratio in Europe was 0.75 (GCCA, 2021). Figure 3.4 shows the share of supplementary cementitious materials used in European cement. Regional availability of fly ash, blast furnace slag, and limestone impacts its use as a clinker substitute, given the cost of transporting these materials from a longer distance (DIW, 2014). The availability of fly ash is dependent on the share of coal in the fuel mix of local power generation. Poland uses around 7 % of fly ash in cement production, higher than the European average of 2 %. The usage of slag is seen to be the highest in Austria (GCCA, 2021).

### *India*

The share of blended cement has increased in the Indian cement industry, which has reduced the clinker factor. Main clinker substitutes are fly ash and blast furnace slag. Portland Pozzolana cement (PPC) has the highest share in blended cement production, followed by Portland slag cement (PSC) (WBSCD, 2018).





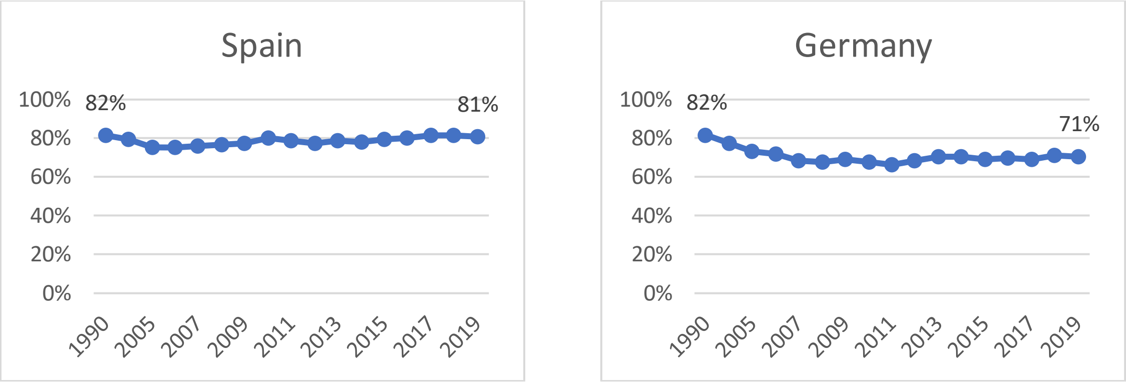


**Figure 3.4 Clinker to cement ratio in India, Italy, Spain, Germany from 1990 to 2019 (GNR, 2021)**

***China***

China has one of the lowest clinker to cement ratio globally. Clinker substitutes commonly used in China are blast furnace slag, fly ash and gangue (CCA, 2011). The ratio increased from 0.57 in 2014 to 0.64 in 2018. The main reasons for the increase are overcapacity, which reduces momentum for more blending to replace clinker, and changes to cement standards, eliminating a grade of composite cement (IEA, 2020a). Figure 3.5 shows clinker ratio of China using different sources (Andrew, 2019).

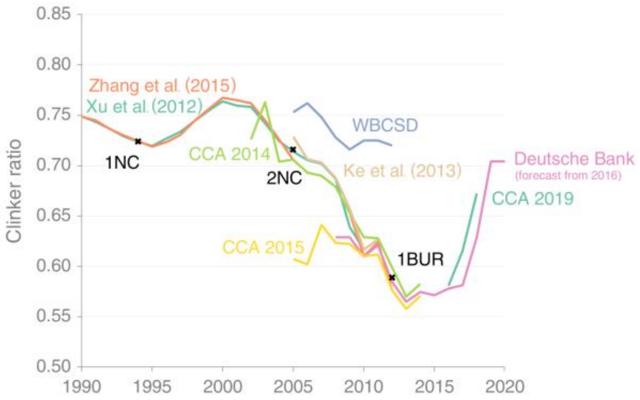


**Figure 3.5 Clinker to cement ratio of China (Andrew, 2019)**

## 3.4 Government policies

China has announced “dual carbon” goals to peak carbon emissions by 2030 and achieve carbon neutrality by 2060 (Carbon brief, 2021). Europe also aims to be carbon neutral by 2050. It has announced its collective goal to reduce net greenhouse emissions by 55 % from 1990 levels by 2030 (Weforum, 2021). Within Europe, Germany has set a reduction target of 49-51 % by 2030 for the cement sector (NewClimate, 2020). India has not announced any net-zero targets yet.

## 3.5 Cement manufacturer commitments

Many large cement manufacturing companies have voluntary taken climate commitments. As per science-based target, many big manufacturers in India such as ACC limited, UltraTech cement limited, Shree Cement Limited, Ambuja Cement, Dalmia Cement have committed to reducing their CO2 emissions (Science Based Targets, 2021). Dalmia Cement has announced its plan to become carbon negative by 2040 and build CCUS facility (with an amine-based process) with a capacity of 0.5 Mt CO2 per year (Global CCS Institute, 2019).

In Europe, TITAN Cement group, Holcim Ltd., Heidelberg cement have committed to reduce their emissions. In addition, Heidelberg cement has announced its plan to build first carbon neutral cement plant (HeidelbergCement, 2021). In China, Asia cement corporation and Taiwan cement corporation have committed to reduce GHG emissions (Science based targets, 2021).

# 4. Methodology

This chapter describes the research method and assumptions used in the model. First, the conceptual framework of the model is described in section 4.1. This is followed by an explanation of the model framework in section 4.2 which describes different modelling steps and inputs used. Next, a general description of different scenarios considered is provided in section 4.3. Finally, assumptions about different decarbonisation options are described in detail in section 4.4.

## 4.1 Conceptual framework of the model

This thesis aims to develop an energy transition scenario for the cement industry using a simulation model that models energy flows to achieve net-zero emissions by 2050. This study does not forecast what the future energy flows would be. It instead estimates future energy flows of the industry, given the target of net zero emissions by 2050. For this study, a goal of achieving net-zero emissions from the cement industry is set beforehand. Decarbonisation scenarios are then developed to reach this goal. Backcasting technique fits such scenario planning as it is used to assess the feasibility of a desired sustainable future. It helps in answering the question – *what must happen to reach this desired sustainable future*. It is also helpful to use backcasting when a highly complex and persistent problem requires significant change from current trends (Dreborg, 1996).

For this model, energy backcasting framework by Robinson (1982) is taken as a conceptual framework. The framework consists of six steps as described below:

1) *Specification of goals and constraints*
   The goal of energy transition for the cement industry is to achieve net zero emissions by 2050.

2) *Description of current energy consumption and production*
   In the second step, the current energy consumption of the cement industry is analysed for different countries. The thermal and electrical energy intensity of cement production and production processes are also described.

3) *Outline of future economy*
   In the third step, future cement activity till year 2050 will be determined. This will be by determining the correlation between GDP per capita and cement activity per capita. Furthermore, different scenarios are outlined such that goal of net zero emissions is achieved.

4) *Energy demand analysis*
   Once the decarbonisation scenarios are constructed, the simulation model obtains energy demand in different scenarios.

5) *Energy supply analysis*
   Once the energy demand is known, total primary energy is calculated.

6) *Implications of the energy transition*

   The environmental impactions of different scenarios are looked in terms of cumulative $CO_2$ emissions. Finally, the paths that lead to these scenarios are compared to the business-as-usual scenario.

## 4.2 Model explanation

### 4.2.1 Basic framework of the model

Backcasting framework is used to develop a simulation model which models energy transition scenarios for the cement sector till 2050. The model's decarbonisation pathways are constructed with assumptions about the country's socio-economic conditions, energy efficiency, fuel share, and technology share. The modelling focuses on decarbonising thermal energy use by substituting fossil fuel use with low carbon fuels such as biomass, hydrogen, and electricity. Depending on the assumptions in scenarios, fossil fuel use gets phased out rapidly or slowly. It is also assumed that electricity used for the cement industry gets decarbonised over the years with an increase of renewables. The analysis is carried out using the Python programming language.

The simulation model is run to obtain energy demand and $CO_2$ emissions over the years in different scenarios. Figure 4.1 illustrates the steps to model the cement sector. First, the amount of cement produced is modelled for different countries. This is done by modelling cement consumption per capita as a function of GDP per capita. As clinker is the most energy intensive part of cement production, reducing clinker content in cement is essential to reduce emissions. Clinker activity over the years is obtained by reducing the clinker to cement ratio in different scenarios.

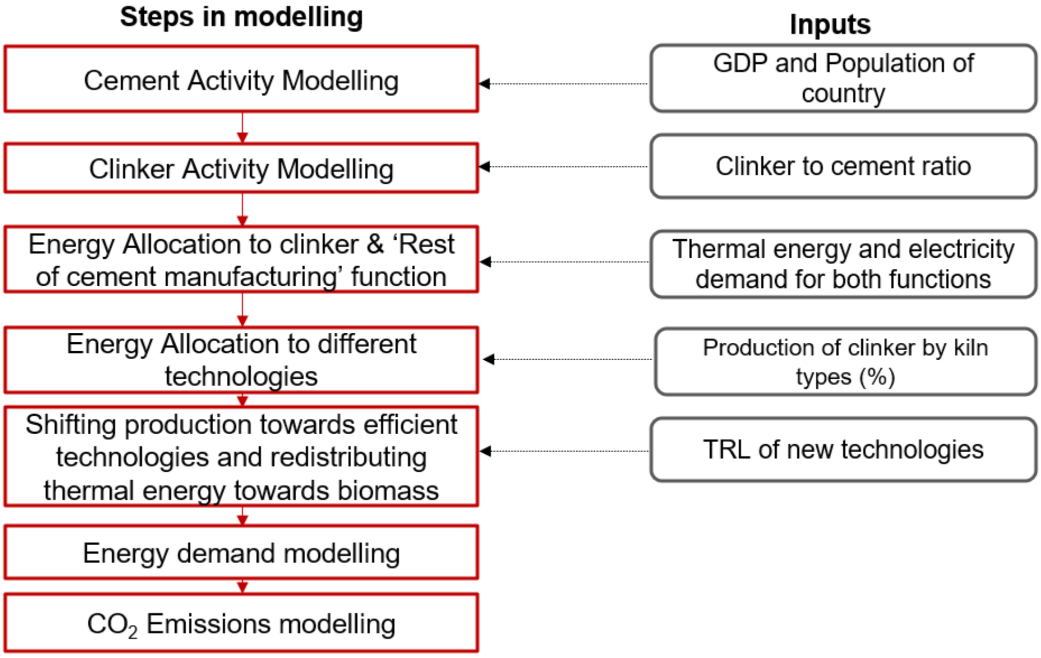


**Figure 4.1 Framework of energy modelling**

After activity modelling, energy modelling begins by creating energy functions. Energy functions are used to split an economic sector into its subcategories or different production process. Figure 4.2 shows the cement production process and division of different processes into energy function. Cement sector is divided into *clinker* function and '*rest of cement process'* energy functions. As clinker production is the most energy intensive process, energy function is created for it. Rest of cement making processes includes quarrying raw materials, crushing and grinding raw materials. These processes are combined and taken as a single function as these processes majorly consume electricity. Carbon capture technology is also included in '*rest of cement process'* function.

The next step in modelling is energy allocation to main technologies used in cement production for the base year. Then, the energy allocation to functions is changed over the years by first shifting cement production towards efficient technolgies and later increasing the share of alternative fuels in fuel mix. The assumptions for energy allocation to functions and technologies are explained in detail in further sections. Finally, different assumptions of clinker to cement ratio, efficiency improvements, technology deployment year, rate of adoption of technology and material efficiency are taken in different scenarios to obtain energy demand.

Energy of a sector is calculated as:

$$FuEB(y+1) = FuEB(y) * (1 + dAct) * (1 - dEff) * (Tshare\ (y+1))/(Tshare\ (y))$$

in which:

*FuEB* = Energy use of an energy function for a particular technology in year *y+1*

*y* = year number

*dAct* = fractional change in activity (sector and country specific)

*dEff* = fractional change in specific energy use (sector, country, and maybe also technology specific)

*Tshare*(t) = share of technology in the functional activity.

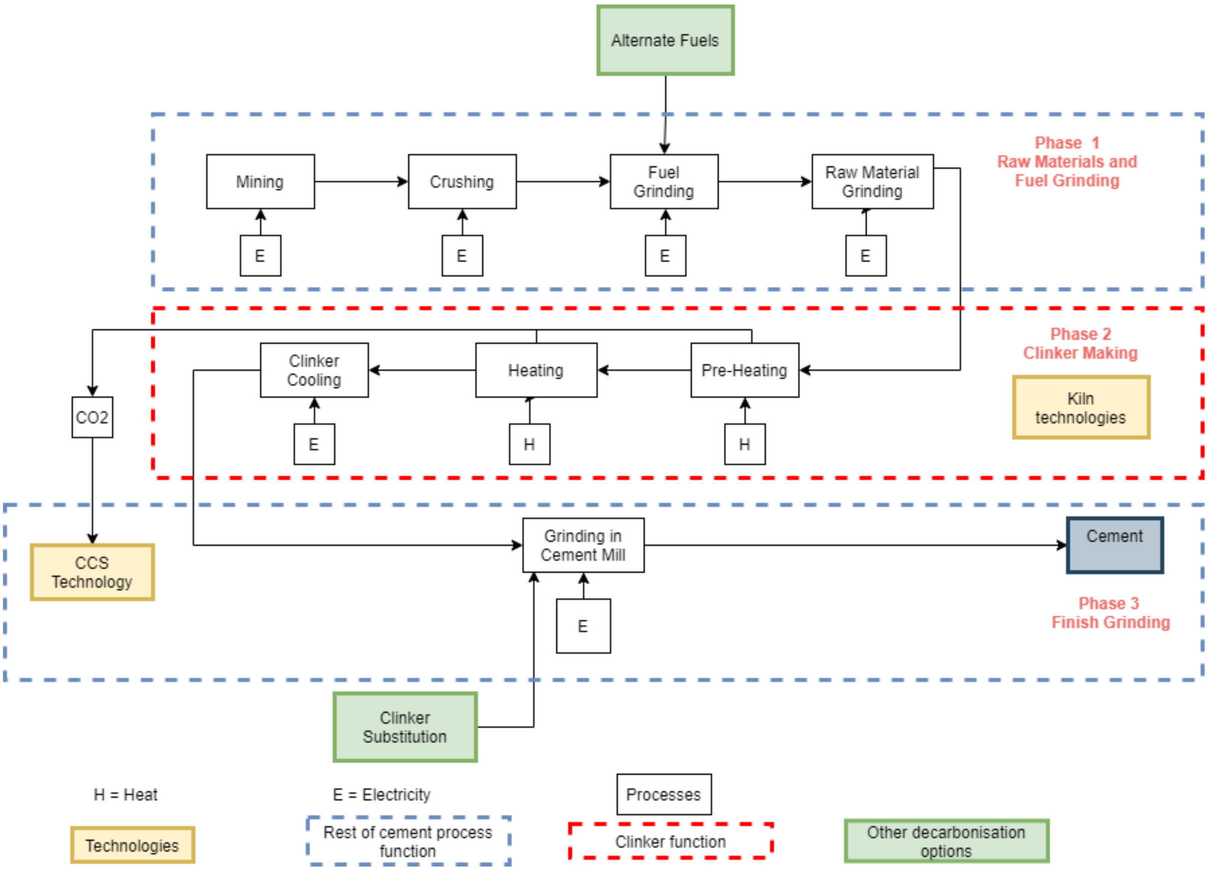


**Figure 4.2 Division of cement production processes into energy functions**

### 4.2.2 Energy demand for the base year

In the model, 2018 is considered the base year. The geographic scope of the model is EU-28, India and China. Final energy use by the cement sector for each country is calculated by taking a time step of one year.

Global Cement and Concrete Association (GCCA) provides thermal energy consumption data for the cement sector in India, most European countries and aggregated data for Europe. Data for China is taken from different sources and is stated in Appendix. The GCCA data comprises alternative fossil fuel and mixed waste, biomass and fossil fuel. This data is taken as thermal energy consumption for the base year. Since, for modelling, the data for coal, oil and natural gas is needed separately, the GCCA data for fossil fuel is split using the percentage share of individual fossil fuels in the IEA's energy balance of the non-metallic sector.

If GCCA data is not available for a country, a bottom-up estimate of thermal energy demand is done. Then, this calculated thermal energy demand is split into alternative fossil fuel and mixed waste, biomass, and fossil fuel using respective fuel share in Europe from GCCA data. The fossil fuel is further split using the percentage share of individual fossil fuels in the non-metallic sector. Figure 4.3 illustrates how thermal consumption data is calculated.

For electricity energy demand, bottom-up estimates are done for all countries.

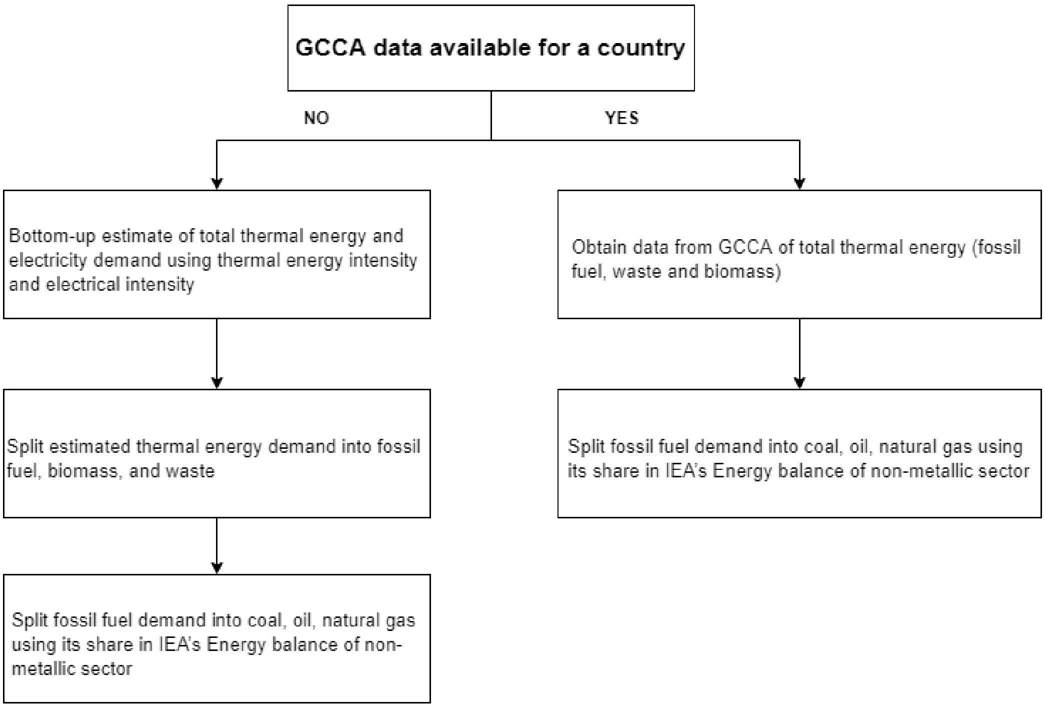


**Figure 4.3 Estimation of energy demand in base year**

### 4.2.3 Cement and clinker activity modelling

GDP per capita or GDP is commonly used to project cement demands. However, other factors such as population, urbanisation rate, fixed assets investment, and cement consumption intensity are also used in addition to GDP.

van Ruijven et al. (2016) used GDP per capita to predict cement demand. Wang et al. (2011) determined a correlation between urbanisation rate and China's cement production. Additionally, Wei (2018) used population size, urbanisation rate, fixed assets investment and GDP per capita to project China's cement demand in 2030.

In this thesis, cement activity per capita is modelled as a function of GDP per capita for different countries. Other parameters are not considered since there is limited public data available for many countries. Cement activity is modelled by running regression models that relate cement per capita and GDP per capita.

Van ruijven et al. (2016) showed that nonlinear inverse models are best fit to correlate cement activity per capita (C) and country's GDP per capita (GDPpc). Hence, the following nonlinear inverse equation is used to model cement activity:

$$C = a * e^{(\frac{b}{GDPpc})}$$

For European countries, activity modelling is done by classifying countries as west and east European countries. Then, data for west European countries is gathered to generate a single curve that best fits all Western European countries. The same thing is done for Eastern European countries. For China and India, modelling is done separately. After modelling cement activity, clinker activity is obtained by using clinker to cement ratio and cement production. Then, the clinker to cement ratio is reduced by different rates in different scenarios and is explained in further sections.

For calculating dAct (fractional change in activity) of cement and clinker, cement and clinker activity is modelled till 2050. dAct is defined as

$$\mathrm{dAct} = -1 + \frac{\mathrm{Act(y+1)}}{\mathrm{Act(y)}} = -1 + \frac{\mathrm{pop(y+1)}}{\mathrm{pop(y)}} * \frac{\mathrm{f(GDPpc(y+1))}}{\mathrm{f(GDPpc(y))}}$$

Where Act(y) - cement (or clinker) activity in year y,

pop(y) -population in year y,

GDPpc(y) - GDP per capita in year y.

### 4.2.4 Energy Allocation to functions

As seen in figure 4.2, heat use in cement production occurs mainly for clinker production. Therefore, the consumption of coal, oil and natural gas is only allocated to clinker function. For the '*rest of cement process'* function, coal, oil, and natural gas consumption is assumed to be zero.

Electricity is used for all cement processes, and hence, it needs to be divided between functions. Electricity use in *clinker* function occurs for running kiln motors and cooling of clinker. In the *'rest of cement process'* function, electricity use is mainly for grinding processes. Electricity allocation to clinker and 'rest of cement process' functions is done as follows:

$$\boldsymbol{Electricity\ allocation\ to\ clinker\ function}\ (\%) = \frac{\boldsymbol{Ec * Clinker\ to\ cement\ ratio}}{\boldsymbol{Ec * Clinker\ to\ cement\ ratio + Er}} * \mathbf{100}$$

$$\boldsymbol{Electricty\ allocation\ to\ rest\ of\ cement\ processes\ function}\ (\%)$$
$$= \mathbf{100} - \boldsymbol{Electricity\ allocation\ to\ clinker\ function}\ (\%)$$

where, $E_c$ - *Electricity consumption for clinker production per ton of clinker*

$E_r$ – *Electricity consumption for the rest of cement processes per ton of cement*

### 4.2.5 Energy allocation to technologies

Clinker can be produced in different kiln types: dry with preheater and precalciner, dry with preheater and without precalciner, dry without preheater, mixed kiln type, semi wet or semi dry wet or shaft kiln. For *clinker* function, energy is allocated to different kilns using the share of clinker produced in different kiln types.

For the *'rest of cement process'* function, mainly grinding processes are considered. Several grinding technologies exist, such as vertical roller mill, ball mill, high pressure grinding roller. The share of cement produced in these technologies is unknown. Hence, energy allocation to the *'rest of cement process'* function is done considering ball mill*,* the most used grinding technology.

In mitigation scenarios, both fuel and process emissions are assumed to be captured by MEA scrubbing, a post-combustion carbon capture technology. This technology is considered part of *'rest of cement process'* function. The impact of this technology on thermal energy use and electricity use is modelled and is explained in later sections. A general framework for energy allocation to technologies is shown in figure 4.4 .

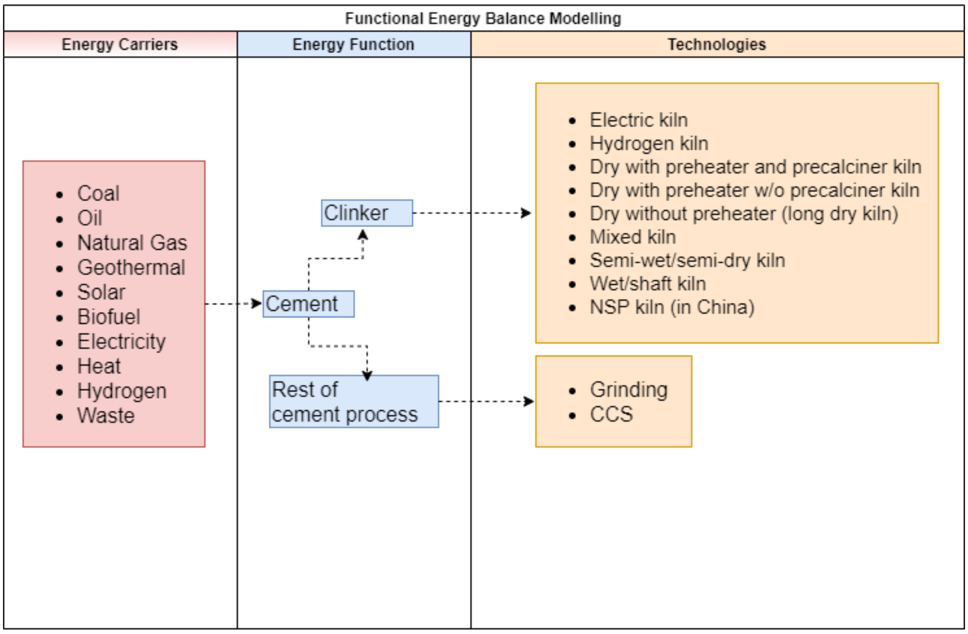


**Figure 4.4 Framework for Energy allocation to technologies**

## 4.3 Scenario description

Business as usual scenario and three mitigation scenarios (Mitigation 1- M1, Mitigation 2- M2, and Mitigation 3- M3) are considered to model decarbonisation pathways using conventional and emerging technologies. Emerging technologies such as an electric kiln, hydrogen kiln, material efficiency and novel cement are assumed in different scenarios. Table 4.1 shows decarbonisation options pursued in different scenarios. It is noted that the decarbonisation of the cement sector will rely not only on the emerging technologies but also on solving the financial and legislative challenges associated with these technologies.

M1 scenario is assumed to be the least innovative and ambitious of all mitigation scenarios. This decarbonisation pathway is likely to occur in countries lacking the financial capacity to transition to green technologies. The M2 scenario is considered the middle of the road scenario, with new kiln technologies included. Finally, M3 is assumed to be more ambitious with all decarbonisation options included. Although M3 is considered the most ambitious, it is still representative of the potential of emerging technologies.

As there has been a successful demonstration of CCS in cement production, CCS is implemented in all scenarios. Furthermore, in all scenarios, CCS is assumed to reach a certain level of capture rate. As electric and hydrogen kilns are still in the research phase, how quickly these technologies will be adopted is unknown. These technologies are included in the M2 and M3 scenarios with different rates of adoption. Novel cement is considered only in the M3 scenario due to numerous technical and economic barriers associated with scaling its production.

| | **Decarbonisation options** | **BAU Scenario** | **M1 Scenario** | **M2 Scenario** | **M3 Scenario** |
|---|---|---|---|---|---|
| **Conventional options** | Reducing clinker to cement ratio | + | ++ | ++ | ++ |
| | Thermal energy efficiency improvement | + | + | ++ | ++ |
| | Electrical energy efficiency improvement | + | + | + | + |
| | Biomass | + | + | ++ | +++ |
| | Waste | + | +++ | ++ | + |
| **Emerging options** | Electric Kiln | - | - | + | ++ |
| | Hydrogen Kiln | - | - | + | ++ |
| | Material efficiency | - | - | + | ++ |
| | Novel cement | - | - | - | + |
| | CCS | - | +++ | ++ | + |

**Table 4.1 Decarbonisation options in different scenarios**

***-  = decarbonisation option is not pursued***

***+/++/+++ = decarbonisation option is pursued to a moderate/strong/very strong extent***

**Business as usual (BAU) scenario:**

- No adoption of CCS
- Only conventional decarbonisation options used

In the BAU scenario, only conventional decarbonisation options such as energy efficiency improvements, reduction of clinker use, use of alternative fuel are modelled. No new kiln technology is introduced in this scenario.

Based on the climate commitments of countries, decarbonisation of the power sector is assumed. The emission factor of grid electricity is assumed to reduce at a linear rate for all countries. For Europe, the power sector is assumed to be decarbonised by the year 2050. For China, based on its carbon-neutral goal of 2060, the power sector is assumed by 2060. For India, no net-zero targets have been announced yet. Hence, the power sector is also assumed to be assumed by 2060. Assumptions about decarbonisation of electricity remain the same for all the scenarios.

**Mitigation 1 (M1) Scenario:**

- Slow adoption of CCS
- Only conventional decarbonisation options used

This scenario builds on the narrative that only conventional decarbonisation options would be adopted except for CCS. The adoption rate of CCS is slower as the M1 scenario is considered to have lesser innovation and ambition than other mitigation scenarios. The implementation of hydrogen and electric kilns is not considered due to financial and technical challenges. In addition, the use of alternative fuel is taken to be higher than in the BAU scenario.

**Mitigation 2 (M2) Scenario:**

- Moderate rate of adoption of CCS
- Shift to electric and hydrogen kilns (slow transition)
- Use of blue and green hydrogen

This scenario is assumed to have more innovation than the M1 scenario. Electric and hydrogen kiln technologies are introduced in this scenario. Hydrogen kiln is introduced in the year 2035. Heat is generated in hydrogen kiln using blue and green hydrogen. First, blue hydrogen is used for the short term, and later, green hydrogen is used per the assumption of increased renewable capacity. Blue hydrogen is used for the short term until 2040, and later, green hydrogen is used. The use of alternative fuel is taken to be higher than in the M1 scenario. Material efficiency strategies are also included.

**Mitigation 3 (M3) Scenario:**

- Faster adoption of CCS

- Shift to electric and hydrogen kilns (fast transition)
- Use of green hydrogen

In this scenario, all decarbonisation options are considered. This scenario is most ambitious and innovative. Hydrogen and electric kiln technologies are assumed to have a higher adoption rate than in M2. Only the use of green hydrogen is assumed in this scenario. Novel cement is also introduced in this scenario. Material efficiency is adopted at a higher rate.

## 4.4 Modelling Decarbonisation options

In this section, assumptions for modelling different decarbonisation options are explained. The following decarbonisation options are modelled:

- *Reduction of clinker use*
- *Kiln thermal efficiency improvements*
- *Alternative fuel*
- *Milling/grinding electrical efficiency improvements*
- *Material efficiency*
- *Use of novel cement*
- *Carbon capture technologies*

### 4.4.1 Reduction of clinker use

One of the primary ways to reduce process emissions from cement production is to reduce the clinker content in the cement. It is technically possible to reduce the clinker to cement ratio to 0.5 without changing fundamental cement properties (CSI, 2017). The clinker to cement ratio is assumed to linearly decrease to 0.52 by 2050, based on the GCCA (2021) forecasts. This reduction in clinker use is assumed to happen with the availability of clinker substitutes such as calcined clays and natural pozzolans.

For most countries, clinker to cement ratio (CCR) data is available from 1990 to 2018. The clinker to cement ratio is reduced over time using the historical rate of decrease of CCR. The average annual rate of decrease of CCR is used to model CCR. For some countries in Europe, the clinker to cement ratio increases from 1990 to 2018. For these countries, CCR is decreased by using the rate of decrease of CCR of EU-28 average.

The annual rate of decrease of CCR for a country is calculated as:

$$Rate = 1 - \left(\frac{CCR\ in\ 2018}{CCR\ in\ 1990}\right)^{\left(\frac{1}{28}\right)}$$

In the mitigation scenario, the rate of decrease is 1.25, 1.5, and 1.75 times the rate of decrease in the BAU scenario. The clinker to cement ratio is then decreased to 0.52 using the rate of decrease as per the scenario. Finally, using the rate of decrease of CCR, fractional change of cement (or clinker) activity is calculated as described in section 4.2.3.

### 4.4.2 Kiln thermal energy efficiency improvements

It is well known that thermal energy demand decreases by shifting towards more efficient kiln technologies. All countries are seen to be moving in this direction. Therefore, the focus of this model is also on shifting towards more efficient dry kilns and new kiln technologies such as hydrogen or electric kilns as and when they are introduced in the market. The framework for modelling currently used kilns and new kilns are described below.

*Modelling conventional kiln technologies shares in BAU/Mitigation scenarios:*

Over the years, it has been observed that there is a shift towards dry kilns due to their low thermal energy intensity. Therefore, for modelling future kiln technology shares, the share of dry kilns is increased, and the share of other types of kilns is decreased. This is done by phasing out the least inefficient kiln types. The order of most efficient to least efficient kiln type is as follows - dry with preheater and precalciner, dry with preheater and without precalciner, dry without preheater, mixed kiln type, semi wet or semi dry, wet or shaft kiln.

The first step in modelling kiln shares is to increase the share of the most efficient dry kilns (*dry with preheater and precalciner* and *dry with preheater and without precalciner*) each year. This is done using historical rate of change of dry kilns. Next, the least inefficient kiln type for that year is identified and its share is decreased. The share of the least inefficient kiln is decreased such that the overall share of all kiln types is 100%. This continues until the most inefficient kiln is phased out, and then the next inefficient kiln type is reduced. If only dry kilns are left, the share of the less efficient dry kiln (*dry with preheater and without precalciner*) is also reduced until the more efficient dry kiln (*dry with preheater and precalciner*) is 100%.

*Modelling new technology kiln shares in mitigation scenarios:*

Electric and hydrogen kilns are introduced in the future in the M2 and M3 scenarios. Electric kiln is assumed to be the most energy efficient with specific energy intensity – 2680 MJ/tonne of clinker, which is lower than the most efficient dry kiln. On the other hand, there has been no publicly available study stating energy consumption for hydrogen kiln. Therefore, it is assumed to be as efficient as the most efficient dry kiln (*dry with preheater and precalciner*).

Electric kiln is introduced in the year 2030 and hydrogen kiln in 2035. Electric kilns are introduced earlier than hydrogen as the current TRL level of electric is higher than that of hydrogen. These new kiln technologies are modelled using the S-curve.

When the electric and hydrogen kilns are introduced, we follow the same procedure to reduce the share of the most inefficient kilns present at that time, maintaining the overall share to be 100%.

The share of hydrogen and electric kiln is modelled using the following equation:

$$Scurve_t = \frac{0.5}{(1 + e^{(-k*(t-a))})^b}$$

The parameters *a*, *k,* and *b* are chosen based on the following assumptions:

- Market entry year of the kiln technology
- Share of the technology in 2050
- The maximum share each kiln technology can reach is 50%.

In M2 scenario, the share of electric and hydrogen kiln is based on their share in IEA Net zero study. M3 scenario is considered more ambitious than M2 scenario It is further assumed that the shares of these kiln technologies in M3 is twice that of in the M2 in 2050. The year in which kiln technology is introduced and share it reaches in 2050 is shown in table 4.2.

| | **Electric kiln (M-2 scenario)** | **Hydrogen kiln (M-2 scenario)** | **Electric kiln (M-3 scenario)** | **Hydrogen kiln (M-3 scenario)** |
|---|---|---|---|---|
| **Market entry year** | 2030 | 2035 | 2030 | 2035 |
| **Share by 2050 (%)** | 10 | 5 | 20 | 10 |

**Table 4.2 Assumptions about electric and hydrogen kiln share and market entry**

*Calculating the fractional change in specific thermal energy use (dEff-thermal):*

Once the share of all kiln technologies is obtained, average thermal energy is calculated each year to calculate thermal energy efficiency improvements. The average annual rate of decrease of specific thermal energy from 2018 to 2050 is taken as *dEff* (fractional change in specific thermal energy use).

Average specific thermal energy consumption (SEC) for a year is obtained as follows:

$$\text{Average SEC}_t = \sum_i \text{Kiln}_{i,t} * \text{SEC}_{i,t}$$

where,
$t$ - year,
$i$ - kiln type,
$Kiln_{i,t}$ - share of kiln type *i* in year *t,*
$SEC_{i,t}$ - Specific energy of clinker production in kiln type *i* in year *t.*

### 4.4.3 Electricity efficiency improvement (dEff- electrical)

As stated earlier, the focus of this research is on decarbonising thermal energy use. Hence, electricity demand is modelled by using only autonomous energy efficiency improvement. In all pathways, an annual efficiency improvement of 0.5 % is assumed.

### 4.4.4 Alternative fuel

After incorporating all the above improvements, FuEB (final energy demand) is computed. Initial results show that energy demand for all energy carriers changes over time, not mimicking the real world due to efficiency and activity changes.

In the case of western European countries, without fossil fuel redistribution to alternative fuels, there is a decline in energy demand of all energy carriers, including biomass and waste. This is due to *dAct* being negative and the product of *(1+dAct)* and *(1-dEff)* being less than 1. However, European countries' energy statistics show that demand for biomass and waste has been increasing or reached a saturation after increasing.

In case of India, as cement demand increases, *dAct* is positive and the product of *(1+dAct)* and *(1-dEff)* is greater than one till year 2050. This increases energy demand of all energy carriers. Since fossil fuel had a much larger share than biomass and waste in 2018, fossil fuel remains very high, whereas biomass and waste remain very low.

In case of China, *dAct* is positive until 2037 and later becomes negative. A similar effect is seen for China as well. Hence, the energy demand of China peaks and stabilises later.

Therefore, for all countries, fossil fuel energy is redistributed towards biomass and waste. This redistribution is done to redistribute energy from fossil fuel to alternative fuels, keeping total energy demand constant. This redistribution is based on an S-curve which depicts the share of alternative fuels in total thermal energy demand (from alternative fuel and fossil fuel). The maximum share of alternative fuel in different scenarios is shown in table 4.3. The S-curve is modelled to mimic countries that already have a high share of waste and biomass, such as Germany and Austria.

| Scenarios | Maximum share of Waste | Maximum share of Biomass |
|---|---|---|
| **BAU** | 60 % | 25 % |
| **M1** | 62.5 % | 27.5 % |
| **M2** | 70 % | 30 % |
| **M3** | 60 % | 40 % |

**Table 4.3 Maximum share of waste and biomass in total thermal energy demand**

### 4.4.5 Material Efficiency

Cement demand can be reduced by less use of cement in concrete mix and with increased life of buildings. This is modelled as material efficiency in M2 and M3 scenario. In both scenarios, material efficiency is modelled by decreasing cement activity by 1 % each year starting from 2025 till maximum material efficiency is achieved. In the M2 scenario, the maximum material efficiency that can be achieved is 10 %, whereas, in M3, 20% is assumed.

### 4.4.6 Novel cement

Many types of novel cement exist in the pilot and demonstration stage in the market, but only a few have been commercialized so far. Many studies forecast that novel cement will not have a significant share in total production as the raw materials required at that scale will not be available. As per the *Concrete Future- Roadmap to Net Zero* report by the GCCA, novel cement will reach 1 % and 5 % of the total production in 2030 and 2050, respectively (GCCA, 2021).

For the sake of simplicity, only one type of novel cement is assumed. In the M3 scenario, Belite Ye'elimite-Ferrite (BYF), a novel cement, is introduced in 2030 and assumed to reach 5% of total cement production by 2050. One of the main reasons for assuming low uptake is the lack of availability of expensive aluminous materials (Cao et al., 2021).

The impact of this novel cement on thermal energy demand and $CO_2$ emissions is modelled. Production of BYF cement is modelled using S-curve. BYF is considered in the model for the following reasons. First, it has a high TRL level and has been funded by Horizon 2020 project by the EU (EU Buildup, 2015). Second, this cement can be manufactured in existing cement plants without any significant change in cement making process. Third, it also has significant potential to reduce process $CO_2$ emissions (29%) and thermal energy demand (35%) compared with OPC (Cao et al., 2021).

### 4.4.7 Carbon capture technology

$CO_2$ emissions from fossil fuel and alternative fuel combustion and the calcination process are assumed to be captured by CCS technology. The market entry for CCS is taken to be in the year 2025, and its adoption rate is modelled as an S-curve reaching a 90% capture rate by 2050. The $CO_2$ capture rate for different scenarios is shown in figure 4.5.

Since many CCS technologies are in the testing phase, Monoethanolamine (MEA) scrubbing, a post-combustion $CO_2$ technology, is selected in modelling. This technology is considered amongst others for the following reasons. Firstly, this technology is the most mature among other $CO_2$ capture technologies and has achieved successful large-scale demonstrations at cement plants (Plaza et al., 2020). Secondly, it is also likely to reach high installation rates as it can be retrofitted in an existing cement plant without affecting cement production.

The impact of MEA scrubbing technology on thermal and electrical energy use is also modelled. For each tonne of $CO_2$ captured by this technology, 3.5 GJ of thermal energy and

0.47 GJ of electrical energy is used (Voldsund et al., 2019). The thermal energy used by CCS is assumed to be provided by biomass in all scenarios.

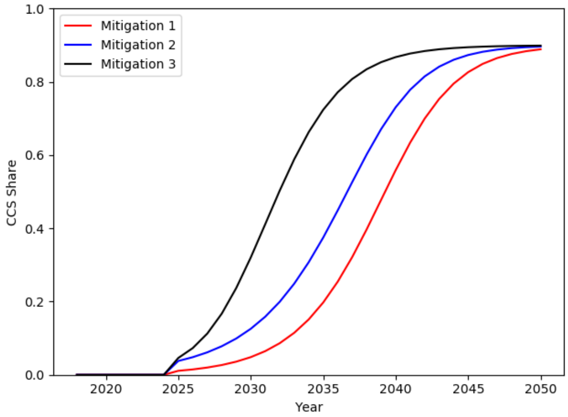


**Figure 4.5 Carbon capture rate for different scenarios**

## 4.5 Calculation of $CO_2$ emissions

Several assumptions have been taken for calculating emissions from the use of different energy carriers. First, biomass combustion is assumed to be carbon neutral, assuming that the cultivation of biomass and associated land-use change is sustainable. Second, the emission factor for mixed waste is taken as the average of different types of waste as the exact composition of waste used in the cement industry is unknown. Next, biogenic carbon emissions released from the combustion of waste with the biogenic fraction is assumed to be carbon neutral. The following types of waste are considered which are commonly used in cement industry – waste oil, plastics, animal meal, waste tyres and rubber, sewage sludge (dried), mix of special waste with saw dust, solvents and residues from distillation (Obrist et al., 2021).

Furthermore, the emission factor used for blue hydrogen assumes that blue hydrogen is produced from natural gas via steam methane reforming and includes CCS use to reduce emissions by 80 to 90 %. Green hydrogen is produced by electrolysis using renewable electricity (PEMBINA Institute, 2020). Data sources used for emission factors of different energy carriers is stated in Appendix E.

## 4.6 Carbon budget

The goal of the thesis is to develop low carbon pathways for the cement sector. To understand the impact of these pathways on the climate, how well these pathways align with climate policies needs to be understood. The most common metric used for climate change mitigation is an increase in global average temperature increase based on the Paris Agreement. The Paris Agreement's defined target is *"[...] holding the increase in the global* *average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels"* (UNFCC, 2015). Due to the strong correlation between temperature and $CO_2$ concentration in the atmosphere, this temperature target can be converted to a target of cumulative $CO_2$ emissions.

The implications of the energy transition of the cement industry are understood using the global carbon budget. For *SQ4*, the share of cumulative emissions of mitigation pathways in the remaining global carbon budget is computed. The share of cumulative emissions of a mitigation pathway in the remaining global carbon budget can be defined as the carbon space occupied by the country's cement industry in the remaining budget.

The remaining global carbon budget is taken as the difference between the total carbon budget available, since the pre-industrial era, to stay within a particular temperature limit with a certain probability, and the carbon emitted till 2019. Since the total carbon budget depends on how probable it is to stay within a certain temperature, a probability value of 50% is assumed for simplicity. For a 50 % chance of staying below 1.5°C and 2°C, the remaining global carbon budget from 2020 onwards is 500 Gt and 1350 Gt, respectively (IPCC, 2021).

# 5. Cement Production Results

In this chapter, the correlation between GDP per capita and cement activity per capita is discussed in section 5.1. In section 5.2, the results of cement demand projections for different countries are shown. Finally, the reason for using a simplified approach for determining cement demand is explained in section 5.3.

## 5.1 Relationship between GDP per capita and cement activity per capita

A good fit with the exponential regression model for India and China is seen in figure 5.1. For European countries, it is good in capturing the trend of activity change. Furthermore, the activity versus GDP for West EU is seen to be decreasing slightly, whereas, for east EU, it seems to be mostly stable. For both East EU and west EU, it is projected that the activity vs GDP will converge to around 0.4. For India, activity vs GDP is seen to be rising rapidly, and this rate of increase is expected to slow down later. For China, the trend is similar to India, albeit the rate of increase is lesser and is expected to stabilize sooner.

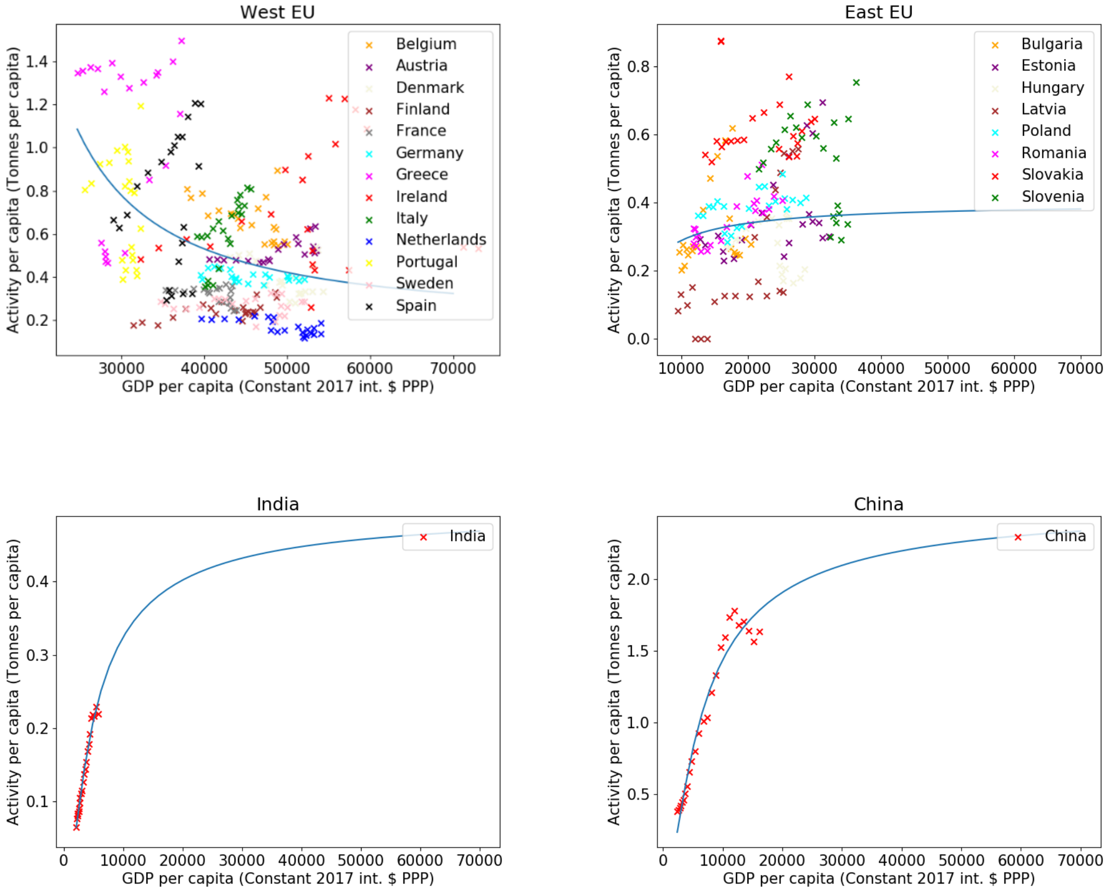


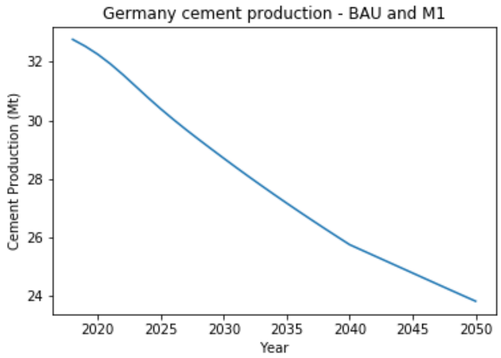
**Figure 5.1 Estimated Cement activity per capita vs GDP per capita for different countries (group of countries)**

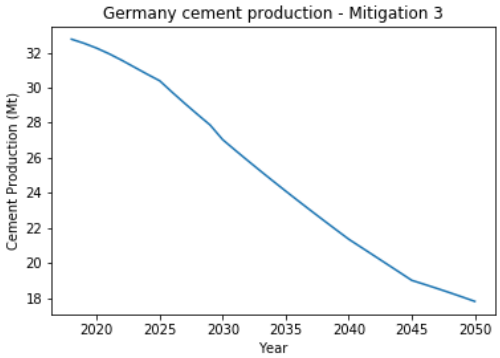
## 5.2 Cement Demand projection

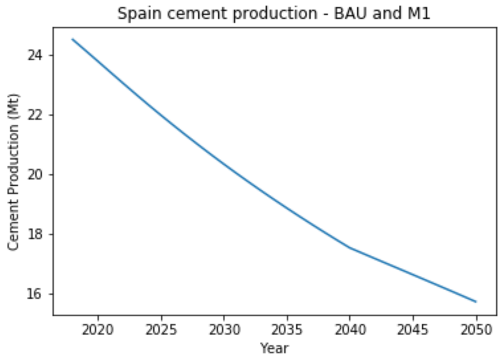
Based on the obtained activity vs GDP projections above, the cement demand for all the countries is estimated. For Germany, Spain and Italy, cement production is seen to be decreasing in all scenarios (figure 5.1). However, the rate of decrease is higher in M2 and M3 due to material efficiency and the introduction of novel cement.

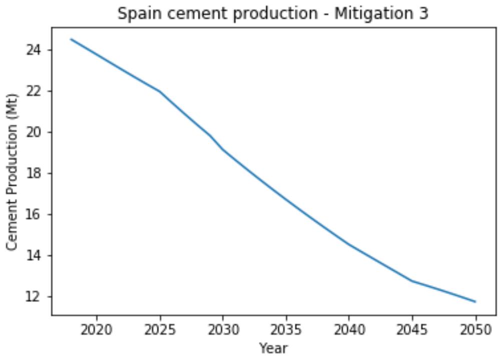
For India, cement production is increasing in the BAU scenario, which is consistent with the projection above and since India's GDP and population are expected to grow (figure 5.2). However, in M2 and M3, demand peaks and later decreases due to material efficiency and novel cement.

In China’s case, cement production is seen to be peaking around 2040 in BAU and M1 scenario due to its GDP growth rate decreasing and due to its population decline (figure 5.2). M2 and M3 also show a steady decline after an increase due to the same factors outlined above.









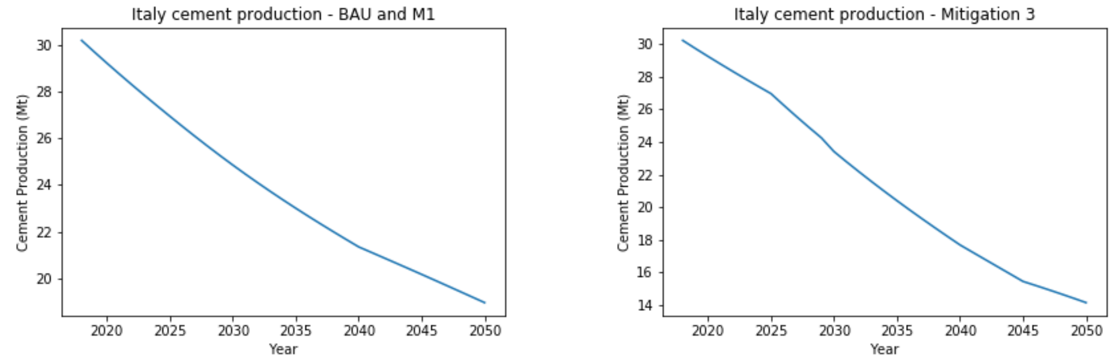


Figure 5.1 Cement activity projections in different scenarios for Germany, Spain and Italy

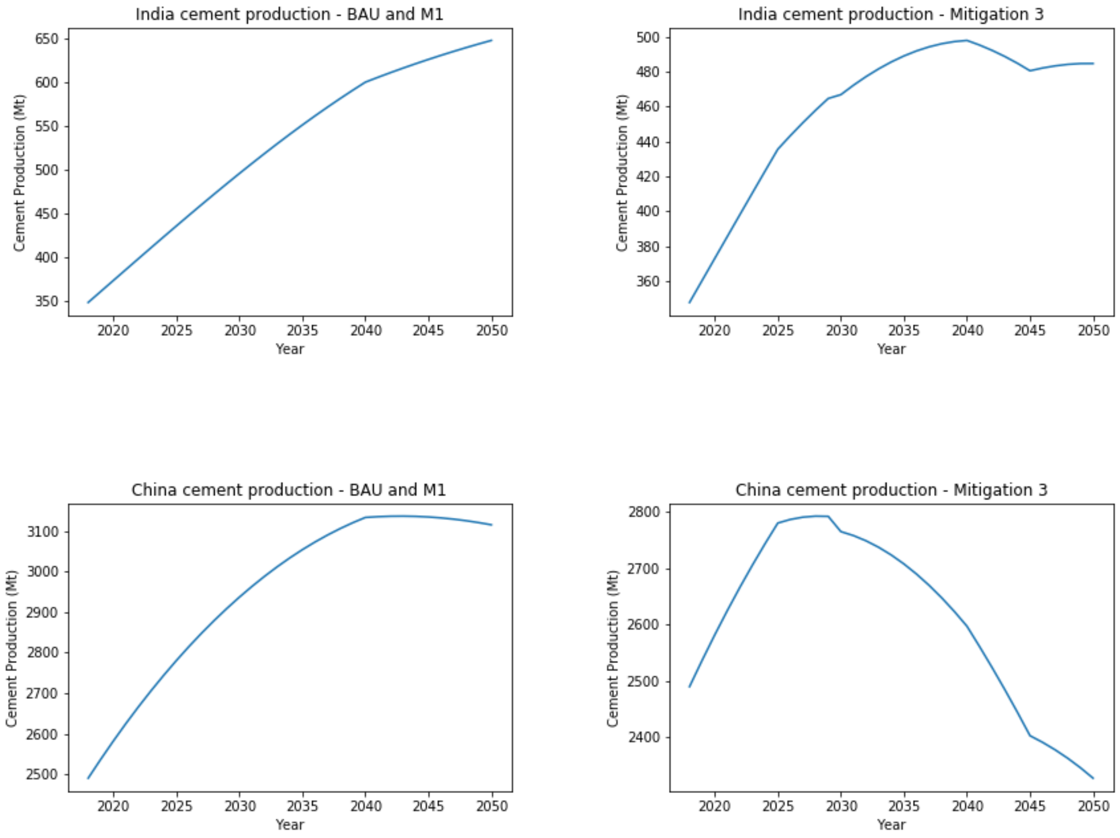


Figure 5.2 Cement activity projections in different scenarios for India and China

## 5.3 Discussion

This thesis uses a simplified approach for modelling cement demand by using only GDP per capita. One of the reasons for using only GDP per capita is that it is known how GDP per capita will change in future based on various studies. If parameters such as urbanisation rate and fixed asset investment were used, it is essential to know how these parameters will change until 2050. Furthermore, since these different parameters rely on many external factors and can vary quite a bit by region, it is difficult to predict them accurately and thus not included in the model.

Specifically, for China, Cao et al. (2016) showed that GDP per capita and fixed asset investment are the main factors that influence cement demand. Therefore, if more parameters such as fixed investment and urbanisation rate were to be considered in the model, cement demand might be different. Moreover, if fixed assets investment were to be used, it might be better to use a polynomial function (local minima and maxima) which can increase and decrease over time.

# 6. Energy Demand Results

In this chapter, *SQ3 is* answered, which is stated below.

***SQ3: How would the energy demand for the cement industry develop?***

The following sections of this chapter discuss how energy demand develops in different pathways - BAU (in section 6.1), M1 (in section 6.2), M2 (in section 6.3) and M3 (in section 6.4). Next, the electricity demand of different scenarios is compared in section 6.5. Finally, the year in which fossil fuel is phased out is discussed in section 6.6.

Before the analysis, graphs for energy demand for Germany and Spain are shown, followed by India, China, and Italy. Energy demand graphs of other countries can be found in the Appendix A. Next, the graphs for kiln distribution for Germany are shown as a single example (figure 6.4). Kiln distribution graphs for other countries can be found in the Appendix B.

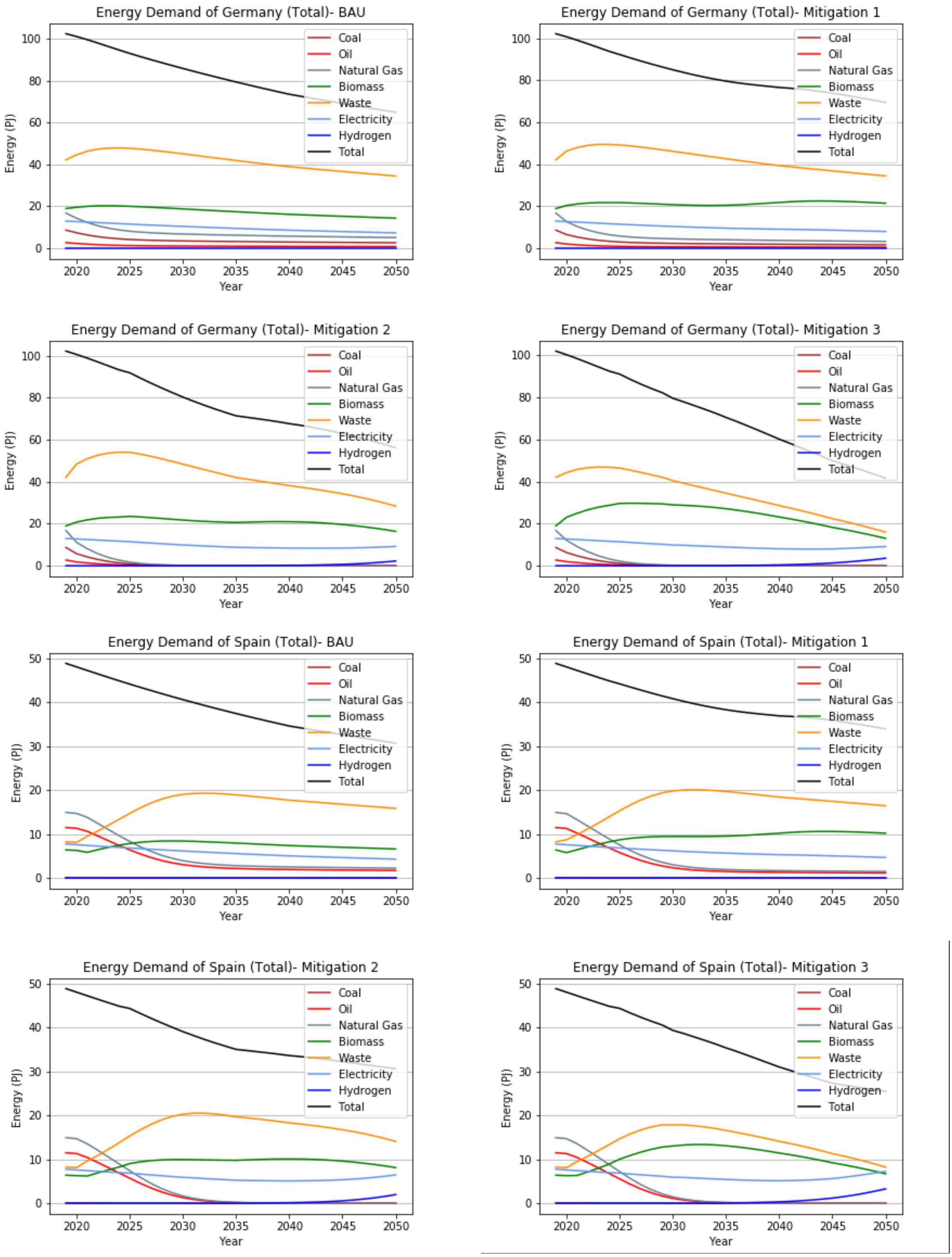


**Figure 6.1 Energy demand for the cement industry in Germany and Spain**

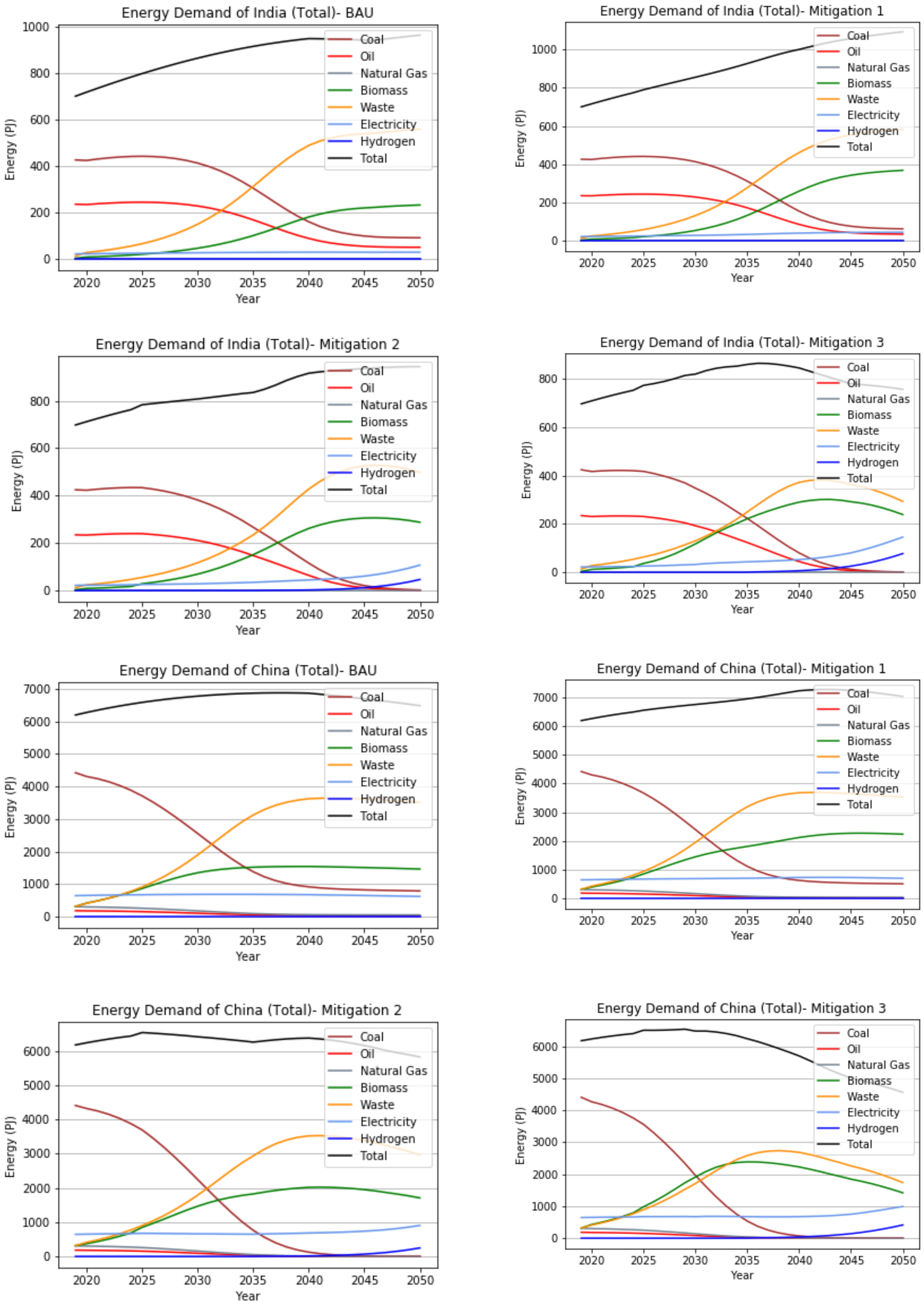


Figure 6.2 Energy demand for the cement industry in India and China

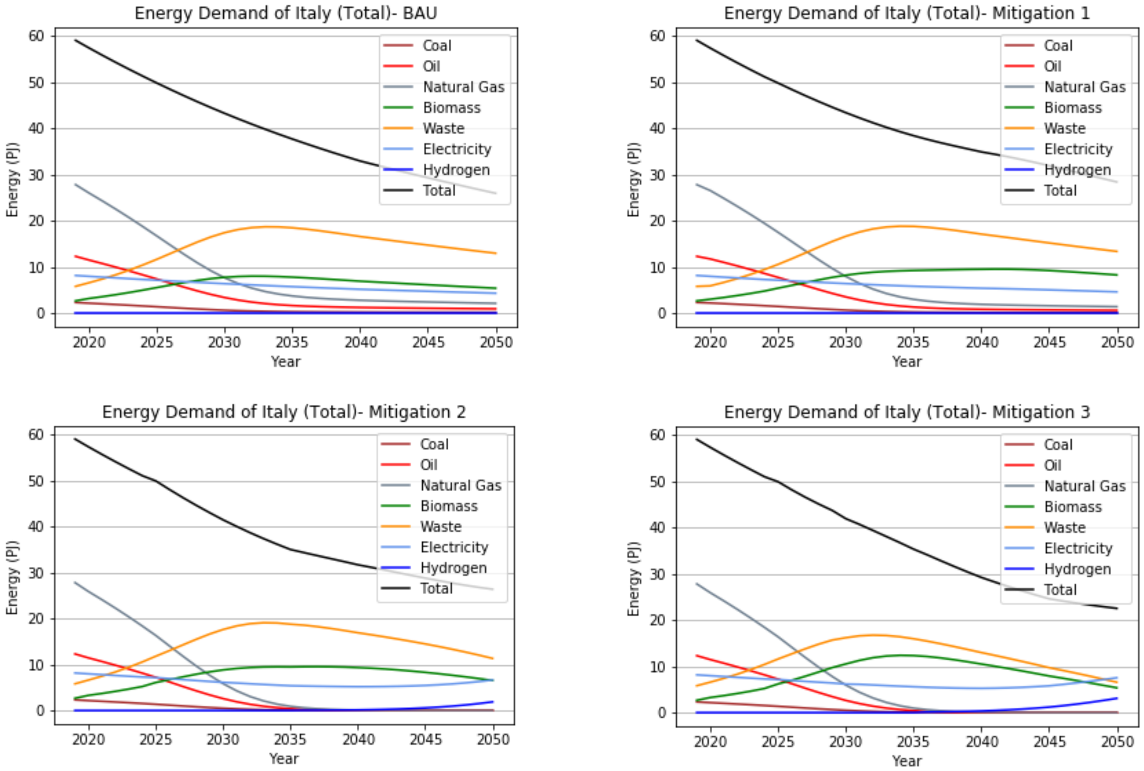


Figure 6.3 Energy demand of cement industry in Italy

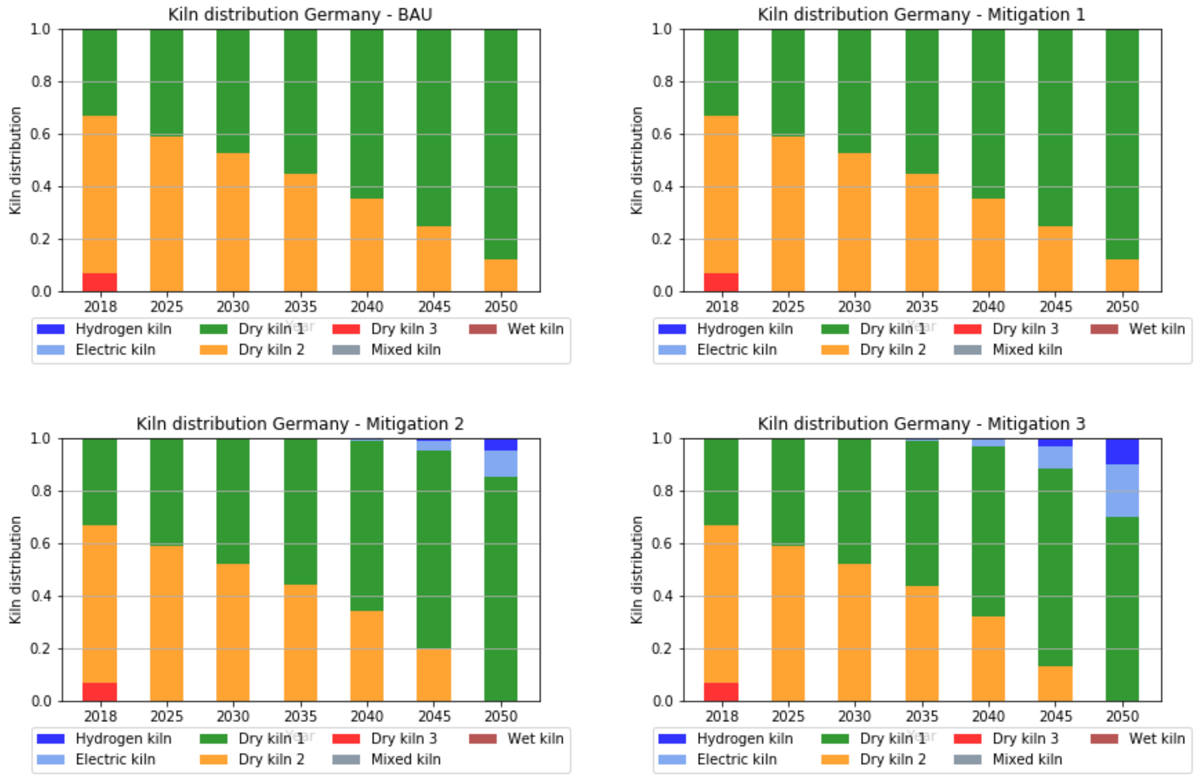


**Figure 6.4 Cement kiln distribution in Germany**

*Note- Dry kiln 1 refers to dry with preheater & precalciner; dry kiln 2 refers to dry with preheater without precalciner; dry kiln 3 refers to dry without preheater*

## 6.1 BAU scenario

In the BAU, only conventional decarbonisation options are implemented. CCS option is not considered. This scenario is taken as a reference to compare with other mitigation scenarios.

The model redistributes fossil fuel to biomass and waste, keeping the total thermal energy demand constant. As the uptake of waste and biomass increases, different fossil fuels decline as a proportion of their share in total fossil fuel demand. However, all fossil fuel does not get phased out in BAU, as the total fossil fuel use share is kept to 15 %. For example, in the case of Germany, in the base year, the share of waste and biomass of the total thermal energy demand is 47 % and 21 %, respectively. The maximum share waste and biomass can reach in the BAU scenario is 60 % and 25 %. Hence, the maximum uptake of alternative fuels is reached in a few years.

For Italy, the share of waste and biomass of the total thermal energy demand in the base year is 10 % and 5 %, respectively. Hence, the uptake of waste and biomass keeps rising until it reaches the assumed maximum share. In Italy, the share of natural gas in total fossil fuel energy demand is high in the base year. Hence, a sharp decline in natural gas is seen over the years.

Compared to Italy, Spain has lower cement demand but has higher energy use due to its high clinker to cement ratio of 0.8. The share of waste and biomass is 17 % and 11 %, respectively. Hence, a similar trend is observed as Italy for the energy demand of waste and biomass

In India, the total energy demand increases as the cement demand rises. The base year has a meagre share of waste and biomass in thermal energy use at 3% and 1 %, respectively. Hence, demand for waste and biomass keeps increasing and stabilises when it reaches the maximum share in total thermal energy demand. China also follows a similar pattern as India of increasing total energy demand. Like India, the reliance on coal remains high in China as well. Furthermore, due to the assumption of an equal share of waste and biomass in the base year, waste and biomass demand remains the same in the initial years.

From the assumptions taken regarding the development of alternative fuels, it can be seen that Germany reaches peak demand for alternative fuels much earlier due to its high initial share of alternative fuels. In comparison, Italy reaches peak demand later due to its low initial share of alternative fuel.

## 6.2 M1 scenario

In the M1 scenario, only conventional options are adopted, and no innovation is considered apart from CCS. Clinker factor reduction is assumed to be more ambitious than the BAU scenario.

Results for all countries show that show that in the M1 scenario, fossil fuel demand is lower than the BAU scenario. However, there is an increase in the use of biomass as thermal energy used by CCS technology is assumed to be supplied by biomass. Therefore, as the uptake of CCS increases over the years, biomass demand rises. Furthermore, the development of fossil fuel and alternative fuel demand is similar to the BAU scenario.

## 6.3 M2 scenario

Compared to the M1 scenario, the M2 scenario has additional decarbonisation options such as electric and hydrogen kiln and material efficiency. In addition, there is increased energy efficiency and faster reduction of clinker compared to the M1 scenario. This scenario also assumes that the reliance on fossil fuel decreases by increasing the uptake of alternative fuels.

Results show lower demand for fossil fuel and alternative fuel for European countries than the M1 scenario; specifically, the reduction in fossil fuel demand is higher than alternative fuels. The decline can be attributed to reduced cement demand due to material efficiency and electric and hydrogen kiln adoption. Furthermore, analysis of energy demand for clinker production (clinker function) shows that demand for fossil fuel and alternative fuel starts decreasing from 2025 due to material efficiency adopted from that year.

## 6.4 M3 scenario

M3 scenario is the most ambitious and innovative of all the scenarios. It has higher adoption of material efficiency and electric and hydrogen kilns. The scenario also includes the production of novel cement.

For European countries, it is observed that total fossil fuel demand is slightly higher in M3 as compared to M2 but is still lower than M1. The higher demand is mainly due to assumptions of fossil fuel redistribution to biomass and waste. Nevertheless, the total demand for fossil fuel and alternative fuel remains lower in M3 than in other mitigation scenarios. In addition, other decarbonisation options such as higher material efficiency and the use of novel cement contribute to the lower energy demand. In India and China, demand for fossil fuel is lower in M3 than in other scenarios.

For all the countries, it is also observed that the demand for thermal energy for CCS increases rapidly, which is assumed to be supplied by biomass, compared to other mitigation scenarios. The higher demand is due to the faster adoption of CCS in M3.

## 6.5 Electricity demand

In the BAU scenario, total electricity demand decreases for European countries due to decreased cement production. On the other hand, there is an increase in electricity demand for China and India due to an increase in cement production.

Four types of electricity demand are distinguished in this study. The first is for clinker production, and the second is for other cement processes, mainly grinding. The third is electricity used to operate CCS technology in mitigation scenarios. Finally, the use of electricity to heat electric kiln in the M2 and M3 scenarios.

Results show that for all the scenarios, electricity use is highest for clinker production until 2050. The second highest use is for grinding technologies. Once the electric kilns reach their maximum share, electricity use by electric kilns becomes as high as grinding technologies. Furthermore, electricity use for CCS technologies increases as the CCS adoption rate increases. However, CCS technology's electricity use remains the lowest compared to its use for other processes and technologies.

## 6.6 Phasing out of fossil fuels

The share of fossil fuel in the base year determines their phase out. Fossil fuels decline as a proportion of their share in total fossil fuel demand. The fossil fuel source with the highest share in total thermal energy demand gets phased out the last and vice-versa. Fossil fuels do not get phased out in the M1 scenario as the share of fossil fuels is kept to 10% in total thermal energy demand. The year in which fossil fuels get phased out in M2 and M3 scenarios is shown in table 6.1.

It is found that fossil fuels get phased out around the same year in both M2 and M3 scenarios. Within Europe, fossil fuel is phased out much earlier in Germany as compared to Italy and Spain. In the case of India and China, it is found that coal is not phased out, although its share remains very low (less than 0.3%). In the case of India, due to rising cement demand, no phase out of fossil fuels occur until 2050.

In conclusion, fossil fuel demand strongly depends on how fast there is an uptake of alternative fuels. Furthermore, it is found that total energy requirement declines as the uptake of different mitigation options are increased.

| | **Mitigation 2 scenario** | | | **Mitigation 3 scenario** | | |
|---|---|---|---|---|---|---|
| **Country** | Coal phase-out year | Oil phase-out year | Natural gas phase-out year | Coal phase-out year | Oil phase-out year | Natural gas phase-out year |
| **Germany** | 2036 | 2034 | 2038 | 2037 | 2034 | 2038 |
| **Italy** | 2043 | 2047 | 2048 | 2043 | 2046 | 2048 |
| **Spain** | 2032 | 2044 | 2045 | 2032 | 2044 | 2044 |
| **China** | No | 2046 | 2047 | No | 2045 | 2046 |
| **India** | No | No | NA | No | No | NA |

**Table 6.1 Year of phase out of fossil fuel for different countries (No - no phasing out, NA - no use of energy carrier)**

# 7. Emission Results

In this chapter, *SQ4 is* answered, which is stated below.

***SQ4: What are the implications of this energy transition in terms of cumulative emissions?***

This chapter begins with the graphs of $CO_2$ emissions by different countries. Graphs for emissions for Germany and Spain are shown, followed by India, China, and Italy. Emission graphs for other countries are added in Appendix.

After the graphs section, a comparison of cumulative emissions of different mitigation scenarios is made in section 7.1. Direct emissions (process and fuel emissions) and indirect emissions are also analysed. Finally, in section 7.2, implications of the energy transition for 1.5°C and 2°C targets of the Paris Agreement are studied.

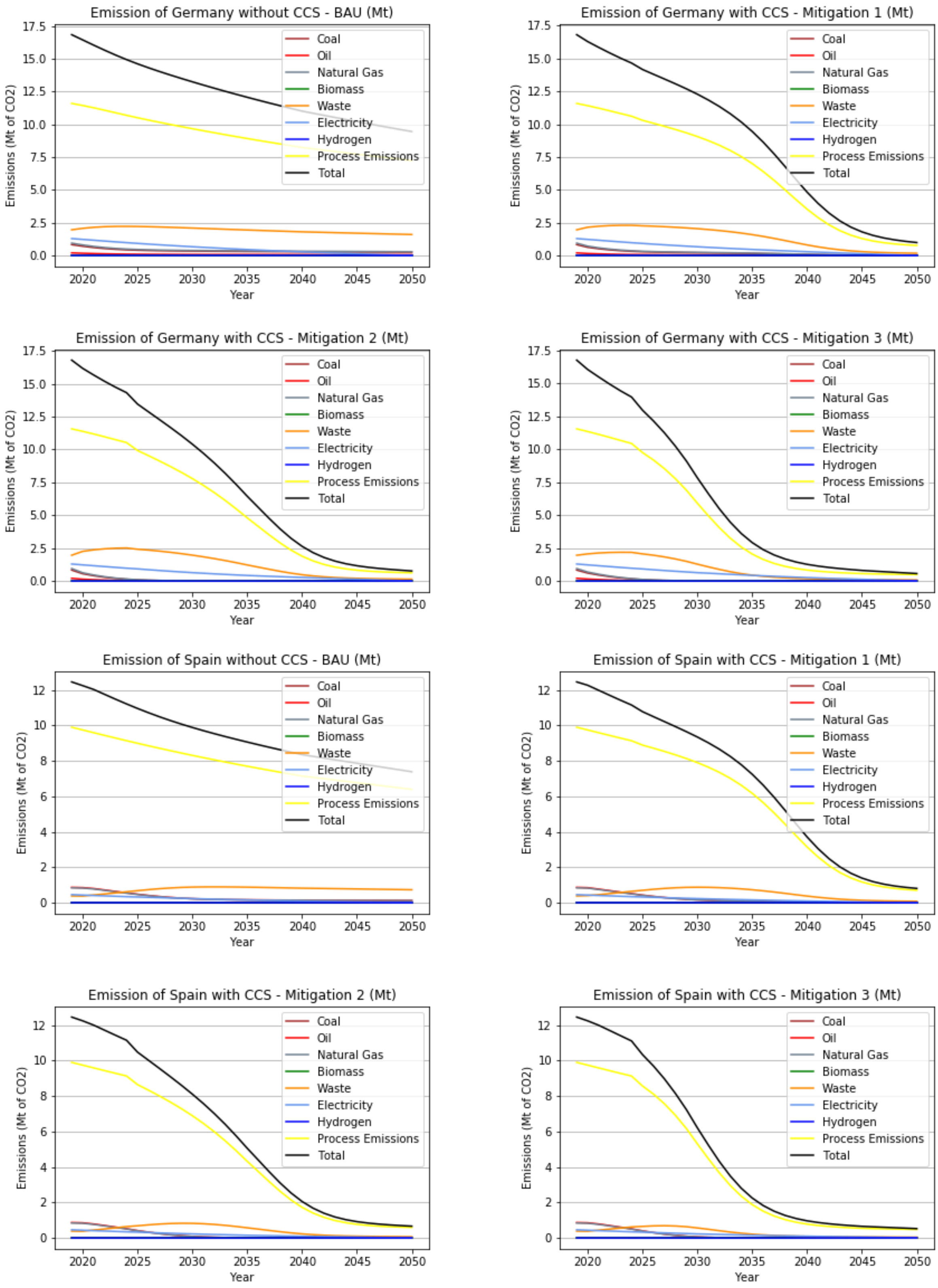


**Figure 7.1 Emissions of cement industry in Germany and Spain in different scenarios**

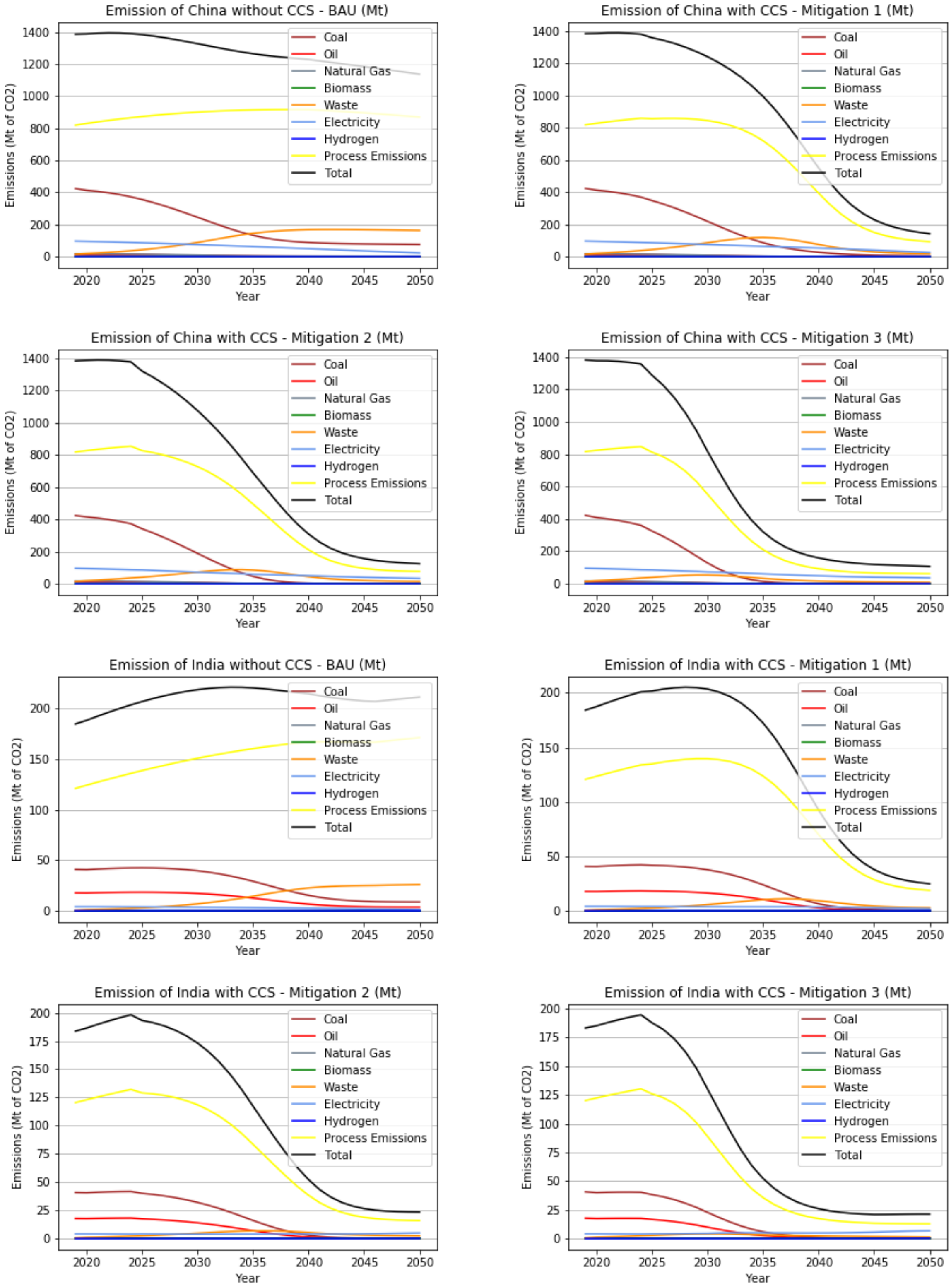


Figure 7.2 Emissions of cement industry in China and India in different scenarios

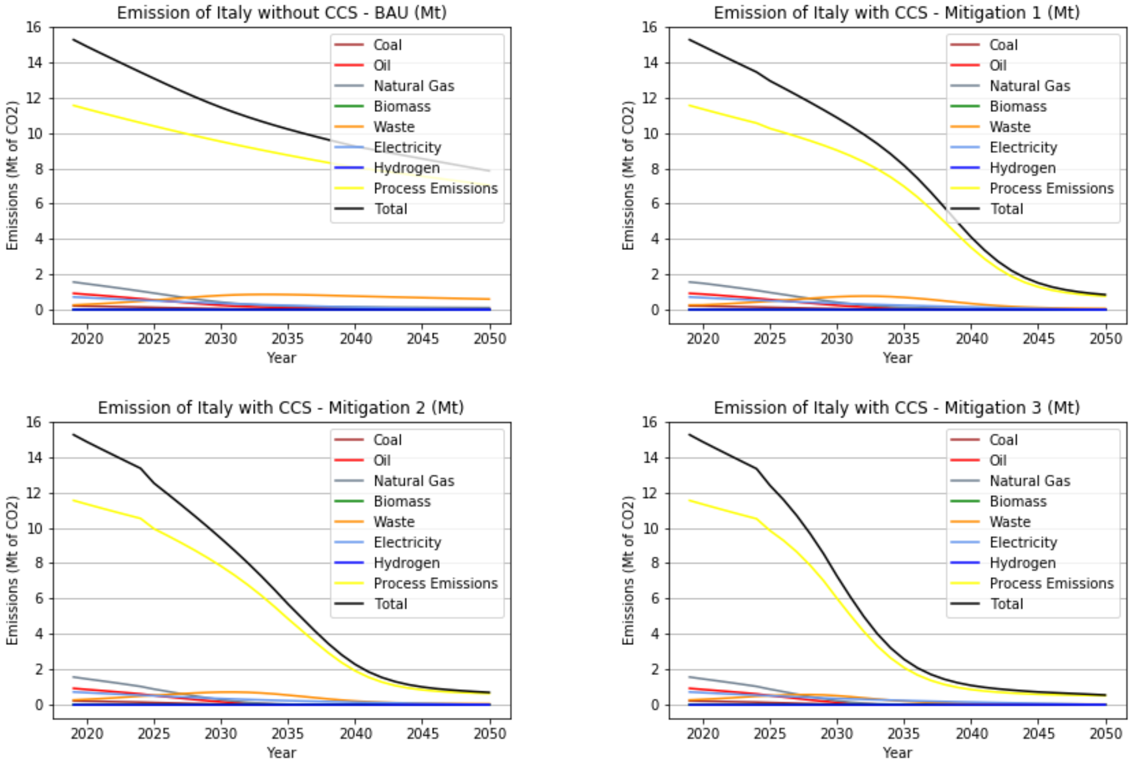


Figure 7.3 Emissions of cement industry in Italy in different scenarios

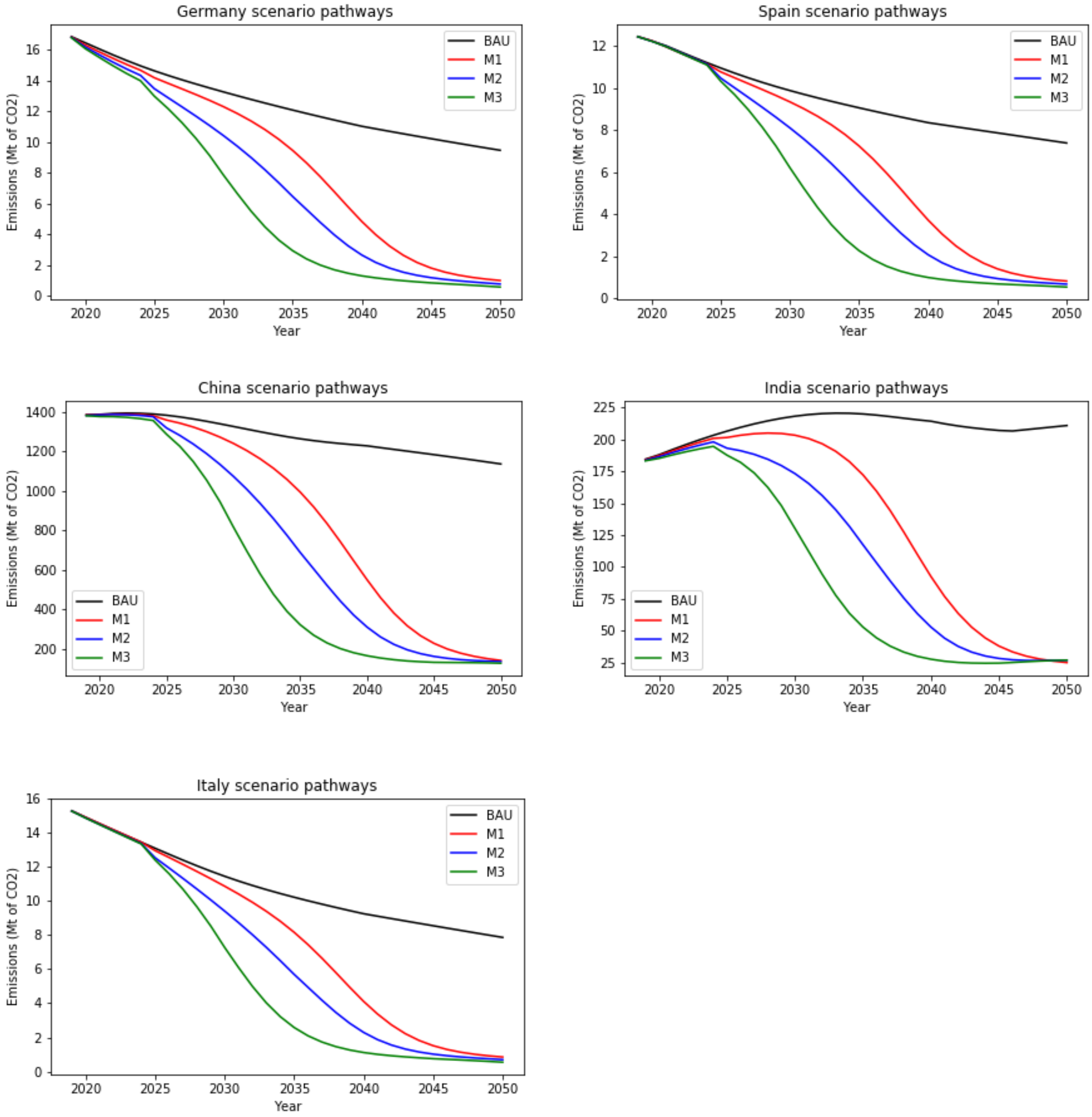


**Figure 7.4 Emission scenarios pathways for cement industry in Germany, Spain, China, India and Italy**

## 7.1 Comparison of scenarios

In this section, cumulative emissions from 2018 to 2050 are analysed and compared to the BAU scenario. The reduction in cumulative emissions is compared with and without CCS, as shown in table 7.1. Although CCS is implemented in all mitigation scenarios, emissions are first analysed if CCS is not implemented. This is done to understand the role of different decarbonisation levers.

| | **With CCS** | | | **Without CCS** | | |
|---|---|---|---|---|---|---|
| **Country** | **M1 scenario** | **M2 scenario** | **M3 scenario** | **M1 scenario** | **M2 scenario** | **M3 scenario** |
| **Germany** | 39 % | 48 % | 66 % | 7 % | 20 % | 33 % |
| **Italy** | 23 % | 33 % | 42 % | 2 % | 11 % | 18 % |
| **Spain** | 31 % | 41 % | 52 % | 4 % | 14 % | 25 % |
| **China** | 43 % | 52 % | 63 % | 7 % | 23 % | 35 % |
| **India** | 31 % | 42 % | 55 % | 1 % | 11 % | 21 % |

**Table 7.1 Cumulative emissions (2018 to 2050) reductions in mitigation scenarios as compared to BAU scenario**

First, cumulative emissions reduction are analysed without considering the use of CCS. In all mitigation scenarios, cumulative emissions decrease as compared to the BAU scenario. Among all the mitigation scenarios, emission reduction is found to be lowest in M1. Since the M1 scenario only includes improvements in energy efficiency, clinker factor and increased use of alternative fuels, the impact of these options is seen to be moderate. In the case of countries like India and Italy, decarbonisation options implemented in the M1 scenario seem insufficient.

In the M2 scenario, additional decarbonisation options such as electric and hydrogen kiln and material efficiency are included. The reductions in cumulative emissions are found to be in the range of 11-23 % for different countries. Although emissions decrease compared to the BAU scenario, the reduction is not substantial compared to the M1 scenario.

In the M3 scenario, electric and hydrogen kiln reaches twice the share as in the M2 scenario. The use of novel cement is also included. With higher rates of material efficiency and electric and hydrogen kiln, the emission reduction is highest in the M3 scenario.

Now, emissions are analysed with CCS technology implemented in the model. There is a significant reduction in emissions observed after the introduction of CCS. As observed earlier, the M3 scenario has the highest reduction in cumulative emissions compared to the BAU scenario. This is because of the faster adoption of CCS and other mitigation options. In other mitigation scenarios, cumulative emission reductions are lower due to slower adoption rates of CCS.

It is not possible to eliminate emissions even if all existing kilns are replaced with hydrogen and electric kilns as process emissions from calcination will persist. Hence, CCS is expected to be the leading decarbonisation technology with the most impact on emissions.

***Analysis of fuel emissions and process emissions***

As described before, emissions from cement production can be classified into fuel emissions, process emissions and indirect emissions from electricity and hydrogen production. Process emissions can be mitigated mainly by lowering the clinker to cement ratio and implementing CCS and material efficiency. Fuel emissions can be mitigated by all measures discussed before.

The share of process emissions and fuel emissions in total emissions is analysed. Process emissions directly result from clinker production, whereas fuel emissions are directly impacted by the type of fuel used for clinker production. Therefore, in the beginning, fuel emissions have a higher share since countries rely primarily on fossil fuels for their cement production. As biomass uptake increases, fuel emissions decrease, and the share of process emissions increase in total emissions.

Within Europe, Germany has much lower fuel emissions from the start due to high biomass use. In terms of shares in total emissions, China and India have a lower share of process emissions since their clinker to cement ratio is much lower than European countries.

| | **Fuel emissions** | | | **Process emissions** | | |
|---|---|---|---|---|---|---|
| **Country** | **M1 scenario** | **M2 scenario** | **M3 scenario** | **M1 scenario** | **M2 scenario** | **M3 scenario** |
| **Germany** | 94 % | 97 % | 98 % | 93 % | 95 % | 96 % |
| **Italy** | 97 % | 98 % | 99 % | 93 % | 95 % | 96 % |
| **Spain** | 95 % | 97 % | 98 % | 93 % | 94 % | 95 % |
| **China** | 95 % | 97 % | 98 % | 89 % | 91 % | 92 % |
| **India** | 93 % | 96 % | 98 % | 84 % | 86 % | 89 % |

**Table 7.2 Decrease in fuel and process emissions in 2050 for mitigation scenarios as compared to the 2018 levels**

Further analysis is also done to understand the role of CCS in process and fuel emissions, as shown in table 7.2. Results show that fuel emissions are almost mitigated in the M3 scenario for all countries whereas process emissions are mitigated to a slightly lesser extent. For example, in India and China, 8% and 11% of process emissions are left compared to 2018 levels. This is mostly because of increasing cement (clinker) demand in these countries.

The following main conclusions can be drawn from the emission pathways results. Firstly, in European countries, the significant emissions which remain are only process emissions. Secondly, mitigation of both process and fuel emissions is faster when CCS is implemented.

***Analysis of indirect emissions***

Indirect emissions result from the generation of hydrogen and electricity. Results show that electricity emissions are higher in the M3 scenario than in the M2 scenario, with increased electricity use due to the high share of electric kilns and faster adoption of CCS. Furthermore, as electricity is assumed to be decarbonised by 2060 in India and China, electricity emissions remain high until 2050 in these countries.

Electricity emissions are analysed further. The breakdown of electricity emissions shows that electricity emissions are the highest from the production of clinker. The second highest electricity emissions are from grinding processes until an electric kiln is introduced. With the faster adoption of an electric kiln, the emission from electricity use to heat electric kiln become as high as from clinker production.

The use of hydrogen for heating hydrogen kilns starts from the year 2035 in M2 and M3 scenarios. Although blue hydrogen is used only from 2035 to 2040 in the M2 scenario, it constitutes a significant portion (30-40 %) of emissions arising from hydrogen use. On the other hand, in the M3 scenario, only the use of green hydrogen is assumed. Hydrogen emissions are higher in the M3 scenario than M2 due to the higher share of hydrogen kiln.

## 7.2 Implications for net-zero transition

Residual emissions remain in all scenarios, and therefore, net-zero emissions are not achieved. It is further found that compared to the base year, a similar level of emission reduction is achieved in all mitigation scenarios in 2050. However, cumulative emissions vary a lot. For example, in Italy, emissions in 2050 reduce by 94 % in M1 and 96% in M3 compared to the 2018 level. Compared in terms of cumulative emissions, results show that pursuing the M1 pathway instead of the M3 pathway adds an extra 37% emissions compared to M1. Similar results are seen for other countries as well. This implies that the path taken for decarbonisation is more important than achieving the net-zero emission target.

| **Target** | **India (M1)** | **India (M2)** | **India (M3)** | **China (M1)** | **China (M2)** | **China (M3)** |
|---|---|---|---|---|---|---|
| **1.5°C** | 0.9 % | 0.7 % | 0.6 % | 5.3 % | 4.5 % | 3.6 % |
| **2°C** | 0.3 % | 0.3 % | 0.2 % | 2 % | 1.7 % | 1.3 % |

**Table 7.3 Share of cumulative emissions of the mitigation pathways in the remaining global carbon budget corresponding to 1.5°C and 2°C**

An analysis is also done to understand what the cumulative emissions from the cement sector mean to achieve 1.5°C and 2°C targets. This has been done by calculating the share of carbon space occupied by Indian and Chinese cement production in the remaining global carbon budget corresponding to 1.5°C and 2°C, as shown in table 7.3. Only India and China are considered due to their high cement production capacity.

Analysis shows that the Chinese cement industry occupies a high share in the remaining global carbon budget corresponding to the 1.5°C limit. The cumulative emissions of the mitigation pathways compared consider the use of CCS. If CCS is not used, the carbon space occupied by Indian and Chinese cement companies increases up to 2 times the estimated carbon space. This would have significant implications for both the 1.5°C and 2°C targets. Furthermore, the mitigation pathways of China’s cement industry are in line with China’s commitment (INDC) to peak emissions by 2030 or before.

# 8. Discussion

This chapter will discuss the method and result of the thesis. First, the uncertainty regarding various decarbonisation approaches is discussed in section 8.1. Second, implications of transition pathways and what should be done for deeper decarbonisation is discussed in section 8.2. Next, the results of this study are compared to relevant studies (section 8.3), and the limitation of the study is discussed (section 8.4). Finally, recommendations for the study are stated in section 8.5.

## 8.1 Uncertainty in modelling assumptions

There are several uncertainties associated with scenario modelling, as for some of the decarbonisation options, broad assumptions have been taken.

***Carbon capture technologies***

Results show that one of the crucial technologies required for rapid emission reduction is CCS. The requirement of CCS increases with fewer mitigation options adopted. For example, in the case of Germany, the required CCS capacity in the M1 scenario reaches 8 MT by 2050. The CCS capacity reduces to 5 MT in the M3 scenario. In the case of India, the CCS capacity requirement is very high, ranging from 127 MT to 184 MT by 2050. Thus, the model assumes the availability of large CCS capacity to achieve rapid decarbonisation. The storage infrastructure is implicitly assumed with the assumption of capturing 90 percent emissions by 2050. However, there remains high uncertainty regarding the adoption rate of CCS to the level required.

Currently, the globally installed CCS facilities can store 40 MT of $CO_2$ per year. Most of this captured $CO_2$ is reinjected into oil and gas fields to extract more fossil fuel (Page et al., 2021). In addition, there are very few geological $CO_2$ sites at present. Therefore, the biggest bottleneck for the fast adoption of CCS is the storage and transportation infrastructure required for the vast amount of captured $CO_2$.

The next uncertain assumption about CCS is its thermal energy consumption. It is assumed that this thermal energy is supplied by biomass to achieve negative emissions. However, if thermal energy required by CCS is to be supplied by fossil fuels, more thermal energy will be required to capture additional emissions from fossil fuel combustion. In practice, it is possible to utilise the excess heat generated during cement production for capturing emissions. However, this is not considered as the waste heat recovery (WHR) system has been not considered in the model. If WHR had been implemented, biomass used for thermal energy could have been reduced.

Furthermore, the model assumes the use of MEA scrubbing technology in all countries to simplify calculations. However, many research projects for CCS technologies such as calcium looping, oxyfuel combustion and direct separation are also being conducted, which could play a role in the future.

### Alternative fuel use

Another uncertain assumption is about alternative fuel use. For countries with currently low alternative fuel share, the share is assumed to increase similarly to Germany and Austria, which have achieved faster adoption of alternative fuels. It remains to be seen whether countries like India and China which have huge waste requirements can meet these needs by 2050. As per current predictions, many studies (CMA India, n.d.-b; SINTEF, n.d.) suggest that India and China can increase waste fuel in cement kilns due to their increasing municipal solid waste. Cement manufacturers in both countries plan to substitute 20-30 % of fossil fuel used with waste in the next decade. Cement manufacturers in China plan to increase the use of plastic and industrial waste as fuel. CMA India (n.d) shows that with the current amount of municipal solid waste generated in India, it is possible to substitute up to 10-15 % of the fossil fuels used in cement kilns by 2025.

Similar uncertainty remains in biomass as well, as other sectors compete for biomass use, whether the cement sector will achieve and sustain such a high share of biomass remains uncertain.

### Electric and hydrogen kiln

Electric and hydrogen kiln are still in the prototype stage today. Hence, it is not possible to accurately predict the share of electric and hydrogen kilns. The electric and hydrogen kiln uptake assumptions have largely been made based on their current TRL and literature.

### Clinker to cement ratio

The clinker to cement ratio is assumed to linearly decrease to 0.52 by 2050 based on the GCCA forecast (GCCA, 2021). It is assumed that with the availability of calcined clays and natural pozzolans. However, the use of these clinker substitutes depends on their cost and regional availability.

### Lack of data

The uncertainty in modelling also arises from a lack of data. Hence, there is a need to take broad assumptions or skip certain aspects in energy modelling. For example, in the case of China, the current use of biomass and waste is unknown. Furthermore, there is a lack of publicly available data for the urbanisation rate of countries and fixed asset investment into the construction sector, due to which simplified assumptions for cement demand projection have been taken.

## 8.2 Deep decarbonisation

Results from *SQ4* show that carbon space occupied by Indian and Chinese cement production would have significant implications for the 1.5°C target. In other words, even in the most ambitious M3 scenario, the Chinese and Indian cement industries will consume 4.2% of the total remaining carbon budget together. Therefore, it is crucial that countries, especially developed countries, try to reduce their emissions even further than suggested in this study since developing countries, primarily concentrated in Asia and Africa, will increase their cement production in the future.

To understand how emissions can be reduced further, residual emissions are analysed. The breakdown of residual emissions in 2050 shows that the residual emissions majorly consist of process emissions. Thus, residual process emissions need to be tackled with additional measures. As clinker substitution is achieved to its maximum potential in all scenarios, other mitigation options such as novel cement, $CO_2$ capture, and material efficiency should be adopted at a higher level.

It is also observed that fuel emissions have been mitigated to a large extent due to fuel switching to biomass, hydrogen, and electricity. The residual fuel emissions which remain in 2050 are mostly from waste use. For further mitigation of fuel emissions, uptake of hydrogen and electric kilns should increase, which would replace the use of waste in dry kilns.

## 8.3 Comparison to other studies

The goal of this thesis is to understand the role of different energy carriers in achieving net-zero emissions. Results of this study are compared with similar studies found in the literature. Studies that include scenario analysis focusing on a single emerging technology are excluded. Comparison has been made with *IEA Net Zero 2050 (2021)* and *IEA Technology Roadmap (2018)* studies, which includes various mitigation options. The IEA Net-zero study considers all decarbonisation options used in this study except for novel cement. IEA Technology Roadmap (2018) uses only decarbonisation options such as energy efficiency, clinker to cement reduction, CCS, and material efficiency.

The basis of comparison of these studies is the thermal energy demand in 2050. As IEA (2021) and IEA (2018) are being conducted at a global level, the countries' energy demand cannot be compared on absolute values. Therefore, the basis of comparison is the thermal energy mix in 2050. M2 scenario and IEA (2021) have similar assumptions, with around a total 15 % share of electric and hydrogen kilns. In addition, the M1 scenario and IEA (2018) study are similar with no adoption of electric and hydrogen kiln and novel cement. Table 8.1 shows the thermal energy mix of mitigation scenarios of this study, IEA (2018) and IEA (2021).

In this thesis, the same assumptions for all countries are used regarding fuel switch to alternative fuel and penetration of electric and hydrogen kiln. Hence, for a given decarbonisation pathway, a similar thermal energy mix is reached by all countries in 2050. Furthermore, the role of fossil fuel becomes significantly less in 2050 as compared to the IEA studies.

| | This study (M1 scenario) | This study (M2 scenario) | This study (M3 scenario) | IEA Net-zero 2021 | IEA Cement Roadmap 2018 |
|---|---|---|---|---|---|
| **Coal** | 3 - 8 % | 0 - 3 % | 0 - 0.2% | 0 % | 40 % |
| **Oil** | 1 - 4 % | 0 - 4 % | 0 - 0.1% | 0 - 20% | 10 % |
| **Natural gas** | 0 - 6% | 0 % | 0% | 40 % | 10 % |
| **Biofuel** | 27 % | 27 % | 28 - 31% | 35 % | 10 % |
| **Waste** | 62 % | 60 - 62 % | 43 - 46% | 0 - 20% | 20 % |
| **Hydrogen** | 0 % | 5 - 6 % | 10 - 11% | 0 - 15% | 0 % |
| **Electricity** | 0 % | 6 - 9 % | 13 - 18% | 0 - 15% | 0 % |

**Table 8.1 Comparison of thermal energy mix in 2050 with similar studies**

Comparison between the IEA (2018) study and M1 scenario and the IEA (2021) study and M2 scenario yield similar conclusions. Firstly, there is a higher reliance on fossil fuels in IEA studies, especially natural gas, whereas, in this thesis, there is more reliance on alternative fuels, like waste and biofuel. Moreover, in this study, fossil fuel use has been almost phased out in all mitigation scenarios.

## 8.4 Limitations of the study

In this thesis, it has been attempted to include as many decarbonisation options as possible. However, some decarbonisation options have been left out. For example, the waste heat recovery (WHR) system commonly used in India and China is not considered as the current implementation rate of this mitigation strategy is not known for all countries. Thus, the on-site power generated by the WHR system is not considered, and thereby, the emissions from electricity use could be overestimated.

Another mitigation strategy used is increasing the use of alternative fuels in all scenarios. Alternative fuel use, specifically biomass, can increase thermal energy demand due to its lower calorific value (Benhelal et al., 2013). However, since the exact composition of biomass and waste is unknown, the increase in thermal energy demand cannot be computed.

Another limitation is that naturally occurring re-carbonation is not considered. Many studies show that cement naturally absorbs up to 23 % of emissions over its lifetime (Stripple et al., 2018). The scope of the study is limited to cement production and does not look at its entire lifecycle.

In this study, the model calculates the combined effect of introducing different mitigation options at once, making it difficult to compute the contribution of each mitigation option separately. This would have made the comparison with other studies more detailed and comprehensive.

## 8.5 Recommendations for future research

Other than the previously mentioned limitations, some more things could improve this study. For instance, this study does not include any cost parameters. Fuel costs and technology costs could have been considered for deciding which kiln technology would be preferred in the future.

Furthermore, this study utilizes the historical rate for phasing out inefficient kiln technologies. Another consideration for future work could be to classify cement plants based on their age. For plants that are older than a certain age, they could be phased out with newer kiln technologies. Medium age and new plants could be retrofitted with CCS.

# 9. Conclusion and Recommendations

This chapter will discuss the main conclusions obtained from all the research questions in section 9.1. Next, recommendations to the cement industry (in section 9.2) and policymakers (in section 9.3) regarding conventional and emerging decarbonisation options are discussed.

## 9.1 Conclusion

This study aimed to develop decarbonisation pathways for the cement sector to achieve net-zero emissions by 2050. The main research question that has been looked at is:

***"What is the role of different energy supply-side options for the cement industry for transitioning towards net-zero emissions by 2050?"***

The main research question can be answered now that the analysis of energy and emissions has been done. In chapter 6, energy demand analysis showed how energy demand would develop in different scenarios. However, the role of different energy carriers has not been analysed so far. The role of different energy carriers depends on the assumptions taken for decarbonisation, such as uptake of alternative fuel, hydrogen and electric kiln and is analysed below for the three mitigation pathways.

Fossil fuel is found to play an important role in the short to medium term since the transition to alternative fuel takes time. In India and China, coal use remains high in the next two decades due to relatively slower uptake of alternative fuels and rising cement demand. In European countries, the role of natural gas is seen to be relatively moderate in the short term, as there is faster uptake of alternative fuels.

In the medium to long term, the role of alternative fuels is seen to be very important as fossil fuels begin to phase out. The role of biomass is seen to be particularly important due to its carbon neutrality. Biomass also plays a role in providing thermal energy for operating CCS technology.

Electricity and hydrogen are found to have moderate roles since electric kilns and hydrogen kilns are introduced later and their shares are quite low compared to conventional kilns. Electricity demand increases due to CCS as well, but this demand is not very high. It is important to note, low carbon energy carriers can only eliminate only fuel related emissions. For mitigating process emissions, decarbonisation options such as the uptake of material efficiency, novel cement and CCS and reduction of clinker to cement ratio have been implemented.

Next, main conclusion found from sub research questions are discussed:

### *SQ1: "What are the characteristics of the cement sector in terms of the sector's energy use, its decarbonisation options, cement manufacturers' commitments and relevant government policies?"*

First, *SQ1* is answered by providing an overview of countries' energy use, decarbonisation options and climate commitments made by the cement manufacturers. Following observations are made for India, China, and European countries - Italy, Germany, and Spain. India and China have a high share of fossil fuels in their thermal energy demand. European countries are ahead of India and China regarding their alternative fuel use but are behind in thermal energy efficiency. When looking at the clinker to cement ratio, China has the lowest clinker to cement ratio, followed by India, Germany, Italy, and Spain. Finally, many major European and Indian cement companies have committed to reducing their $CO_2$ emissions. Regarding energy efficiency measures, China and India have already installed kilns of BAT standard and, hence, have limited improvement potential.

### *SQ2: "How will the demand for cement develop?"*

SQ2 looks at cement demand projections for countries. It is seen that for EU countries, demand either decreases or remains constant. For India, demand is seen to rise rapidly in earlier years, with the growth rate decreasing over time. For China, demand is also seen to rise, with the maximum cement production reaching around 2040.

### *SQ3: "How would the energy demand for the cement industry develop?"*

In chapter 6, total energy demand for different decarbonisation scenarios is analysed and compared to the business-as-usual scenario. The total energy demand of European countries is declining, and of India and China, it is increasing. The demand for fossil fuel decreases for all countries by 2050. Alternative fuel demand depends on its initial share in total thermal energy demand. Countries with an initially low share of alternative fuel have faster growth of alternative fuel demand and vice-versa. Biomass demand for CCS also increases with greater adoption rates.

The M2 and M3 scenario results show that coal and oil could be phased out sooner than natural gas for European countries. For China, oil and natural gas phase-out occur around the same year, and coal is phased out in some years. For India, no phase-out of fossil fuel occurs, although the share of fossil fuel remains very low.

### *SQ4: "What are the implications of this energy transition in terms of cumulative emissions?"*

In chapter 7, cumulative $CO_2$ emissions for different decarbonisation scenarios are analysed. Results show that the Chinese cement industry occupies a significant share of the remaining carbon budget corresponding to 1.5°C limit target. Furthermore, if CCS technology is not adopted, carbon space occupied by Indian and Chinese cement industry would increase up to two times.

## 9.2 Recommendations to the cement industry

### ***Energy efficiency***

The model made assumptions about electric and hydrogen kilns as per their maturity level and mitigation potential. In reality, the deployment of these technologies would be dependent on policies and economic incentives. Until new kilns are not deployed, the short term focus should be improving energy efficiency. Cement manufacturers should invest in upgrading existing kilns to BAT technology kilns which are currently the dry kiln with preheater and precalciner. New cement kilns if being deployed should only be of BAT standards to avoid lock-in of emissions.

### **Electricity**

Electricity demand will increase with the increased use of CCS. Cement plants should adopt waste heat recovery (WHR) technologies to generate electricity. Besides WHR technologies, cement plants should invest in both onsite and offsite renewable electricity production to reduce reliance on grid electricity.

### ***Alternative fuel use***

The cement industry in India and China still has very high use of fossil fuels. In addition, given the increasing waste in India, the adoption of waste is an opportunity to solve the waste problem and decrease the reliance on fossil fuel, mainly imported coal. The cement industry in these countries should increase alternative fuels by implementing good waste management practices.

### ***Clinker substitution***

As fly ash and blast furnace slag will decline over the years, with the decarbonisation of the power sector, cement plants should look for other clinker substitutes, preferably in their geographical proximity. For instance, China has large stockpiles of clay available, which could be used as calcined clay. India has fly ash and blast furnace slag available in the short to medium term. But in the longer term, calcined clays could be used as an option. European cement plants could use large volcanic rocks and ash stocks available in Greece and Italy as clinker substitutes.

### ***Carbon capture use***

Results show that CCS is the only option to mitigate emissions substantially, especially the process emissions. Hence, retrofitting cement plants with carbon capture equipment will be necessary, especially for the new cement plants added in the last decade. Furthermore, cement plants with access to sustainable biomass could use biomass combined with CCS to generate net negative emissions.

The captured $CO_2$ from the cement industry presents an opportunity for its use in industrial processes. Currently, captured $CO_2$ is mainly used for enhanced oil and gas recovery. The cement industry could industrial symbioses to create more sustainable products in the chemical and construction sectors. Specifically, captured $CO_2$ can be used to make value-added chemicals and to cure concrete instead of using water (CEMBUREAU, 2020).

***Material efficiency***

Results show that adopting material efficiency measures have a moderate impact on emission reduction. However, in practice, cement is used in concrete composition on an average of 20% more than recommended by international standards (Favier et al., 2018). Thus, to reduce cement demand, better standards for concrete mix should be developed. Furthermore, for the adoption of material efficiency, action would be required from actors in the construction sector.

Furthermore, cement companies should set voluntary climate commitment goals based on science-based targets. Setting these climate targets sends a signal to policymakers and investors about a need for low carbon transition.

## 9.3 Policy recommendations

***Carbon capture technology***

Governments will have to plan for the storage and transport infrastructure of the large volume of $CO_2$. The cement industry's CO2 transport and storage network should be developed considering geological storage sites' potential and proximity to cement plants. In China and Europe, identification of industrial CO2 sources and potential geographical storage has already been done (IEA, 2021a). However, in the case of India, this mapping has not been done, but studies show that the potential for $CO_2$ storage capacity in saline aquifers (291 Gt of $CO_2$) is much higher than $CO_2$ storage capacity through enhanced oil recovery (2.8 Gt of $CO_2$) (Vishal et al., 2021). Thus, if the saline storage capacity in India is managed properly, it can store the estimated CO2 from the cement plants quite easily.

Furthermore, many countries will require a legal framework for building CCS infrastructure (Lehne & Preston, 2018). In addition, for $CO_2$ storage under land, public acceptance would also be required.

***Alternative fuel use***

Governments should create waste management regulations that encourage increased use of alternative fuel use by in cement plants. Furthermore, the regulations should promote alternative fuel use in cement plants instead of landfilling and incineration.

***Clinker substitution***

The use of low carbon cement in the market should be encouraged by standardising low carbon cement. Furthermore, as conventional clinker substitutes such as fly ash and slag are depleting, access to new clinker substitutes such as calcined clays and pozzolana should be facilitated. It is also necessary that clinker to cement ratio standards get updated for increased use of clinker substitutes.

### *Electricity and Hydrogen infrastructure*

With the deployment of electric and hydrogen kilns, the need for clean electricity and low carbon hydrogen will increase. There will also be an additional need for electricity to operate carbon capture technologies. Thus, reliable renewable energy and hydrogen infrastructure would be needed to meet the increased demand. The planning and deployment of the required infrastructure should start now to avoid any delay in the uptake of new kiln technologies. Furthermore, the cost of renewable energy and hydrogen should not remain a barrier to the uptake of new kiln technologies.

### *Financial support*

One of the commonly used policy approaches is carbon pricing. Carbon prices should be high enough to incentivise cement producers to invest in low carbon technologies and novel cement production. Furthermore, government subsidies should be in place for faster adoption of expensive technologies such as hydrogen and electric kiln technologies and CCS.

For accelerating decarbonising in developing countries, additional financial support would be needed. TERI (2021) shows that Indian cement plants have been experiencing declining profits over the last few years, despite the energy efficiency measures. International climate finance could support in scaling up the green transition in developing countries.

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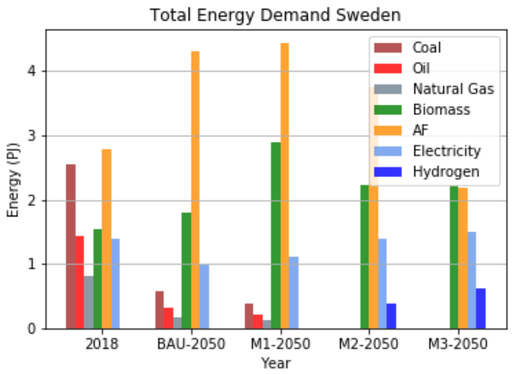
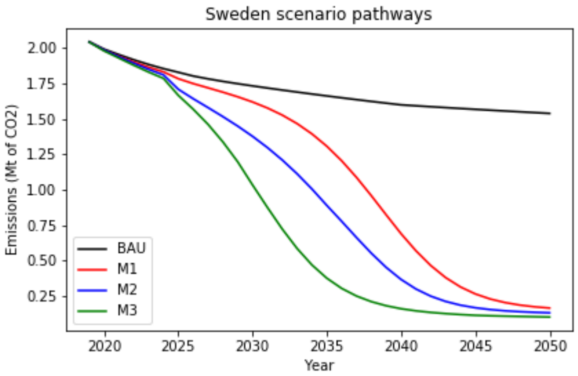
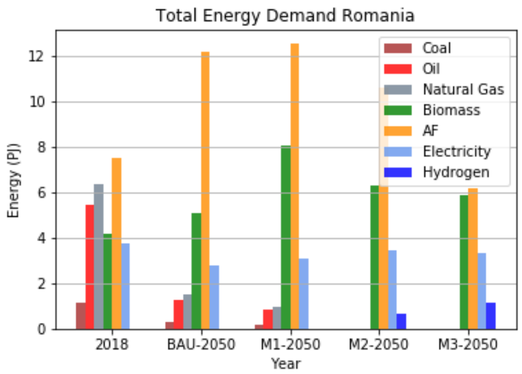
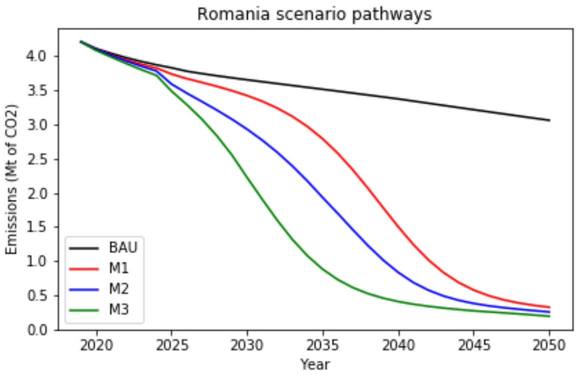
# Appendix

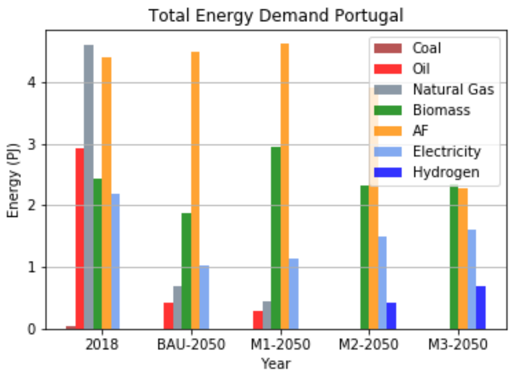
## Appendix A: Graphs of total energy demand and scenario pathways for the other countries

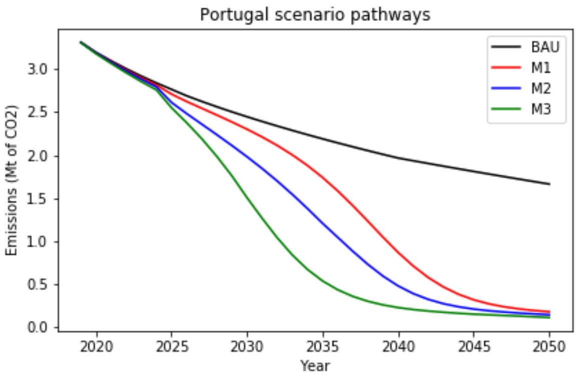


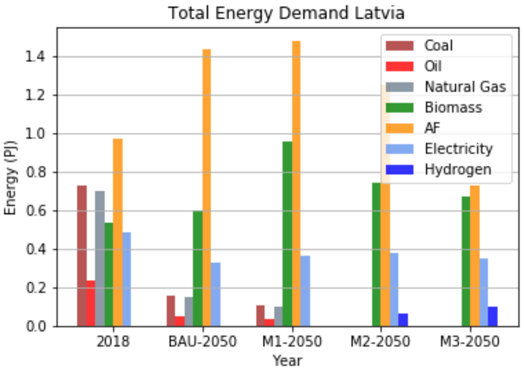


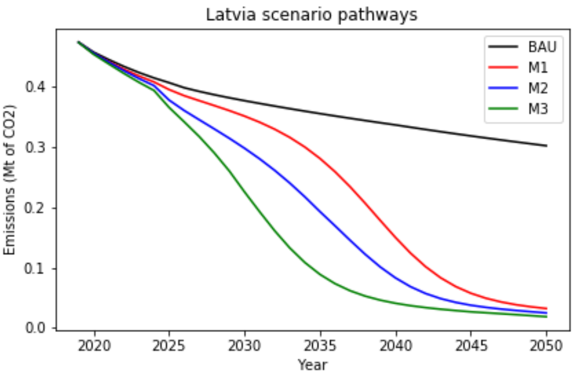


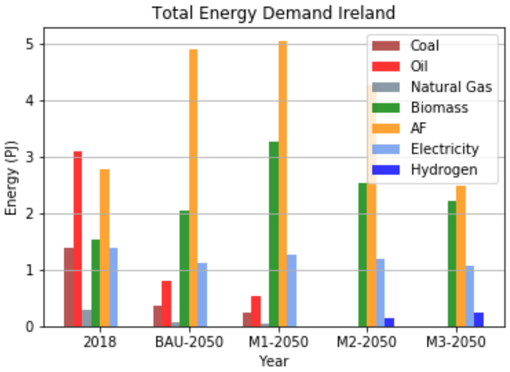


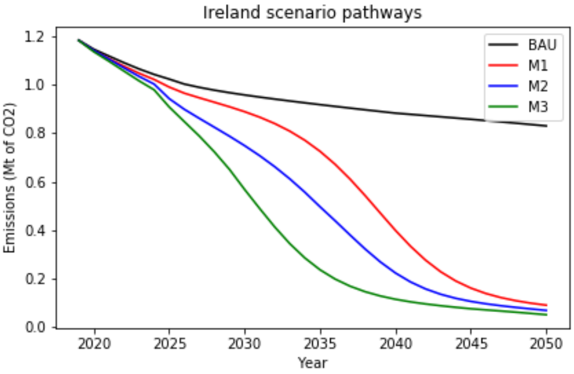





Total Energy Demand Latvia
Energy (PJ)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
2018
BAU-2050
M1-2050
M2-2050
M3-2050
Year
Coal
Oil
Natural Gas
Biomass
AF
Electricity
Hydrogen


Latvia scenario pathways
Emissions (Mt of CO2)
0.0
0.1
0.2
0.3
0.4
2020
2025
2030
2035
2040
2045
2050
Year
BAU
M1
M2
M3


Total Energy Demand Ireland
Energy (PJ)
0
1
2
3
4
5
2018
BAU-2050
M1-2050
M2-2050
M3-2050
Year
Coal
Oil
Natural Gas
Biomass
AF
Electricity
Hydrogen


Ireland scenario pathways
Emissions (Mt of CO2)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
2020
2025
2030
2035
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2045
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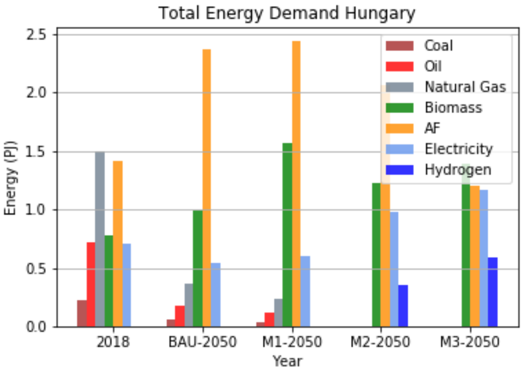
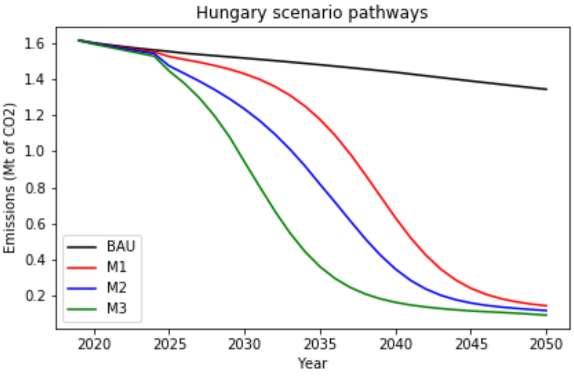
Year
BAU
M1
M2
M3


Total Energy Demand Hungary
Energy (PJ)
0.0
0.5
1.0
1.5
2.0
2.5
2018
BAU-2050
M1-2050
M2-2050
M3-2050
Year
Coal
Oil
Natural Gas
Biomass
AF
Electricity
Hydrogen


Hungary scenario pathways
Emissions (Mt of CO2)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
2020
2025
2030
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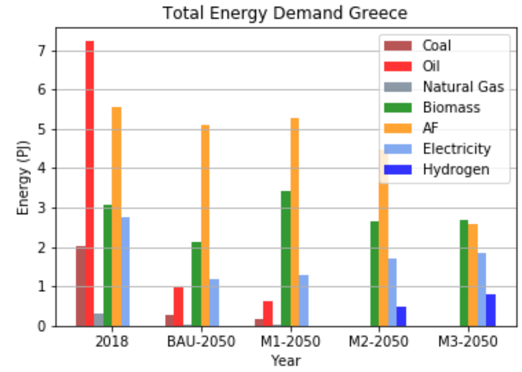
2040
2045
2050
Year
BAU
M1
M2
M3


Total Energy Demand Greece
Energy (PJ)
0
1
2
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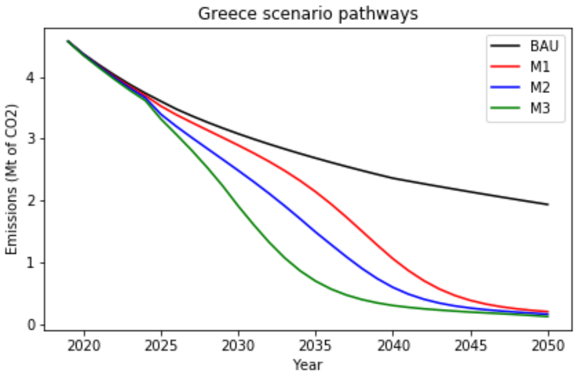
4
5
6
7
2018
BAU-2050
M1-2050
M2-2050
M3-2050
Year
Coal
Oil
Natural Gas
Biomass
AF
Electricity
Hydrogen


Greece scenario pathways
Emissions (Mt of CO2)
0
1
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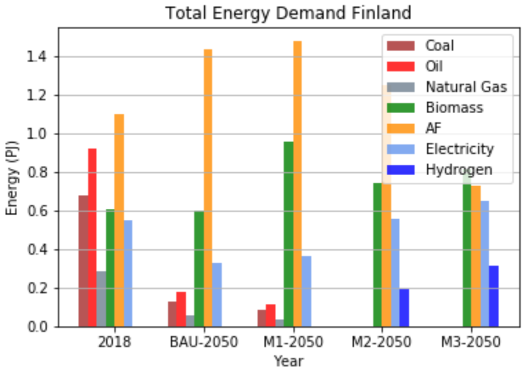
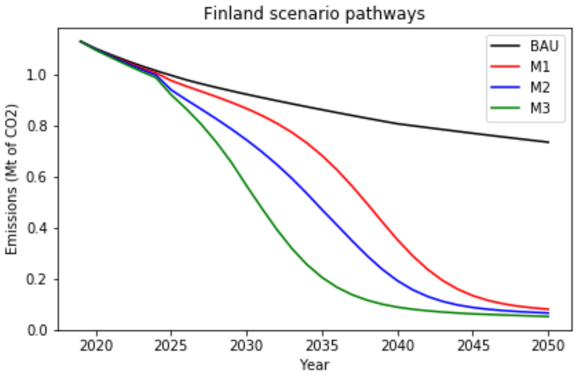
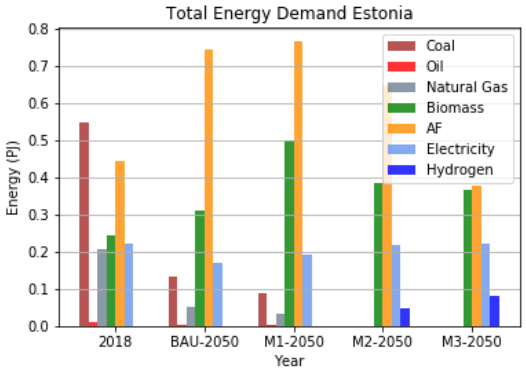
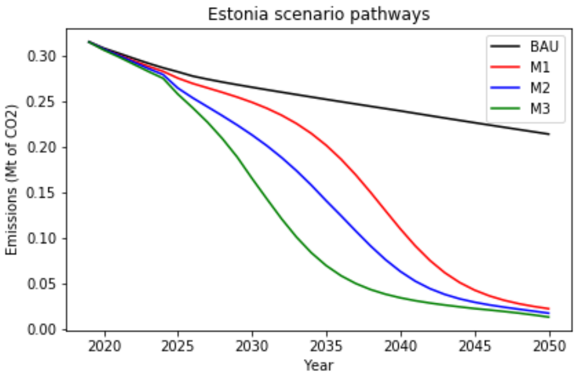
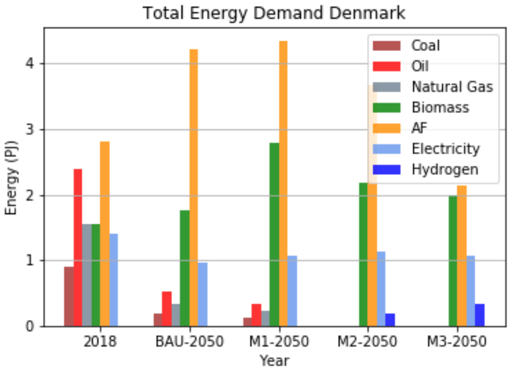
3
4
2020
2025
2030
2035
2040
2045
2050
Year
BAU
M1
M2
M3

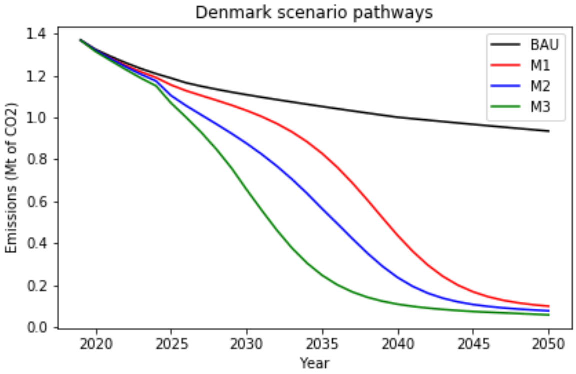

Total Energy Demand Finland
Energy (PJ)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
2018
BAU-2050
M1-2050
M2-2050
M3-2050
Year
Coal
Oil
Natural Gas
Biomass
AF
Electricity
Hydrogen

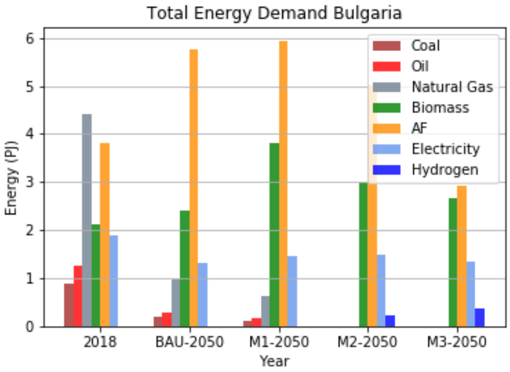

Finland scenario pathways
Emissions (Mt of CO2)
0.0
0.2
0.4
0.6
0.8
1.0
2020
2025
2030
2035
2040
2045
2050
Year
BAU
M1
M2
M3

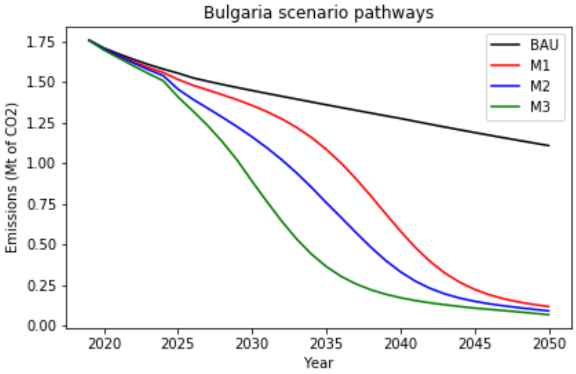

Total Energy Demand Estonia
Energy (PJ)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
2018
BAU-2050
M1-2050
M2-2050
M3-2050
Year
Coal
Oil
Natural Gas
Biomass
AF
Electricity
Hydrogen

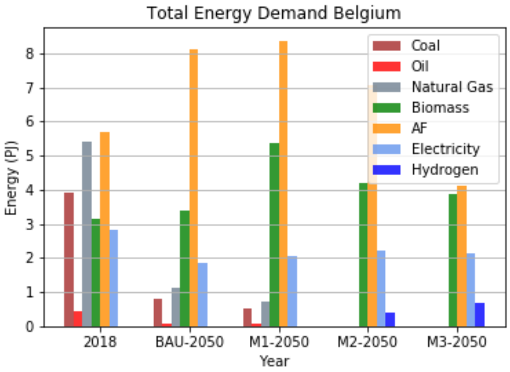

Estonia scenario pathways
Emissions (Mt of CO2)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
2020
2025
2030
2035
2040
2045
2050
Year
BAU
M1
M2
M3

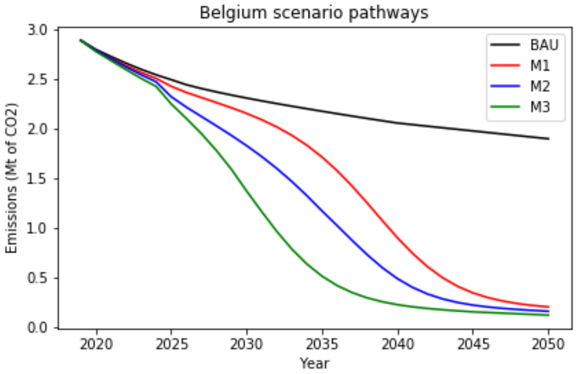

Total Energy Demand Denmark
Energy (PJ)
0
1
2
3
4
2018
BAU-2050
M1-2050
M2-2050
M3-2050
Year
Coal
Oil
Natural Gas
Biomass
AF
Electricity
Hydrogen

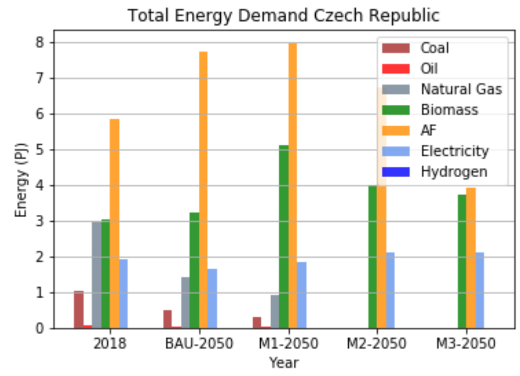

Denmark scenario pathways
Emissions (Mt of CO2)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
2020
2025
2030
2035
2040
2045
2050
Year
BAU
M1
M2
M3

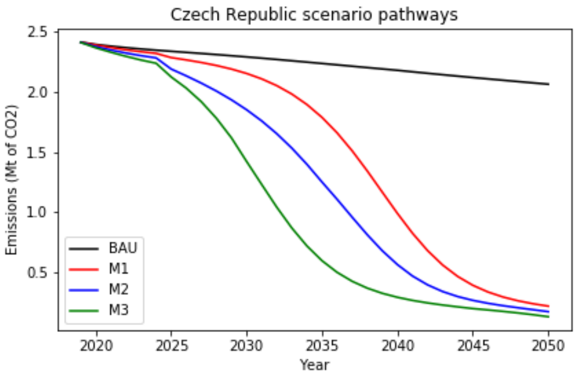

Total Energy Demand Bulgaria
Energy (PJ)
0
1
2
3
4
5
6
2018
BAU-2050
M1-2050
M2-2050
M3-2050
Year
Coal
Oil
Natural Gas
Biomass
AF
Electricity
Hydrogen

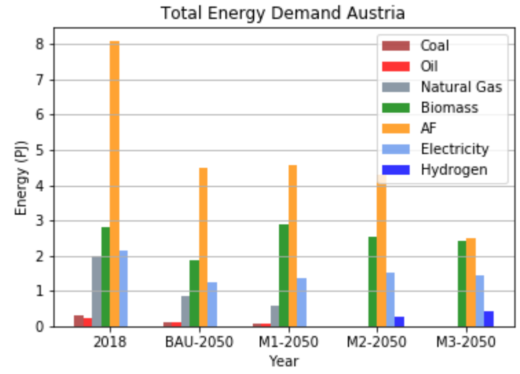

Bulgaria scenario pathways
Emissions (Mt of CO2)
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2020
2025
2030
2035
2040
2045
2050
Year
BAU
M1
M2
M3

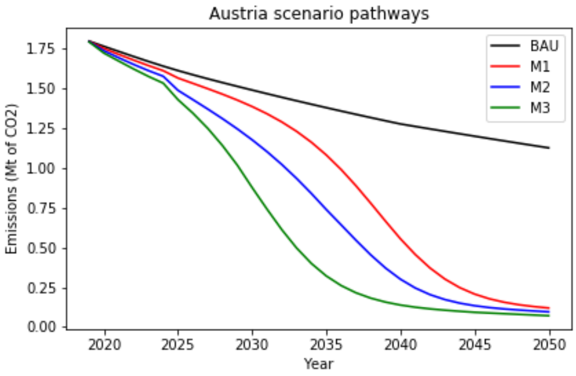

Total Energy Demand Belgium
Energy (PJ)
0
1
2
3
4
5
6
7
8
2018
BAU-2050
M1-2050
M2-2050
M3-2050
Year
Coal
Oil
Natural Gas
Biomass
AF
Electricity
Hydrogen

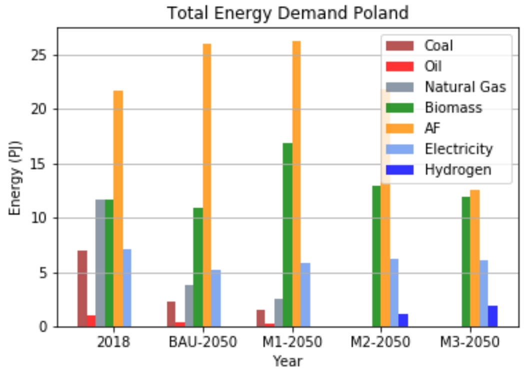

Belgium scenario pathways
Emissions (Mt of CO2)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
2020
2025
2030
2035
2040
2045
2050
Year
BAU
M1
M2
M3

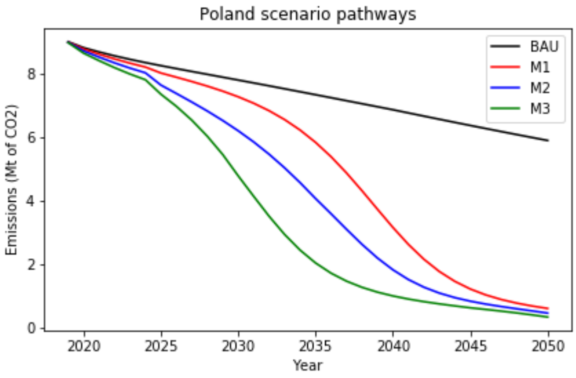

Total Energy Demand Czech Republic
Energy (PJ)
0
1
2
3
4
5
6
7
8
2018
BAU-2050
M1-2050
M2-2050
M3-2050
Year
Coal
Oil
Natural Gas
Biomass
AF
Electricity
Hydrogen


Czech Republic scenario pathways
Emissions (Mt of CO2)
0.5
1.0
1.5
2.0
2.5
2020
2025
2030
2035
2040
2045
2050
Year
BAU
M1
M2
M3

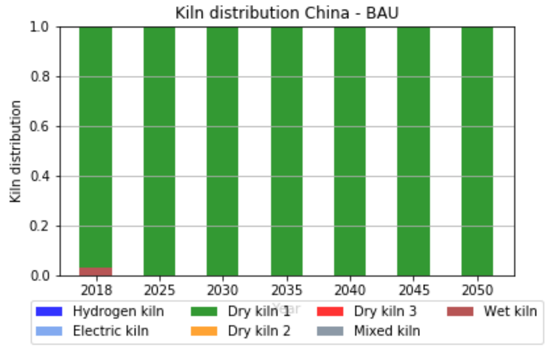

Total Energy Demand Austria
Energy (PJ)
0
1
2
3
4
5
6
7
8
2018
BAU-2050
M1-2050
M2-2050
M3-2050
Year
Coal
Oil
Natural Gas
Biomass
AF
Electricity
Hydrogen

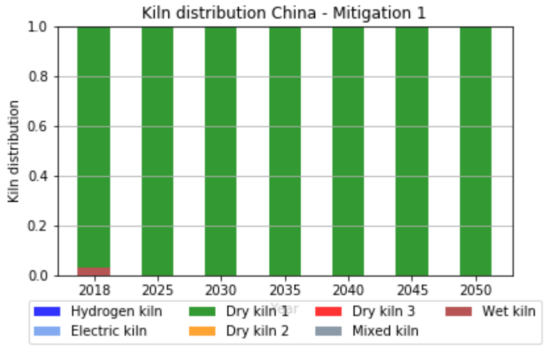

Austria scenario pathways
Emissions (Mt of CO2)
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2020
2025
2030
2035
2040
2045
2050
Year
BAU
M1
M2
M3

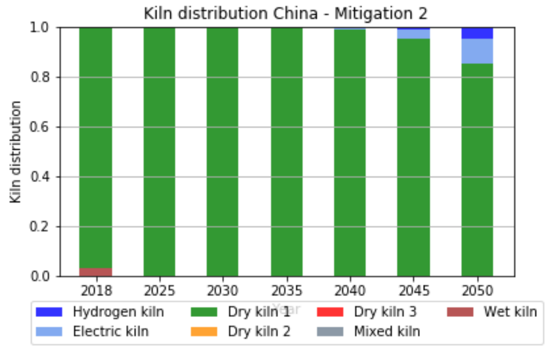

Total Energy Demand Poland
Energy (PJ)
0
5
10
15
20
25
2018
BAU-2050
M1-2050
M2-2050
M3-2050
Year
Coal
Oil
Natural Gas
Biomass
AF
Electricity
Hydrogen

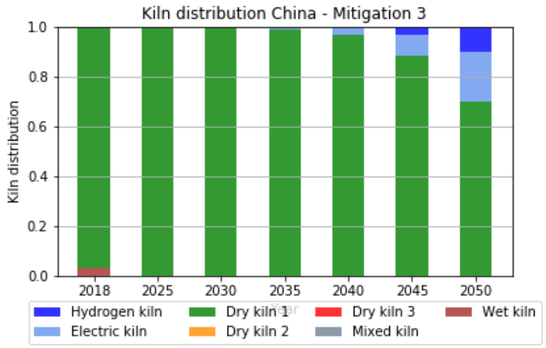

Poland scenario pathways
Emissions (Mt of CO2)
0
2
4
6
8
2020
2025
2030
2035
2040
2045
2050
Year
BAU
M1
M2
M3

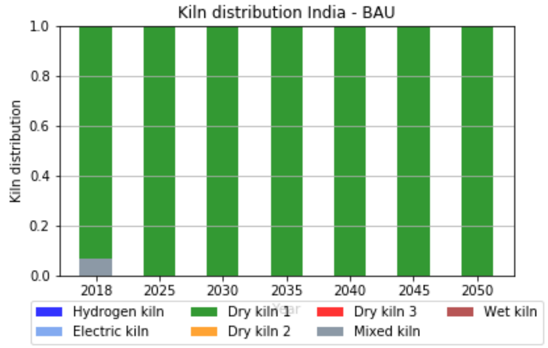
## Appendix B. Kiln Distribution for China, India, Spain, and Italy

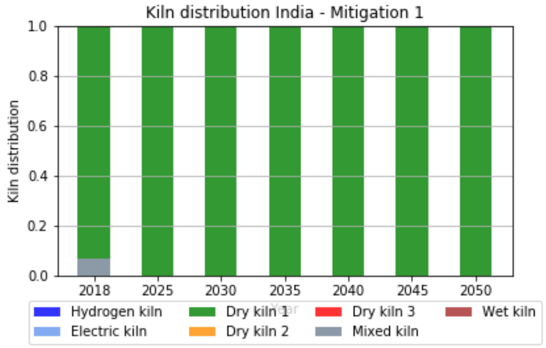


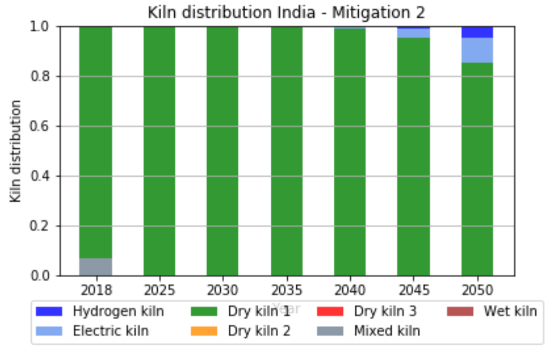


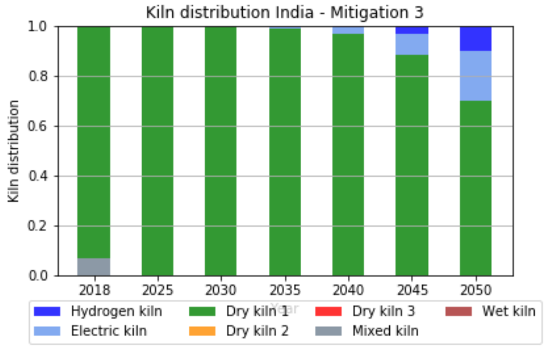




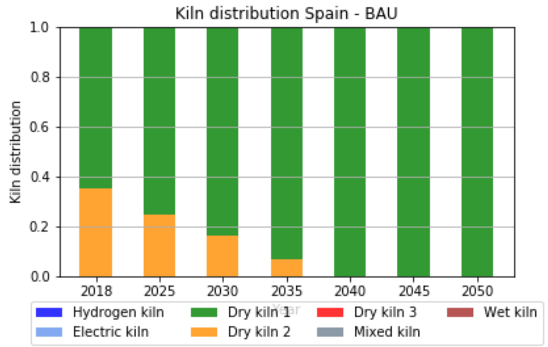


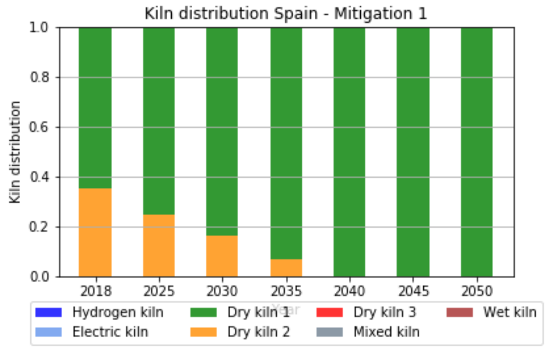


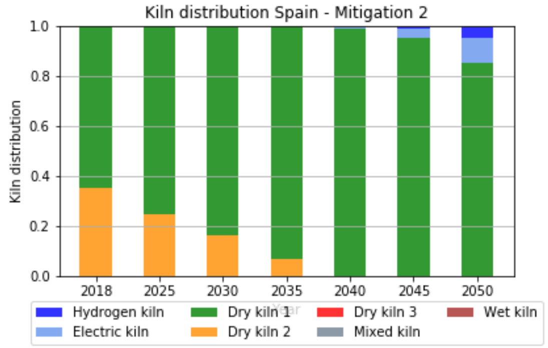


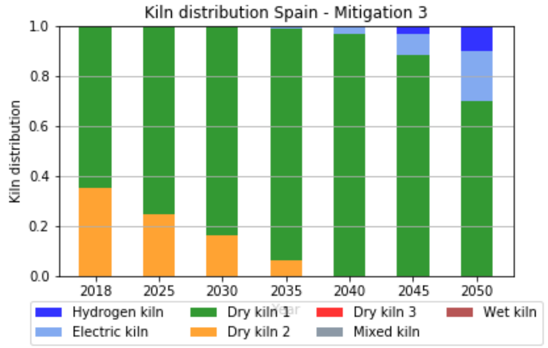


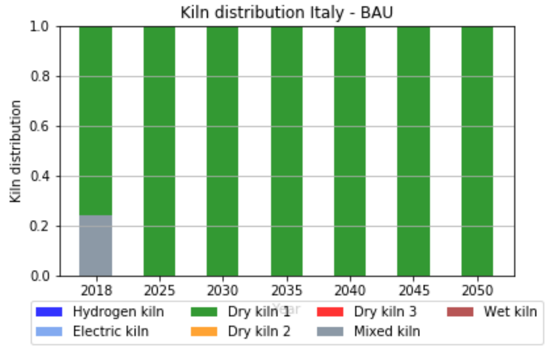
*Note- Dry kiln 1 refers to dry with preheater & precalciner; dry kiln 2 refers to dry with preheater without precalciner; dry kiln 3 refers to dry without preheater*

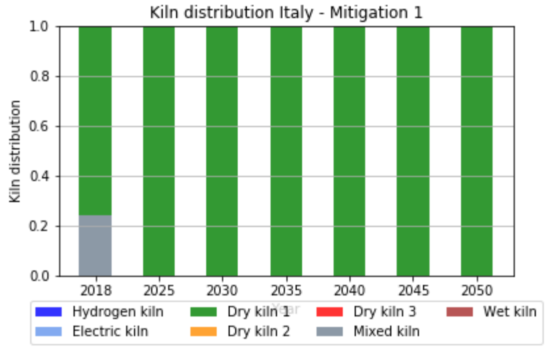


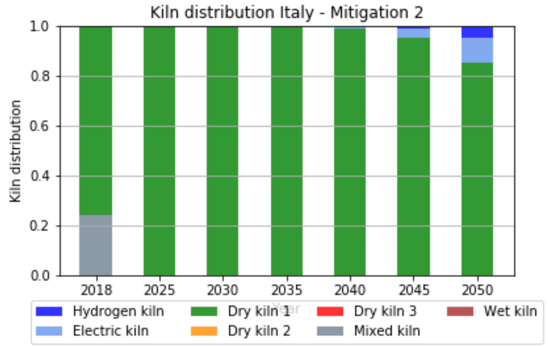


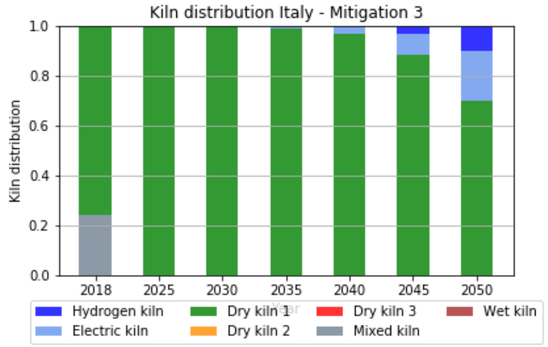












*Note- Dry kiln 1 refers to dry with preheater & precalciner; dry kiln 2 refers to dry with preheater without precalciner; dry kiln 3 refers to dry without preheater*

## Appendix B: Data sources for European countries, China, and India

| Objective | Data | Reference |
|---|---|---|
| Cement production | GDP per capita | (World Bank, n.d.) |
| | Population | (United Nations, n.d.) |
| | Cement demand | (Andrew, 2019) |
| | | |
| Thermal energy efficiency* | Production of clinker by kiln type | (GCCA, n.d.) |
| | Thermal energy consumption per ton of clinker | (GCCA, n.d.) |
| | | |
| Clinker demand* | Clinker to cement ratio | (GCCA, n.d.) |
| | | |
| Energy demand in the base year* | Thermal energy consumption per ton of clinker | (GCCA, n.d.) |
| | Electricity consumption per ton of cement | (GCCA, n.d.) |
| | Thermal energy mix | (GCCA, n.d.) |
| | | |
| $CO_2$ emissions | Emission factors for fuel | (Energy Transition model, n.d.) |
| | Emission factors for grid electricity | (Carbonfootprint, 2020) |

*Note: * denotes data sources for these objectives are different for China and are stated in Appendix C*

## Appendix C: Data sources for China

| Objective | Data | Reference |
|---|---|---|
| Thermal energy efficiency | Production of clinker by kiln type | (Liu et al., 2021) |
| | Thermal energy consumption per ton of clinker | (Cao et al., 2021) |
| | | |
| Clinker demand | Clinker to cement ratio | (IEA, 2020a) |
| | | |
| Energy demand in the base year | Thermal energy consumption per ton of clinker | (Cao et al., 2021) |
| | Electricity consumption per ton of cement | (Cao et al., 2021) |
| | Thermal energy mix | (Cao et al., 2021) |

## Appendix D: Data used for energy and emissions modelling

| | | Germany | Italy | Spain | India | China |
|---|---|---|---|---|---|---|
| | Clinker to cement ratio in 1990 | 0.82 | 0.71 | 0.82 | 0.86 | 0.73 |
| | Clinker to cement ratio in 2019 | 0.71 | 0.77 | 0.81 | 0.67 | 0.64 |
| **Thermal energy consumption per ton of clinker by kiln type in 2018 or after deployment of the kiln (GJ/ton of clinker)** | Hydrogen kiln | 3700 | 3630 | 3480 | 3090 | 3400 |
| | Electric kiln | 2680 | 2680 | 2680 | 2680 | 2680 |
| | Dry with preheater & precalciner | 0 | 3630 | 3480 | 3090 | 3400 |
| | Dry with preheater without precalciner | 3720 | 3990 | 3530 | 0 | 0 |
| | Dry without preheater | 0 | 0 | 0 | 0 | 0 |
| | Mixed kiln type | 3700 | 4770 | 0 | 3320 | 0 |
| | Semi-wet or Semi-dry kiln | 3800 | 3890 | 0 | 0 | 0 |
| | Wet kiln | 0 | 0 | 0 | 0 | 3510 |
| **Production volumes of clinker by kiln type in 1990 (%)** | Dry with preheater & precalciner | 14% | 22% | 36% | 64% | 81% |
| | Dry with preheater without precalciner | 53% | 14% | 47% | 0% | 0% |
| | Dry without preheater | 0% | 0% | 0% | 0% | 0% |
| | Mixed kiln type | 16% | 29% | 17% | 36% | 0% |
| | Semi-wet or Semi-dry kiln | 18% | 36% | 0% | 0% | 0% |
| | Wet kiln | 0% | 0% | 0% | 0% | 19% |
| | Dry with preheater & precalciner | 33% | 76% | 65% | 93% | 97% |
| | Dry with preheater without precalciner | 60% | 0% | 35% | 0% | 0% |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Production volumes of clinker by kiln type in 2018 (%)** | Dry without preheater | 7% | 0% | 0% | 0% | 0% |
| | Mixed kiln type | 0% | 24% | 0% | 7% | 0% |
| | Semi-wet or Semi-dry kiln | 0% | 0% | 0% | 0% | 0% |
| | Wet kiln | 0% | 0% | 0% | 0% | 3% |
| **Energy demand in 2018 (GJ)** | Coal | 8775798 | 2379788 | 69874 | 416000000 | 4360000000 |
| | Oil | 2736585 | 12679737 | 11657700 | 230000000 | 182000000 |
| | Natural gas | 16987617 | 28673325 | 15148101 | 0 | 305338000 |
| | Biomass | 19200000 | 2745772 | 6478584 | 3390000 | 312000000 |
| | Electricity | 13186800 | 8344800 | 7884000 | 21515600 | 639878400 |
| | Hydrogen | 0 | 0 | 0 | 0 | 0 |
| | Waste | 42700000 | 5985048 | 8359464 | 12600000 | 311633149 |
| | Share of waste in thermal energy for 2018 (%) | 47% | 10% | 17% | 3% | 6% |
| | Share of biomass in thermal energy for 2018 (%) | 21% | 5% | 11% | 1% | 6% |
| | Emission factor for grid electricity in 2018 (ton of $CO_2$/ GJ) | 0.10 | 0.09 | 0.06 | 0.19 | 0.15 |

## Appendix E: Emission factors

| **Energy carriers** | **Emission factor (tonne of $CO_2$ / GJ)** |
|---|---|
| **Coal** | 0.096 |
| **Oil** | 0.0755 |
| **Natural gas** | 0.0564 |
| **Biomass** | 0 |
| **Green hydrogen** | 0.00265 |
| **Blue hydrogen** | 0.02705 |
| **Mixed waste** | 0.0465 |

*Note: Emission factor of mixed waste is calculated as average of different waste used in cement kilns as stated in chapter 4.*