# IAM project – adding cement product chain to the South African MESSAGE model.

*Project report by Philip Gjedde (2022) in course “Integrated Assessment Modelling, EP8900”.*

### Introduction

The cement industry is among the five highest energy consuming industries and is responsible for 11% of global energy consumption (105 EJ in 2009) (IEA, 2011). In 2010 cement production accounted for 26% of global CO2 emissions (IEA, 2012). Emissions of 2.3 Gt CO2 was from the cement industry in 2009, 1.1 Gt CO2 were energy related and the rest was process related. An effect of the process related emissions makes the cement industry an even higher emitter than simply through energy consumption, and it makes it a problem to be solved independently parallel to the climate change caused by energy consumption.

Therefore, including the cement industry in national and international policy decisions for a sustainable future is vital. The question becomes especially important when modelling substituting technologies for ordinary Portland cement or carbon capture and storage (CCS) technologies as the process related emissions from clinker production are disconnected from the energy grid that is usually the focus of IAMs.

Cement production is an especially interesting technology because the process emissions from the calcination process in clinker production cannot be optimized technologically: You can substitute clinker *e.g.,* use wood as construction material, or other compositions of cement with less clinker (fly ash, GGBFS), or you can capture the process emissions with CCS. Other materials will have different properties and it is unlikely that we will ever be able to fully replace cement as a commodity in the construction sector. While it would be interesting to see technologies that substitute clinker it is not studied herein. CCS use more energy and therefore the benefit of CCS is only feasible if the energy used to capture the carbon is from a non or low-emitting energy source *e.g.,* wind, solar, nuclear, or hydro power.

### Goal

In this study, three cement producing technologies are added to the MESSAGEix IAM with data for South Africa: Portland cement (conventional), Portland cement with CCS, and Portland cement with optimized dry kiln. The goal is then to see in what scenario CCS becomes preferable related to the conventional technology but also allowing the conventional technology to be environmentally optimized, through minimizing energy consumption in an optimized dry kiln, which in turn also decrease cost from energy consumption.

## Method

The code for the IAM model can be found in file “South\_Africa\_cement-Final.ipynb”.

#### Demand

Cement demand is based on exogenous GDP of South Africa (Fricko et al., 2017). Bas van Ruijven’s formula, based on regression analysis, is used to predict per capita cement consumption from 2020-2070. The parameters a = 487 indicates the “per capita saturation level of cement consumption”, and b = -3047 indicates the “income level at which the maximum consumption occurs”. See equation 1:

It is economically infeasible to transport cement long distances, except with ships. For simplicity, shipping of cement is excluded from the scenario and it is thereby assumed that all cement demand and supply is domestic to South Africa in the scenarios discussed in this report.

#### Inputs and outputs

The cement demand creates demand for multiple commodities down the product chain – one of these commodities is clinker, which from an environmental perspective is the most interesting part of the product chain since the production of clinker has the direct emissions and also consumes the most energy. The product chain has been added to the South African model as described in Figure 1.

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Figure 1: Flow diagram of the cement product chain. To every technology/process is also an energy input and a cost related. The Clinker-Burning technologies all have fuel inputs as well.

#### Resources

Multiple parts of the cement product chain are added to the IAM so that the commodity output from the virtual technology “Resource\_mine” can be evaluated. This allows for further development of the model – for example if it is desired to couple the IAM with LCA to see possible resource depletion. In such a development, one should remember to also develop the background life cycle inventory relevant for the system and not forget to avoid double counting energy consumption. The multiple steps allow for different commodity inputs at each step, but currently only limestone is used as a raw resource output from “Resource\_mine” and there is still a focus on energy consumption and emissions rather than resource use.

#### Technology cost and energy consumption

Clinker production comprises the most energy intensive step in cement manufacture, accounting for about 90% of the overall energy use. This is the reason for choosing alternative technologies for clinker production rather than technologies in the actual cement grinder. The energy consumption for the technologies can be divided into fuel and electricity, the energy consumption for each technology is given in Table 1 along with the economic cost of introducing the technology.

Table 1: Energy consumption and cost for clinker technologies.

|  |  |  |  |
| --- | --- | --- | --- |
| **Technology** | **Fuel consumption (GWa/Mt)** | **Electricity consumption (GWa/Mt)** | **Variable cost (USD/Mt)** |
| Conventional clinker burning | 0.09513 | 0.02378 | 100 |
| Clinker burning with optimized dry kiln | 0.04915 | 0.01836 | 190 |
| Clinker burning with CCS | 0.09814 | 0.03691 | 272.5 (until 2050)  242.5 (from 2050) |

Values for the technologies are taken from Kermeli (2014) and converted to the appropriate units. Kermeli did not include the price for conventional clinker burning, instead this value is taken from Kandaswamy (2018) which brings high uncertainty to the base cost of a cement plant.

The optimized dry kiln technology is taken from table 9 in (Kermeli, 2014) and was called “Conversion to Dry precalciner Kiln” and is considered the best available technology of 2010. The clinker burning with CCS from the same source but in table 17 with technology name “Post-combustion (absorption tech.)”.

#### Emissions

Cement production has three sources of emission: Electricity consumption, fuel extraction and combustion, and direct process emissions from the calcination process. Emissions related to electricity, fuel consumption, and fuel combustion is already included in the South Africa model, while direct process emissions are added.

Direct process emissions from the technologies: “Clinker\_burning” and “Clinker\_burning\_dry\_kiln” are 0.5262 tonne per tonne clinker production (IPTS/EC, 2010), which in the MESSAGEix model is given as follows:

However, the “Clinker\_burning\_CCS” is Mt per Mt clinker, the negative value means that for every ton clinker produced 0.17 Mt is absorbed from the chimney. However, notice in Table 1 that fuel and electricity input increases as well. The lowest emission possible from fuel and electricity input to the clinker burning CCS is 0.1734 Mt per Mt clinker. The CCS technology therefore captures all and a bit more – which in practice would mistakenly suggest that is taken from the atmosphere. However, the minimum possible emission from the fuel and electricity input is not obtained in any of the scenarios.

#### Share constraints

There is a share constraint on the commodity “clinker” from the technology “clinker burning with CCS” of 0.7. This is because it is assumed that only half of the clinker production can be done with CCS due to the fact that captured would have to be transferred to a storage site – therefore there is a need for a specific infrastructure and a suitable location for said task. Also, the high investment cost of CCS makes it an infeasible investment for cement plants producing less than 4-5 kt per day.

#### Other assumptions

I am not adding growth activity constraints on the cement technologies. For now, I also assume that all costs except variable costs are similar between the technologies, and therefore only variable costs are introduced to the model. Since capacity, investment costs, and fixed costs are not implemented, the life time of any technology is irrelevant to the model.

#### Scenarios

The preference of the technologies change depending on which scenario is followed by the model. Since MESSAGEix always try to minimize economic cost, the implementation of the *optimized dry kiln* or *CCS* for clinker production is enticed by either emission taxes, boundaries, or subsidies. I introduce emission boundaries.

## Results

By evaluating the difference between the baseline and cement scenario either introduced to emission bounds or not, I examine how cement demand affects the South African model and what the preferred energy structure looks like at the lowest possible CO2 emissions optimized to lowest cost. The results chapter is based on the model’s variables: Emissions (EMISS), activity (ACT), commodity price (PRICE\_COMMODITY), and the aggregated cost (the objective function OBJ).

The clinker technologies all use fuel and electricity from the secondary level. Therefore, the activities evaluated are of technologies with electricity or fuel (coal, fueloil, lightoil, and gas) output to the secondary level.

**Emissions**The addition of cement demand and production leads to higher emissions due to the higher demand for energy and fuel as well as direct emissions from the clinker production. However, it is possible to reduce the extra emission to a fraction of what is already emitted as seen in Figure 2.

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Figure 2: Mt CO2 emissions from 4 scenarios: Baseline and cement scenario with either low emissions (due to emissions bounds) or high emissions (no emission bounds).

**Activity**

When cement is added to the South African model without setting emission bounds, slightly more activity is seen for fossil fueled energy producing technologies (coal and oil). Transport, feedstock, export, and import activities has no change. But also hydro, biogas, nuclear and solar power has no change meaning that the extra required energy demand is met by combustion of fossil fuels. See the appendix for the activity table.

When boundaries are strict, meaning the lowest possible emission boundary is set, lower activity is seen from coal power plants, gas combined cycle plants, igcc plants, and oil plants. Meanwhile, carbon capture and storage gas plants increase in activity along with less CO2 intensive energy sources: Nuclear, solar, coal liquefaction, and wind power. See Figure 3.

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Figure 3: Activity in MWa for all technologies producing electricity to the secondary level. All activity is in the cement scenario but where there are either high emissions due to the absence of emission bounds, or low emissions due to emission bounds.

Specifically for the clinker and cement production, the CCS and optimized clinker technologies are only used at the lowest emission bound, indicating that it is cheaper to optimize the energy producing infrastructure than it is to optimize the cement producing infrastructure. The CCS technology is also used to its fullest extend, and in the lowest emission scenario the optimized clinker burning is only used to substitute where CCS is not possible (modelled with the introduction of share constraint for CCS), see Figure 4. Therefore, if clinker production must be improved, it should start with CCS wherever possible rather than the optimized kiln technology. This means that despite a lower cost and energy consumption of the optimized kiln, the CCS technology is cheaper per CO2 emission saved. CCS is used before 2040, meaning that even before the cost drops for the technology, it is still preferred over the optimized kiln.

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Figure 4: The activity of clinker producing technologies in the cement scenario where the lowest possible bound of 211Mt CO2 is set. For other bounds, only conventional clinker burning is used.

The preferred choice of fuel for the different scenarios are expected to be dependent on the commodity price which changes differently dependent on the emission bounds introduced to the scenario. As shown in Figure 5, gas replaces light oil when emission bounds have been introduced to the cement scenario, while coal replaces fuel oil when no emission bounds are introduced. When emissions bounds are not introduced, coal is preferred due to smaller costs. The commodity prices are seen in Table 2 and 3 and shows the strong relation between change of fuel with price change.

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Figure 5: Activity of fuel producing technologies with output of the fuels that are used by clinker production.

Table 2: No emissions bounds, commodity prices in million USD per MWa.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Commodity|level** | **2020** | **2030** | **2040** | **2050** | **2060** | **2070** |
| coal|secondary | 285 | 41 | 37 | 37 | 37 | 38 |
| fueloil|secondary | 174 | 225 | 250 | 287 | 331 | 376 |
| gas|secondary | 448 | 186 | 172 | 164 | 208 | 112 |
| lightoil|secondary | 262 | 85 | 90 | 171 | 199 | 150 |

Table 3: Commodity prices in million USD per MWa when bounds are made to have low emissions. No value was given from the model results meaning that the use of gas instead of lightoil in 2020 could be coincidental.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Commodity|level** | **2020** | **2030** | **2040** | **2050** | **2060** | **2070** |
| coal|secondary | 2771 | 4238 | 5605 | 10059 | 16362 | 26629 |
| fueloil|secondary | 2039 | 3231 | 5130 | 8226 | 13237 | 21369 |
| gas|secondary | 0 | 2150 | 3926 | 5978 | 9615 | 15516 |
| lightoil|secondary | 0 | 2698 | 4778 | 7074 | 11591 | 18932 |

**Cost**

The objective function (summed cost) is 66135.5 million USD or 89535.0 million USD for the high emission and low emission cement scenario, respectively. It is 63014.6 million USD and 84006.0 million USD for the high and low baseline scenario, respectively. In a cement scenario with a CO2 emission bound on 500 Mt per year on average, the objective function was 67692.6 million USD, and clinker burning activity showed no use of CCS or optimized kiln. The objective function for that bound was 64385.9 million USD in the baseline scenario. Figure 6 shows the cost difference between the cement and baseline scenarios with different CO2 emission bounds, the curve is shown in the figure as *a* in a linear equation *ax+b* to support what visually is only a small difference.

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Figure 6: Objective function or aggregated cost in million USD for 6 different scenarios: The cement and baseline scenarios at three different emission bounds.

The same technologies, and therefore cost, is used to meet the cement demand when no bounds or 500Mt bound is introduced. Simultaneously there is a cost increase. The difference in price between cement and baseline is higher for the 500 Mt bound scenario than the scenario where no CO2 bounds have been made. This cost difference must stem from a more costly energy production since there is no difference in the use of clinker technology. The even greater difference in cost in the lowest CO2 bound scenarios is mostly caused by the optimized kiln and CCS clinker technologies that makes extra costs on top of the more expensive energy infrastructure.

## Discussion

**What can be said from the results**

While it is possible to greatly reduce the emissions from clinker and thereby cement production, it comes at a high cost. The use of the new clinker technologies included in this study is not worthwhile compared to investing in the energy sector itself. CCS is a better investment than the optimized dry kiln despite the lower variable cost for the latter technology. In the emission bound cement scenario the commodity price for electricity drops to 0 in 2050 and forward which is likely causing the model to prefer CCS over the optimized dry kiln, since CCS reduce expensive fuel use while the dry kiln is only able to reduce the electricity consumption which is anyway for free. In other words, optimizing the dry kiln is unnecessary since the electricity is at no apparent cost – or there is a mistake in the model.

Adding cement to the South Africa scenario does not make a significant difference compared to the emissions and activities already given in the baseline scenario. A greater impact was expected based on literature stating that 26% of global emissions were caused by cement production. This is either a result of a miscalculated GDP, cement demand from GDP, or because South Africa has lower GDP and assumed cement demand than the majority of the world. If further work is to be made on this model, the cement demand should be checked and potentially corrected. It is very unlikely that the emission factors are wrong, since almost half, and therefore over 10% of emissions are from direct process emissions of the clinker production which is far above what is seen in

**Shortcomings of the current model**

In this study it was assumed that cement is not included in the energy demand from the industry end-use sector – this is unlikely true, meaning that the cement demand in the cement scenario double counts the demand for cement. However, the direct emissions from the clinker production are not related to any energy consumption and are therefore not accounted for in the original South African model. The current model suggests that CCS is not invested in until the energy sector is developed fully, including CCS technology for power plants such as coal liquefaction and gas with CCS. Since these technologies seem to be worthwhile investments, it is possible that the price set for clinker production with CCS or clinker production with optimized dry kiln is imprecise. In further use of this model, a sensitivity analysis of the technologies’ costs should be made and compared to the costs of other CCS technologies as well.

The prices for using clinker technologies are only given as variable costs. Therefore, the speed of change from one technology to another is likely exaggerated as there is no value lost from fixed cost in a clinker kiln that still has capacity for years to come. Fixed costs, investment costs, and capacity should be part of a more developed model. I expect that such an addition to the model would result in a higher minimum emission and higher costs due to the mentioned value loss.

The demand for cement is based on exogeneous values, but if an endogenous demand is calculated in the MACRO model it would be possible to have cement production feedback loops based on GDP change resulting from the commodity production.

The current IAM model used in study falls short on including multiple impact categories. Mineral resource use is of importance to batteries and solar power. Land use and land use change, biodiversity impacts on terrestrial, freshwater, and marine environments are also affected by wind power and hydro power. The potential radiation from nuclear power is also not included in the current IAM model. For an IAM model to include these impact categories, one could couple IAM with life cycle assessment (LCA).

The addition to the model is currently over complicated. The energy and fuel consumption, emissions, costs, and cement output could have been aggregated into one technology with said inputs and outputs. But with the expanded system it would be possible to add more details to the system, for example if other commodities were needed to produce the commodity output. Multiple studies have worked towards coupling LCA and IAM and mentions the importance of using a background life cycle inventory that matches the time forecasted in the IAM to the best extent (Gibon et al., 2015). The use of key commodities, like clinker, will for similar reasons be beneficial to base on endogenous demand. The increasing and decreasing use of the commodity could then be coupled with LCA or LCA-like categories for different time steps.

The extraction (EXT) variable can be directly used by adding resource­\_volume and resource\_remaining parameters in units of mega tonnes. This way, the bound\_extraction\_up parameter can also be introduced to model policies regarding the use of specific resources. At this point, the MESSAGE model would already be able to evaluate policies with a circular economy perspective. The inclusion of a circular economy perspective would also make it more worthwhile to compare technologies that substitute clinker with another commodity, like simply building houses of wood.

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