Enriching IAM scenarios for effective pLCA integration: A clinker case study

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Abstract

Integrated assessment models are increasingly used to build prospective life cycle databases. While these models provide projections on an economy-wide scale, they lack detail, with most industries aggregated at sector level. These models also suffer from a low technological resolution and tend to neglect technologies that may enter the market in the future. This limitation prevents the modelling of several industries in a prospective LCA. This paper aims at bridging the gap between LCA and IAMs by means of an econometric model, using the cement industry as a case study. . While this model sits outside of the integrated assessment model, it ensures consistency with the model's scenario by using data from integrated assessment model to build its projections. The model estimates the capital stock required, the fuel mix in the kiln, the most cost effective kiln type and finally the capital stock composition.. This was done for a baseline, moderate and climate stringent scenario, for the EU, USA and Canada. The projections of the model were integrated into a prospective life cycle assessment to determine the global warming potential of clinker. Results show an increase in alternative fuel use, especially for the EU. The use of natural gas increases for the USA and Canada but remains negligent for the EU. Kilns with carbon capture are adopted, provided the carbon tax is high enough and the alternative fuel share is not too high.

Highlights

- An econometric cement model is built to complement IMAGE's projections
- Review of the cement industry's fuel choice
- Fuel choice and investment into kiln types is determined
- Projections are made for clinker production in the EU, USA and Canada
- Projections are integrated in a prospective consequential LCA

Keywords

Prospective LCA, Consequential LCA, integrated assessment model, cement industry, econometric model, cost optimization

Abbreviations

BAT	best available technology
CAPEX	capital expenditure
CCS	carbon capture and storage
CHP	combined heat and power
GDP	gross domestic product
GWM	global waste management

GWP	global warming potential
IAM	Integrated assessment model
LCIA	life cycle impact assessment
MEA	monoethanolamine
MSW	municipal solid waste
NMM	non-metallics minerals
OPEX	operating expenditure
pLCA	Prospective life cycle assessment
RCP	representative concentration pathway
SB	submodule
SCM	supplementary cementitious materials
SSP	Shared socioeconomic pathway
WtE	waste to energy

1 Introduction

Developing a scenario consistent inventory model, which incorporates aggregated Integrated Assessment Model (IAM) data into a detailed LCA database, remains one of the key issues of prospective life cycle assessment (pLCA). pLCA is a novel approach which is typically used to assess the potential industrial scale environmental impact of technologies under development. By shifting the focus of the LCA to the future, users can assess the environmental impact of technologies during the development phase and use the results to improve the technology.

In order to perform a pLCA, users must account for how the innovative technology will change in the future as well as how the fore- and background system will change (Buyle et al., 2019). While early work tended to neglect evolutions in the background system, several projects have since developed datasets which consider the future socio-economic trends. Most promising is the recent work on the premise software package, which builds prospective datasets using projections from Integrated Assessment Models (IAMs) (Sacchi et al., 2022). IAMs are economy-wide models which can produce a range of consistent scenarios in line with the shared socioeconomic pathways (SSPs) (Riahi et al., 2017) and representative concentration pathways (RCPs) (van Vuuren et al., 2011).

While previous research efforts have addressed the need for a consistent background system, the low level of detail of IAMs has restricted the number of industries for which projections could be integrated in the prospective dataset. IAMs make projections mostly on a sector level, not an industry level. In addition, IAMs suffer from a low technological resolution and tend to neglect technologies that may enter the market in the future. As a result, the projections are not detailed enough to model specific industry developments in current prospective LCA practice. Ideally this could be solved by directly modelling the industry in the IAM. However, IAMs are rarely open source, and their complexity prevents outsiders from modelling within the IAM.

Sector specific changes can be modelled separately, yet care needs to be taken when modelling industries outside of the IAM, to ensure that the future pathway of the industry lines up with the prospective scenario from the IAM. Langkau et al. (2023) address the need for a scenario consistent prospective LCA and developed a stepwise approach for scenario-based inventory modelling. Part of the approach, named SIMPL, discusses how users can determine how key factors may affect parameters in the inventory model using a causal loop diagram. While this approach is an important step in ensuring a consistent inventory model, the approach does not answer how users can determine values for the parameters, given the scenario. Instead, the approach sticks to worst, best and average values. Additional work is needed to develop scenario consistent pathways for industries outside of the IAM.

Previous research gaps are in particular relevant when assessing the cement industry. This industry has a high environmental impact, being responsible for about 7% of global CO_2 emissions (IEA). In spite of this, the technological resolution of the cement industry in IAMs is low, with most models aggregating the industry to the non-metallics minerals (NMM) sector (Kermeli et al., 2019). One of the few IAMs that does model the cement industry separately is IMAGE (Stehfest et al., 2014). However, several key issues were identified in how IMAGE models the cement industry. First, the historic energy use from the entire NMM sector is used as a basis for the cement industry's energy model (Müller et al., 2024). This overestimates the use of natural gas in the energy mix, which predominately comes from other industries of the NMM sector like the glass and ceramics industry (European Commission et al., 2023). Second, there is a lack of emerging technologies included in the model. Roadmaps highlight the potential of innovative burners to allow for electric heating and hydrogen combustion in the kiln (European Commission, 2018; Material Economics, 2019). IMAGE only models the use of two carbon capture technologies (excluding a third unspecified kiln): post-combustion carbon capture with monoethanolamine (MEA) and oxyfuel carbon capture. However, the key benefits of the former are not included, namely its potential to be introduced earlier onto the market and the possibility to retrofit the technology on existing kilns. Additionally other partial carbon capture technologies such as Leiliac's direct separation technology provide a unique benefit (IEA Greenhouse Gas R&D Programme (IEA GHG), 2009; Leilac, 2021). This technology only captures emissions from the calcination of limestone, but its relatively low investment cost could make it an attractive option for the industry. This is especially the case when low carbon heating options are used. Lastly, IMAGE focusses solely on the production of clinker. This approach neglects several options for improvement such as novel supplementary cementitious materials (SCMs), novel cement types and reductions in the use of cement and concrete due to optimized material use (Favier et al., 2018).

In summary, the IAM's scenario projections of the cement industries cannot be used to model the cement industry in a prospective LCA, inducing the need for a separate model alongside the IAM. Given this context, the general objective is to develop an econometric model for the cement sector that complements the IAM's projections but adds the technological detail necessary to integrate the projections into an LCA. The focus of this paper lies on the energy demand of the cement industry. Heating of the kiln makes up around a third of clinker's global warming potential and is currently not explicitly modelled by IAMs, which instead have modelled the energy choices made by the NMM sector as a whole.

To model the energy choices made by the cement industry, in the inventory model of a prospective LCA, it is important to first identify the key variables at play. Therefore, a literature review on the cement industry's energy use is performed. Next, Results from the investigation are used to develop a behavioral model that works alongside the IAM. The model estimates the cement industry's energy demand and investment choices based on economic data. Economic models and principles are used that are similar to those used in the IAM. The model's main source of economic input data, e.g., prices, taxes and product demand, comes from the IAM's projections. This way the projections are in line with the IAM as best as can be without directly modelling within the IAM. Any technologies not already modelled in the IAM are not included. In the final step, the projections from the model are integrated into a prospective LCA in order the assess the future environmental impact of the cement industry.

2 Material and methods

2.1 Literature review

Globally, the dominant fuels in the cement industry are coal and petcoke, with a combined share of 70% in 2019 (Global Cement and Concrete Association, 2023). Throughout the years the industry has gradually switched fuel types to lower its carbon emissions. In most countries, the use of alternative fuels has increased, as the combustion of these fuels emits on average less CO_2 than coal, but also because the combustion of biogenic carbon is sometimes considered as carbon neutral (GIZ-LafargeHolcim, 2019). Some countries have been able to increase their use of natural gas in kilns thanks to a relatively low price for natural gas in the past years (Global Cement and Concrete Association, 2023; World Cement, 2013).

For switching to natural gas no additional investments are required. On the contrary, if a cement kiln would use only natural gas, the storage, grinding, handling and dosing systems required for solid fuels would not need to be purchased. However, combustion and process parameters would need to be altered to ensure the quality of the clinker (Akhtar et al., 2013). This requires expertise, which is currently lacking. The fluctuating price of natural gas may also prevent cement producers from making the switch.

Alternative fuels consist of combustible waste, such as refuse derived fuels, sewage sludge and meat and bone meal. In contrast to fossil fuels, the price of alternative fuels does not conform to standard market operations with equilibrium market prices and can vary widely depending on the quality of the fuel, location and landfill tax (European Commission et al., 2023). Alternative fuels have on average a lower price compared to fossil fuels. Cement producers may even ask a gate fee from the waste providers for taking in their waste if the landfill tax is high enough (International Finance Corporation, 2017). However, the use of alternative fuels require additional investments into storage, grinding, handling and dosing systems (GIZ-LafargeHolcim, 2019). In addition, some fuels may require pre-processing. A study made by ecofys revealed that the adoption rate of alternative fuels is highly dependent on local factors (de Beer et al., 2017). The most deciding factors for the adoption rate are regulations and landfill taxes or bans, the ease with which cement manufacturers can obtain permits to combust alternative fuels and the availability of local alternative fuels.

Historic trends show an almost linear increase in alternative fuel share in most regions (Global Cement and Concrete Association, 2023). However, there are several cases where a sudden change in cement demand disturbs this trend. This is likely because alternative fuel use cannot keep up with large increases of demand due to supply constraints. In countries such as Austria and Germany the uptake of alternative fuels seems to be slowing down as cement companies there are nearing high levels of substitution and it becomes more difficult to increase the share due to technical factors.

In the future, cement producers may switch to electric heating or (green) hydrogen fuel. Most reports consider hydrogen only being used as a partial fuel substitute, because of the difference in combustion and flame characteristics with other fuels (Cembureau, 2019; d'Hubert, 2022; Mineral Products Association, 2019). However, novel burners are being developed, with pilot tests showing that it is feasible for hydrogen to be used as the main fuel in the kiln (thyssenkrupp, 2023). Electric heating technologies such as the RotoDynamic Heater and electric plasma heaters are currently still under development, though the first electric kiln could be in operation by 2024 (CemNet, 2023).

Carbon tax is an important tool to steer decision makers' choices in IAMs (Mundaca et al., 2019). Carbon taxes have been implemented for several decades in various parts of the world (Haugland, 1993). The cement sector has been largely protected from these taxes despite being a large emitter of CO_2. This was done as cement producers compete in international markets and a high carbon tax would economically disadvantage the local producers (Dahlby et al., 2019; Vilella and Arribas, 2016). This may change in the future as border carbon adjustments are planned in several parts of the world, which will tax emissions from imported products (Cosbey et al., 2021; European Commission, 2021). A carbon tax would increase the cost of using fuels and thus making clinker production more expensive. As a result, cement suppliers more likely to switch to low carbon fuels. Alternatively, cement suppliers may invest in carbon capture technologies if the carbon tax is high enough to warrant their high capital expenditure (CAPEX) and the additional operating expenditure (OPEX) to capture and store CO_2. Cement suppliers using carbon capture technologies will face different costs for the combustion of fuels than those without. Therefore, the adoption rate of carbon capture must be accounted for, when estimating the industry's energy use under an econometric model.

To summarize, switching to natural gas is possible, but cement producers may be hesitant at first due to a lack of experience with the fuel and uncertainty on its long-term fuel price. Countries may switch to natural gas due to carbon taxes making it a relatively cheaper alternative to coal and petcoke. Alternative fuels are a different case. Cement producers are, to some extent, constrained in their use of alternative fuels due to local factors, but also technical constraints. For the future, carbon capture technologies are expected to play a significant role when determining the energy mix of the cement industry. For this paper the focus lies on three regions, namely Europe, Canada and the USA. A specific feature in Europe is the extensive use of alternative fuels, which is far above the world average. Canada and the USA on the other hand are unique examples of regions that have opted to use natural gas in kilns, reaching a share of 23% in 2019 (Global Cement and Concrete Association, 2023). Both countries also face difficulties in raising their alternative fuel use. Both countries have a low landfill tax, a large amount of space available to landfill and permits to combust alternative fuels are difficult to obtain (IEA Bioenergy, 2014). This paper includes two carbon capture options, namely oxyfuel carbon capture and post-combustion carbon capture. The same carbon capture options present in IMAGE. Likewise, this paper does not include novel heating options such as electric heaters, as these technologies are not modelled in IMAGE.

2.2 The model

Building on the insights from the literature review, the proposed model to estimate the cement industry's energy demand and investment choices is divided into four submodules (see **Fig. 1**). These are sequentially run, with the output of previous submodules used as inputs to model decisions in the current model. In the first submodule (SB1), the minimal additional capital stock required to fulfill the projected clinker demand from the IMAGE scenario is calculated. This data is necessary to determine the energy demand, a key variable in the second submodule (SB2). In the second submodule, the yearly average energy mix per kiln type is determined. Three kiln types are considered: a kiln without CCS, a kiln with post combustion capture using MEA and a kiln with oxyfuel carbon capture. In section 2.1 it was identified that alternative fuels are supply driven, while decision on fossil fuels are mainly demand or price driven. To determine the shares of each fuel SB2 is split into SB2a and SB2b. In SB2a, the share of alternative fuels is determined. In SB2b the share of each fossil fuel type is determined. The third submodule (SB3) identifies the kiln type a cement producer will most likely invest in. it is assumed that this decision is purely driven by a desire to maximize profits. The most cost-effective kiln type is determined for each year using a cost-benefit analysis. In the last submodule (SB4), the capital stock composition of the yearly added capital is determined using the results from the first and third submodule. Finally, the yearly average fuel mix can be determined using the results from the second and fourth submodule.

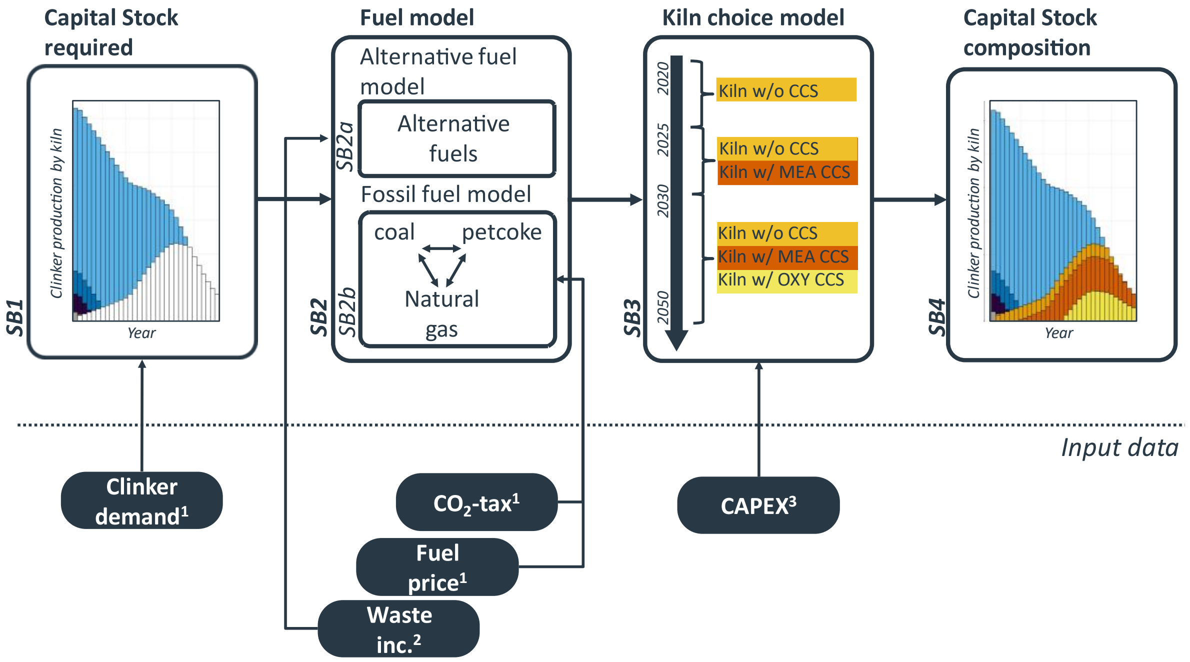

Fig. 1 The energy model (data source 1 = IMAGE, 2= Gómez-Sanabria et al. and 3=CEMCAP)

2.2.1 Submodule 1: Capital stock required

The submodule starts from the observed capital in 2019. A fixed deprecation rate of one over the average lifetime of a kiln is used for the historic capital. With an average lifetime of 40 years, the yearly deprecation rate becomes 2.5% (Cembureau, 2013). The historic capital is subdivided into six kiln types in line with the GNR database, from wet kilns to dry kilns with preheater and precalciner. Phasing out technologies works its way from the least to the most efficient kiln type. Next, the necessary additional capacity to meet demand is determined, given the projected clinker demand from the IMAGE scenario. Any newly installed capital is assumed to have a lifetime of 40 years.

2.2.2 Submodule 2: fuel model

2.2.2.1 SB2a: the alternative fuel model

In the second submodule, the alternative fuel share is first determined in SB2a. A logit model was selected to ensure that shares operate within the zero-one interval and to take into account the decrease in growth seen with countries with high alternative fuel shares (Global Cement and Concrete Association, 2023). A logit model was formed on three parameters: energy demand, policies on waste management and a time trend (see

$$S_{AF,r} = \ln\left(\frac{f_{AF,r}}{1 - f_{AF,r}}\right) \qquad \text{Eq 1)}$$

$$f_{AF,r} = a_r + b_r(t - 2005) + c_r E_r + d_r I_r \qquad \text{Eq 2)}$$

With:

- $S_{AF,r}$ = alternative fuel share of region r
- t = year (2005 = year 1)
- E_r = energy demand for cement industry per region, indexed (base year = 2005)
- I_r = MSW incineration per region, indexed (base year = 2005)
- a_r, b_r, c_r and d_r are the regional coefficients to be estimated

and **Error! Reference source not found.**). Future energy demand is determined using the capital stock data from the first submodule. An average energy efficiency per kiln type is determined using data from the GNR database (Global Cement and Concrete Association, 2023). The energy efficiency of all new kilns is equal to the Best Available Technology (BAT) value (=3.0GJ/t clinker) (ECRA, 2017). This does not include electricity or energy that may be needed for CCS.

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The amount of incinerated municipal solid waste (MSW) was taken as a proxy for a region's policies on waste. MSW incineration is not modelled in IMAGE. Data from a global waste management (GWM) model is used instead (Gómez-Sanabria et al., 2022). While the data comes from a different model, the projections do follow the SSPs, just as IMAGE. In the GWM model, municipal solid waste generation is estimated using GDP per capita and urbanization rate. The generated MSW is disaggregated into waste generated per waste type. MSW management narratives are formed based on the SSP scenarios. These narratives determine the amount of waste per waste management option. Unlike IMAGE, the GWM model does not follow the RCP's. Instead, the model follows a moderate and strong waste strategy pathway for each SSP. The model was fitted on historic data for all three regions, from 2005 till 2019.

2.2.2.2 SB2b: the fossil fuel model

Following the alternative fuel share, the share of each fossil fuel is determined in SB2b. An econometric model of input demand functions is used to determine the shares. The dynamic linear logit model was chosen for this study (see **Eq 3** and **Eq 4**) (Considine and Mount, 1984). This model was selected because, unlike other frequently used models like the translog model, it does not violate the properties dictated by neoclassical production theory (Moody, 1996). More specifically, the input demand functions of the model should have non-negative solutions, be homogenous of degree zero in prices, have cross price effects that are symmetric and guarantee global curvature. As a logit model, the projected shares fall within the zero-one interval. This ensures that shares cannot be negative. This has allowed it to be used as both a simulation and forecasting model (Lutton and LeBlanc, 1984; Moody, 1996).

In **Eq 4** $\lambda \ln(Q_{i,t-1})$ is the lagged term and can be included to take the delay in response to price changes into account (Considine and Mount, 1984). The autocorrelation and partial autocorrelation function is used to determine if a lagged term is needed. A fixed effect estimator can be added to take regional differences into account.

$$w_{i,\mathrm{r},t} = \frac{e^{f_{i,\mathrm{r},t}}}{\sum_{i=1}^{n} e^{f_{i,\mathrm{r},t}}} \tag*{Eq 3)}$$

$$f_{i,\mathrm{r},t} = \beta_i + \sum_{j=1}^{n} \beta_{ij} \ln P_{j,\mathrm{r},t} + \lambda \ln Q_{i,\mathrm{r},t-1} + F_{i,r} \qquad \text{Eq 4)}$$

With:

- $w_{i,r,t}$ = cost share of fossil fuel i for region r in year t
- $P_{i,r,t}$ = price of fossil fuel i for region r in year t [usd2010/GJ]
- $Q_{i,r,t-1}$ = quantity of fossil fuel i used for region r in year t-1 [GJ]
- F_r = fixed effect of fossil fuel i for region r
- $\beta_{i,}$ β_{ij} and λ are the coefficients to be estimated

Zero degree homogeneity in prices is imposed in the linear logit function (Eq 4) when:

$$\sum_{j=1}^{n} \beta_{ij} = x \qquad \text{Eq 5)}$$

x is an arbitrary constant and is set to zero in this study. Imposing zero-degree homogeneity ensures that results are not determined by the absolute values of the prices, but their relative price differences.

Symmetry is imposed when:

$$\beta_{ij}^{*} = \beta_{ji}^{*} \qquad \text{Eq 6)}$$

Where:

$$\beta_{ij}^{*} = \frac{w_{ij}}{w_{i,t}^{*}} \qquad \text{Eq 7)}$$

Doing so ensures that the cross-substitution effect from fuel a to fuel b is equal to that of fuel b to fuel a. Symmetry is imposed on all observations if $w^*_{i,t}$ is set equal to the predicted shares for each observation.

A linearized form of Eq 3 and Eq 4 is used for estimation (see Eq 8). For N fuels, a set of N-1 equations is needed:

$$\begin{aligned}
\ln\left(\frac{w_{i,\mathrm{r},t}}{w_{N,\mathrm{r},t}}\right) = \beta_i &+ \sum_{k=1}^{i-1} (\beta_{ki}^{*} - \beta_{kN}^{*}) w_{k,t}^{*} \ln\left(\frac{P_{k,r,t}}{P_{N,r,t}}\right) \\
&- \left[\sum_{k=1}^{i-1} \beta_{ik}^{*} w_{k,t}^{*} - \sum_{k=i+1}^{N} \beta_{ik}^{*} w_{k,t}^{*} - \beta_{iN}^{*} w_{i,t}^{*}\right] \ln\left(\frac{P_{i,\mathrm{r},t}}{P_{N,\mathrm{r},t}}\right) \\
&+ \sum_{k=i+1}^{N-1} (\beta_{ik}^{*} - \beta_{kN}^{*}) w_{k,t}^{*} \ln\left(\frac{P_{k,\mathrm{r},t}}{P_{N,\mathrm{r},t}}\right) + \lambda \ln\left(\frac{Q_{i,\mathrm{r},t-1}}{Q_{N,\mathrm{r},t-1}}\right) + F_{i,r}
\end{aligned} \qquad \text{Eq 8)}$$

The cross- and own-price elasticities are calculated using Eq 9 and Eq 10.

$$E_{ik} = w_k^{*}\left(\beta_{ik}^{*} - \sum_{j=1}^{N} w_j \beta_{jk}^{*}\right) + w_k \qquad for\ i \neq k \qquad \text{Eq 9)}$$

$$E_{ii} = w_i^* \left(\beta_{ii}^* - \sum_{j=1}^{N} w_j \beta_{ji}^* \right) + w_i - 1 \quad \text{Eq 10)}$$

With:

- E_{ik} = the cross-price elasticity
- E_{ii} = the own-price elasticity

If the lagged term is included, the short- and long-run price elasticities are calculated. The short-run price elasticities E^{SR} are equal to the static price elasticities E calculated in **Eq 9** and **Eq 10**. The long-run price elasticities is calculated using **Eq 11**.

$$E_{ij}^{LR} = \frac{E_{ij}^{SR}}{1-\lambda} \quad \text{Eq 11)}$$

To estimate the coefficients of the model, **Eq 8** is fitted onto historical data using seemingly unrelated regression (Zellner, 1962). This is done in in two steps. In the first step, the model is fitted with $w^*_{i,t}$ set equal to the actual historical share. In the second step, an iterative procedure is used where $w^*_{i,t}$ is set equal to the predicted shares of the previous estimation run. This is done until the predicted shares from the previous run are equal to the predicted shares from the last run.

To predict the future shares, the model is again run in two steps. In the first step $w^*_{i,t}$ is set equal to the shares from the previous year. In the second step, $w^*_{i,t}$ is set equal to the predicted shares of the previous run and the model is run several times over till the predicted shares of the previous run are equal to those of the last run. These steps are performed starting from the historic year till 2050.

The model is run separately for kilns without CCS, kilns with post combustion carbon capture with MEA and kilns with oxyfuel carbon capture. $P_{i,r,t}$ is equal to the fossil fuel price plus the carbon tax the cement producer needs to pay when combusting the fuel. For kilns with carbon capture, $P_{i,r,t}$ is equal to the sum of the fossil fuel price, the carbon tax for all non-captured CO_2 emissions of the fuel and the OPEX for the captured CO_2 emissions of the fuel. All price data is adjusted for inflation and converted to USD2010. Kilns without CCS have no lagged term in their introduction year. For the introduction year an iterative process is used in which the model is run until the quantity of the lagged term equals the quantity predicted for that year.

Results of the linear logit model are compared with the model used by IMAGE and the translog model, a frequently used model derived from a cost function. More information on the two alternative approaches can be found in appendix A. Both SB2a and 2b were fitted on historical data. See appendix B for the data sources.

2.2.3 Submodule 3: kiln choice model

In the third submodule, the most cost-effective kiln type is determined for each year. The break-even price, i.e. the price for clinker ($P_{clinker,t}$) where the net present value equals zero, is calculated for each kiln (see **Eq 12**). The kiln with the lowest break-even price is deemed the most cost-effective kiln for that year. Values for the total plant cost are taken over from CEMCAP (Voldsund et al., 2019). The cost for cement production and carbon capture is also taken over from CEMCAP, but energy prices are replaced by the yearly energy prices from the IMAGE scenario. The discount rate is set at 8%, the same value used in CEMCAP. Investment cost of the cement plant is spread out over 2 years (years -1 and 0). Investment cost of the carbon capture plant is spread out over 3 years (year -2 till year 0). How much is invested in those years is taken over from CEMCAP. The model assumes that investors have limited foresight and use the energy prices and taxes of the first year of production to estimate the break-even price. The fuel shares are likewise used from the first year of production and come from the second submodule.

$$NPV = -0.5 * \frac{TPC_{cement\ plant}}{(1+r)^{-1}} - 0.5 * \frac{TPC_{cement\ plant}}{(1+r)^{0}} - 0.4 * \frac{TPC_{cc\ plant}}{(1+r)^{-2}} - 0.3 * \frac{TPC_{cc\ plant}}{(1+r)^{-1}} - 0.3 * \frac{TPC_{cc\ plant}}{(1+r)^{0}} + \sum_{t=1}^{lt} \left[\left(P_{clinker,t} - C_{clinker,t} - C_{carbon\ capture,t} * \left(EF_{fuel\ mix} * E_{clinker} + EF_{clinker} \right) \right) \frac{Q_{clinker,t}}{(1+r)^{t}} \right] \quad \text{Eq 12)}$$

With:

- $TPC_{cement\ plant}$ = total plant cost for the cement plant [usd2010]
- $TPC_{cc\ plant}$ = total plant cost for the carbon capture plant [usd2010]
- $P_{clinker,t}$ = selling price of clinker at year t [usd2010/t clinker]
- $C_{clinker,t}$ = operational cost to produce clinker at year t (including carbon tax, excluding carbon capture costs) [usd2010/t clinker]
- $C_{carbon\ capture,t}$ = operational cost to capture CO_2 emissions at year t [usd2010/t clinker]
- $EF_{fuel\ mix}$ = CO_2 emission factor of the fuel mix [t_{CO2} /GJ]
- $EF_{clinker}$ = CO_2 emission factor of clinker [$t_{CO2}/t_{clinker}$]
- $E_{clinker}$ = energy used for heating of the kiln [$GJ/t_{clinker}$]
- $Q_{clinker,t}$ = production of clinker by cement plant at year t [t clinker]
- r = the discount rate

2.2.4 Submodule 4: capital stock composition

In the last submodule, the capital stock composition of new installed capital is determined and the total energy mix. Results from submodule 1 are used to determine how much new capital will be installed in each year. Only one kiln type can be invested in per year, per region. Which kiln type is invested in depends on the results from submodule 3. Next, the total energy mix is calculated from the capital stock composition and the yearly fuel mix per kiln type, from submodule 2.

2.3 Prospective consequential LCA

The results of the model are used to compute the inventory flows for clinker production in a prospective consequential LCA. The global warming potential of the functional unit of producing 1t of clinker is assessed in 2020, 2030, 2040 and 2050 using ReCiPe 2016 v1.03 as the impact assessment method (Huijbregts et al., 2017). This is done for all three regions. The ecoinvent 3.9.1 consequential database is used for the background system (ecoinvent, 2022). This database is transformed using premise to include projections from IMAGE scenarios for the background system (Maes et al., 2023; Sacchi et al., 2022). As for the scenarios, the SSP-2 baseline, SSP-2 RCP2.6 and SSP-2 RCP1.9 scenarios are used for both the model and the backround system.

A clinker market is developed for each region. In the market flow, the production of clinker is divided under the three kiln types assessed in the model (see Fig. 2). Life cycle inventories for the three kilns were taken over from (Müller et al., 2024). Results from the model are used to adjust the kiln shares in the market mix and to adjust the fuel use per kiln type, the emissions from combustion and the fuel related carbon capture. Average shares are used for the fuel and technology mix, in order to capture the industrial dynamics of the cement industry in the future.

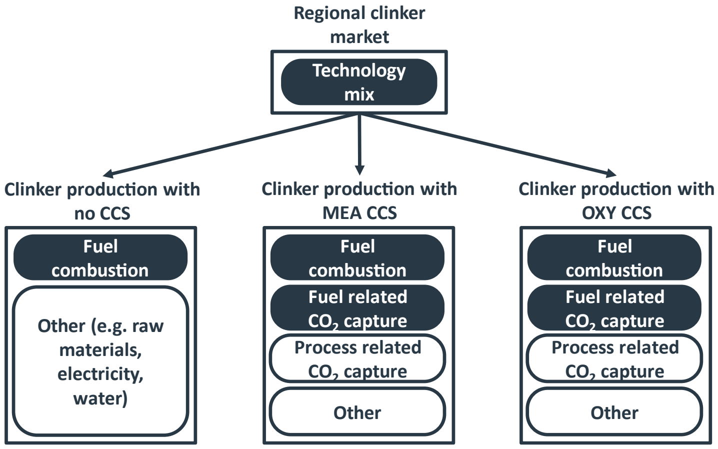

Fig. 2 Inventory system for clinker production

The use of alternative fuels is modelled in the background system. The supply of alternative fuels is partially constraint. Supply depends on the amount of waste generated by the region and its waste management strategy. The consequence of an increased demand of the fuel by an industry depends on the waste management strategy employed by the country or region. In regions with a strong waste management strategy, the landfilling of waste is either banned or discouraged by a high landfill tax. In these cases, alternative fuels are always used as a fuel source and an increased demand of waste by the cement industry can only be met by transferring waste that could have been used in another industry to the cement industry. Following the EU Landfill Directive, all member states are expected to lower their landfill rate to below 10% by 2035 (EU, 2018). In the background system, the use of alternative fuels in the cement industry in the EU, is modelled to impact the Waste to Energy (WtE) market. Any increase in demand for alternative fuels by the cement industry will be met by diverting waste from the WtE market. The loss in energy output from the WtE market, as a result of the diverted waste, is made up for by the Combined Heat and Power (CHP) market and the electricity market.

On the other hand regions with a weak waste management strategy, such as the US and Canada, do not fully utilize combustible waste as fuel, and landfill a large percentage of this potential fuel source. In these cases an increase in demand of waste can be met by diverting waste from landfill (Consequential-LCA, 2023). In the background system, the use of alternative fuels in the cement industry for the US and Canada is therefore modelled with this additional environmental benefit. See the appendix C for more detail on how these inventories were modelled.

3 Results and discussion

3.1 The fuel model

3.1.1 SB2a: the alternative fuel model

Statistical analysis showed a a minimum R^2 of 0.54 for the alternative fuel model (see appendix B). The results are significant for most coefficients except d_r, which relates to waste incineration. The alternative fuel share grows quickly for the EU, dominating the fuel mix by 2050 (see Fig. 3). This is in line with Cembureau's roadmap, which projects an alternative fuel share of 90% by 2050 (Cembureau, 2020), though the share increases at a more rapid pace in the model. A possible explanation for this, is the increased competition between industries to obtain alternative fuels (de Beer et al., 2017). An increase in competition would slow down the pace at which the cement industry can increase its alternative fuel share and is currently not considered in the model.

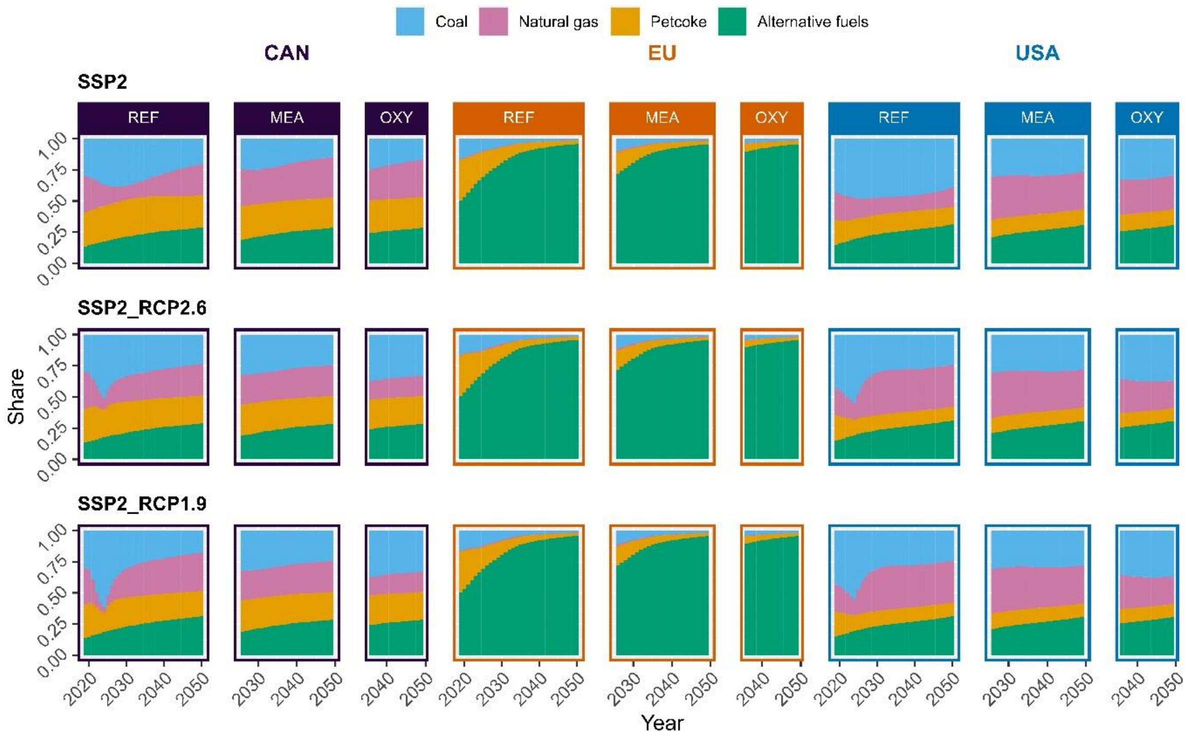

Fig. 3 Projected fuel shares per kiln type

The alternative fuel share grows moderately in the USA and Canada, but is far below what is projected in roadmaps (Cement Association of Canada, 2023; PCA, 2021). This is because the increase in incinerated MSW is low in the GWM model for both regions. Additionally, the cement demand growth substantially so consequently the demand for energy grows as well. The supply of alternative fuels is supply driven and cannot keep up with this growth which in turn negatively affects the alternative fuel share.

Since the demand for cement is determined by GDP in IMAGE and is the same for all scenarios, the alternative fuel shares do not differ much between scenarios . The projected waste incineration also did not change much between the GWM's scenarios, despite the room for growth in Canada's and USA's waste management strategy.

When comparing the results of this model with that of IMAGE, the use of alternative fuels is much lower in IMAGE's projections. There are several reasons why the projections of the two models differ so much. First, IMAGE only considers biomass as an alternative fuel source for the cement sector. Next, in IMAGE's fuel model, the market share of biomass and fossil fuels is determined in a single model based on fuel price (Kermeli et al., 2019). Finally, the use of alternative fuels is lower in other industries within the NMM sector. The alternative fuel market share of the cement industry in IMAGE, which uses the NMM sector as a proxy, is therefore much lower.

3.1.2 SB2b: the fossil fuel model

The own and cross-price elasticities derived from SB2b are presented in **Table 1**. From the price elasticities of natural gas, it can be seen that natural gas is quite sensitive to price changes and mainly competes with coal. This shows in the scenarios for the USA and Canada, where the natural gas share temporary declines due to a price increase at the start (see **Fig. 3**). In the SSP2 RCP2.6 and 1.9 a carbon tax is introduced in 2025. In these scenarios the natural gas share rapidly picks back up from its decline. The use of the natural gas is lower for kilns with CCS, since the impact of the carbon tax is lessened by capturing the CO_2. In line with the EU's historic fuel choices, the share of natural gas remains low, despite its relative energy price decreasing in projections. The share of petcoke in the fuel mix barely changes in the projections. This on account of natural gas and petcoke being weak substitutes. Coal and petcoke are substitutes, but their prices follow a similar trend.

Table 1. Results linear logit model: long-run price elasticities E_{ij} of the mean cost shares.

		Price(j)		
		Coal	**Natural gas**	**Petcoke**
Demand(i)	**Coal**	-0.735 (0.254)	0.546 (0.165)	0.19 (0.166)
	Natural gas	2.23 (0.674)	-2.25 (0.754)	0.025 (0.329)
	Petcoke	0.302 (0.265)	0.00977 (0.128)	-0.312 (0.295)

The projected fuel mix of this paper's model differs considerably with that of IMAGE. In IMAGE, natural gas has a large contribution in the mix, even for the EU. This is because IMAGE uses the NMM sector's fuel mix as a proxy for the cement industry's fuel mix. In IMAGE the use of coal and petcoke is aggregated. Their share is initially higher in IMAGE than in this paper's model, but later on drops in favor of natural gas.

The statistical analysis showed an adjusted R squared above 0.9 for all equations (see appendix B). However, the standard error of some coefficients was quite high. The model was fitted on 14 datapoints for each region, for each equation of the set. The degrees of freedom is therefore relatively low, which could explain the high standard error.

3.2 The kiln choice model

The uptake of CCS technologies varies substantially in the scenarios (see Fig. 4) and is largely dependent on the carbon tax. In SSP2 no carbon tax is implemented, thus there is no financial incentive to make the investment into CCS. In the SSP2 RCP2.6 scenario a carbon tax is implemented, which is almost the same across the three regions. The carbon tax does not become high enough to warrant the purchase of post combustion carbon capture using MEA. However, the tax does warrant the investment of oxyfuel carbon capture for the USA and Canada. The carbon tax has less of an effect in the EU, due to the large share of alternative fuels, which are partially biogenic. CO_2 emissions from biogenic content are excluded from taxation. The SSP RCP1.9 scenario has the highest carbon tax, leading to investments in MEA carbon capture from 2025 till 2035, whereafter oxyfuel carbon capture becomes the dominant technology. This is the case for all three regions.

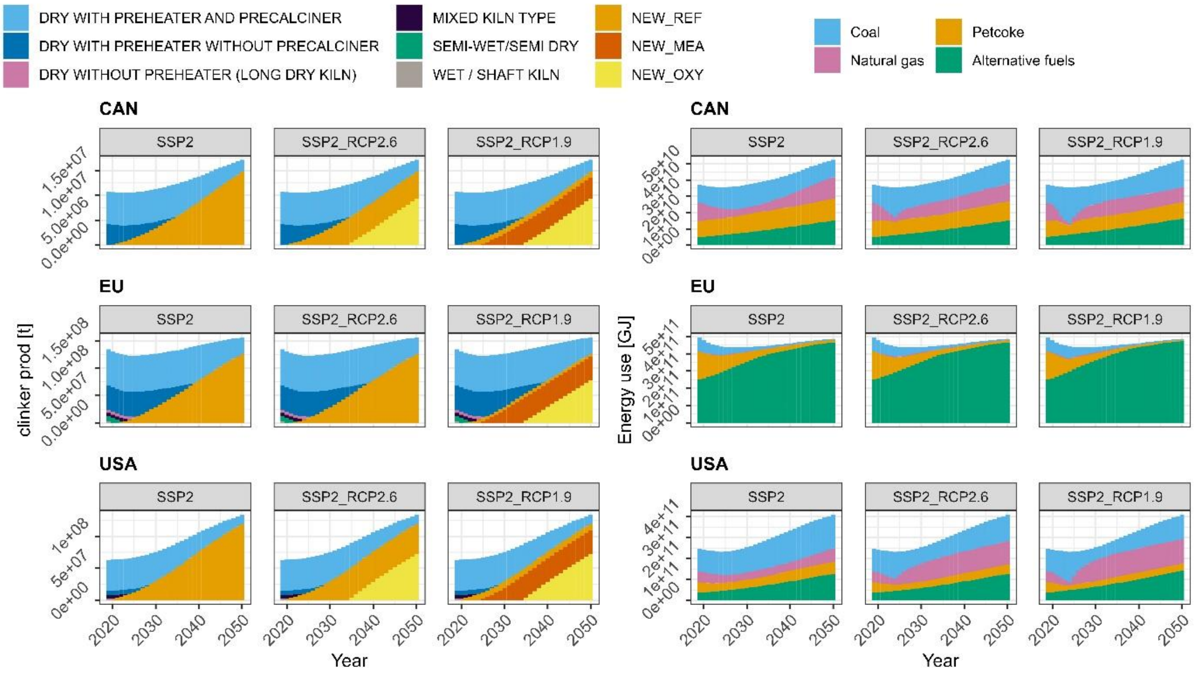

Fig. 4 projected capital growth (left pane) and projected fuel use (right pane)

Just as in the model, IMAGE projected no investments into CCS in the SSP2 baseline scenario. In the SSP2 RCP2.6 scenario, the investment in CCS is much higher in the IMAGE model. This could be because of differences in the estimated values for the CAPEX and OPEX, the lower share of alternative fuels in IMAGE's mix and the model used in IMAGE for technology choices, which does not rely on cost optimization.

The total energy use is shown in **Fig. 4** (right side). The EU shows a slight decrease in energy use due to a stable cement demand and an increase in energy efficiency from new kilns. The energy use in the USA and Canada increases substantially due to the industry's growth. Despite this growth, the use of solid fossil fuels remains stable and the increase in energy is instead mostly answered by natural gas and alternative fuels.

3.3 Prospective consequential LCA

The results of the life cycle impact assessment (LCIA) are quite different for the scenarios (see Fig. 5). Starting from SSP2, the GWP of 1kg of clinker production moderately decreases for all regions in the future. There is not a large difference between the EU and the USA and Canada despite their different fuel mix composition. This can be explained by the larger environmental benefit that the USA and Canada receive for using alternative fuels, because there the landfilling of waste is avoided in contrast with the EU where waste has to be diverted from WtE plants. This larger environmental benefit and the use of natural gas makes up for its lower share of alternative fuels in the results.

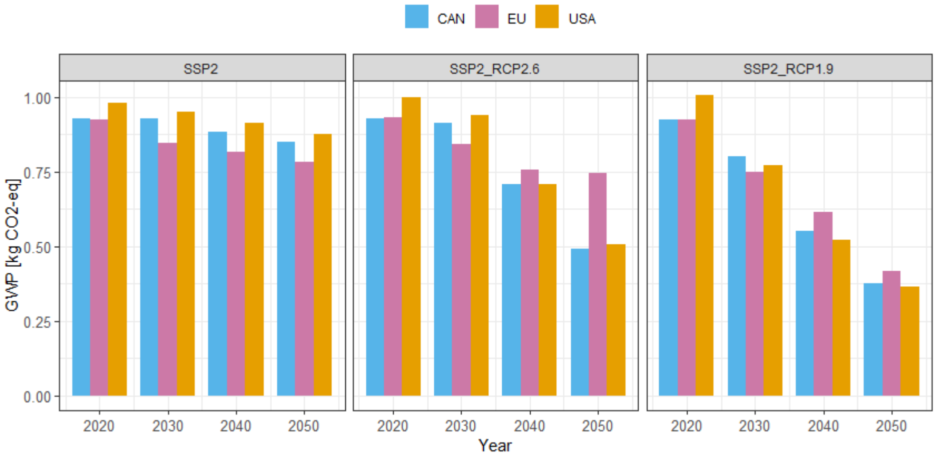

Fig. 5 GWP of 1kg clinker production

In the SSP2 RCP2.6 scenario, there is a substantial decrease in GWP for the USA and Canada, because of the investments made in CCS starting from 2035. In the SSP2 RCP1.9 scenario the GWP decreases significantly for all three regions due to their investments in CCS starting from 2025. The GWP of the EU is still the highest. This is mainly because the USA and Canada have a higher share of kilns with CCS as they invest more in additional capital to meet the increased cement demand.

Even in the SSP2 RCP1.9 scenario, the GWP is still relatively high in 2050. This is in part due to the impact assessment method that was chosen. In ReCiPe 2016, the GWP of CO_2 from fossil fuels is the same as those from biogenic content. There are other impact assessment methods who consider the use of bioenergy carbon neutral and when combined with CCS carbon negative. If such an impact assessment method would be used, the GWP would, for instance, be around 0.12 kg CO_2-eq lower for the EU by 2050. To further decrease the GWP in the RCP19 scenario, a higher adoption rate of CCS is needed. This can only be achieved by retrofitting older kilns which is currently not an option in the model.

4 Conclusions

The goal of this study was to develop projections for the cement industry which can be integrated into a prospective consequential LCA and ensure scenario consistency with the underlying IAM scenario. This was done as the cement industry is currently not accurately represented in most IAMs. Projections for the cement industry are either fully or partially aggregated with those of the NMM sector. This study has shown that because of this aggregation, the use of natural gas by the cement industry is overestimated in IMAGE, while the use of alternative fuels is underestimated. When integrating projections from IAMs to an LCA it is important to disaggregate the projections to the industrial level.

The GWP of the cement industry can be reduced to 0.4kg CO_2-eq per kg clinker in the future, in the current model. This reduction is made possible by an increased use of natural gas and alternative fuels and a high adoption rate of kilns with CCS. The share of alternative fuels and its environmental impact is largely determined by the waste management strategy employed in the region. How the waste management strategies develop in IAM scenarios has largely been uninvestigated despite its importance to the cement industry and other sectors. Further work is needed to determine how the waste management strategy may change in the future and how increased competition of alternative fuels may affect the cement industry.

Under a moderate carbon tax the adoption rate of kilns with CCS is influenced by the fuel mix. Especially alternative fuels have a considerable impact on this choice, as a large part of their emissions are not taxed. In the current modelling approach, the share of alternative fuels is kept the same across all kiln types. Because the alternative fuel share has shown to affect the adoption rate of kilns with CCS, it may be interesting to disaggregate the alternative fuel share between existing kiln types and how this develops in the future. This way, all or nothing scenarios avoided. Instead cement plants which do not have access to large supplies of alternative fuels may invest in CCS even if the average cement plant would not.

The scope of this study lied on the production of clinker. In the future this will be expanded to include projections from cement production. Potential changes that could occur in the future are changes to the availability of existing SCMs and the introduction of novel SCMs or cement types. These changes will impact the demand of clinker which in turn will affect the need for additional capital and the alternative fuel share. The number of innovative technologies included in the model will also be expanded. In the current model only innovative technologies already included in the IAM were considered. Technologies that were not included but could be interesting for future research are partial carbon capture technologies, and alternative heating options for the kiln.

To conclude, this study has shown how to disaggregate projections from an IAM using an econometric model, shown how the cement industry may develop in the future under the IAM scenarios and how this affects the industry's GWP using a prospective consequential LCA. Results of these projections, further information on the life cycle inventories and the code behind the econometric model are made available in the appendices. It is important to note that because the focus of this paper's LCA was on the dynamics of the cement industry, average shares were used for the fuel mix and technology mix. However, users are advised to convert these market shares to marginal mix shares when using these projections in a consequential LCA.

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