Assessing the EU ETS with a bottom-up, multi-sector model

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ABSTRACT

The European Emissions Trading System (EU ETS) is the central pillar of the European Union's (EU) response against climate change. This trading mechanism is considered, from the theoretical point of view, as the most cost-effective method to reduce greenhouse gases (GHG). However, previous studies show that the agents who participate in these markets may behave in a way which may lead to inefficient CO2 prices, creating doubts about the static and dynamic efficiency of the system. This paper analyses these possible anomalies by first trying to model the ETS in a more realistic way, addressing some of the limitations of previous models, and second, by comparing the results with real market transactions. For this, a bottom-up, multi-sector model has been built, which represents the EU ETS in an integrated, cross-sectoral way, paying particular attention to the interactions among the most emissions intensive industries. The results show the benefits of this modelling approach and how it better reflects real market conditions. Some preliminary conclusions regarding the behaviour of the agents in the ETS market are also presented.

POLICY RELEVANCE

Low allowance prices in the EU ETS have put into question the dynamic efficiency of the EU ETS system, prompting various ideas for structural reform. However, determining the right reform also requires estimating correctly how agents will respond to it. This paper proposes a tool to realistically simulate the EU ETS under the assumption of rational agents, and compare it to real market outcomes, in order to understand better the behaviour of agents in this carbon market, and therefore how to design better policies.

KEYWORDS: EU Emissions Trading Scheme, industrial emissions, emissions pricing, company behaviour, abatement costs

JEL Codes: Q31, Q37; Q48; Q56, Q58

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1 Introduction

The European Emissions Trading System (EU ETS) is currently immersed in its second structural reform, which mainly addresses the excess emission allowances (EUA) in circulation in the market, and which have resulted in a drop in the price of CO_2 and created uncertainty about its dynamic efficiency (Grosjean et al. 2016). The reform is aimed at improving the system for the fourth phase, which will begin in 2021.

However, under the assumption of rational agents in the market, the measures that are being discussed, like the Market Stability Reserve (MSR[1]) already adopted, would have no impact on the prices of GHG emissions (Neuhoff et al., 2015). Rather, the market would only be driven by rational expectations of the allowances' demand and supply. But the rational agents assumption may not hold: prior literature has highlighted possible deviations from rational behaviour in the carbon market, due to the endowment effect[2] (Ellerman and Reguant, 2008) or bounded rationality (Richstein et al., 2015). If present and significant, these deviations would change the effects of policies that assume rational agents, and would therefore require a different design for these policies.

Therefore, before proposing changes in the ETS or assessing its outcomes it would be advisable to gain a better understanding of the actions of market players (Hintermann et al., 2015). There are two options for this. One is to formulate models that allow for simulating deviations from economic rationality. An example is Richstein et al. (2015), who use Agent Based Modelling to represent the interactions between carbon and electricity markets in Europe. Unfortunately, these authors model the ETS as composed solely by the electricity sector which, as will be explained later, may be an oversimplification. In addition, it is very difficult to simulate realistically non-rational behaviour, since there are many deviations from rational one that can take place.

The other option is to use models that assume an economically-rational behaviour of the agents, and compare results to real market outcomes. There are in literature many

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[1] The MSR is a self-regulatory mechanism to control the allowances in the market. In case there is too much liquidity of EUAs, this mechanism withdraws rights of the market. Conversely, if a shortage occurs, rights of the reserve would be injected.

[2] The endowment effect is the phenomenon in which economic agents value more the own asset than they would be prepared to pay for it (e.g., Bischoff and Meckl, 2008).

examples of these models that represent or include carbon markets, with different modelling approaches. These can be classified into general equilibrium models (top-down) or partial equilibrium models (bottom-up). Most analytical approaches that model the whole ETS are top-down (De Bruyn et al., 2008; Monjon and Quirion, 2009; Paltsev et al., 2005). These models can provide a general overview of reality but do not generally incorporate details of each possible emission abatement alternative, therefore losing detail in the representation of the sectors. By contrast, bottom-up models allow for a higher level of technology details (e.g., models TIMES, POLES, PRIMES, or Santamaría et al., 2014; Brunke and Blesl, 2014; Wesselink and Deng, 2009), but do so at the cost of not representing the economy as a whole. There are also hybrid proposals that try to reap the benefits of each of the modelling approaches (Böhringer and Rutherford, 2008; Rodrigues and Linares, 2014; Rodrigues and Linares, 2015).

However, there is one important limitation in all the models reviewed and mentioned above. Most of them lack detail about abatement options outside from the energy sector, something very important for simulating correctly the ETS. And those which do include technological detail for industrial abatement options (such as e.g. Santamaria et al, 2014; or Monjon and Quirion, 2009) do so only for some sectors, or without including the sectors relevant to the ETS in a single model.

If sectors are represented individually or separately, which requires setting an equivalent mitigation share for each sector, it will never be possible to achieve a representation of the most-efficient allocation of mitigation efforts across sectors (which is achieved by the ETS market): the marginal cost of abatement for each sector will be determined by the pre-determined mitigation effort required, which of course may not be optimal. As a result, abatement costs will be higher than optimal in the aggregate outcome (although maybe not at an individual sector level, depending on the mitigation effort assumed).

The only way to solve this, and to represent correctly the allocation of the mitigation effort done by the market, is to represent all ETS-relevant sectors together. This also requires representing the influences on and relationships between different sectors participating in the market. For example, if the cement industry decides to reduce its GHG emissions by shifting to electricity, the electricity sector will have to produce more, thus increasing its emissions, and therefore changing its demand for allowances. This would replicate what a real market does.

To address these issues, this study develops a bottom-up optimization model to represent the ETS market considering multiple sectors linked together, and under a rational-agent assumption. The model proposed allows analysing in detail technological abatement measures for different sectors, including investment in new technologies, and determines the potential for reducing GHG emissions, according to its marginal cost. The model includes five of the most emission-intensive industries in the ETS, which together represent more than 80% of the EU ETS emissions (steel, cement, refining, tiles and bricks, and electricity generation). Compared to previous approaches, the model brings together the level of technological detail at the industry level provided by previous studies, but adds to it the connection between sectors only available in top-down models. With this, and as will be shown later, the estimation of market outcomes is improved. Of course, it must be acknowledged that a perfect fit will be difficult to attain: perfect information rarely exists in real markets, so model results should always be considered at most a reasonable approximation.

Also, a practical application is presented, and Spain is used as a country representative of the entire EU ETS due to its pattern of energy consumption and industrial emissions, which, as can be seen in Table 1, is quite similar to the aggregated EU structure. However, the point is not to replicate exactly the EU ETS, but rather to show how a multi-sector model is able to produce a better fit to reality.

		2005		2010		2012	
		Spain	EU+	Spain	EU+	Spain	EU+
Share of ETS GHG emissions (%)	Combustion (Heat and power)	64,5%	72,1%	58,0%	73,0%	65,6%	73,5%
	Oil refining	8,1%	7,0%	10,3%	6,8%	10,6%	6,8%
	Cement and clinker	14,9%	7,3%	14,6%	6,4%	10,1%	6,1%
	Iron and steel industry	4,3%	6,1%	5,9%	5,7%	4,5%	5,5%
	Ceramics and tiles	2,7%	0,8%	1,7%	0,7%	1,3%	0,6%
	Others	5,6%	6,7%	9,4%	7,5%	7,8%	7,4%
Intensity	Manufacturing GHG intensity (Kg CO2 eq. per €05)			0,766	0,540	0,763	0,492
	Industrial Energy Intensity (Koe per €05)	0,122	0,124	0,094	0,109	0,103	0,105

Table 1. Industrial GHG emissions and intensities in Spain and total covered by the EU ETS. Source: EEA, Eurostat (for manufacturing GHG intensity) and IDAE (for Industrial Energy Intensity).

This paper is structured as follows. Section 2 describes the model used. Then, in section 3 the results obtained are described and, in Section 4, these results are compared with actual data. Finally, some conclusions and recommendations are offered in Section 5.

2 The model

To carry out this study, a multi-sector, bottom-up engineering model based on Santamaría et al. (2014) and Linares et al. (2008) has been formulated. In addition to the sectors of steel, cement, and oil refining; tiles, bricks and electricity production were added. Also, as has already been mentioned, all these sectors are linked together, taking into account the interrelationships between them.

For each sector, the different current production processes and technologies are defined as well as the alternatives technically feasible to reduce GHG emissions (see the Annexes for more information about the processes and technologies modelled). The description of the sectors and their technical capabilities for improvement were obtained from the literature, supported by the assessment of experts from industry.

The model calculates the optimal strategy to meet demand (for each of the sectors) at the lowest cost given different emission reduction scenarios compared to the baseline situation (Business As Usual, BAU). It determines the optimal combination of internal abatement possibilities of emissions from each sector, covering, in this way, a greater level of detail.

The model considers demand as inelastic and exogenous, which is not considered a particularly limiting assumption, as shown in previous studies of the sectors studied (Cook, 2011; Monjon and Quirion, 2009).

Imports of goods from the ETS-sectors are permitted (intermediate and final products) in case that domestic production is rendered less competitive than imported production. Although there are more than purely economic factors when determining the substitution of domestic production by imports, this study considers this assumption as a sufficiently valid approximation (see Santamaria et al, 2014, for an estimation of the changes when Armington elasticities are introduced).

The complete model is conceptually shown in Figure 1. Each of the industries described above seeks to minimize its own cost function under technical and other constraints. Therefore, the problem to be solved corresponds to several simultaneous optimizations. In addition to the constraints that affect each sector, the sectors are connected through the price of electricity (endogenous), fuel prices, and the global constraint for GHG emissions which is the one that represents the emissions trading market. Annex I provides the representation of each sector modelled, as well as a description.

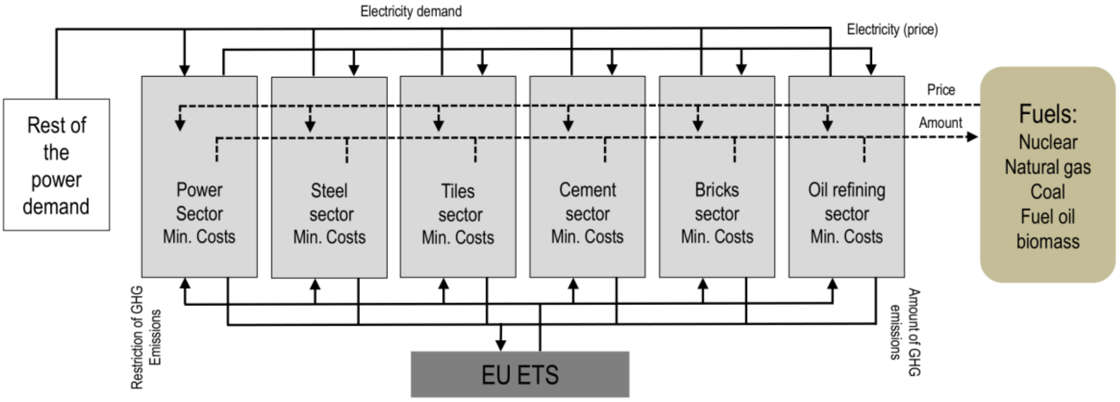

Figure 1. Conceptual scheme of the integrated model. Source: Authors.

As mentioned above, the carbon market is represented by a constraint for GHG emissions that covers all sectors. The model determines the sectors that can reduce their GHG emissions at the lowest cost for a given level of emissions reduction. For this, it takes into account the changes in production processes applicable to each sector, as well as investments in new, more efficient technology and with lower emissions. This endogenously (through the dual variable of the constraint) yields a marginal cost of reduction of the ton of CO_2 eq. emitted, which should be equivalent to the price of the emission allowance in the market under the assumptions of perfect competition and rational agents.

The model also includes interactions with other energy and climate policies in Europe (although only for ETS sectors). Renewable energy is partially modelled through the power mix and the demand of fuels by the industry. Energy efficiency is included in the engineering description of technologies and production processes. Annex II provides the complete formulation of the model.

3 An application to Spain as a representative case

In this section the model is applied to Spain, as a case study representative enough to illustrate the advantages of the multi-sector modelling in the ETS (see Table 1). An ex-post analysis is carried out for Phase II of the EU ETS, to check if the marginal reduction costs obtained from the model correspond to the prices of the allowances for the European carbon market. Then, the results are compared with the actual outcomes of the EU ETS, collected from the European ETS registry (European Union Transaction Log, EUTL).

This analysis is performed for 2008 (the first year of Phase II of the ETS), 2012 (the last year for which actual transactions data are available), and also, as an additional sensitivity analysis, for the 2012 conditions that were projected at the time of the EU reform[3]. The

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[3] Annex IV shows an application of the model to analyse the expected prices of the EU ETS if the economic crisis had not taken place. Again, the model shows results consistent with the expected outcome.

baseline year for calculating emissions reductions is 2005. The main input data for the sectoral exogenous demand and other parameters of the model are detailed in Annex III.

3.1 Validation of the model

To confirm the consistency of the results obtained by the model, intermediate and final results of energy consumption, costs, and GHG emissions (both from fossil fuel combustion and production processes) were tested for each of the sectors. The key figures are given below for 2008 and 2012.

The model covers 86% of emissions subject to the EU ETS in 2012, which amounted to 135.6 Mton. 0 provides a comparison of real emissions data for each of the sectors with those obtained by the model. As can be seen, the results fit quite well the actual emissions. The difference in the steel sector has to do exclusively with the emissions accounting method used. Here, as for all sectors, the accounting method proposed by IPCC (2006) is used, which is the one consistent with the EU ETS; the Spanish inventory uses instead a simplified method.

Emissions data ($MtCO_2$)	**2008**		**2012**	
	(real)	**(model)**	**(real)**	**(model)**
Power generation	98,27	98,00	86.97	90.18
Oil refining	13,93	14,06	14.39	15.30
Iron and steel*	7,69	11,13	6.05	11.13
Cement and clinker	23,40	24,90	13.73	12.39
Ceramics and tiles	3,97	6,22	1.82	3.51
Bricks and roof tiles				

Note: *The model calculates emissions for the steel sector with a methodology based on (IPCC, 2006).

Table 2. Comparison of real industrial GHG emissions in Spain and those obtained by the model. Source: Compiled by the authors and EEA.

The fidelity of the model was also validated through the electricity mix obtained. Table 3 shows the electricity production mix of the model and its variation compared to reality. It should be noted that some technologies increase their production in the model, absorbing pumping. This result comes from the fact that the model represents electricity demand by a reduced number of load blocks, and hence is not able to capture the detail required to simulate pumping.

[GWh]	2008			2012		
	Real	**Model**	***Variation***	**Real**	**Model**	***Variation***
Coal	46.508	49.302	*-6%*	57.662	57.630	*0%*
Combined cycle	93.198	94.416	*-1%*	42.510	46.383	*-9%*
Cogeneration	26.721	26.474	*1%*	33.767	33.731	*0%*
Wind	32.160	32.173	*0%*	48.508	47.254	*3%*
Hydro	20.957	21.039	*0%*	19.455	19.514	*0%*
Small hydro	4.640	4.616	*1%*	4.646	4.653	*0%*
Nuclear	56.460	58.129	*-3%*	61.470	60.833	*1%*
Solar photovoltaic	2.498	2.495	*0%*	8.202	8.188	*0%*
Solar thermal	15	15	*0%*	3.444	3.451	*0%*
Biomass	2.869	2.856	*0%*	4.755	4.782	*-1%*

Table 3. Comparison between real power generation mix and replicated by the model. Source: Compiled from model and REE.

3.2 The benefits of multi-sector modelling

The benefits of a multi-sector modelling of the relevant GHG-emitting sectors compared to a piecemeal analysis like the one offered by previous approaches are analysed now. The results are presented as marginal abatement cost curves (MACC or MAC curve) to show the marginal prices corresponding to different mitigation efforts. Figure 2 shows two MAC curves. One of them is called ‘synthetic’, and is built by adding all the emissions abatement possibilities of the sectors studied in a piecemeal way, not accounting for the interactions that can occur between sectors as explained in previous sections. The other curve, resulting from the model proposed, is called ‘integrated’ and includes interactions between sectors in the carbon market.

By definition, a joint optimization will allow discovering cheaper options for abatement. When sectors are optimized independently an exogenous decision about the mitigation effort for each sector is needed, which of course will not necessarily be optimal. This is particularly noticeable in the right-hand side of the MAC curves (that is, the parts representing more extreme mitigation targets).

The results agree quite well with these intuitions. Comparing the two previous MAC curves (Figure 2), it is observed that the integrated MACC shows lower marginal abatement costs overall. For low emission reductions, the abatement costs are almost equal. This is because in these first stages it is the power sector that reduces emissions in both situations (integrated and synthetic MACC). However, if the GHG emission abatement is increased, the curves start to diverge. For example, for a reduction of 25%, marginal costs change from 6 to 13 € per ton CO_2 eq. Given the current European GHG emissions reduction target for 2020, of 21% compared to 2005, it seems certainly convenient to consider these differences because they can result in significant deviations in estimated allowance prices.

This integration also approximates more reliably lower abatement costs in the ETS. If we look at the reduction between 2005 and 2015, the MACC returns a price of 3€ per ton CO_2 eq., similar to current prices. The latest European Commission projections to 2020 indicate that a fall in EU28 emissions between 2012 and 2020 of 18% would have a marginal cost of just over 6 € per ton CO_2 eq. which again is similar to the model results (European Commission 2014). Other studies, however, could overestimate the cost of CO_2 by looking at various sectors in an isolated way (e.g. Santamaría et al., 2014).

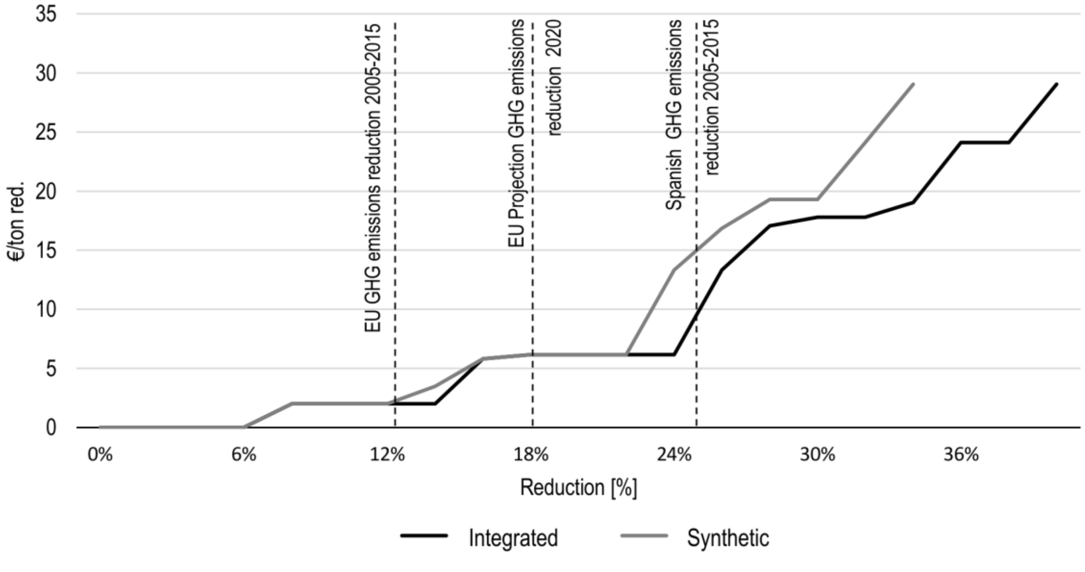

Figure 2. Comparison between integrated and synthetic MAC curves.

Source: Authors based on modelling results.

It is also interesting to analyse how much this estimation of allowance prices differs from others methodologies that only look at the electricity sector as representative for the whole ETS (e.g. Richstein et al., 2015). Figure 3 shows a comparative graph with the integrated MACC and an electricity sector-only MACC. As expected, it can be seen that the abatement costs from the electricity-only MACC are higher than those of the integrated one. Again, the cost of CO_2 is also higher by using only the electricity sector as a reference.

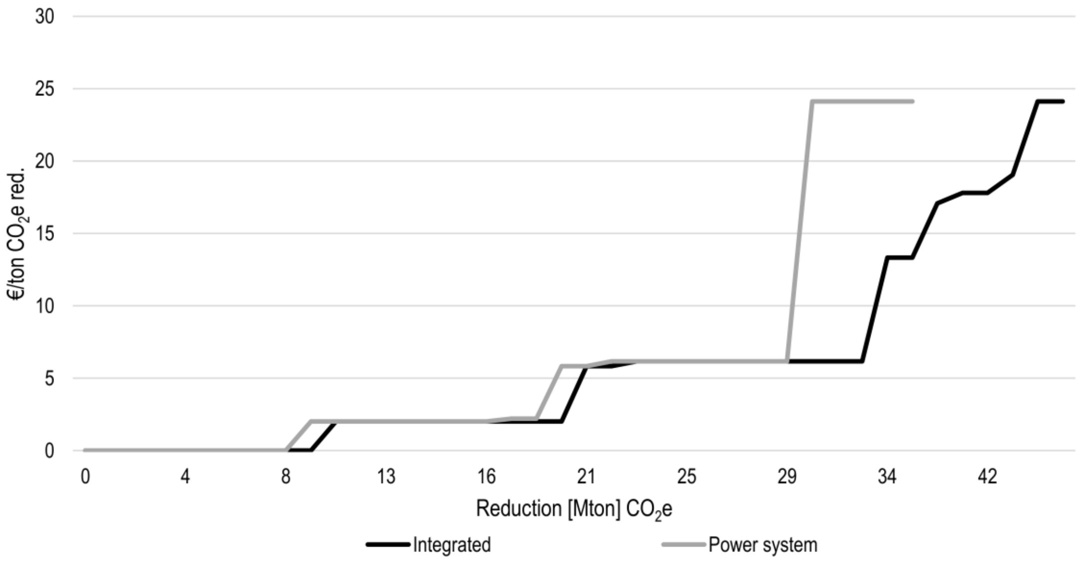

Figure 3. Comparison between MAC curve of the electricity sector and the integrated MACC. Source: Authors based on modelling results.

Finally, Table 4 summarizes the differences between 2008, 2012 and the 2012 “expected” described in section 3.1 and Annex IV.

Year	CO2 price [€/ton CO2e]		Explanation
	Model (MAC)	market (average)	
2008	17,54	22,00	The fuel prices were, on average, lower than those at the end of phase II. It was the year with the highest emissions in phase II, due to a greater amount of industrial production. This means higher marginal costs of reduction to reach the same target of maximum GHG emissions.
2012	6,16	7,33	GHG emissions from EU ETS sectors this year were in the phase II average. The industrial production declined since 2007. Although fuel prices were higher than in 2008, less effort was required (regarding reduction costs) to achieve the same levels of GHG emissions reduction.
2012 (expected)	29,04	N/A	In this scenario, both industrial production and fuel prices are higher than 2008 and 2012. As a result, the MACC has higher marginal cost.

Table 4. Comparison between CO_2 prices in different years (2008 and 2012) and scenarios (2012 “expected”). Source: Authors based on modelling results and SendeCO2.

Unfortunately, it was not possible to compare the present results with those coming from a hybrid model, since such a tool was not available. As mentioned earlier, these models are typically less detailed and offer smoother MAC curves, but it cannot be said whether the carbon prices predicted by the present model will be higher or lower than theirs.

4 Comparison with actual transaction data (EUTL)

As stated in the introduction, a second objective of this research is to test the validity of the assumption of rational agents in the ETS market, by comparing the model results with real market outcomes and observing the deviations from them. Given the complexity of this analysis, this should only be considered a first approximation that only points out the deviations, if any, and does not try to explain them in depth.

Under the assumptions considered in the model, a company/installation involved in the carbon market should sell its allowances and reduce emissions internally when the allowance market price is higher than its marginal abatement cost. Alternatively, it should buy allowances when its marginal abatement costs are above the market price. Finally, in case the company does not need to reduce emissions or buy allowances, its opportunity cost would be zero and, therefore, it should sell its allowances at any price.

However, that does not need to be the real behaviour of agents in the market. Company's strategies will be subject to their own level of market knowledge, hedging for future uncertainty (production, regulation, economy, etc.), transaction costs, financial reasons, or the willingness to speculate with this 'product'. Most agent behaviour studies are based on surveys (e.g., Martin et al., 2014) and few studies use transaction data from EUTL to study in the European market. Most of them focused on phase I (Betz and Schmidt, 2016). The studies that address the analysis of EU ETS behaviour find a high percentage of agents (who are usually small and with little market experience) who passively participate in the market (Martin et al., 2014). For example, Betz and Schmidt (2016) finds that only half of the companies are active in the market. However, larger agents do use other strategies like hedging (Neuhoff et al. 2012). Those analyses also coincide in considering transaction costs as the main barrier to entry into the market (Martin et al., 2014; Jaraitė-Kažukauskė and Kažukauskas, 2015; Naegele and Zaklan, 2016).

In order to test which of these two narratives is correct, it is needed to compare the results of the model with the real outcome of the agents as reflected in the EUTL database. The summarized data of estimated prices, transactions and allowance allocations from this database is presented in Table 5. It can be appreciated that the participation of the different sectors in the market varies, which may be explained by differences in expertise or resources to trade in the market, but also by deviations from rational behaviour.

Another factor to consider is the level of over-allocation of each sector. Overallocation may result, if agents are not rational, in lower opportunity costs for the allowances and therefore a deviation from the model results. This phenomenon is present since the beginning of Phase II in all sectors, except the power sector (see Table 5).

Spain (2012)	Average acquisition price 2011-2012	Average sale price 2011-2012 (€/EUA)	Free allocation (MEUA)	Emissions (Mton CO2e)	Over-allocation (%)	Volume of acquisition /free allocation (%)	Volume sale/free allocation (%).	Variation in GHG emissions (%) (2005-2012)	Accumulated variation in: emissions / free allocation (%)
Steel	7,00	6,94	12,20	6,05	102%	74%	229%	-22,8%	-45,0%
Combustion	7,42	7,33	72,84	89,04	-18%	191%	190%	-24,7%	17,3%
Oil refining	7,66	7,73	19,75	14,39	37%	32%	35%	-2,7%	-20,4%
Ceramics	9,09	9,69	5,60	1,82	208%	15%	52%	-63,0%	-58,0%
Cement	9,43	9,45	29,53	13,73	115%	46%	85%	-49,9%	-39,7%

Table 5. Estimated average price and over-allocation of EUA per sector. Source: Autors, from EUTL, EEA.

A first result that may be observed from this table is that there is correlation between the EUA prices traded for each sector and their over-allocation (hence pointing to a non-rational behaviour of the agents). Rather, it seems that the prices of each sector have to do with the size of the facilities, experience in market trading, etc. For example, it can be observed the prevalence of small-sized ceramic facilities in EUTL database, which also tend to trade at less favourable prices. This result coincides with the conclusions of the previous literature (e.g. Betz and Schmidt, 2016).

Now, an analysis of deviations of agents' behaviour from the rational one is carried out separately for each sector. To do that, the abatement costs for each sector (shown in Figure 4 as the marginal costs of abatement of GHG emissions obtained by the non-integrated version of the model) are compared with the ETS market price (SendeCO2, 2015).

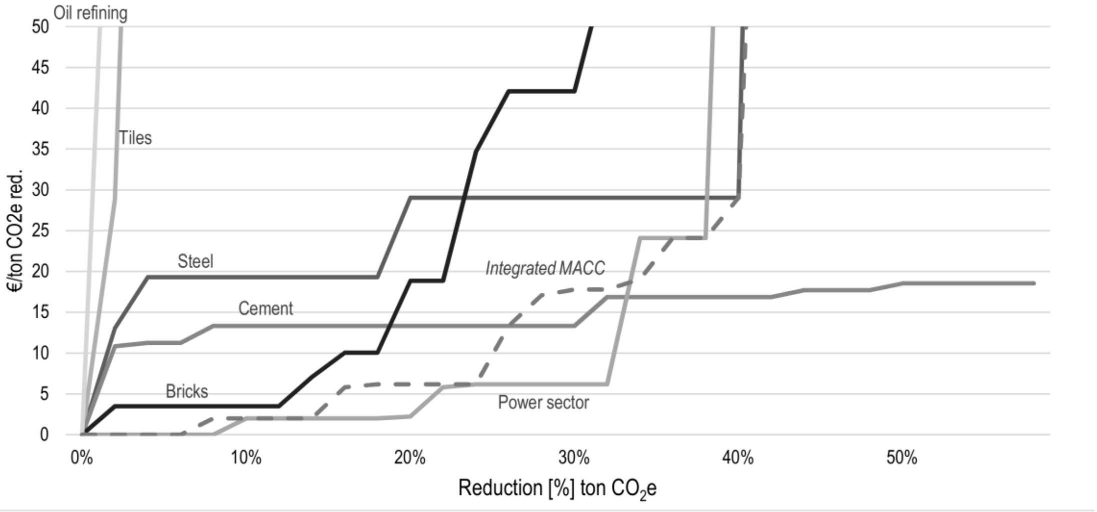

Figure 4. MAC curves by sector for Spanish industry in 2012 (without integration between sectors). Source: Authors based on modelling results.

Considering that the average annual price of the EUA was 7.33€ (SendeCO2, 2015) for 2012, in Table 6 a qualitative analysis of the agent decisions is given[4].

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[4] For this analysis, it has been considered the transactions between "Operator Holding Accounts (OHAs)," which represent the installation regulated under the EU ETS, and "Personal Holding Accounts" (PHAs)," which are voluntary accounts to trade with CO_2 allowances by unregulated entities.

Sector	MAC [€/ton red.]	Variation of production (2005-2012)	Overallocation	Expected behaviour	Real behaviour and possible explanations
Steel	29	-23,8%	Yes	The marginal abatement cost for this sector is higher than the ETS price, so the sector should buy allowances, independently of the overallocation, and not reduce emissions.	Large selling activity and increase in specific emissions (the loss in production is larger than the emissions reduction). Consistent with the fact that there is over-allocation.
Combustion	6	8,5%	No	The abatement cost is lower (but similar) than the average price of EUAs. It would be expected that this sector reduced emissions internally and sold the allowances to the market.	The transaction data of EUTL indicate a higher activity than in other sectors. No differences between sales and purchases, which is consistent the fact that there is no over-allocation and the price of the EUAs was similar to the abatement cost.
Oil refining	92	1,7%	Yes	Oil refining have high marginal abatement costs so they should buy allowances rather than reduce internally.	This sector shows reductions in emissions, and at the same time more sales than purchases. It seems that they are purchasing allowances to compensate the emissions reduction, but at the same time cashing in the overallocation.
Ceramics (bricks)	130	-81,8%	Yes	Large number of small installations, which may indicate a greater difficulty in the operation with the EU ETS. Abatement costs are larger than ETS prices, but there is a large overallocation and drop in production. If rational, agents would buy allowances.	Transaction data indicate that in this sector, there are more sales than purchases. Added to the fact that emissions reduction is lower than the loss in production, would point out to a clear desire to cash in the overallocation, instead of dealing with allowances in a rational way.
Ceramics (roof tiles)	888				
Cement	19	-68,3%	Yes	Although marginal abatement costs are quite low, they are above the EUA´s average prices. Therefore, the sector should buy allowances.	There are more sales than purchases, contrary to the expected outcome. Again, the explanation is similar to the refining and ceramics sectors.

Table 6. Qualitative analysis of the sectors behaviour. Source: CORES (2016), EEA (2014;2015), EUROFER (2016), Hispalyt, (2015), INE (2016), Oficemen (2013), REE (2013), and authors based on modelling results.

Therefore, and to summarize, it can be observed that not all sectors behave in an economically-rational way. The power sector does, but in the ceramics, oil refining, steel and cement sectors the significant overallocation may be complicating the analysis. This is more visible in the ceramics sector, probably because of the lack of sophisticated traders.

5 Conclusions

The work and the results presented allow to put forward two conclusions that are very relevant for the current regulation and future design of the European Union ETS but also for other carbon markets across the world.

First, when assessing policies that affect carbon markets, the present research found that the market should be modelled taking into account all the relevant sectors and their interactions. This allows for not imposing separate (and somehow artificial) mitigation shares for each sector[5], which in turns represents better the real outcome of a market: least cost options across all sectors are identified, and the interaction between sectors taken into account.

As has been shown in the comparison of results, not accounting for all sectors (e.g. looking only at the electricity sector), or not taking into account the interactions between sectors, results in overestimating allowance prices, or underestimating the potential for emissions abatement at a given price. This of course is very relevant to policy design, since the real outcomes from the policy may deviate significantly from the simulated ones just for this reason. In this regard, this bottom-up model can incorporate all these elements with a high-enough degree of technological detail for most of the largest emitting sectors. Of course, the model still has some limitations, such as the lack of consideration of transaction costs, which have been shown to play a non-negligible role in ETS trading, or the assumption of perfect information, which is rarely met in the real world. It would also be advisable to include other elements such as hedging or financial strategies that may alter the behaviour of the agents in the market.

However, that would introduce further complexity, and more parameters that are difficult to control for. It therefore makes more sense to test the validity of the assumption of

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[5] It should be noted that political economy concerns may sometimes justify separated sectoral targets. But that is not the current option chosen under the EU ETS.

rational agents - which is much simpler to model - and compare it to the real outcomes of the ETS. Again, this test is very relevant for policy design. If agents are shown to behave rationally, certain policies such as the MSR may be useless to improve the efficiency of the market.

In this sense, and although preliminary, the results show differences in the behaviour of the sectors: the power sector seems to behave rationally, but in the case of ceramics, steel, cement and oil refining overallocation seems to be playing a significant role, with agents selling allowances even if their abatement costs are higher than ETS prices. That would point out to the need to consider sector-differentiated policies, to account for these differences in their behaviour.

It can be also observed that the prices that different sectors pay for their allowances differ, which may reflect a different ability to play in the market. This is an important market failure which should be taken into account, and which deserves further investigation.

The simulation of the interplay between technologies, costs and agents could improve the design of carbon mitigation policies. This is particularly needed now in the European Union, given the need to adjust the EU ETS, but also in many other countries where carbon markets are just being implemented. This paper hopes to contribute to the right design of these markets by helping to understand which are the basic requirements for modelling the ETS and the rational behaviour of its agents.

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ANNEXES

- Annex I Schemes of modelled sectors
- Annex II Formulation of the model
- Annex III Input data for the model
- Annex IV A sensitivity analysis

Annex I Schemes of modelled sectors

1 Steel

Steel production can be divided according to the oven used: basic oxygen furnace (BOF), to melt pig iron; and electric arc furnace (EAF), mainly used for scrap metal but also fed by pig iron. The model implemented takes into account the limitations of the mixture of raw materials to be included in each of the ovens. The main sources of GHG emissions in the process are also represented, through pig iron, coke, DRI[1], etc., as well as indirect emissions due to electricity consumption.

Figure 1 schematically represents the model of the steel production process.

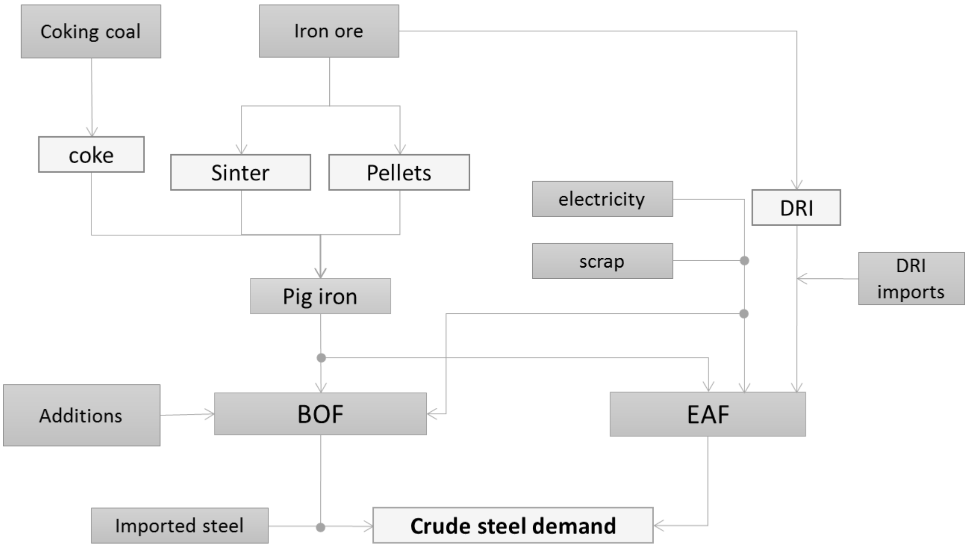

Figure 1. The steel production process. Source: Authors from Santamaría et al. (2014).

2 Cement

Integrated plants of clinker (the main element for the production of cement) and cement plants use different raw materials such as limestone and clay to obtain clinker. To feed the furnaces, different fuels can be used, including coke, coal, natural gas, waste oils, and tires. In the production of clinker, different technologies are also considered, from wet to dry.

The representative model considers the two types of cement-producing facilities, integrated cement plants, and grinding mills, which use imported clinker for the production of cement (see Figure 2). The model minimizes the production costs of seven types of cement, as well as the possibility that it could be imported. This approach does not take into account transportation costs. The literature argues that transporting clinker by road is only profitable at distances less than 200 km (Szabo et al., 2006).

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[1] Iron which occurs from direct reduction of iron ore.

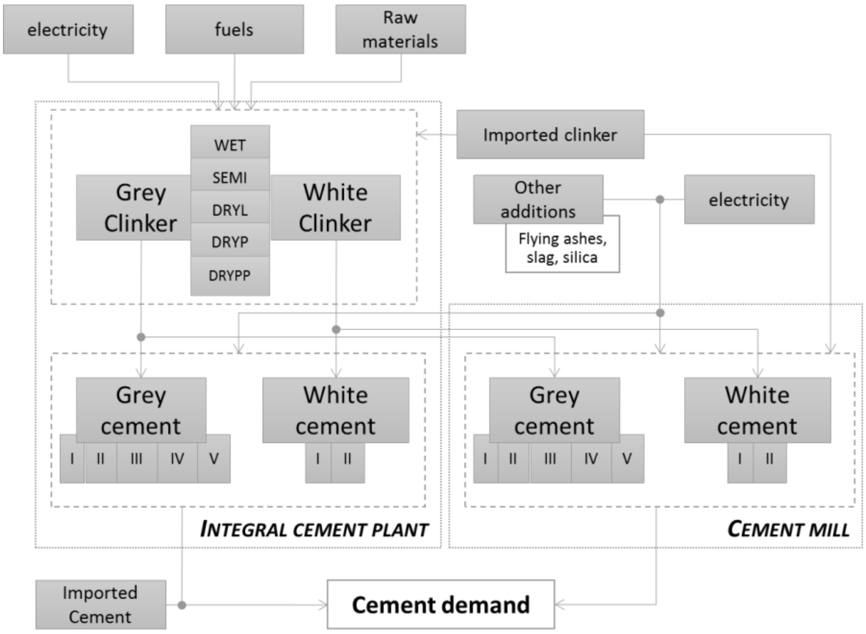

Figure 2. The manufacturing process for clinker and cement for Spain. Source: Authors from Santamaría et al. (2014).

3 Oil refining

Refineries can be classified according to their complexity. Simple refineries, with low conversion, are less able to obtain light products (gas fuel, gasoline, etc.), which are the most popular. Conversely, the more complex ones (in which additional modules are added), have a higher conversion capacity. Refineries with FCC (fluid catalytic cracking system) modules belong to the conversion scheme. If the refinery incorporates HC modules (hydrocracker) and coker, it is classified as deep conversion. The model includes octane, sulphur level, and density requirements, although in a linear, simplified way.

In Figure 3 can be seen the relationship between the different processes to obtain oil products.

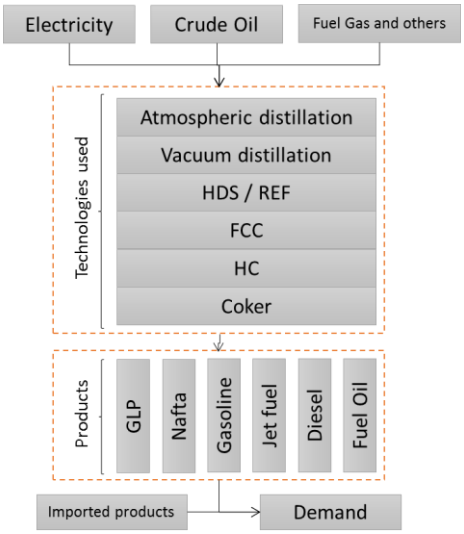

Figure 3. The oil refining process. Source: Authors.

4 Bricks and tiles

Figure 4 shows the interaction between the different processes and facilities for the manufacturing of ceramic tiles represented in the model. The model takes into account the production of up to five final products from two types of furnaces: tunnel and roller kilns. Also considered are the process and indirect emissions due to power consumption, and the possibility of using cogeneration. Possibilities such as improved insulation of furnaces, a new capability for heat recovery, or the use of pre-furnaces are also modelled.

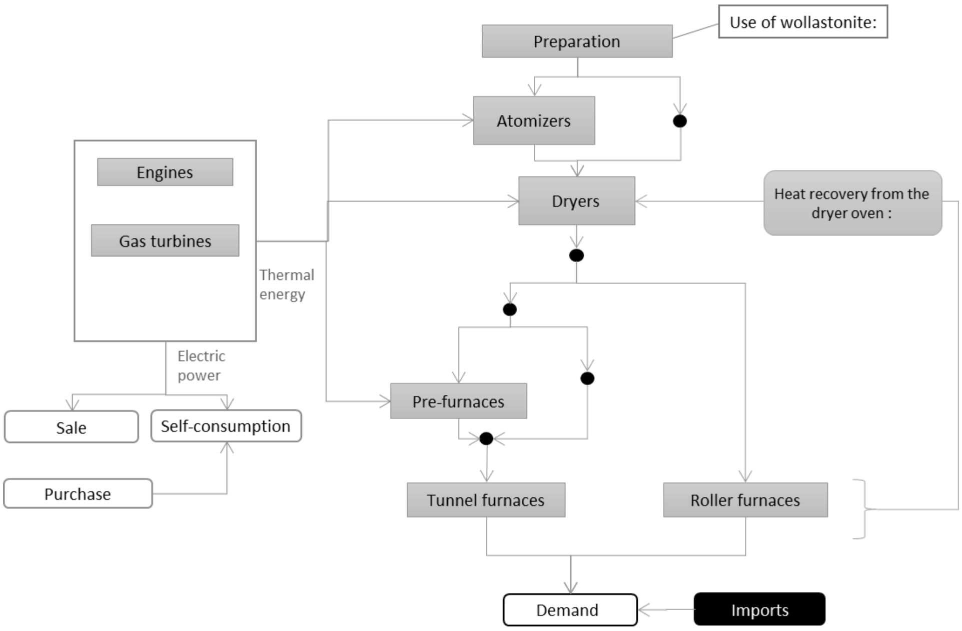

Figure 4. **The manufacturing process of ceramic tiles. Source: Authors.**

Although some facilities change, as can be seen in Figure 5, the production process of the bricks and roof tiles industry is similar to the tiles industry described above.

In this case, three different types of furnaces for the production of bricks and roof tiles are taken into account: Hoffmann, tunnel, and roller kilns. The model considers different options for reducing emissions, due to the process or due to the consumption of fossil fuels and electricity. Within these options are included the possibility of using pre-furnaces and heat recovery, or heat and power through cogeneration. The details of the different variables taken into account for the calculation of the cost of reducing emissions in this sector are provided in Annex II.

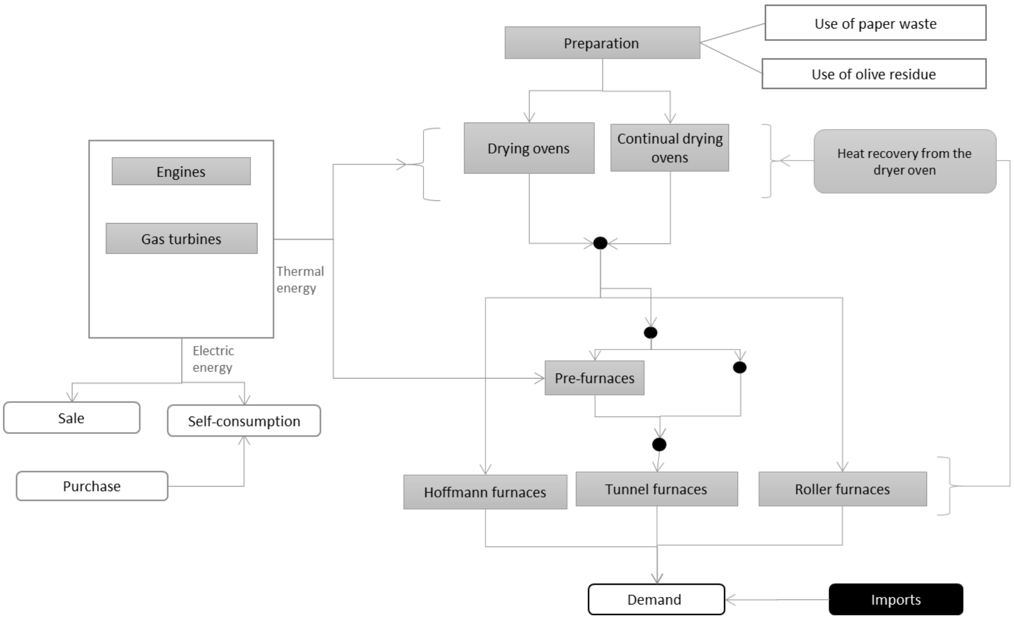

Figure 5. The manufacturing process of bricks and tiles. Source: Authors.

5 Power sector

The representation of the power sector is based on Linares et al. (2008). Different generation technologies, as well as their restrictions and capabilities, are represented. The model takes into account energy policies and investment opportunities. It also seeks the economically optimal choice to satisfy electricity demand, including the demand from the industrial sectors studied. Furthermore, the model considers, as in the other sectors analysed, the potential of reducing GHG emissions.

Annex II Formulation of the model

1 Mathematical structure of the model

$$Min. Costs: \sum (Power\ gen. cost\ + Steel\ sector\ cost + Cement\ sector\ cost + Tiles\ and\ bricks\ sector\ cost + Oil\ refining\ sector\ cost\ )$$

Constraints:

Steel sector

Subject to:
1) Steel produced + imported ≥ Steel demand
2) Requirements of raw and intermediate materials (coke, sinter, pellets, scrap, fuel, etc.)
3) Constraints for pig iron consumption and DRI to EAF process
4) Produced steel ≤ Maximum capacity (BOF, BF, EAF)

Cement Sector

Subject to:
1) Cement produced ≥ Cement demand
2) Energy contained in fuels ≥ Energy for the production of clinker
3) Consumption of raw materials (limestone and clay)
4) Cement produced (gray and white) ≤ Cement production capacity (gray and white)
5) Clinker produced (gray and white) ≤ Clinker production capacity (gray and white)
6) Consumption of cement clinker (whole plants + mills) ≤ Clinker produced + imported clinker
7) 65% of the fuel must be coke (to reflect the limitation of the combustion process)

Oil refining Sector

Subject to:
1) Satisfaction of the different types of demand (gasoline, jet fuel, diesel, fuel oil)
2) Mass balances between stages and processes (atmospheric distillation, reforming, HDS, FCC, HC, coker)
3) Requirements for self-consumption of LPG and supply of vacuum distillation
4) Maximum capacities of the processes (atmospheric distillation, reforming, HDS, FCC, HC, coker)
5) Compliance with specifications (NOx, octane, etc.)
6) Energy Consumption ≤ Energy provided

Tiles Sector

Subject to:
1) Production + Imports (tiles, floor tiles and extruded) ≥ Demand
2) Amount of fuel consumed ≥ Energy consumption of each installation (direct and with cogeneration)
3) Tiles production ≤ Installed capacity + new capacity
4) Quantity of raw materials used ≥ Raw materials required
5) Electricity produced = Electricity sold + self-consumed electricity

Bricks Sector

Subject to:
1) Production + Imports (bricks, roof tiles and other) ≥ Demand
2) Amount of fuel consumed ≥ Energy consumption of each installation (direct and with cogeneration)
3) Bricks and roof tiles production ≤ Installed capacity + new capacity
4) Quantity of raw materials used ≥ Raw materials required
5) Electricity produced = Electricity sold + self-consumed electricity

Power Sector

Subject to:
1) Balance of demand (power output = power demand)
2) Availability of installed power (generated power ≤ Installed capacity * load factor)
3) Energy available in the reservoirs and run-of-the-river hydro
4) Balance in pumping storage
5) Limitation of emissions of SO_2, NOx and particulates
6) Maximum installed capacity of renewable and nuclear technologies
7) Annual limit of installation of new CCGTs and coal power plants
8) Minimum annual production with plants that use natural gas (for backup)

Common constraint

BAU GHG emissions (1 - % reduction) ≥ Total GHG Emissions

Source: Authors.

2 Notation

Sets:	
p	Implementation period (years)
$exec$	Execution of MAC curve
s	Subperiods (month - workable day, month –non-working day)
n	Load blocks (hours of the day)
$comb$	Fuel type
$coke(comb)$	Fuel coke
$bio(comb)$	Biogas
$comg(comb)$	Gas (Natural gas and biogas)
$cofc(comb)$	Fuels (coke and fuel oil)
$ele(comb)$	Electricity
$elec$	Buy ($ein(elec)$) and sell ($eout(elec)$) electricity
cog	Possibility of cogeneration
$tcog$	Type of cogeneration (gas turbine, internal combustion engine)
$cogy(cog)$	With cogeneration
$cogn(cog)$	Without cogeneration
$crct$	Characteristics of the energy savings measures
$tst(crct)$	Thermal energy savings
POWER SECTOR	

ct	Power technologies (Nuc, ncoal, icoal, CCGT, F-G, Hyd_Res, Hyd_ror, Wind, ORSR, NRSR, Pump)
$cex(ct)$	Existing power technologies
$ct\_eol(ct)$	Existing wind power technologies
$ctweol(ct)$	Existing power technologies (without wind farms)
$tecr$	Renewable technology
$ctnoint(ct)$	No intermittent power technologies
$h(ct)$	Adjustable power stations
$f(ct)$	Flowing hydraulic power
$b(ct)$	Pump (hydraulic power)
$cn(ct)$	New power technologies
$pollut$	Pollutants (NOx, NO_2, particles)
STEEL	
trs	Type of raw materials and energy
$trdr(trs)$	DRI (raw material)
$trsc(trs)$	Scrap (raw material)
$der(trs)$	Type of iron and coal products (intermediate)
$dere(der)$	Type of iron and coal products with direct GHG emissions
$ddr(der)$	DRI (intermediate)
$drsd(der)$	Iron and coal products (intermediate without DRI)
pgi	Type of pig iron
$tot(pgi)$	Total of pig iron
$pgbe(pgi)$	Both of pig iron (BOF and EAF)
$pea(pgi)$	Pig iron EAF
$pgb(pgi)$	Pig iron BOF
ts	Types of steel
$tsim(ts)$	Imported steel
$tsb(ts)$	Steel from BOF
$tea(ts)$	Steel from EAF
$tbe(ts)$	Steel from BOF and EAF
ps	Processes (BF, BOF, EAF, DRI)
$psb(ps)$	BF process
$psbo(ps)$	BOF process
$pse(ps)$	EAF process
$psd(ps)$	DRI process

$psbe(ps)$	BOF and EAF process
OIL REFINING	
cr	Type of crude (for amna, arabian light, Brent, forcados, maya)
m	Modules (atmospheric distillation, reformed, HDS1, HDS2, HDS3, atmospheric vacuum, FCC, HC, coker)
$mre(m)$	Module (reformed)
$mra(m)$	Atmospheric distillation
$hed(m)$	HDS desulfurized extraction
$prtc$	Products of crude (intermediate and final)
$aur(prtc)$	Products to self-consumption (fuel gas, fuel oil)
$rfn(prtc)$	Reformed naphtha
$bu(prtc)$	Butane
$ln(prtc)$	Light naphtha
$ng(prtc)$	Natural gas
$inpr(prtc)$	Entry to final products
$gb(inpr)$	Entry to final products (gasoline from butane)
$gln(inpr)$	Entry to final products (gasoline from light naphtha)
$ijf(inpr)$	Entry to final products (jet fuel)
$ijf2(inpr)$	Entry to final products (jet fuel from HDS1 and HC)
$di(prtc)$	Diesel
$ga(prtc)$	Gasoline
$jf(prtc)$	Jet fuel
$prc\ (prtc)$	Products of crude (intermediate)
$ex\ (prc)$	Extractions (1st, 2nd, and 3rd) from HDS
$1ex(ex)$	1st extraction
$2ex(ex)$	2nd extraction
$3ex\ (ex)$	3rd extraction
$pin\ (prc)$	Entry of products into the modules
$pcru(pin)$	Crude oil
$ir\ (prtc)$	Imported products (H_2, natural gas)
$hir(ir)$	Imported products (H_2)
crc	specifications of the final products (density, sulfur, cetane)
$dr(prtc)$	Final products of oil refining
$pfcc(prtc)$	Products of crude (intermediate from FCC)
$se(crc)$	Specifications (sulfur)

$de(crc)$	Specifications (density)
$ce(crc)$	Specifications (cetane)
$ro(crc)$	Specifications (octane)
su	Sulfur content
$ws(su)$	Without sulfur (or it is not considered)
$ss(su)$	With sulfur
CEMENT	
tc	type of cement (grey and white Clinker, plaster, pozzolanas, slag, fly ash)
tcl	Type of clinker production (wet, semidry, dry, etc.)
in	Parts of a plant (integral plant, cement mill)
cl	Type of clinker (grey and white)
mcl	Raw material to clinker
TILES	
$ttrm$	Type of tiles and raw materials
$tt(ttrm)$	Type of tile (red paste tiles, white paste tiles, red paste stoneware, porcelain and white paste stoneware and extruded tiles)
$twe(tt)$	Type of tiles without extruded tiles
$wo(tt)$	Wollastonite
$ttw(tt)$	Product with Wollastonite
$dftt(tt)$	Product with double firing
$tfg(ttrm)$	Frits and glazes
int	Facilities tile factory
$ki(int)$	Type of kiln (tunnel kiln, roller kiln)
$kti(int)$	Tunnel kiln
$irt(int)$	Heat recovery
$pkt(int)$	Pre-kiln
$ite(int)$	Facilities with electricity consumption
$icg(int)$	Facilities with energy consumption from cogeneration
$iwk(int)$	Process (without kilns)
$iat(int)$	Atomizer
per	Types of performance (thermal, electric, load factor)
$tep(per)$	Thermal performance
$eep(per)$	Electric performance
smt	Energy saving measures:

	smt1: optimization of combustion air flow and furnace pressure curve. smt2: heat the combustion air of the furnace with cooling gas fireplace. smt3: Increase solids content of the slurry atomizer and automatic control of the humidity in atomizers
$smtk(smt)$	Energy saving measures to kilns (smt1, smt2)
$eci(crct)$	Power consumption increase (facilities)
fir	Type of cooking in tiles production
$df(fir)$	Double firing bake
$carb$	Characteristics of carbonate product according to the raw material
$perc(carb)$	Percentage of carbonate
BRICKS	
$tbrm$	Products and raw material
$tb(tbrm)$	Type of products (bricks wall, face bricks, roof tiles, others)
$brm(tbrm)$	Raw material
$rmpm(tbrm)$	Raw material: waste paper and marc
$cla(tbrm)$	Raw material: clay
$wp(tbrm)$	Raw material: waste paper
$mab(tbrm)$	Raw material: marc
inb	Facilities of bricks factory
$kb(inb)$	Type of kiln
$kbi(inb)$	Tunnel kiln
$pkb(inb)$	Pre-kiln
$drb(inb)$	Dryers (continuous dryer and camera dryer)
$irb(inb)$	Heat recovery
$itb(inb)$	Facilities with electricity consumption
$icgb(inb)$	Facilities with energy consumption from cogeneration
$prb(inb)$	Raw material preparation
smb	Energy saving measures: smb1: optimization of combustion air flow and furnace pressure curve. smb2: heat the combustion air of the furnace with cooling gas fireplace.
ar	raw material extraction location (ar1: good, ar2: medium, ar3: bad)
$ar12(ar)$	Raw material extraction location (ar1, ar2)
$cabb$	Carbonate content of the raw material

Parameters:	
tp_p	Discount rate
$ccomb_{comb}$	Fuel costs
$cgc_{per,tcog}$	Characteristics of cogeneration (performances)
$tppk$	Thermal performance pre-kiln
nss	Thermal performance of dryers
$maxbg$	% Of natural gas to biogas
bau	Amount of GHG emissions in business as usual scenario
red	% of GHG reduction
$emco_{comb}$	GHG emission factor (fuels)
$emcar$	GHG emissions (carbonate)
$capbg$	Maximum availability of biogas
POWER SECTOR	
$invcp_{cn,p}$	Investment costs of the new power capacity
$invef_{ct}$	Reverse efficiency
$days_s$	Number of days corresponding to each day s
$comregesp_{tecr}$	Operation and maintenance “special regime”
$prem$	Premium
$del_{p,s,n}$	Electricity demand (without industry)
$deli_{p,s,n}$	Electricity demand matrix (industry)
$prodeol_{p,s,n}$	Wind power generated
$loadf_{ct}$	Load factor
$indcob$	Coverage rate of non-intermittent electric generation (reserves)
$aporhid_{h,s}$	Hydraulic contribution
$fluy_{f,s}$	Available flowing power
$bomax_b$	Maximum pumping power
$cont_{ct,pollut}$	Level of emissions of SO2, NOx, and particulates
$maxco_{p,pollut}$	Maximum level of emissions (except CO_2)
$pinsmcn_{cn}$	Maximum installed power for each type of new plant
eme_{ct}	GHG emission factor
STEEL	
els_{ts}	Electricity consumption factor
$prms_{trs}$	Price of raw materials

$cprs_{ps}$	Fixed and variable costs (by process)
$cinst_{ps}$	Cost of investments (process)
$pimst$	Price of imported steel
$mxs_{der,trs}$	Mix of products
$pars_{drsd}$	Parameters for pig iron
$stde$	Steel demand
$mcst_{ps}$	Maximum capacity (process)
$emsd_{der}$	GHG emission factor (direct)
ems_{tot}	GHG emission factor (indirect)
OIL REFINING	
$elr_{pin,cr}$	Electricity consumption factor
$pcru_{cr}$	Price of crude (for amna, arabian light, Brent, forcados, maya)
$cfvr_{pin,cr}$	Fixed and variable operation costs
$cinvr_{pin,cr}$	Investment costs
$pimop_{ir,cr}$	Price of other imported product
$pimp_{dr,cr}$	Price of imported final product
$fac_{crc,prc,cr}$	Conversion factors
$demr_{dr}$	Demand of refining products
$fluj$	Flows
$mez1$	Mixing matrix (modules)
$mez2$	Mixing matrix (intermediate flows)
$mez3$	Mixing matrix (entrance to final products)
$mez4$	Mixing matrix (entrance to modules)
$capacity_{prc}$	Maximum input capacity to the modules
$dhds_{ex,crc,cr}$	HDS specifications of the final products (density, sulfur, cetane)
$dref_{crc,cr}$	Reformed specifications
$spf_{di,se}$	Fuel specifications
$tcr_{pin,cr}$	Thermal consumption (refining)
$pcomb_{aur,cr}$	Calorific value of fuels
$emr_{pn,cr}$	GHG emission factor by product
$emcor_{prtc}$	GHG emission factor
CEMENT	
$elcl_{tcl,cl}$	Electricity consumption factor (clinker production)

$elc_{in,tc}$	Electricity consumption factor (cement production)
$prmc_{mcl,cl}$	Price of raw materials
$cfvc_{in}$	Fixed and variable costs (current production capacity of cement)
$cfvcl_{in}$	Fixed and variable costs (current production capacity of clinker)
$pimc_{cl}$	Price of imported cement
$pimcl_{cl}$	Price of imported clinker
dce_{tc}	Cement demand
$ctcl_{tcl,cl}$	Thermal consumption for clinker
$pck_{mcl,cl}$	Raw material in clinker
$cce_{in,tc}$	Capacity of cement production
$ccl_{tcl,cl}$	Capacity of clinker production
rmk_{cl}	Cement raw materials
$emc_{mcl,cl}$	GHG emission factor
TILES	
$prmt_{tt}$	Price of raw materials
$cfvt_{int}$	Fixed and variable costs (current production capacity)
$cifvt_{int}$	Fixed and variable costs (new capacity)
$csmt_{smt}$	Saving energy measures costs
$cinvt_{int}$	Investment costs (ovens, pre-ovens, dryers, systems, heat recovery, and others)
$ccgt_{tcog}$	Investment costs (cogeneration)
$cikt_{kt}$	Investment costs (energy saving measures)
$pimt_{tt}$	Price of imported tiles
$cicot_{comb}$	Investment costs (fuel switching)
dti_{tt}	Tiles demand
fco_{comb}	Conversion factor for fuel
ebt_{int}	Extra requirements of double-firing
$ects_{int,tt}$	Energy consumption of furnaces with standard insulation
$ecti_{int,tt}$	Energy consumption of furnaces with improved insulation
$rkdt_{irt}$	Heat recovery (oven - dryer)
svw	Energy savings by use of wollastonite
$cst_{smt,tst}$	Characteristics of the energy saving measures
cot_{fir}	Percentage of double firing bake
cti_{int}	Capacity of tiles production
mxw	Maximum amount of available wollastonite

$carc_{carb}$	Average carbonate content of the raw material
swt_{tt}	Specific weight of the tiles
but_{itad}	Minimum contribution of burners in a dryer and an atomizer
$pct_{ite,tt}$	Power consumption (facilities)
$trtkd$	Energy recovery between dryer and kiln
$ccgt_{tcog}$	Capacity of cogeneration production
$cpcot_{comb}$	Current fuels mix
$ccikt_{kt}$	Current capacity of an insulate furnaces
$carbt_{tt}$	Carbonate content
$cks_{irt,ki}$	Kiln – dryer connection
BRICKS	
$prmb_{brm}$	Price of raw materials (raw materials, paper waste, residue oil)
$cfvb_{inb}$	Fixed and variable costs (current production capacity)
$cifvb_{inb}$	Fixed and variable costs (new capacity)
$csmb_{smb}$	Saving energy measures costs
$cinvb_{inb}$	Investment costs (ovens, pre-ovens, dryers, systems, heat recovery, and others)
$cpcgb_{tcog}$	Investment costs (cogeneration)
$cikb_{kb}$	Investment costs (energy saving measures)
$pimb_{tb}$	Price of imported industrial ceramics (bricks and tiles)
$cicob_{comb}$	Investment costs (fuel switching)
dbi_{tb}	Bricks demand
nsb	Thermal performance of dryers
ebb_{inb}	Extra requirements of double-firing
$ecb_{inb,tb}$	Energy consumption of facilities
$ecbi_{inb,tb}$	Energy consumption of furnaces with improved insulation
$tpbk$	Thermal performance of pre-kiln
$csb_{smb,tst}$	Characteristics of the energy saving measures
$cvpw$	Calorific value * performance of a paper waste
$cvma$	Calorific value * performance of a marc
$rkdb_{irb}$	Heat recovery (oven - dryer)
cbi_{inb}	Capacity of bricks production
bub	Minimum contribution of burners in dryer and atomizer
$pcb_{ibe,tb}$	Power consumption (facilities)
$trbkd$	Energy recovery between dryer and kiln

$pcob_{tb}$	Power consumption for other equipment
yac_{cabb}	Utilization of each area (raw material)
$maxwp$	Maximum of waste paper
pwp_{tb}	Maximum % of waste paper in a final product
$cwpp_{tb}$	Relation waste paper - product
$cpwp$	% of installations of raw material (waste paper) near to factories
$maxm$	Maximum of marc
pma_{tb}	Maximum % of marc in a final product
$cmap_{tb}$	Relation marc - product
$cpma_{ar}$	% of installations of raw material (marc) near to factories
$cpcgb_{tcog}$	Capacity of cogeneration production
$ccikb_{kb}$	Current capacity of insulate furnaces
$cpcob_{comb}$	Current fuels mix
$carbb_{cabb,ar}$	Carbonate content
$cksb_{irb,kb}$	Kiln – dryer connection

Variables:	
POWER SECTOR	
$PINS_{cn,p}$	New installed capacity
$PGEN_{ct,p,s,n}$	Electricity power generation by each technology
$PINSACUM_{ct,p}$	Cumulative installed capacity in each period (auxiliary variable)
$RES_{h,p,s}$	Level of reservoirs
$PBOMB_{b,p,s,n}$	Pumping capacity
STEEL	
QRS_{trs}	Amount of raw materials and energy (Iron, coking coal, DRI imported)
QDE_{der}	Amount of iron and coal products (intermediate)
QPI_{tot}	Amount of pig iron
QST_{st}	Amount of steel
QSC_{ps}	Amount of bought scrap
$INST_{ps}$	Investment in new capacity
OIL REFINING	
$QCRU_{cr}$	Quantity of crude (for amna, arabian light, Brent, forcados, maya)
QH_{cr}	Quantity of hydrogen (for amna, arabian light, Brent, forcados, maya)

QNG_{cr}	Quantity of external combustion natural gas (for amna, arabian light, Brent, forcados, maya)
$QIMP_{ir,cr}$	Quantity of others imported products
$IMP_{dr,cr}$	Quantity of final imported product
	Auxiliary variables
$MODUL_{m,pcr,cr}$	Product output of each module
$INPUT_{m,cr}$	Product entry in each module
	Oil Refining Products
$PRCR_{pfr,cr}$	Final products
$ENTRPR_{pcr,su,cr}$	Entry to final products
$CORRINTER_{fluj,cr}$	Intermediate flows
$MINV_{prc,cr}$	Investment in new capacity
$ICOR_{aur,cr}$	Self-consumption of refining products
$ECOR_{aur,cr}$	External consumption of fuels
CEMENT	
$QCP_{in,tc}$	Cement produced
$QCI_{in,tc}$	Imported cement
$QCLI_{cl}$	Imported clinker
$QCL_{tcl,cl}$	Clinker produced
$QCOM_{tcl,comb}$	Amount of fuel (cement)
$QRM_{mcl,cl}$	Amount of raw materials (limestone and slate) for clinker production
$INVC_{in,tc}$	Investment in new production capacity of cement
$INVCL_{tcl,cl}$	Investment in new production capacity of clinker
TILES	
$QTP_{int,tt}$	Tiles produced
QTI_{tt}	Imported tiles
$QCOT_{comb,cog}$	Amount of fuel (tiles)
$QEIN_{int,tt}$	Energy consumption of facilities
$QCGT_{int,tcog,tt}$	Fuel consumption in cogeneration by facility
$QIKT_{int,tt}$	Current availability of improved furnace insulation
$QBT_{int,tt}$	Use of double-firing in standard ovens
$QBIT_{int,tt}$	Use of double-firing in insulated ovens
QWO_{tt}	Use of wollastonite
$QTPS_{smt,int,tt}$	Amount of product passes through other savings measures (kilns)

$QTPSA_{tt}$	Amount of product passes through other savings measures (atomizers)
$INVT_{int}$	Investment in new production capacity of tiles
$QRMT_{tt}$	Amount of raw material
$ETCG_{elec}$	Electricity from cogeneration
$INCG_{tcog}$	Investment of cogeneration capacity
$ICOT_{comb}$	Investment in a fuel switch
$IIKT_{ki}$	Investment in a furnace insulation
BRICKS	
$QBP_{kb,tb}$	Bricks produced
QBI_{tb}	Imported bricks
$QCOB_{comb,cog}$	Amount of fuel (bricks)
$QEB_{inb,tb}$	Energy consumption of facilities
$QCGB_{inb,tcog,tb}$	Fuel consumption in cogeneration by facility
$QIKB_{inb,tb}$	Current availability of improved furnace insulation
$QBB_{inb,tb}$	Use of double-firing in standard ovens
$QBIB_{inb,tb}$	Use of double-firing in insulated ovens
$QBPS_{smt,inb,tb}$	Amount of product passes through other savings measures (kilns)
$QBPSA_{tb}$	Amount of product passes through other savings measures (atomizers)
$QRMB_{brm,ar}$	Amount of raw material per product
$QCL_{cabb.ar}$	Amount clay per area (raw material)
$QPW_{ar.tb}$	Amount of paper waste (raw material)
$QMA_{ar,tb}$	Amount of marc (raw material)
$INVB_{inb}$	Investment in new production capacity of bricks
$QBPS_{smb,tb}$	Amount of product passes through other savings measures (kilns)
$EBCG_{elec}$	Electricity from cogeneration
$IBCG_{tcog}$	Investment of cogeneration capacity
$ICOB_{comb}$	Investment in a fuel switch
$IIKB_{kb}$	Investment in a furnace insulation

3 Objective function

Minimize costs:

$$Min.costs =$$

- **Power system:**

$$\sum_{cn,p}\left(tp_p * invcp_{cn,p} * PINS_{cn,p}\right) + \sum_{ct-comb,p,s,n,ct}\left(tp_p * ccomb_{ct-comb,p} * invef_{ct} * PGEN_{ct,p,s,n} * days_s\right)$$

$$+ \sum_{ct,tecr,p}\left(tp_p * comregesp_{tecr} * PINSACUM_{Ct,p}\right)$$

$$+ \sum_{cex,p,s,n}\left(tp_p * prem_{cex} * PGEN_{cex,p,s,n} * dias_s\right) +$$

- **Steel:**

$$\sum_{trs}(prms_{trs} * QRS_{trs}) + \sum_{ps}\left(prms_{trsc} * QSC_{ps}\right) + cprs_{psb} * QPI_{tot} + \sum_{psbe-tbe}\left(cprs_{psbe} * QST_{tbe}\right) + cprs_{psd}$$

$$* QDE_{ddr} + \sum_{ps}\left(cinst_{ps} * INST_{ps}\right) + pimst * QST_{tsim} +$$

- **Cement:**

$$\sum_{mcl,cl}(prmc_{mcl,cl} * QRM_{mcl,cl}) + \sum_{in}\sum_{cl}\left(cfvc_{in} * QCP_{in,cl}\right) + \sum_{tcl,cl}(cfvcl_{tcl,cl} * QCL_{tcl,cl}) + \sum_{cl}(pimcl_{cl} * QCLI_{cl})$$

$$+ \sum_{cl}(pimc_{cl} * QCI_{cl}) + \sum_{in}\sum_{cl}\left(pimcl_{cl} * INVC_{in,cl}\right) + \sum_{tcl}\sum_{cl}\left(pimcl_{cl} * INVCL_{tcl,cl}\right) +$$

- **Oil Refining:**

$$\sum_{cr}\left(pcru_{cr} * INPUT_{pcru,cr}\right) + \sum_{ir,cr}\left(pimop_{ir} * QIMP_{ir,cr}\right) + \sum_{pin,cr}\left(cfvr_{pin,cr} * INPUT_{pin,cr}\right)$$

$$+ \sum_{pin,cr}\left(cinvr_{pin} * MINV_{pin,cr}\right) + \sum_{dr,cr}\left(pimp_{dr} * IMP_{dr,cr}\right) +$$

- **Tiles**

$$
\begin{aligned}
&\sum_{cog,comb}\left(ccomb_{comb} * QCOT_{comb,cog}\right) + \sum_{tt}(prmt_{tt} * QRMT_{tt}) + \sum_{int}\left(cfvt_{int} * \sum_{tt} QTP_{int,tt}\right) \\
&\quad + \sum_{tcog}\sum_{int,tt}\left(cifvt_{int} * QCGT_{int,tcog,tt}\right) + \sum_{smb,ki}\sum_{tt}\left(csmt_{smt} * QTPS_{smt,ki,tt}\right) \\
&\quad + \sum_{int}(cinvt_{int} * INVT_{int}) + \sum_{tcog}\left(ccgt_{tcog} * INCG_{tcog}\right) + \sum_{comb}(cicot_{comb} * ICOT_{comb}) \\
&\quad + \sum_{kt}(cikt_{kt} * IIKT_{kt}) + \sum_{tt}(pimt_{tt} * QTI_{tt}) +
\end{aligned}
$$

- **Bricks:**

$$
\begin{aligned}
&\sum_{cog,comb}\left(ccomb_{comb} * QCOB_{comb,cog}\right) + \sum_{brm,ar}\left(prmb_{brm} * QRMB_{brm,ar}\right) + \sum_{inb}\left(cfvb_{inb} * \sum_{tb} QBP_{inb,tb}\right) \\
&\quad + \sum_{tcog}\sum_{inb,,tb}\left(cifvb_{inb} * QCGB_{inb,tcog,tb}\right) + \sum_{smb}\sum_{tb}\left(csmb_{smb} * QBPS_{smb,tb}\right) \\
&\quad + \sum_{inb}(cinvb_{inb} * INVB_{inb}) + \sum_{comb}(cicob_{comb} * ICOB_{comb}) + \sum_{tcog}\left(ccgb_{tcog} * IBCG_{tcog}\right) \\
&\quad + \sum_{kb}(cikb_{kb} * IIKB_{kb}) + \sum_{tb}(pimb_{tb} * QBI_{tb})
\end{aligned}
$$

Where:

4 Constraints

The objective function is subject to the following restrictions.

4.1 General

GHG emissions

$$bau * (1 - red) \geq \sum Sectoral\ emissions\,, \qquad where:$$

Power sector:

$$\sum_{ct,p,s,n} \left(eme_{ct} * PGEN_{ct,p,s,n} * days\right)$$

Steel:

$$\sum_{dere} \left(emsd_{dere} * QDE_{dere}\right) + \left(ems_{pgb} * QPI_{tot}\right)$$

Cement:

$$\sum_{comb} \left(emco_{comb} * \sum_{tcl} QCOM_{tcl,comb}\right) + \left(emc_{mcl,cl} * QRM_{mcl,cl}\right)$$

Tiles:

$$\sum_{comb} \left(emco_{comb} * \sum_{cog} \left(QCOT_{comb,cog}\right) * fco_{comb}\right) + \left(\sum_{tt} \left(carbt_{tt} * QTP_{ki,tt}\right) - \sum_{wo} QWO_{wo}\right) * emcar$$

Bricks:

$$\sum_{comb} \left(emco_{comb} * \sum_{cog} \left(QCOB_{comb,cog}\right) * fco_{comb}\right) + \sum_{cabb,ar12} \left(carbb_{cabb,ar12} * QCL_{cabb,ar12}\right) * emcar$$

Oil refining:

$$\sum_{pin,cr} \left(emr_{pin,cr} * INPUT_{pin,cr}\right) + \sum_{aur} \left(emcor_{aur} * \sum_{cr} ICOR_{aur,cr}\right) + \left(emcor_{ng} * \sum_{cr} ECOR_{ng,cr}\right)$$

4.2 Steel

Steel demand > Steel produced + Steel imported

$$QST_{ts} + QST_{tsim} = stde$$

Maximum production capacities

Steel produced < Maximum capacity (BOF, EAF)

$$QPI_{tot} \leq mcst_{psb} + INST_{psb}$$

$$QST_{ts} \leq mcst_{ps} + INST_{ps}$$

$\forall\ ts, ps\ (to\ BOF\ and\ EAF\ process)$

$$QDE_{ddr} \leq mcst_{psd} + INST_{psd}$$

Requirements of raw materials for coking coal and iron

$$QDE_{der} * mxs_{der,trs} = QRS_{trs}$$

$\forall\ der, trs[\ if\ mxs(der, trs)]$

BF process for the production of pig iron (sinter, pellets, DRI and coke)

$$prs_{drsd} * QPI_{tot} = QDE_{drsd}$$

$\forall\ drsd$

$$\sum_{pgbe} QPI_{pgbe} = QPI_{tot}$$

BOF Process for the production of steel (scrap, pig iron, sinter, pellets, and coke)

$$QST_{st} * 0.94 = QPI_{pgb} + QSC_{psbo}$$

Scrap < 30% of raw material

$$QSC_{psbo} \leq \left(QPI_{pgb} + QSC_{psbo}\right) * 0{,}3$$

Pig iron > 70% of raw material

$$\left(QPI_{pgb} + QSC_{psbo}\right) * 0{,}7 \leq QPI_{pgb}$$

EAF Process for the production of steel (scrap, pig iron, DRI, sinter, pellets, and coke)

1 ton of steel needs 1.13 ton of scrap, DRI or pig iron

$$QST_{tea} * 1{,}13 = QRS_{trdr} + QDE_{ddr} + QPI_{pea} + QSC_{pse}$$

Pig iron and DRI < 30% of raw material

$$QRS_{trdr} + QDE_{ddr} + QPI_{pea} = \left(QRS_{trdr} + QDE_{ddr} + QPI_{pea} + QSC_{pse}\right) * 0.3$$

Total steel produced is the sum of EAF + BOF

$$QST_{ts} = QST_{tsb} + QST_{tea}$$

4.3 Cement

Cement demand > Cement produced + imported

$$dce_{tc} \leq \sum_{in} \left(QCP_{in,tc}\right) + QCI_{tc}$$

$\forall\ tc$

Cement produced< Maximum production capacity of cement + investment in new capacity

$$\sum_{tc} \left(QCP_{in,tc}\right) \leq \sum_{cl} \left(cce_{in,cl} + INVC_{in,cl}\right)$$

$\forall\ in$

Clinker produced in integral plant < Maximum production capacity of clinker + investment in new capacity

$$\sum_{cl} (QCL_{tcl,cl}) \leq \sum_{cl} \left(ccl_{tcl,cl} + INVCL_{tcl,cl}\right)$$

$\forall\ tcl$

Energy (total calorific value) of the fuels used > Energy used in the production of clinker

$$\sum_{cl} (QCL_{tcl,cl} * ctcl_{tcl,cl}) \geq \sum_{comb} (QCOM_{fcl,comb})$$

$\forall\ tcl$

Consumption of raw materials (white and clinker)

$$\sum_{tcl} (QCL_{tcl,cl} * ctcl_{tcl,cl}) \leq \sum_{mcl} (QRM_{mcl,cl})$$

$\forall\ cl$

Clinker consumption for cement (integral plants + mills) < Clinker produced + Clinker imported

$$\sum_{cl} (QCP_{in,tc} * rmk_{cl}) \leq \sum_{tcl,cl} \left(QCL_{tcl,cl}\right) + \sum_{cl} (QCLI_{cl})$$

$\forall\ in$ *(grey and white cement)*

65% of fuel has to be coke (to reflect the limitation of combustion processes)

$$\sum_{tcl,cl}(QCL_{tcl,cl} * ctcl_{tcl,cl}) * 65\% \leq \sum_{tcl,coke}(QCOM_{tcl,coke})$$

4.4 Oil refining sector

Satisfaction of demand

$$\sum_{cr} \left(PRCR_{dr,cr} + IMP_{dr,cr} \right) \geq demr_{dr}$$

$\forall\, dr$

Maximum capacities

Atmospheric distillation ≤ Max. capacity + investment in new capacity

$$\sum_{cr} INPUT_{prc,cr} \leq capacity_{prc} + \sum_{cr} MINV_{prc,cr}$$

$\forall\, prc$

Vacuum distillation ≤ Max. capacity + investment in new capacity

$$\sum_{cr} INPUT_{pfcc,cr} \leq capacity_{pfcc} + \sum_{cr} MINV_{pfcc,cr}$$

$\forall\, pfcc$

Mass balances in the refinery

$$MODUL_{m,prc,cr} = INPUT_{pin,cr} * fac_{crc,prc,cr}$$

$\forall\, m, prc, cr$

Products

$$PRCR_{pfr,cr} = \sum_{inpr} ENTRPR_{inpr,ws,cr} + MODUL_{m,pcr,cr}$$

$\forall\, pfr, cr$

Flows

$$\begin{aligned}\sum_{m}\left(MODUL_{m,pctr,cr} * mez1_{pctr,m}\right) &= \sum_{fluj(conditional)}\left(CORRINTER_{fluj,cr} * mez2_{pctr,fluj}\right)\\ &+ \sum_{inpro(conditional)}\left(ENTRPR_{inpr,ws,cr} * mez3_{pctr,cr}\right)\\ &+ \sum_{pin(conditional)}\left(INPUT_{pin,cr} * mez4_{pctr,pin}\right) + QIMhP_{ir,cr}\end{aligned}$$

$\forall\, prtc, cr$

Other requirements

Supply to vacuum distillation < Atmospheric residue

$$INPUT_{mra,cr} \leq MODUL_{mra,'destatm',cr}$$

$\forall\, mra, cr$

Diesel sulfur ≤ Sulfur maximum allowed

$$\begin{aligned}&\sum_{ex}\left(fac_{se,ex,cr} * ENTRPR_{ex,ws,cr} + dhds_{ex,se,cr} * ENTRPR_{ex,ss,cr}\right) + dhds_{3ex,se,cr} * MODUL_{hed,2ex,cr}\\ &\qquad \leq spf_{di,se} * \left(\sum_{ex}\left(ENTRPR_{ex,ws,cr} + ENTRPR_{ex,ss,cr}\right) + MODUL_{hed,2ex,cr}\right)\end{aligned}$$

$\forall\, cr$

Density of diesel produced ≤ Maximum density of diesel

$$\begin{aligned}&\sum_{ex}\left(ENTRPR_{ex,ws,cr} + ENTRPR_{ex,ss,cr}\right) + MODUL_{hed,2ex,cr}\\ &\qquad \leq spf_{di,de} * \sum_{ex}\left(\frac{ENTRPR_{ex,ws,cr}}{fac_{de,ex,cr}} + \frac{ENTRPR_{ex,ss,cr}}{dhds_{ex,de,cr}}\right) + \left(\frac{MODUL_{hed,2ex,cr}}{dhds_{3ex,de,cr}}\right)\end{aligned}$$

$\forall\, cr$

Minimum cetane in diesel set ≤ Cetane diesel

$$\begin{aligned}&spf_{di,ce} * \sum_{ex}\left(\frac{ENTRPR_{ex,ws,cr}}{fac_{de,ex,cr}} + \frac{ENTRPRS_{ex,ss,cr}}{dhds_{ex,de,cr}}\right) + \left(\frac{MODUL_{hed,2ex,cr}}{dhds_{3ex,de,cr}}\right)\\ &\qquad \leq \sum_{ex}\left(\frac{ENTRPR_{ex,ws,cr}}{fac_{de,ex,cr}} * fac_{ce,ex,cr} + \frac{ENTRPR_{ex,ss,cr}}{dhds_{ex,de,cr}} * dhds_{ex,ce,cr}\right)\\ &\qquad + \left(\frac{MODUL_{hed,2ex,cr}}{dhds_{3ex,de,cr}} * dhds_{ex,ce,cr}\right)\end{aligned}$$

$\forall\, cr, hed, 2ex, 3ex, de, ce$

Sulfur in jet fuel ≤ Maximum allowed

$$PRCR_{pfr,cr} = ENTRPR_{ijf,ws,cr} * fac_{se,1ex,cr} + ENTRPR_{ijf2,ws,cr} * dhds_{1ex,se,cr} \leq spf_{jf,se} * \left(ENTRPR_{ijf,ws,cr} + ENTRPR_{ijf2,ws,cr}\right)$$

$\forall\, cr$

Jet fuel density ≤ Maximum density allowed

$$\left(ENTRPR_{ijf,ws,cr} + ENTRPR_{ijf2,ws,cr}\right) \leq spf_{jf,de} * \left(\frac{ENTRPR_{ijf,ws,cr}}{fac_{de,1ex,cr}} + \frac{ENTRPR_{ijf2,ws,cr}}{dhds_{1ex,de,cr}}\right)$$

$\forall\, cr$

Established octane gasoline ≤ Octane gasoline

$$spf_{ga,de} * \left(\frac{ENTRPR_{gb,ws,cr}}{fac_{de,bu,cr}} + \frac{ENTRPR_{gnl,ws,cr}}{fac_{de,ln,cr}} + \frac{MODUL_{mre,rfn,cr}}{dref_{de,cr}}\right) \leq \frac{ENTRPR_{gb,ws,cr}}{fac_{de,bu,cr}} * fac_{ro,bu,cr} + \frac{ENTRPR_{gnl,ws,cr}}{fac_{de,ln,cr}} * fac_{ro,ln,cr} + \frac{MODUL_{mre,rfn,cr}}{dref_{de,cr}} * dref_{ro,cr}$$

$\forall\, cr$

Gasoline sulfur < Maximum allowed

$$ENTRPR_{gb,ws,cr} * fac_{se,bu,cr} + ENTRPR_{gnl,ws,cr} * fac_{se,ln,cr} + MODUL_{mre,rfn,cr} * dref_{se,cr} \leq spf_{ga,se} * \left(ENTRPR_{gb,ws,cr} + ENTRPR_{gnl,ws,cr}\right)$$

$\forall\, cr$

Gasoline density <Maximum allowed

$$ENTRPR_{gb,ws,cr} + ENTRPR_{gnl,ws,cr} + MODUL_{mre,rfn,cr} \leq spf_{ga,de} * \left(\frac{ENTRPR_{gb,ws,cr}}{fac_{de,bu,cr}} + \frac{ENTRPR_{gnl,ws,cr}}{fac_{de,ln,cr}} + \frac{MODUL_{mre,rfn,cr}}{dref_{de,cr}}\right)$$

$\forall\, cr$

Energy Consumption

$$\sum_{pin,cr} tcr_{pin,cr} * INPUT_{pin,cr} \leq \sum_{aur,cr} \left(pcomb_{aur,cr} * ICOR_{aur,cr}\right) + \left(pcomb_{ng,cr} * ECOR_{ng,cr}\right)$$

4.5 Tiles

Demand (red paste tiles, white paste tiles, red stoneware, porcelain and white stoneware tiles, and extruded tiles) ≥ Produced + imported

$$dti_{tt} \leq \sum_{ki}\left(QTP_{ki,tt}\right) + QTI_{tt}$$

$\forall\ tt$

Amount of fuel consumed * energy factor ≥ Fuel energy consumption of each installation (direct and cogeneration)

$$\sum_{comb,cogn}\left(QCOT_{comb,cogn} * fco_{comb}\right) \geq \sum_{int,tt}\left(QEIN_{int,tt}\right) + \sum_{cofc,cogn}\left(QCOT_{comb,cogn} * fco_{cofc}\right) * 6\%$$

Fuel to cogeneration

$$\sum_{comb}\left(QCOT_{comb,cogy} * fco_{comb}\right) \geq \sum_{int,tcog,tt}\left(QCGT_{int,tcog,tt}\right)$$

Current energy mix and investment in fuel switching

$$\sum_{cog}\left(QCOT_{comb,cog} * fco_{comb}\right) \leq \sum_{comb,cog}\left(QCOT_{comb,cog} * fco_{comb}\right) * cpcot_{comb} + ICOT_{comb} * fco_{comb}$$

$\forall\ comb$

Energy consumption of each installation (direct and through cogeneration) ≥ Energy of each installation (depending on the amount of product)

$$\begin{aligned} QEIN_{int,tt} * nss[\ if\ pkt(int)] + \sum_{int,tcog,tt}\left(QCGT_{int,tcog,tt}\right) * cgc_{per,tcog}\ [if\ icg(int)] \\ = \left(QTP_{int,tt} - QIKT_{int,tt}[if\ ki(int)] + QBT_{int,tt} * ebt_{int}\right) * ects_{int,tt} \\ + \left(QIKT_{int,tt} * ecti_{int,tt} + QBIT_{int,tt} * ebt_{int}\right)[if\ ki(int)] \end{aligned}$$

- Saving heat recovery

$$-\sum_{irt}\left(QTP_{irt,tt} * rkdt_{irt}\right)\ [if\ irt(int)]$$

- Savings pre-kiln

$$-\sum_{tcog}\left(QCGT_{pkt,tcog,tt} * cgc_{per,tcog} * tppk\right)\,[if\ kti(int)]$$

- Energy savings by using wollastonite

$$-\,QWO_{tt} * savw[if\ kti(int)]$$

- Other savings measures

$$-\sum_{smk}\left(QTPS_{smk,int,tt} * cst_{smk,tst}\right)[if\ ki(int)]$$

$$-\left(QTPSA_{tt} * cst_{smt3,tst} * ects_{int,tt}\right)[if\ iat(int)]$$

+ Extra requirements for double firing

$$+\left(QTP_{int,tt} - QIKT_{int,tt}\right) * ects_{int,tt} + \left(QIKT_{int,tt} * ecti_{int,tt}\right) * ebt_{int} * cot_{df}[if\ dftt(tt)]$$

$\forall\ int, tt$

Production ≤ New capacity + installed capacity

Kilns

$$\sum_{tt}\left(QTP_{int,tt}\right) \leq INVT_{int} + cti_{int}$$

$\forall\ inst$

Pre-kilns

$$\sum_{pkt}\left(QTP_{pkt,tt}\right) \leq \sum_{kti}\left(QTP_{kti,tt}\right)$$

$\forall\ tt$

Max useful energy to pre-kiln from cogeneration

$$\sum_{pkt}\left(QTP_{pkt,tt}\right) \geq \sum_{pkt,tcog,tt}\left(QCGT_{pkt,tcog,tt}\right) * cgc_{tep,tcog} * tppk/0{,}4$$

$\forall\ tt$

Amount of wollastonite ≤ Maximum amount of wollastonite available

$$\sum_{ttw} QWO_{ttw} \leq mxw$$

Maximum wollastonite per product

$$\frac{QWO_{ttw}}{carbt_{ttw}} \leq \sum_{ki} \left(QTP_{ki,ttw}\right)$$

$\forall\, ttw$

Raw materials needed:

$$QRMT_{wo} = \sum_{ttw} QWO_{ttw}$$

$$QRMT_{tt} = \sum_{ki} \left(QTP_{ki,tt}\right) - QWO_{tt}[if\ tttw(tt)]$$

$\forall\, tt$

$$QRMT_{tfg} = \sum_{twe} \left(\sum_{ki} \left(QTP_{ki,twe}\right) / swt_{twe} \right)$$

Energy of atomizer and dryer

$$\left(QEIN_{itad,tt} * nss + \sum_{tcog} \left(QCGT_{itad,tcog,tt} * cgc_{per,tcog}\right) \right) * but_{itad} \leq QEIN_{itad,tt} * nss$$

$\forall\, itad, tt$

Electricity consumption

Total power consumption ≥ Processed product in each installation * power consumption of each facility

$$\sum_{cogy} QCOT_{ele,cogy} \geq \sum_{ite} \sum_{tt} \left(QTP_{ite,tt} * pct_{ite,tt}\right) + \sum_{smk,ki} \left(QTPS_{smk,ki,tt} * cst_{smk,eci}\right) + \sum_{tt} \left(QTPSA_{tt} * cst_{smt3,eci}\right) + \sum_{irt,tt} \left(QTP_{irt,tt} * rkdt_{irt}\right) * trtkd$$

Self-consumption electricity < Power consumption

$$ETCG_{ein} \leq \sum_{cogy} QCOT_{ele,cogy}$$

Electricity from cogeneration > Sold electricity + self-consumption electricity

$$\sum_{tcog}\sum_{icg,twe}\left(QCGT_{icg,twe} * cgc_{eep,tcog}\right) \geq \sum_{elec} ETCG_{elec}$$

Amount of product in each process

$$QTP_{iwk,tt} \geq \sum_{ki} QTP_{ki,tt}$$

$\forall\ iwk, tt$

Amount of production with heat recovery Kiln

$$QTP_{irt,tt} \leq QTP_{ki,tt}$$

$\forall\ tt, irt, ki\ [if\ cks(irt, ki)]$

Amount of product in atomizer

$$QTP_{iat,twe} \geq \sum_{ki} QTP_{ki,twe}$$

$\forall\ twe$

Energy consumption in cogeneration < Current capacity + investment in new capacity of cogeneration

$$\sum_{icg,tt} QCGT_{icg,tcog,tt} \leq cpcgt_{tcog} + INCG_{tcog}$$

$\forall\ tcog$

Investment in new capacity of furnace insulation

Maximum capacity

$$\sum_{tt} QIKT_{ki,tt} \leq ccikt_{ki} + IIKT_{ki}$$

$\forall\ ki$

Production

$$QIKT_{ki,tt} \leq QBT_{tt}$$

$\forall\ tt, ki$

Biogas in cogeneration

$$\sum_{bio,cogy} \left(QCOT_{bio,cogy} * fco_{bio}\right) \leq \sum_{comg,cogy} \left(QCOT_{comg,cogy} * fco_{comg}\right) * maxbg$$

Maximum availability of biogas

$$\sum_{bio,cogy} \left(QCOT_{bio,cogy} * fco_{bio}\right) \leq \sum_{comb,cogy} \left(QCOT_{comb,cogy} * fco_{comb}\right) * capbg$$

4.6 Bricks

Demand (bricks wall, face bricks, roof tiles, others) ≥ Produced + imported

$$dbi_{tb} \le \sum_{kb} \left(QBP_{kb,tb}\right) + QBI_{tb}$$

$\forall\, tb$

Amount of fuel consumed * energy factor ≥ Fuel energy consumption of each installation (direct and cogeneration)

$$\sum_{comb,cogn} \left(QCOB_{comb,cogn} * fco_{comb}\right) \ge \sum_{inb,tb} \left(QEB_{inb,tb}\right) + \sum_{cofc,cogn} \left(QCOB_{comb,cogn} * fco_{cofc}\right) * 6\%$$

Fuel to cogeneration

$$\sum_{comb} \left(QCOB_{comb,cogy} * fco_{comb}\right) \ge \sum_{inb,tcog,tb} \left(QCGB_{inb,tcog,tb}\right)$$

Current energy mix and investment in fuel switching

$$\sum_{cog} \left(QCOB_{comb,cog} * fco_{comb}\right) \le \sum_{comb,cog} \left(QCOB_{comb,cog} * fco_{comb}\right) * cpcob_{comb} + ICOB_{comb} * fco_{comb}$$

$\forall\, comb$

Energy consumption of each installation (direct and through cogeneration) ≥ Energy of each installation (depending on the amount of product)

$$\sum_{kb} QEB_{kb,tb} = \sum_{kb} \left(\left(QBP_{kb,tb} - QIKB_{kb,tb}\right) * ecb_{kb,tb} + QIKB_{kb,tb} * ecbi_{inb,tb}\right) + \left(QIKB_{inb,tb} * ecbi_{inb,tb} + QBIB_{inb,tb} * ebb_{inb}\right)$$

- Savings in pre-kiln

$$-\sum_{tcog} \left(QCGB_{pkb,tcog,tb} * cgc_{per,tcog} * tpbk\right)$$

- Other savings measures.

$$-\sum_{smb} \left(QBPS_{smb,tb} * csb_{smb,tst}\right)$$

- Savings by using paper waste and marc.

$$-\sum_{ar}\left(QPW_{ar,tb}\right) * cvpw$$

$$-\sum_{ar}\left(QPMA_{ar,tb}\right) * cvma$$

$\forall\ tb$

Energy consumption of dryers

$$\sum_{drb}\left(QEB_{drb,tb} * nss\right) + \sum_{drb,tcog}\left(QCGB_{drb,tcog,tb} * cgc_{per,tcog}\right) \geq \sum_{drb}\left(QBP_{drb,tb} * ecb_{drb,tb}\right) - \sum_{irb}\left(QBP_{irb,tb} * rkdt_{irb}\right)$$

$\forall\ tb$

Production ≤ New capacity + installed capacity

Kilns

$$\sum_{tb} QBP_{inb,tb} \leq INVB_{inb} + cbi_{inb}$$

$\forall\ inb$

Pre-kilns

$$\sum_{pkb}\left(QBP_{pkb,tb}\right) \leq \sum_{kbi}\left(QBP_{kbi,tb}\right)$$

$\forall\ tb$

Max useful energy to pre-kiln from cogeneration

$$\sum_{pkb}\left(QBP_{pkb,tb}\right) \geq \sum_{pkb,tcog}\left(QCGB_{pkb,tcog,tb}\right) * cgc_{tep,tcog} * tppk/0{,}4$$

$\forall\ tb$

Amount of production with heat recovery Kiln

$$QBP_{irb,tb} \leq QBP_{kb,tb}$$

$\forall\ tb, irb, kb\ [if\ cksb(irb, kb)]$

Raw materials needed

$$QRMB_{cla,ar} = \sum_{cabb} QCL_{cabb,ar}$$

$\forall\ ar$

$$\sum_{brm} QRMB_{brm,ar3} \leq 0$$

$$QRMB_{wp,ar} = \sum_{tb} QWP_{ar,tb}$$

$\forall\ ar$

$$QRMB_{mab,ar} = \sum_{tb} QMA_{ar,tb}$$

$\forall\ ar$

Total of raw material > Production

$$\sum_{kb,tb} \left(QBP_{kb,tb}\right) - \sum_{rmpm,ar} \left(QRMB_{rmpm,ar}\right) \leq \sum_{ar} QRMB_{cla,ar}$$

Minimum contribution of dryer burners

$$\left(\sum_{drb} \left(QEB_{drb,tb}\right) * nss + \sum_{drb,tcog} \left(QCGB_{drb,tcog,tb} * cgc_{tp,tcog}\right)\right) * bub \ \leq \sum_{drb} \left(QEB_{drb,tb}\right) * nss$$

$\forall\ tb$

Electricity consumption

Total power consumption ≥ Processed product in each installation * power consumption of each facility

$$\sum_{cog} QCOT_{ele,cog} \geq \sum_{ibe} \sum_{tb} \left(QBP_{ibe,tb} * pcb_{ibe,tb}\right) + \sum_{irb,tb} \left(QBP_{irb,tb} * rkdt_{irb}\right) * trbkd + \sum_{kb,tb} \left(QBP_{kb,tb} * pcob_{tb}\right)$$

Self-consumption electricity < Power consumption

$$EBCG_{ein} \leq \sum_{cog} QCOB_{ele,cog}$$

Electricity from cogeneration > Sold electricity + self-consumption electricity

$$\sum_{tcog} \sum_{icgb,tb} \left(QCGB_{icgb,tcog} * cgc_{eep,tcog} \right) \geq \sum_{elec} EBCG_{elec}$$

Amount of product in each process

Raw material preparation

$$QBP_{prb,tb} \geq \sum_{kb} QBP_{kb,tb}$$

$\forall\, tb$

Dryers

$$\sum_{drb} QBP_{drb,tb} \geq \sum_{kb} QBP_{kb,tb}$$

$\forall\, tb$

Amount of raw material by emplacement

$$\sum_{ar} QCL_{cabb,ar} \leq \left(\sum_{kb,tb} \left(QBP_{kb,tb} \right) - \sum_{rmpm,ar} \left(QRMB_{rmpm,ar} \right) \right) * yac_{cabb}$$

$\forall\, cabb$

Biogas in cogeneration

$$\sum_{bio,cog} \left(QCOB_{bio,cog} * fco_{bio} \right) \leq \sum_{comg,cog} \left(QCOB_{comg,cog} * fco_{comg} \right) * maxbg$$

Maximum availability of biogas

$$\sum_{bio,cog} \left(QCOB_{bio,cog} * fco_{bio} \right) \leq \sum_{comb,cog} \left(QCOB_{comb,cog} * fco_{comb} \right) * capbg$$

Others of waste paper

Total

$$\sum_{ar,tb} QWP_{ar,tb} \leq maxwp$$

By product

$$\sum_{ar} QWP_{ar,tb} \leq \sum_{kb}(QBP_{kb,tb}) * pwp_{tb}$$

$\forall \; tb$

$$\sum_{tb} (QWP_{ar1,tb}) * cwpp_{tb} \leq \sum_{kb}(cbi_{kb}) * cpwp$$

Others of marc

Total

$$\sum_{ar12,tb} QMA_{ar12,tb} \leq maxm$$

By product

$$\sum_{ar} QMA_{ar,tb} \leq \sum_{kb}(QBP_{kb,tb}) * pma_{tb}$$

$\forall \; tb$

$$\sum_{tb} (QMA_{ar,tb}) * cmap_{tb} \leq \sum_{kb}(cbi_{kb}) * cpma_{ar}$$

$\forall \; ar$

No simultaneity between waste paper and marc

$$\sum_{ar} (QWP_{ar,tb}) * cwpp_{tb} + \sum_{ar} (QMA_{ar,tb}) * cmap_{tb} \leq \sum_{kb}(QBP_{kb,tb})$$

$\forall \; tb$

Energy consumption in cogeneration < Current capacity + investment in new capacity of cogeneration

$$\sum_{icg,tb} QCGB_{icg,tcog,tb} \leq cpcgb_{tcog} + IBCG_{tcog}$$

$\forall \; tcog$

Investment in new capacity of furnace insulation

Maximum capacity

$$\sum_{tb} QIKB_{kb,tb} \leq ccikb_{kb} + IIKB_{kb}$$

$\forall\ kb$

Production

$$QIKB_{kb,tb} \leq QTP_{tb}$$

$\forall\ tb, kb$

4.7 Power sector

Demand balance

$$\left[\sum_{ct}\left(PGEN_{ct,p,s,n}\right)-\sum_{b}\left(PBOMB_{b,p,s,n}\right)\right]$$
$$\leq\left(del_{p,s,n}+deli_{p,s,n}\right.$$
$$*\left[\left(els_{tsb}*QPI_{tot}+\sum_{tbe}\left(els_{tbe}*QST_{tbe}\right)\right)\right.$$
$$+\left(\sum_{tcl,cl}\left(elcl_{tcl,cl}*QCL_{tcl,cl}\right)+\sum_{in,tc}\left(elc_{in,tc}*QCP_{in,tc}\right)\right)+\left(\sum_{cog}\left(QCOT_{ele,cog}\right)-ETCG_{ein}\right)$$
$$\left.\left.+\left(\sum_{cog}\left(QCOB_{ele,cog}\right)-EBCG_{ein}\right)+\left(\sum_{pin,cr}\left(elr_{pin,cr}*INPUT_{pin,cr}\right)\right)\right]\right)$$

$\forall\, p,s,n$

Installed capacity of wind power and production per MW based on historical series (profiles of wind power generation)

$$PGEN_{ct\_eol,p,s,n}=prodeol_{p,s,n}*PINSACUM_{ct\_eol,p}$$

$\forall\, ct\_eol,p,s,n$

Power output < Installed capacity * load factor

$$PGEN_{ctweol,p,s,n}\leq PINSACUM_{ctweol,p}*loadf_{ctweol}$$

$\forall\, ctweol,p,s,n$

Reserve margin; available capacity needed to meet normal peak demand levels

$$\sum_{ctnoint}\left(PINSACUM_{ctnoint,p}\right)\geq indcob*[max]\left(del_{p,s,n}\right)$$

$\forall\, p$

Hydro reservoir level

$$\sum_{n}\left(PGEN_{ct,p,s,n}*days_{s}\right)-RES_{h,p,s}\ +\ RES_{h,p,s+1}\leq aporhid_{h,s}$$

$\forall\, h,p,s$

Hydro run of river production

$$\sum_{n}\left(PGEN_{f,p,s,n}\right) - RES_{h,p,s} \ + \ RES_{h,p,s+1} \leq fluy_{f,s}$$

$\forall \, f, p, s$

Balance pump-turbine

$$\sum_{s,n}\Big(days_{s} * \left(PGEN_{b,p,s,n} - PBOMB_{b,p,s,n} \ * \ rend\right)\Big) \leq 0$$

$\forall \, b, p$

Maximum pumping production

$$\sum_{s,n}\left(days_{s} * PGEN_{b,p,s,n}\right) \leq bomax_{b}$$

$\forall \, b, p$

Limitation of SO_2 emissions and NOx particles

$$\sum_{cex,s,n}\left(cont_{cex,pollut} * PGEN_{cex,p,s,n} * days_{s}\right) \leq maxco_{p,pollut}$$

$\forall \, p, pollut$

Maximum investment

$$\sum_{p}\left(PINS_{cn,p}\right) \leq pinsmcn_{cn}$$

$\forall \, cn$

Annex III Input data for the model

Industrial demand in Spain for 2008 and 2012:

1 Steel

[Mton]	2008	2012
Steel production	18,64	13,60

Table 1. Steel production in Spain in 2008 and 2012. Source: UNESID, 2014.

2 Cement

In cement production, seven types of cement are taken into account, which can be divided into two types; grey cement and white cement, as shown in Table 2.

Demand [Mton]	Grey cement					White cement	
Year	I	II	III	IV	V	I	II
2008	7	25	1,4	1,8	0,2	0,2	0,9
2012	2,23	8	0,5	0,6	0,1	0,1	0,3

Table 2. Cement demand for Spain in 2008 and 2012. Source: Own calculations from Oficemen.

3 Oil refining

The refining petroleum process of Spain represented in the model should satisfy the production of the main crude products obtained, which are shown in Table 3.

	Demand [Mton]	
Product	2008	2012
Gasoline	10	7
Jet fuel	6	9
Diesel	22	26
fuel oil	10	7

Table 3. The demand of the main petroleum products in 2008 and 2012. Source: CORES.

4 Tiles

The amount of ceramic products such as tiles, stoneware, and extruded tiles produce by Spain is shown in Table 4.

	Demand [Mton]	
Product	2008	2012
Red paste tiles	2,05	1,42
White paste tiles	1,04	0,80
Red stoneware tiles	3,31	2,76
Porcelain and white stoneware tiles	2,58	2,37
Extruded tiles	0,55	0,51
Total	9,54	7,87

Table 4. Tiles demand for Spain in 2008 and 2012. Source: Own calculations from ASCER.

5 Bricks

The model should meet the demand for bricks and roof tiles as Table 5 shows.

	Demand [Mton]	
Product	2008	2012
Bricks wall	9,6	2,5
Face bricks	1,9	0,5
Roof tiles	1,45	0,4
Others	2,1	0,5
Total	15,1	3,9

Table 5. The demand of bricks and roof tiles for Spain in 2008 and 2012. Source: Own calculations from Hispalyt.

6 Power sector

Production of the Spanish mainland and extra-peninsular electricity mix (without taking into account self-consumption losses) is represented on the Table 6.

	Production [MWh]	
Technology	2008	2012
Nuclear	56.460	61.470
Fuel/Gas	9.888	7.541
Coal	46.508	57.662
Combined cycle	93.198	42.510
Cogeneration	26.721	33.767
Thermal renewable	2.869	4.755
Hydro	20.957	19.455
Small hydro	4.640	4.646
Pumping	-3.803	-5.023
Wind	32.160	48.508
Solar photovoltaic	2.498	8.202
Solar thermal	15	3.444

Table 6. Electricity generated in Spain, 2008 and 2012. Source: REE.

Annex IV A sensitivity analysis. The expected prices of the EU ETS

EUA prices in Phase II remained above 12€ until mid- 2011 (see Figure 1). But after the economic crisis, which extended longer than expected, as well as other factors such as the approval of the Energy Efficiency Directive, prices fell below 5€, as Figure 1 shows. These prices are below the levels initially expected when the current phase of the EU ETS was designed. Therefore, it is also interesting to evaluate how well the model can approximate these expected prices, as an indicator of its robustness.

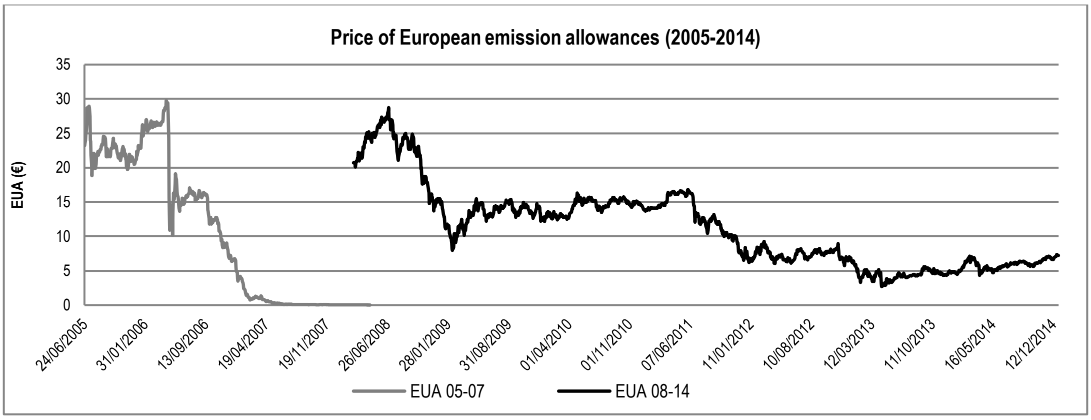

Figure 1. **Evolution of the allowances prices. Source: Bluenext, SendeCO2.**

For this, a scenario that attempts to replicate the planned trends was created (of energy, production, and emissions) before the falling of the price of CO_2. For the formulation of this scenario, the National Allocation Plan (NAP), 2008-2012, was considered. Table 1 shows the data for industrial demand summarized in a "planned scenario" for 2012, compared with the actual data.

Sector	Unit	2012 (real)	2012 ("planned scenario")
Power gen.	TWh	286.94	329.54
Steel	Mton	13.64	18.40
Tiles	Mton	7.87	9.97
Cement	Mton	15.93	36.48
Bricks	Mton	3.92	22.77
Oil refining	Mton	48.79	51.37

Table 1. Industrial production in Spain by scenario. Source: Compiled from: REE, UNESID, Oficemen, Hispalyt, Cores and Spain NAP (2008-2012).

Likewise, fuel price projections in 2012 were estimated based on the prices forecasted before the economic crisis, from the World Energy Outlook 2008 (IEA, 2008). In this way, this section tries to have an estimation of the expected outcomes of the original EU ETS plans without being subjected to the contingencies mentioned above. Table 2 shows the data projections in comparison with the actual prices.

[€/MWh]	2012 (real)	2012 ("planned scenario")
Natural gas (industry)	29.41	41.74
Coal	15.50	17.45
Fuel	42.17	36.96
LPG	65.00	73.89
Gasoline	62.18	59.77
Diesel fuel	61.57	71.76
Coke	20.88	26.25
Natural gas (power)	21.05	30.90

Table 2. Prices of the main fuels used in the model. Source: CORES, Foro Nuclear, IRENA, IEA (2008).

The results obtained with our model for this "planned scenario" (Figure 2) show that the marginal abatement costs of GHG emissions of course increase compared to the actual situation. This is logical because we assume a higher industrial demand and higher energy prices.

Again, this analysis uses Spain as a representative country. It must be taken into account that from 2008-2012, Spain exceeded the emission limits set by the Kyoto Protocol. The maximum allowed to increase was 15% over the base year (1990). Spain emitted an average of 23% more than the base year in the period 2008-2012 (see Table 3). The "effort-sharing" to comply with the Kyoto Protocol was divided into 45% for sectors subject to the EU ETS. Thus, as shown in Table 3, the agents subject to the EU ETS fulfilled their part of the "effort". This was influenced by the fall in industrial production, mainly due to the unforeseen economic crisis.

The results obtained in the "planned scenario" indicate a higher level of emissions than in 2005 for the sectors covered by the EU ETS. Given this, to reach the level of emissions reduction for which the EU ETS is responsible (150 Mton of maximum emissions), the price of CO_2 should have risen above 16 €/ton, as shown in the MAC curve (Figure 2). This marginal cost is similar to the prices of the allowances previous to the economic crisis, which again proves the ability of the model proposed to reasonably represent the EU ETS (as well as the representativeness of the case study chosen).

GHG emissions, Spain [Mton. CO2 eq.]	Emissions 1990	Limit emissions (Kyoto Protocol)	Emissions 2012	Annual average (2008-2012)	Variation with respect to the limit (Kyoto Protocol)
Total emissions	**289,8**	333	341	**358**	+8,7%
Effort EU ETS (45%)	130	150	153	161	n/a
Emissions sectors covered by the EU ETS	n/a	n/a	135,64	138,0	n/a

Table 3. Summary of the Spanish situation regarding compliance with the Kyoto Protocol (period 2008-2012). Source: Authors from EEA.

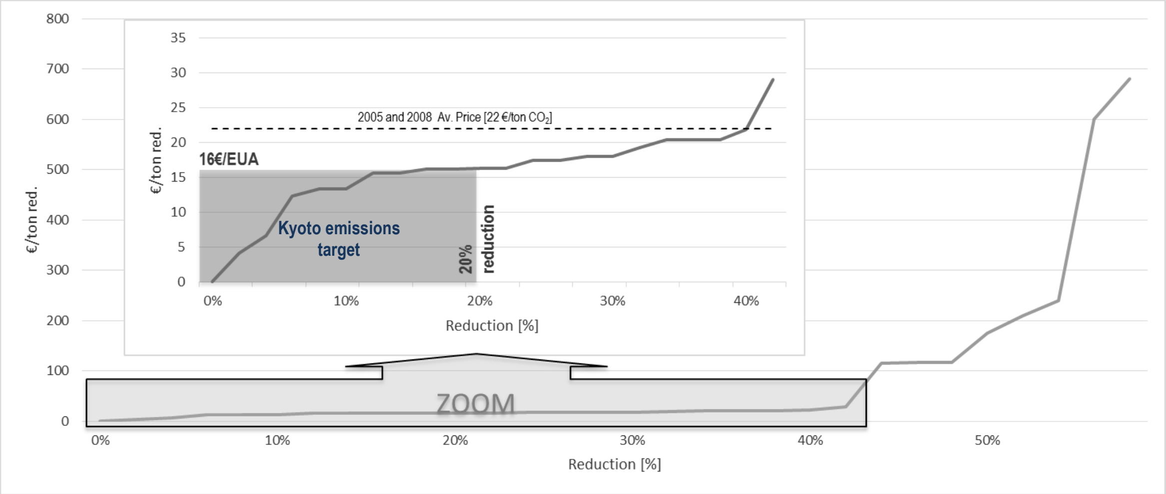

Figure 2. MAC curve to the “planned scenario”. Source: Authors based on modelling results.

As summary, Table 4 shows the differences between the scenarios.

MACC	Real scenario [€/ton CO_2 eq.]		Planned scenario [€/ton CO_2 eq.]
reduction [%]	**Integrated**	**Synthetic**	**Integrated**
0%	0	0	0
10%	2	2	13
14%	2	3	16
20%	6	6	16
24%	6	13	17
30%	18	19	18
40%	29	196	22

Table 4. Summary of marginal costs obtained according to scenario and type of integration. Source: Authors based on modelling results.