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ABSTRACT

The European Emissions Trading System (EU ETS) is the main instrument of the European Union (EU) against climate change. This 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 can behave in a way which may lead to inefficient CO_2 prices, creating doubts about the effectiveness of the system. This paper analyzes these possible anomalies by modeling the EU ETS under a rational market hypothesis and comparing the results with real market transactions. For this, we have built a bottom-up model, which represents the EU ETS in an integrated way, paying particular attention to the interactions among the most emissions intensive industries. The results show the benefits of this integrated modeling approach and how it better reflects real market conditions. We also present some preliminary conclusions regarding the behavior of the agents in the ETS market.

KEYWORDS: EU ETS, industry, GHG emissions, behavior modeling, costs

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

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1 INTRODUCTION

The European Emissions Trading System (EU ETS) is considered the cornerstone of European climate policies. This is an instrument that aims to reduce greenhouse gas (GHG) emissions at the lowest cost and, at the same time, encourage the introduction of low carbon technologies. Like other analogous emission markets in the world, this instrument gives rise to an opportunity cost of the emissions related to certain industrial activities, reflected in the price of the emission allowances (EUA) traded in the market.

The European ETS market was one of the first instruments applied at a supranational level. The first phase (2005-2007) had as goals its practical implementation, learning, and assigning an economic value to CO_2 (Ellerman and Joskow, 2008). Currently, the EU ETS is immersed in its second structural reform, driven mainly to addressing the excess emission allowances (EUA) in circulation in the market. This situation has caused a drop in the price of CO_2 out of the ranges for which this instrument was designed and created uncertainty about its effectiveness. The new reform is aimed at improving the system for the fourth phase, which will begin in 2021.

However, under the assumption of perfect competition in the market, the measures that are being discussed, like the Market Stability Reserve (MSR[1]) already adopted[2], 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 perfect competition assumption may not hold: prior literature has highlighted possible failures in the rational operation of the carbon market: the endowment effect[3] (Ellerman and Reguant, 2008), bounded rationality of the agents (Richstein et al., 2015) or transaction costs (Jaraite and Kažukauskas, 2012). These market failures may prevent the market from achieving the perfectly competitive equilibrium, and also distort the expected effects of different policies that assume rational behaviors of the agents.

Therefore, before proposing changes in the ETS it would be advisable to analyze whether the market is working properly, and gain a better understanding of the behavior of market players. We need to understand better whether the agents are behaving in an economically rational way, and also which are the factors that may be driving their behavior in the future. There are two options for this. One is to formulate models that allow for simulating deviations from economic rationality by the agents. An example is Richstein et al. (2015), who use Agent Based Modeling to represent the interactions between carbon and electricity markets in Europe. Unfortunately, they model the ETS as composed solely by the electricity sector which, as will be explained later, may be an oversimplification.

The other option is to use models that assume an economically-rational behavior of the agents, and compare their results to real market outcomes. There are in literature many examples of models that represent or include carbon markets, with different modeling approaches. These can be classified into general equilibrium models (top-down) or partial equilibrium models (bottom-up). Most of the integrated analytical approaches 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 incorporate details of each possible emission abatement alternative, therefore losing detail in the representation of the market. By contrast, bottom-up models allow for a higher level of energy technology details, but do so at the cost of foregoing a broader overview (e.g., models TIMES, POLES, PRIMES, or Santamaría et al., 2014; Brunke and Blesl, 2014; Wesselink and Deng, 2009). The main disadvantage, when choosing a partial equilibrium model, is the loss of fidelity in the representation of the economy as a whole. However, previous literature indicates that the impact of the carbon price may be negligible from the point of view of the rest of the economy (Ghersi and Hourcade, 2006).

It is also important to note the tendency of top-down models to overestimate the marginal abatement costs of emissions (and hence emission allowance prices). In contrast, bottom-up models tend to underestimate these costs, due to the difficulties of recreating the micro and macroeconomic effects (Kesicki, 2010). Hourcade et al. (2006) and Kuik et al. (2009) provide comparative examples of both types of models. There

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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] See decision of the European Council: http://www.consilium.europa.eu/en/press/press-releases/2015/09/18-greenhouse-gas-emissions-creation-of-market-stability-reserve-approved/

[3] The endowment effect is the phenomenon in which economic agents value more the own asset than they would be prepared to pay for it (eg, Bischoff and Meckl, 2008). For the EU ETS, it means that the opportunity cost that agents assign to their own allowances depend on the allocation method.

are also hybrid proposals that try to reap the benefits of each of the modeling approaches (Böhringer and Rutherford, 2008; Rodrigues and Linares, 2014; Rodrigues and Linares, 2015).

From the European point of view, there are several bottom-up tools that have been used to represent carbon markets (generally within a larger energy-environment scope). POLES ("Prospective Outlook on Long-term Energy Systems") is a partial equilibrium model, with a technological bottom-up approach. POLES is used, for example, by the European Commission for the assessment of impacts on the European energy system. There are examples (Criqui et al., 1999; Criqui and Mima, 2012) in this model for the calculation of CO_2 reduction costs. Hidalgo et al. (2005) integrate the POLES model to calculate the marginal abatement costs of CO_2 in the steel sector. Another widely used model is PRIMES ("Inducing Price Model of the Energy System"), and it is classified, like previous models, as a partial equilibrium bottom-up model. The European Commission commonly uses this model and its variants for energy research (Capros et al., 2013) or for analysis of policy related to the fight against climate change (e.g., Capros et al., 2008). Generally, these models lack detail about abatement options outside from the electricity sector, something which is corrected somehow in (Santamaria et al., 2014). But most of the bottom-up models described still present a relevant limitation: if they account for non-energy sectors, they do so in a non-integrated way, something that can significantly affect the results.

If sectors are represented individually, which requires setting an equivalent mitigation share for each sector, we will never be able 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 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 change its energy mix toward increased power consumption, the electricity sector will have to supply more electricity. This will involve a transfer of the mitigation responsibility from the cement sector to the electricity sector. From the modeling point of view, the sector with the cheapest solution for reducing emissions should be the one to implement it. Another example is the impact of fuel prices in each sector.

To address these issues, this study develops a bottom-up optimization model to represent the optimal functioning of the ETS market in an integrated manner. The model proposed allows analyzing different technological measures and determines the potential for reducing GHG emissions, according to its marginal cost. The model includes five of the most emission-intensive industries. The aim is to represent the theoretical behavior of the main industrial sectors; steel, cement, refining, tiles and bricks, and electricity generation through the calculation of the marginal abatement costs. This work aims to show the benefits of an integrated modeling, which pays special attention to the linkages between sectors.

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.

	Spain		EU+	
Sources of GHG emissions in the EU ETS	**Mton[4] CO_2eq**	**[%]**	**Mton CO_2eq**	**[%]**
Combustion (Heat and power)	89,04	65,6%	1352,58	72,4%
Oil refining	14,39	10,6%	127,48	6,8%
Cement and clinker	13,73	10,1%	106,52	5,7%
Iron and steel industry	6,05	4,5%	106,52	5,7%
Ceramics and tiles	1,82	1,3%	9,32	0,5%
Chemical products	2,24	1,7%	30,40	1,6%
Paper and paperboard	2,61	1,9%	23,98	1,3%
Lime, dolomite and magnesite	1,75	1,3%	31,75	1,7%
Glasses and chips	2,02	1,5%	18,71	1,0%
Primary aluminum	n/a	n/a	0,49	0,0%
Paper pulp	1,07	0,8%	5,78	0,3%
Others	0,91	0,7%	53,47	2,9%
Total	135,64	100%	1867,00	100%

Table 1. Industrial GHG emissions in Spain and total covered by the EU ETS in 2012. Source: EEA.

The results are presented as marginal abatement cost curves (MACC or MAC curve). These curves allow analyzing different technological measures and ordering its potential to reduce GHG emissions by marginal cost (for example, McKinsey & Company, 2007; Economics for Energy, 2011; ESMAP, 2012; Wesselink and Deng, 2009).

This paper is structured as follows. Section 2 describes the model used. Section 3 defines the case study for Spain. Then, in section 4 the results obtained are described and in Section 5, some conclusions and recommendations are offered.

2 THE MODEL

To carry out this study, we have opted for the formulation of an integrated bottom-up engineering model based on Santamaría et al. (2014). In addition to the sectors of steel, cement, and oil refining; tiles, bricks and electricity production were added. Also, as has already been mentioned, we have integrated all these sectors, taking into account the interrelationships between them. The following sections describe how they have been represented. The formulation and input data used are detailed in the annexes.

2.1 General features

The tool presented is a partial-equilibrium, bottom-up linear optimization model that integrates five of the most emission-intensive industrial sectors in the EU ETS (see Table 1): steel, cement, oil refining, tiles and bricks, and electricity generation.

For each sector, the different production processes and technologies are defined as well as the alternatives currently available to improve processes that contribute to reducing GHG emissions and promoting energy savings. The description of the sectors and their technical capabilities for improvement were obtained from the literature, supported by the assessment of experts to represent the industry as realistically as possible.

[4] Megaton. 10^6 ton.

The model calculates the optimal strategy to meet demand 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. Previous studies tend to use, as already mentioned in the introduction, top-down general equilibrium methodologies that are able to reflect more realistically the economy as a whole but losing technological detail. Other methodologies use bottom-up approaches but do not account for the interrelationships between sectors.

The model also considers demand as inelastic, so that although imports are permitted, this feature is also a limitation of the model. Nevertheless, the particularities of the sectors studied make it such that, overall, the demand can be considered relatively inelastic (Cook, 2011; Monjon and Quirion, 2009). The model considers the possibility of imports in case that domestic production is less competitive compared to imported production. This assumption is not quite realistic, as there are more than purely economic factors when determining the change in domestic production due to imports. However, we consider this assumption as a sufficiently valid approximation.

2.2 Sectors covered

In this section we describe the sectors analyzed to represent the performance of the industry under the EU ETS. The chosen sectors, as stated, are steel, cement, oil refining, ceramics (bricks and tiles), and electricity generation. Table 1 shows the weight of each of these sectors as GHG emitters. After the electricity sector (included in the term "combustion"), refining, cement, and steel are the sectors with the largest share of emissions in the EU ETS. As already mentioned, the description and implementation of the sectors in the model is based on Santamaría et al. (2014) and Linares et al. (2008).

2.2.1 Steel sector

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[5], etc., as well as indirect emissions due to electricity consumption.

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

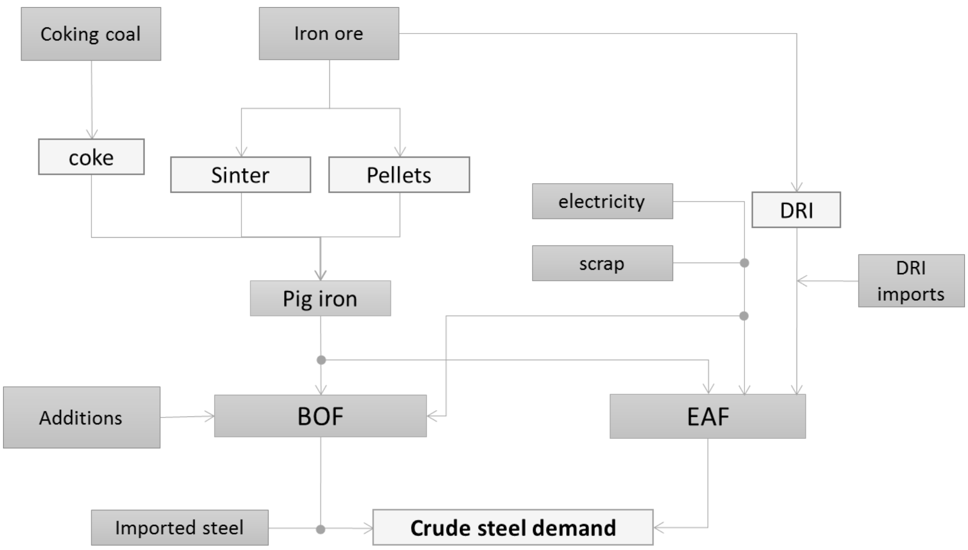

Fig. 1. The steel production process. Source: Authors from Santamaría et al. (2014).

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

2.2.2 *Cement sector*

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.

Clinker production is the most intensive process in terms of GHG emissions, with 0.8 ton CO_2 per ton of white clinker produced and one ton of CO_2 per ton of grey clinker, according to the European benchmark (Oficemen, 2013). The cement production stage has no direct GHG emissions; associated emissions belong to electric mills.

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 Fig. 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).

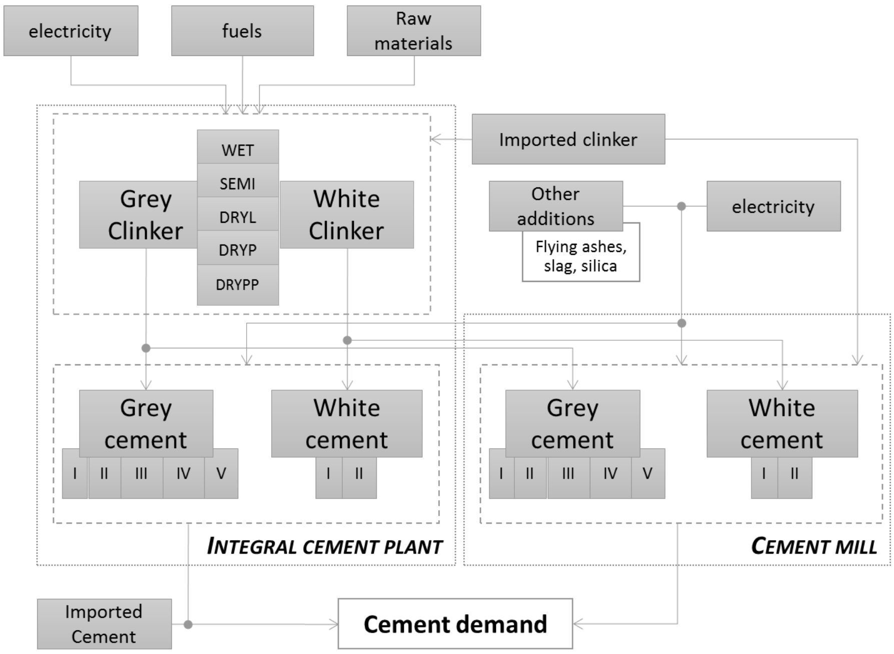

Fig. 2. The manufacturing process for clinker and cement for Spain. Source: Authors from Santamaría et al. (2014).

2.2.3 *Oil refining sector*

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 process begins in the distillation tower. The products obtained pass through different modules according to the final product to be obtained. The catalytic reforming module is dedicated to the processing of heavy naphtha and increasing the octane level. Hydro desulfurization, the sulfur reduction process, is performed on the modules called HDS (hydro skimmer). The remaining modules contribute, as mentioned in the previous paragraph, to increasing the performance of the refineries and their refining conversion capacity. The model also includes octane, sulfur level, and density requirements, although in a linear, simplified way.

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

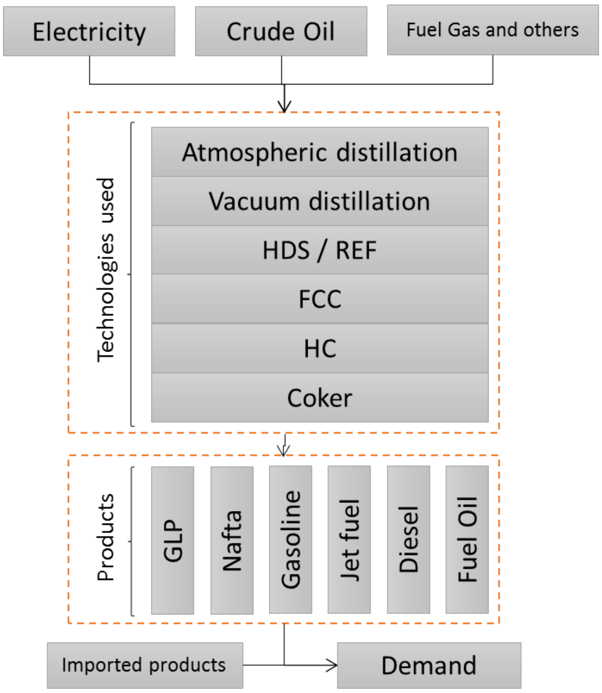

Fig. 3. The oil refining process. Source: Authors.

2.2.4 Bricks and tiles sectors

Fig. 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 modeled.

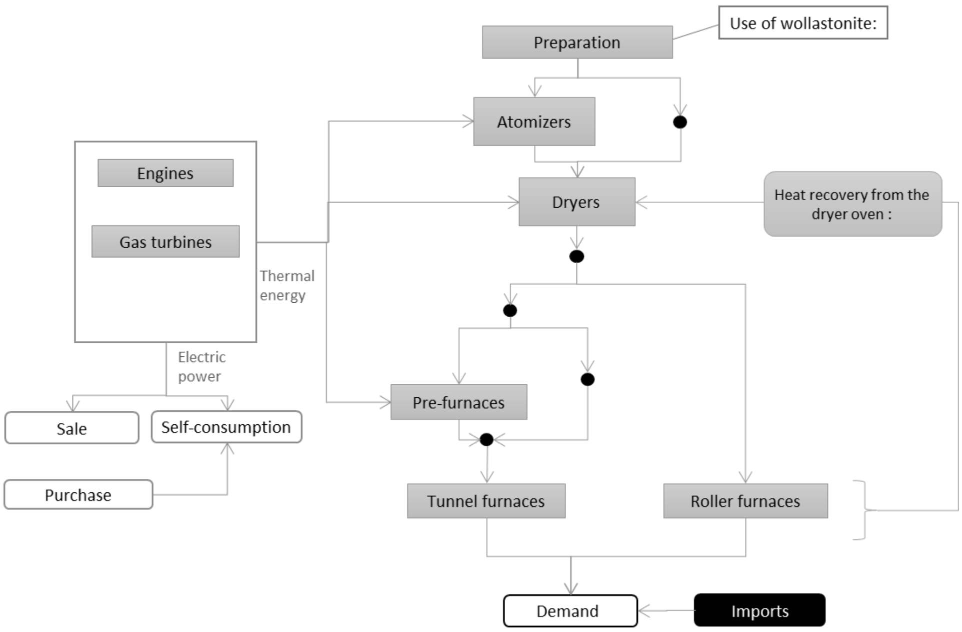

Fig. 4. The manufacturing process of ceramic tiles. Source: Authors.

Although some facilities change, as can be seen in Fig. 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.

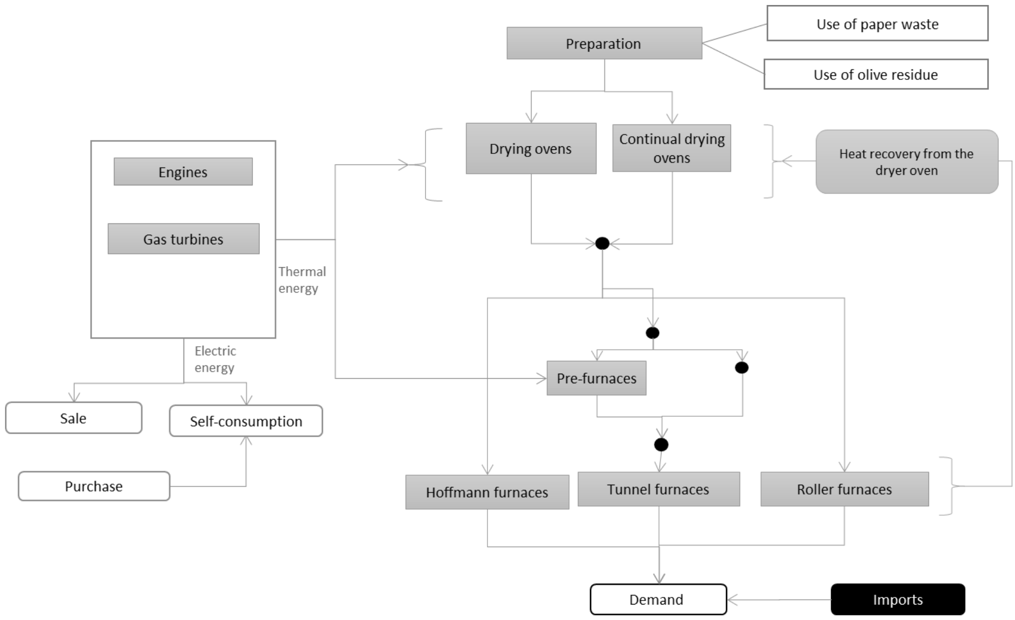

Fig. 5. The manufacturing process of bricks and tiles. Source: Authors.

2.2.5 *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 analyzed, the potential of reducing GHG emissions.

2.3 Other assumptions and considerations

The complete model is conceptually shown in Fig. 6. Each of the industries described above seeks to optimize its own cost function. 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 of GHG emissions.

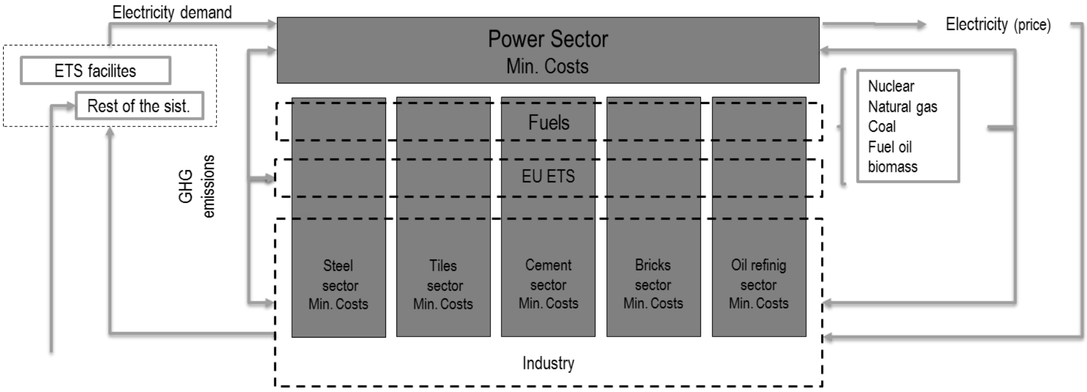

Fig. 6. Conceptual scheme of the integrated model. Source: Authors.

The carbon market is represented by an overall constraint for GHG emissions. The model calculates 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 measures applicable to each sector, as well as investments in new, more efficient technology and with lower emissions. This endogenously yields a marginal cost of reduction of the ton of CO_2 eq. emitted, which is also the price of the emission allowance in the market.

2.4 Mathematical Structure

Fig. 7 represents, in a simplified way, the objective function of the model and the constraints (Annex II provides the complete formulation). The objective function is composed of the costs associated with the production of each of the sectors represented. This function, subject to the corresponding constraints, obtains the optimized solution that satisfies the demand for each of the sectors.

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

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

Fig. 7. Mathematical structure of the model. Source: Authors.

3 AN APPLICATION TO SPAIN AS A REPRESENTATIVE CASE

In this section we apply the model to Spain, as a representative case study (see Table 1), in order to illustrate the advantages of the integrated modeling. We carry out an ex-post analysis, during 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. Moreover, as a sensitivity analysis, we also represent an alternative scenario that simulates the plans for EU ETS before Phase II, that is, without taking into account the contingencies of the economic crisis or subsequent policies such as the Energy Efficiency Directive. This alternative scenario helps to understand the outcome expected by the European Commission to implement the EU ETS and, therefore, the need for further adjustments. Finally, the results are compared with the actual outcomes of the EU ETS, collected from the European ETS registry (European Union Transaction Log, EUTL).

3.1 Input data

For the study of the Spanish industry we establish 2012 as the representative year. This year has been chosen because is the last, at the time of this study, with available data from actual transactions of agents that operate on the market (from EUTL), in accordance with Annex IV of Regulation (EU) No 389/2013.

Below are given the main figures for the sectoral exogenous demand data, which are detailed in Annex I.

3.1.1 Steel

Spain produces about 8.5% of the European steel (EUROFER, 2014).The Spanish steel industry is one of the most efficient of the EU, due to its high percentage of EAF technology installed. In 2011, 75% of Spanish steel was produced exclusively by electric furnaces fed with scrap, compared to 43% of the European average. The total steel production in Spain in 2012 rose to 13.6 Mton (UNESID, 2014), representing 4.5% of emissions covered by the carbon allowances market.

3.1.2 Cement

The cement sector is the third largest emitter of greenhouse gases in the Spanish industry, ahead of the refining and power sectors. Cement contributed about 10% of the EU ETS verified emissions in 2012 (EEA, 2014). Clinker production in Spain is mainly done by a dry method. This technology requires less energy consumption. Together with the drier raw material also available, this allows the Spanish industry to be close to the standards of the best available techniques.

3.1.3 Oil refining

The oil refining sector represents 12% of the GHG emissions associated with the EU ETS in Spain (EEA 2014), and is the second most important sector for this reason, only behind the power sector (see Table 1). To represent the industry, different modules have been taken into account in the ten Spanish refineries. Annex I shows the production data of the sector.

3.1.4 Tiles and bricks

The Spanish tile industry produced 404 million m^2 of tiles and ceramic floor tiles in 2012 (ASCER, 2015). To model the production in this sector, the products were classified as tiles, stoneware or extruded tiles. The amounts of each manufactured product are detailed in Annex I

Spain´s production of building ceramics (bricks and roof tiles) has decreased significantly since 2008, after a steady rise at the beginning of the last decade. In 2012, this sector´s production amounted to 5.2 Mton (Hispalyt, 2015).

3.1.5 Power sector

In 2012, electricity demand in Spain reached 267 TWh, according to Red Eléctrica de España. In that year, the mainland emissions from this sector amounted to more than 80 Mton (REE, 2014). The model represents the total energy mix of electricity production (mainland and islands), as well as the production required for self-consumption. The table with the production data of each of these technologies is included in the next section. The table with the production data of each of these technologies is included in Annex I.

4 RESULTS

In this section, the results of the simulations for the Spanish case are described. First, the validation of the data obtained with the model is shown, to check the accuracy of the results compared to reality. Then, the main results are described. As has been stated in the introduction, one of the objectives of this study is to determine how to improve the results by considering the industrial sectors with their interrelations. For this, MAC curves obtained separately by the analysis of individual sectors are compared with those obtained by examining all the sectors together.

Besides the study of the actual market situation, we also built an alternative scenario, called "planned scenario", which represents the scenario expected for 2012 from the point of view of the preparation of Phase II of the EU ETS, i.e. before 2008. The intention of this scenario is to provide an estimate of the prices of allowances expected for the implementation of the second phase of the EU ETS and, at the same time, check the model's sensitivity to changes in input parameters.

In this section the actual data of the EUA transactions from the EUTL database are also presented. This information, together with the marginal costs of emissions reduction, allows us to undertake a brief evaluation of the agents’ behavior.

4.1 Validation of the model

To confirm the consistency of the data obtained by the model, intermediate and final results of energy consumption, costs, and emissions were tested for each of the sectors. The key figures are given below.

Table 2 shows the evolution of the emissions in Spain for the modeled industries. The model covers 86% of emissions subject to the EU ETS in 2012, which amounted to 135.6 Mton.

<table>
<tr><th>Emissions (MTon)</th><th>1990</th><th>2005</th><th>2012</th></tr>
<tr><td>Power generation</td><td>61.61</td><td>101.24</td><td>80.00</td></tr>
<tr><td>Oil refining</td><td>12.64</td><td>15.46</td><td>14.39</td></tr>
<tr><td>Iron and steel</td><td>13.83</td><td>11.05</td><td>6.05</td></tr>
<tr><td>Cement and clinker</td><td>22.72</td><td>29.45</td><td>13.73</td></tr>
<tr><td>Ceramics and tiles</td><td>0.41</td><td>0.8</td><td rowspan="2">1.82</td></tr>
<tr><td>Bricks and roof tiles</td><td>3.89</td><td>4.1</td></tr>
<tr><td>Total (model)</td><td>115.1</td><td>162.1</td><td>115.99</td></tr>
<tr><td>% Covered model</td><td>87%</td><td>85%</td><td>86%</td></tr>
<tr><td>Total EU ETS</td><td>131.66</td><td>189.85</td><td>135.64</td></tr>
</table>

Table 2. Historical emissions by sector in Spain. Source: NAP 2008-2012; EEA; REE.

Table 3 provides a comparison of real 2012 emissions data for each of the sectors with those obtained by the model. As we can see, our results fit quite well the actual emissions, except for the electricity and the iron and steel sectors. In the electricity sector, the difference can be explained by the fact that the official emissions data are representative of the mainland system exclusively, whereas our model considers the total generation of both the mainland and island systems. The difference in the steel sector has to do exclusively with the emissions accounting method used. In the model, we have followed the criteria proposed by the "IPCC guidelines for national greenhouse gas inventories" (IPCC, 2006). We used the methodology that considers GHG emissions based on the production and use of raw materials (cast iron, sinter, coke, DRI or pellets). This method, recommended by IPCC (2006), is more reliable than the simplified method based on the final product that is used to calculate actual emissions in the Spanish official GHG emissions inventory (which results in lower emissions). When we use this simplified method for our model we obtain results consistent with the official ones.

Emissions data (MTon)	2012 (real)	2012 (model)
Power generation	80.00	90.18*
Oil refining	14.39	15.30
Iron and steel	6.05	11.13**
Cement and clinker	13.73	12.39
Ceramics and tiles	1.82	3.51
Bricks and roof tiles		

Notes: *The model considers the mainland and islands electricity system, while the actual data belongs to the mainland system. **The model calculates emissions for the steel sector with a methodology based on (IPCC, 2006).

Table 3. 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 4 shows the distribution of the electricity production mix of the model and its variation compared to reality. It should be noted that gas combined cycles 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 the use of pumping.

[GWh]	2012 (Real)	2012 (Model)	Variation
Coal	57.662	57.630	0%
Combined cycle	42.510	46.383	-9%
Cogeneration	33.767	33.731	0%
Wind	48.508	47.254	3%
Hydro	19.455	19.514	0%
Small hydro	4.646	4.653	0%
Nuclear	61.470	60.833	1%
Solar photovoltaic	8.202	8.188	0%
Solar thermal	3.444	3.451	0%
Biomass	4.755	4.782	-1%

Table 4. Comparison between real power generation mix and replicated by the model. Source: Compiled from model and REE.

Table 5 shows power production and consumption data by the more intensive service sectors. It may be seen in the case of the cement production industry that power consumption is different when we compare the model with real results. This is because electricity is a minor input in this sector and, therefore, it is difficult to measure accurately with enough precision. Still, the level of validity of the model representation is very high.

[TWh]	2012 (Real)	2012 (Model)
Electricity produced	286,94	287,06
Electricity consumed by the steel sector	14,00	13,98
Electricity consumed by the cement sector	2,00	1,21

Table 5. Comparison of the actual electricity generation and consumption, and the model results. Source: Compiled from the model, Oficemen and IDAE.

4.2 The benefits of an integrated modeling

We now discuss the benefits of an integrated modeling of all GHG-emitting sectors compared to a piecemeal analysis like the one offered by previous approaches in literature. Fig. 8 shows two MAC curves. One of them is called "synthetic", and is formed 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 possible interactions between technologies and emission reduction decisions in the carbon market.

The major source of interaction between sectors is electricity consumption and prices, which connect all sectors. For example, if the steel sector reduces its emissions by resorting to a higher share of EAF, that will mean that electricity demand will increase, as well as electricity prices, in turn affecting back the cost of mitigating emissions in the steel sector and also in the rest of sectors. This effect can result in that synthetic curves might show artificially low mitigation costs, which would then fire back at stronger mitigation targets. It should be noted though that, as previously mentioned, we are assuming an inelastic demand for each sector, so for example we do not account for the correlation between e.g. steel and cement demands. Since we take international fuel prices as given, we do not simulate the effects of Spanish fuel demands on their prices.

On the other hand, by definition, a joint optimization will allow discovering cheaper options for abatement. By modeling all sectors together we are also able to exploit the fact that it is the model which optimizes the level of reduction in each sector and the order in which mitigation actions should be implemented. When we optimize sector by sector we need to exogenously decide the mitigation effort for each sector, 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).

Our results agree quite well with these intuitions. Comparing the two previous MAC curves (Fig. 8), we observe that the integrated MACC shows lower marginal abatement costs overall.

In Fig. 8, it can be seen that for low emission reduction requirements, the abatement costs are almost equal. This is because in these first stages it is the power sector the one that reduces emissions in both situations (integrated and synthetic MACC). However, if the GHG emission abatement requirement is increased, the curves start to diverge. For example, for 14% reduction, marginal costs vary 2 to 3 € per ton CO_2 eq. when we compare the integrated with the synthetic curve. If the GHG emissions reduction is, for example, 24% compared to BAU, the marginal abatement cost increases from 6 to 13 € per ton CO_2 eq. when we move from the integrated to the synthetic curve. Given the current 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.

We can also observe how our integration approximates, with more reliability, the reality of the behavior of the EU ETS. Other studies, however, overestimate the cost of CO_2 by looking at various sectors in an isolated way (e.g. Santamaría et al., 2014).

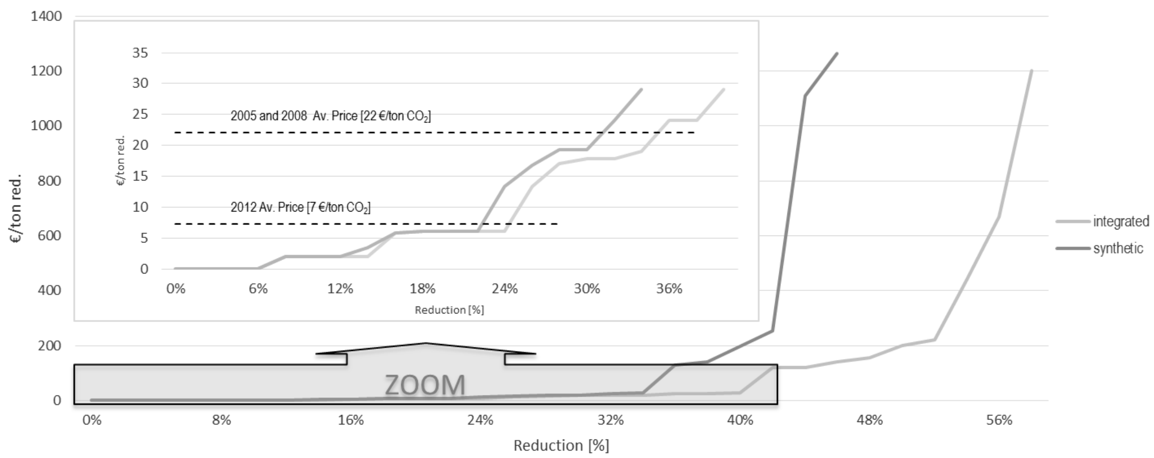

Fig. 8. Comparison between integrated and synthetic MAC curves. Source: Authors.

It is also interesting to analyze how much our estimation of allowance prices differs from others that only look at the electricity sector as representative for the whole ETS (e.g. Richstein et al., 2015). Fig. 9 shows a comparative graph with the integrated MACC and an electricity sector-only MACC. It can be seen that the abatement costs from the electricity-only MACC are higher than those of the integrated one. Again, we see that the cost of CO_2 is also overestimated by using only the electricity sector as a reference.

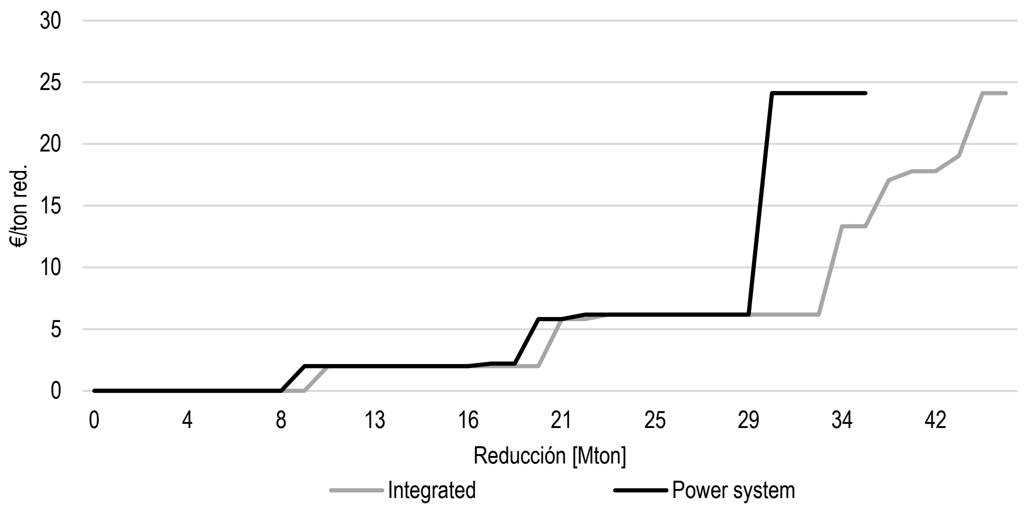

Fig. 9. Comparison between MAC curve of the electricity sector and the integrated MACC. Source: Authors.

4.3 A sensitivity analysis: The expected prices of the EU ETS

EUA prices in Phase II remained above 12€ until mid- 2011 (see Fig. 10). 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 Fig. 10 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.

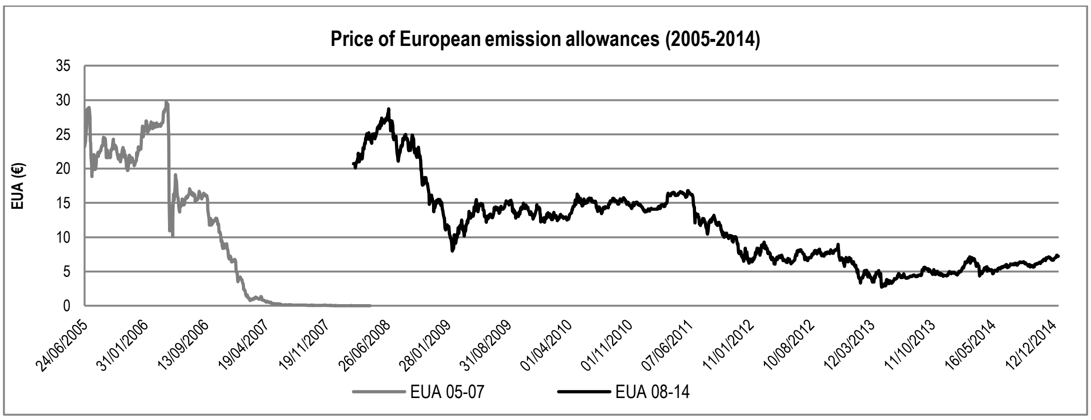

Fig. 10. Evolution of the allowances prices. Source: Bluenext, SendeCO2.

For this, we create a scenario that attempts to replicate the planned trends (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 6 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 6. 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, we try to have an estimation of the expected outcomes of the original EU ETS plans without being subjected to the contingencies mentioned above. Table 7 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 7. 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" (Fig. 11) 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, we use 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 8). 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 8, 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 (Fig. 11). 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 8. Summary of the Spanish situation with regard to compliance with the Kyoto Protocol (period 2008-2012). Source: Authors from EEA.

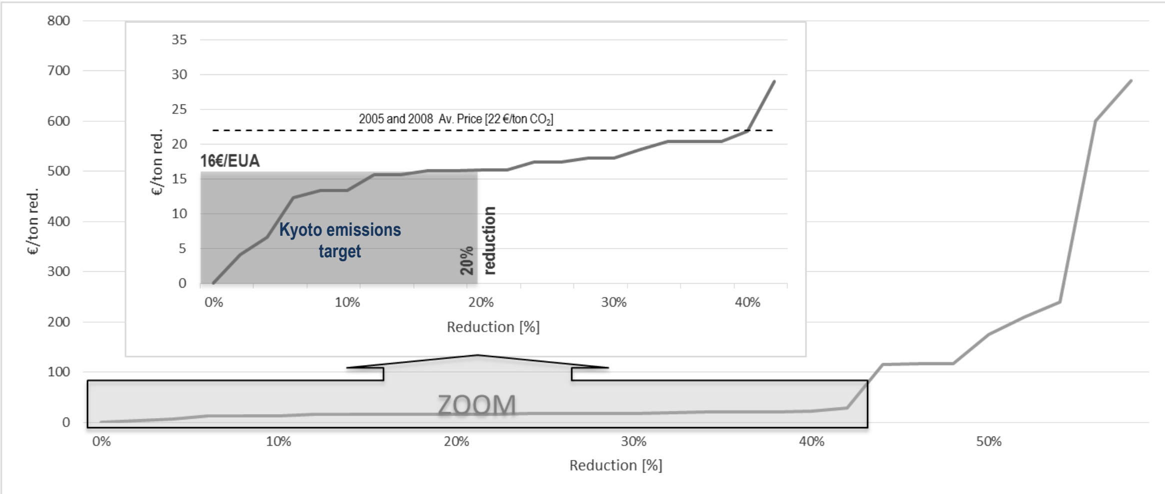

Fig. 11. MAC curve to the "planned scenario". Source: Authors.

As summary, Table 9 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 9. Summary of marginal costs obtained according to scenario and type of integration. Source: Authors.

5 COMPARISON WITH ACTUAL TRANSACTION DATA (EUTL)

Finally, in this last section, and based on the results obtained by our model, we take a first look at the economic rationality of the players in the EU ETS according to actual transactions data.

Economic theory points out that a market instrument like the EU ETS should ensure the achievement of the emissions reductions objectives by minimizing the costs, regardless of the method of allowance allocation (Coase, 1960). Therefore, 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. By contrast, it should buy allowances when its marginal abatement costs are above the market price. In case the company does not need to reduce emissions or buy allowances (for example, if production is lower than expected due to lower demand, or if there has been an excess of free allocation of emissions), its opportunity cost would be zero and, therefore, it should sell its allowances at any price.

Of course, it has to be noted that this is a very crude rationale. In addition, 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". Fig. 12 shows a decision tree that seeks to explain, in simple terms, the strategies to be followed.

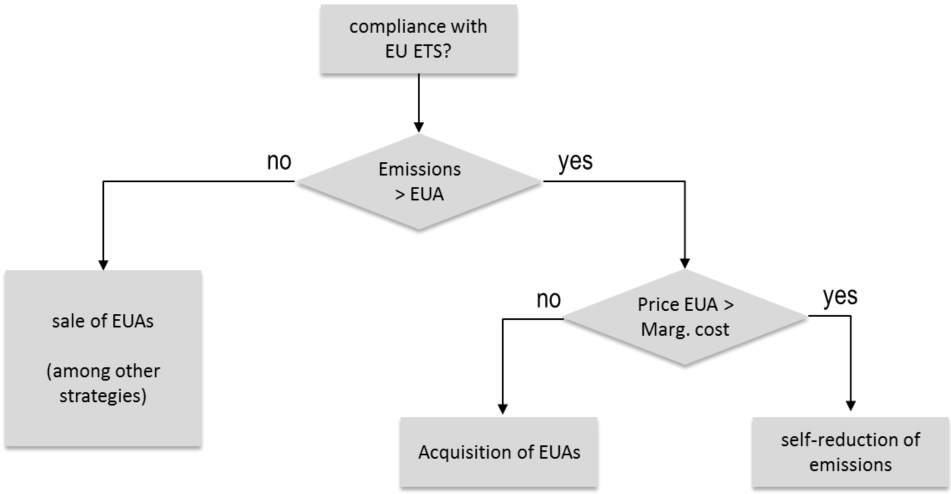

Fig. 12. Outline of possible decisions to make regarding the carbon market. Source: Authors.

As mentioned, the literature found several deviations from the theoretically-optimal operation of the market. For example Naegele (2015) shows the importance of transaction costs in the EU ETS, and concludes that the behavior of the agents in the EU ETS depends on the initial allocation of the allowances. Their analysis uses the EUTL database to come to this conclusion.

In this sense, we also proceed to analyze the transaction data of the allowances in the market and compare it with our results. If the transactions of allowances available in the EUTL (possible acquisition-purchases/transfer-sales), made by the Spanish facilities during the last year are analyzed, we can observe differences in the behavior between sectors. Nevertheless, our analysis does not consider other possible financial strategies like hedging, which are used mostly by large market players (Neuhoff et al. 2012). In this sense, the market players are considered myopic. These assumptions are commonly made in this type of analysis (e.g. Lee and Han 2016). Furthermore, the purpose of the analysis presented in this section is not to reproduce the process of price formation in the market, but to see if the marginal abatement costs obtained with our model fit the market reality.

First, we can see that the price at which the different sectors trade their allowances varies, which may be explained by differences in expertise or resources to trade in the market, but also by over-allocation. This price was calculated taking into account the average spot price of each day that the respective sector transfers/acquires allowances. The summarized data of estimated prices, transactions and allowance allocations is presented in Table 10.

Spain (2012)	Average acquisition price 2011-2012 (€/EUA)	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 (%) (2008-2012)
Steel	7,00	7,61	12,20	6,05	102%	74%	37%	-22,8%	-45,0%
Combustion	7,43	7,22	72,84	89,04	-18%	192%	305%	-24,7%	17,3%
Oil refining	7,66	7,38	19,75	14,39	37%	32%	103%	-2,7%	-20,4%
Ceramics	9,24	8,58	5,60	1,82	208%	17%	89%	-63,0%	-58,0%
Cement	9,46	8,63	29,53	13,73	115%	47%	139%	-49,9%	-39,7%

Table 10. Estimated average price and over-allocation of EUA per sector. Source: EUTL, EEA.

Another factor to consider is the level of over-allocation of each sector. This phenomenon is present since the beginning of Phase II in all sectors, except the power sector. Table 10 shows how some sectors (e.g. ceramics, but also steel and cement) were overallocated, whereas other received less allowances.

Through registry data from the EU ETS, it is also interesting to know the level of transactions per sector. A proxy for this may be the volume of allowances acquired/delivered by a certain sector as a percentage of the allowances allocated to that sector. This information is also presented in Table 10.

No correlation was found between EUA prices of each sector and their over-allocation. Rather, it seems that the prices of each sector have to do with the size of the facilities, experience in market trading, etc. Fig. 13 shows the size of the facilities in terms of their GHG emissions, and in particular we can see the prevalence of small-sized ceramic facilities, which also tend to trade at less favorable prices.

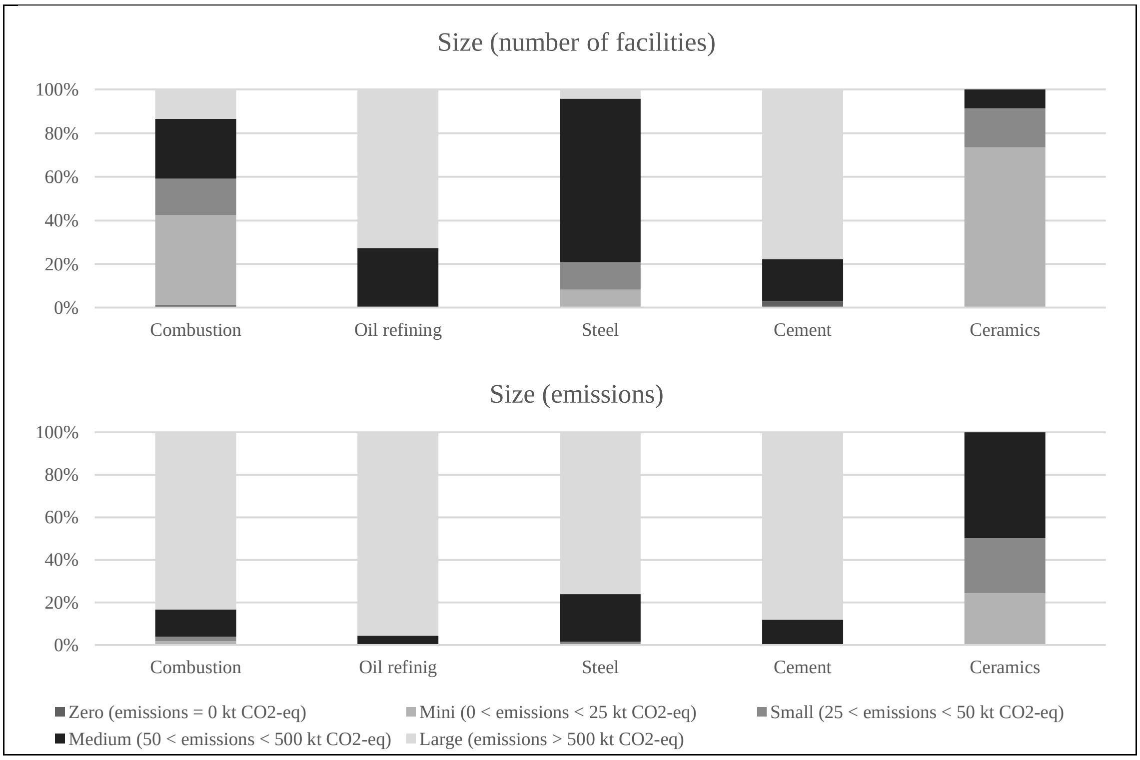

Fig. 13. Size of the installations by sector (based on number of installations and GHG emissions). Source: EEA.

We can also compare the actual transactions data with the abatement costs for each sector and the ETS market prices. In Fig. 14 the marginal costs of abatement of GHG emissions obtained by the model for each sector are shown. Here we present results from the non-integrated version of the model to show the internal abatement cost for each sector. These abatement costs should be compared with the ETS market price (which is obtained with the integrated version of the model).

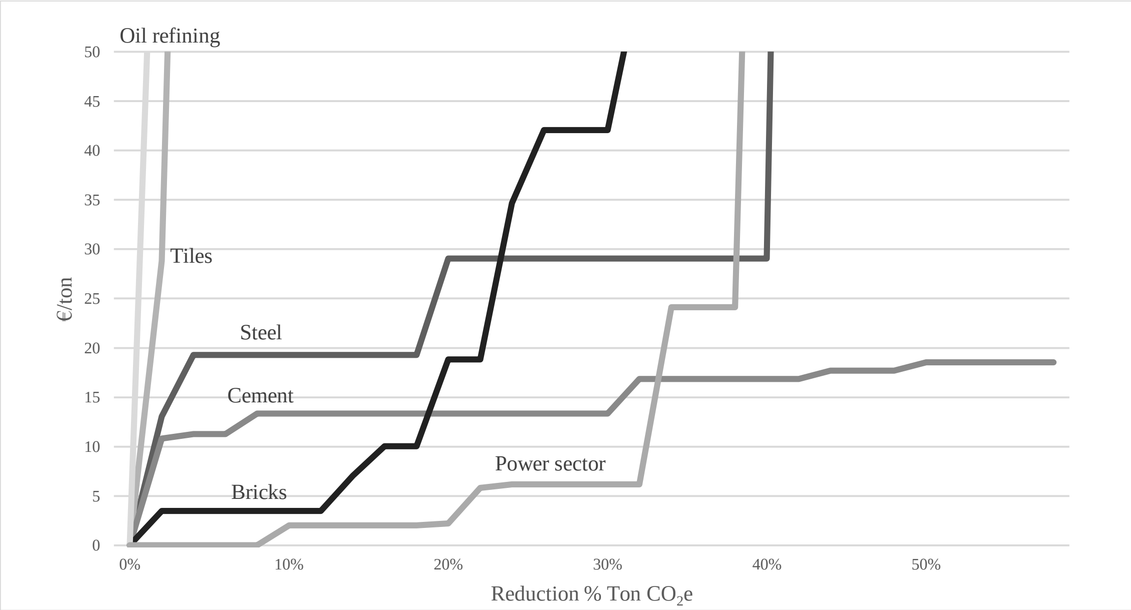

Fig. 14. MAC curves by sector for Spanish industry in 2012 (without integration between sectors). Source: Authors.

By 2012, the steel sector had reduced its emissions more than 20% since 2005 (EEA, 2015). For this year (2012), the sector received an over-allocation of more than double of its verified emissions (EEA, 2015). Considering that the average annual price of the EUA was 7.33€ (SendeCO2, 2015) for 2012, it seems that this sector would have had no problem in meeting the ETS directive. If some companies/installations had a deficit of allowances, according to the MACC for the sector, they would have bought allowances instead of reducing emissions (a 2% reduction has a marginal cost of 13€ per ton CO_2 eq.). This assumption is consistent with the larger activity of buying allowances in this sector (despite the over-allocation).

The electricity sector, which is included in the combustion sector, had significantly reduced its emissions from 2005 to 2012 (almost 25%). However, it was the only sector without free allocation during phase II. The marginal costs of reducing emissions for this sector were very low. For example, it could cut 30% of its GHG emissions at a marginal cost of 6 € per ton CO_2 eq. This cost is lower than the average price of EUAs in 2012. Therefore, it would be expected that this sector reduced emissions internally and sold the allowances to the market. The transaction data of EUTL indicate a greater percentage of selling allowances than of buying. In other words, there are more sales than purchases, which again is consistent with our model predictions. In addition, the power sector includes large companies generally with expertise in markets. Hence, it is not surprising that their purchase prices are the lowest along with those of the steel sector.

The refining sector has only 11 Spanish facilities included in the EU ETS. According to the results of the model, they have high marginal abatement costs (92€ per ton CO_2 eq. for a 2% reduction in emissions). This sector had practically unchanged levels of GHG emissions between 2005 and 2012 with less than 3% drop in their emissions. The over-allocation level is around 37%. With these data, it seems that the rational solution would have been to sell the surplus rights. And indeed, the EUTL data indicate that, for this sector, sales exceeded purchases of allowances in more than two thirds.

The ceramic sector was already mentioned for its large number of small installations, which may indicate a greater difficulty in the operation with the EU ETS. This sector has reduced its production and emissions significantly since 2005, because of the economic crisis; the 2012 production and emissions level was 63% of the 2005 one. This also contributed to a 208% over-allocation. If some installation has a deficit of allowances, there are two possibilities of compliance. In the case of producing bricks and tiles, their marginal costs are lower than the market price, so it would be better to reduce emissions internally. If it comes to the production of roof tile factories, abatement costs are higher, so the strategy would be to buy allowances. Transaction data indicate that in this sector, more than 4/3 of the transactions were transferred (possible sale). This outcome is consistent with previous data.

The cement sector also suffered from a big drop in production due to the Spanish housing bubble. Emissions in this sector decreased by 50% during the period 2005-2012. Besides, in 2012, the cement sector received a 115% of over-allocation. Although marginal abatement costs are quite low (10€ per ton CO_2 eq. to reduce 2% of GHG emissions), they are above the EUA´s average prices. Transaction data should therefore indicate larger sales of EUAs than purchases, and it actually does, which again makes sense from an economic point of view.

6 CONCLUSIONS

Our work and the results presented allow us to put forward two conclusions that we think 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, we found that the market should be modeled in an integrated way, accounting for all the relevant sectors and for their interactions. As mentioned before, our model allows for not imposing separate (and somehow artificial) mitigation shares for each sector, but instead represents the real behavior of a market: least cost options across all sectors are identified, and the interaction between sectors taken into account.

As we have shown in our 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. In this regard, our bottom-up model can incorporate all these elements with a high-enough degree of technological detail for most of the largest emitting sectors.

We have validated our results both for the current situation and for the scenario expected before the economic crisis, and both the allowance prices and the related variables are very much in line with the real values. We therefore think that our model shows a large potential for simulating policies that affect the EU ETS.

Our second conclusion has to do with the behavior of the agents participating in the ETS market. Although preliminary, our results show, in general terms, behaviors consistent with economic rationality: agents sell allowances when it is cheaper to abate emissions internally or when they have over-allocation, and they buy them when the allowance price is lower than their abatement cost. We also observe however that the prices that different sectors pay for their allowances differ, which may reflect a different ability to play in the market.

Of course, there is still much work to do: we need to introduce into our models transaction costs, which have been shown to play a non-negligible role in ETS trading, and also other elements such as hedging or financial strategies that may alter the behavior of the agents in the market. We also need a deeper analysis of real transactions and their fit with the results of rational and non-rational models, in particular for those sectors such as ceramics, with smaller installations and hence stronger concerns about their ability to perform efficiently in the market.

Only if we are able to simulate correctly the interplay between technologies, costs and agents' behavior we will be able to design correctly 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. We hope that our paper will contribute to the correct design of these markets.

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