Modeling the response of industry to environmental constraint

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Abstract

For industry, and especially for large energy consuming industries, energy prices and environmental constraints are the main drivers towards energy efficiency. By this time, many energy efficiency technologies exist on the market and some technological breakthrough processes (e.g. based on Carbon Capture and Storage CCS, or electrolysis in steel industry) are in study to ban traditional CO_2 emitting processes. But their adoption will depend mainly on their economical competitiveness. Emission trading is a new instrument that can modify industry's response by adding a cost to CO_2 emissions.

We use a prospective energy model to assess the response of industry to environmental constraint. It calculates the best economical choices for technology adoption in large energy consuming industries.

The modeling tool is the TIMES model (from the family of the MARKAL models). It is a mathematical model of the energy system of one or several regions that provides a technology-rich basis for estimating energy dynamics over a multi-period horizon.

We illustrate our work by several energy-intensive industrial sectors. We include a full description of multi-option processes involved in the production of paper, glass, cement and steel, providing typical energy consumption in each process step. We identify, for each large energy-consuming industry and for different carbon constraints, the best technologies or optimisations to reduce production cost, and we calculate the energy savings potential and the corresponding CO_2 emission reductions.

Environmental constraints – main drivers towards energy efficiency in industry

For industry, and especially for large energy consuming industries, energy prices and environmental constraints are the main drivers to energy efficiency. In a worldwide competing industry, reducing the production cost by lowering energy uses is one of the major actions to reach competitiveness.

Energy consumption is the major source of CO_2 emissions. As an important CO_2 emitting actor (21% of France total CO_2 emissions in 2005), industry is submitted to legislative pressure to reduce its own CO_2 emissions, and by consequence its own energy consumption. This environmental constraint can be applied in different ways such as carbon taxes (by adding a cost to each ton of CO_2 emitted), CO_2 emission trading schemes (rights to a certain CO_2 quota + CO_2 exchange market), or CO_2 mitigation obligations (obligations to reduce CO_2 emissions to a fixed declining level).

This study is part of a PhD work carried out within a partnership between EDF Research & Development and The Applied Mathematics Center of Ecole des Mines de Paris. The interest for EDF, as a major electricity supplier in Europe, to study large consuming industries is that they are more than simple customers. Their industrial strategy, in terms of investments in their production assets, has an important impact on the total amount of consumed energy. This in turn influences the position of EDF as an important player in the European Union Greenhouse Gases Emission Trading Scheme. In addition, for commercial ambitions, EDF develops energy efficiency services. For these reasons it is important to analyse industrial energy consuming processes and to be able to detect the potential of energy efficiency improvement.

How modeling can help to assess the influence of environmental constraints

PROSPECTIVE MODELING HELPS PROVIDING A CONSISTENT IMAGE OF THE FUTURE

Energy prospective models are a precious tool for decision making. By integrating economic factors and policies in a long term vision, prospective energy models make it possible to trace a consistent picture of the industrial energy systems. Prospective modeling does not aim at providing reliable results for the future. It is not a forecast. It allows us to anticipate a likely framework of evolution starting from plausible scenarios. Within this framework, we lay emphasis on the evaluation of the consequences of an environmental policy, on the selection of energy efficient technologies and the likely trajectories of industrial investment. Cost effects lead to structural change in industry, resulting in the appearance or the disappearance of certain industrial processes.

THE TIMES MODEL AIMS TO SUPPLY ENERGY SERVICES AT A MINIMUM GLOBAL COST

TIMES is a recent development in the evolution of the MARKAL framework, created by the IEA Energy Technology System Analysis Programme (ETSAP) [reference 1-2]. Like MARKAL, TIMES is an economic linear programming model generator for local, national or multi-regional energy systems, which provides a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon. It is usually applied to the analysis of the entire energy sector, but it may also be applied to study in detail single sectors, like the industrial sector in our case. The model aims to supply energy services at a minimum global cost by simultaneously making the best choices in equipment investments and energy supply. TIMES model is based on a reference energy system, which is a network describing the flow of commodities through various processes. A full TIMES scenario consists in four types of input: the final demand for energy services (in our particular case, energy service demand is replaced by the physical production of industrial products), the resource prices, the environmental policy, and the description of a set of technological process options. TIMES is a demand driven model. The demand drivers, e.g. steel production, are exogenous, obtained externally from various industry sources or from our own forecast of industrial evolution. There are many energy prospective models. Each of them is dedicated to a particular problem to be solved.

FULL DESCRIPTION OF THE VARIOUS INDUSTRIAL PROCESS OPTIONS

The large energy consuming industries are considered in terms of physical production. We use the specific energy consumption per ton of manufactured product. Each industry is modeled by a sequence of manufacturing processes, from the raw material to the finished product. By adding the amounts of energy consumed in each step of the whole process, we can calculate the total energy consumption for each manufactured product and for each time period. We then deduce the volume of CO_2 emissions.

In industry, some industrial sectors are very important in terms of energy consumed. Our model includes the following large energy consuming industries:

- Pulp and paper
- Iron and steel
- Glass
- Cement and lime
- Other construction materials (ceramics, tiles and bricks)

These industries belong to the industrial perimeter taken into account in France for the first period (2005-2007) of the Directive 2003/87/CE related to the CO_2 emission trading scheme. Other energy-intensive branches such as chemicals are excluded.

The relevance of an energy prospective model is measured by the number of possible options (energy substitution, technological switch) of the reference energy system. In the case of industry, the interest of our representation, which is very detailed, is to be able to explore the industry's room for manoeuvre to adapt to an economic context, whether it is by the choice of the energy carrier or by the choice of new processes.

We considered 28 routes for the standard reference processes in large energy consuming industries (table 1).

For each industrial subsector we have a Reference Energy System. For example, figure 1 represents the iron & steel industry.

For each industrial subsector, we identify technology options that can reduce energy use. For example in pulp and paper industry, the most significant energy consuming processes are pulping and the drying section of papermaking. The amount of drying energy required (mainly steam) can be reduced by a number of innovative efficient pressing and drying technologies such as "Airless drying processes", "Dry sheet forming processes" and "Condensing belt dryers" [reference 3-6]. Figure 2 shows the main technologies taken into account in the model.

Two case studies: influence of a carbon tax (50 Euro/t) and CO_2 mitigation obligation by a factor of 4

An environmental constraint can be applied in different ways. Our model, based on the minimization of production costs, is particularly useful to study the impact of an additional cost, like a carbon tax. It can also be used to impose a CO2 mitigation level and to calculate the corresponding additional costs to the standard production costs to reach this target.

Two case studies are presented:

1. Influence of a carbon tax.

This scenario supposes an environmental awareness slightly stronger than today. A carbon tax is imposed to all the industrial CO_2 emissions. The price level is fixed at a "reasonable" level, at about double the 2008 CO_2 price (14-30 Euro/t). We suppose a carbon tax of 50 Euro per CO_2 ton for the period of simulation (2000-2050). A constant price rather than an increasing one has been adopted in order to give a better readability of the results, otherwise it would have been difficult to

Table 1: Standard reference processes of the TIMES industry model

Industrial sector	TIMES Code	Technical Description
Gypsum	IGPPPRO00	IPL. Gypsum production Processes
	IPLSHYPRO00	IPL. Semi-hydrate Production Processes
Tile	ITLPRPRO00	ITL. Tiles production Processes
Ceramic	ICRCPRPRO00	ICR. Standard Ceramics Production Processes
	ICRSPRPRO00	ICR. Sanitary Ceramics Production Processes
	ICRRPRPRO00	ICR. Refractory Ceramics Production Processes
Brick	IBRKPRPRO00	IBR. Brick Production Processes
Lime	ILMPPRO00	ILM. Lime production Processes
	ILMQLMPPRO00	ILM. Quicklime Production Processs
Glass	IGHHOLLOW00	IGH. Container Glass Processes
	IGHRCYGH00	IGH. Recycled Container Hollow Processes
	IGFFLATGL00	IGF. Flat Glass Processes
	IGFFIBRGL00	IGH. Fiber Glass Processes
	IGSPCRGL00	IGH. Special Glass Processes
Cement	ICMPPRO00	ICM. Cement production Processes
	IDCLKPPRO00	ICM. Dry Clinker production Processes
Pulp & paper	IPPPRPRO00	IPP. Paper Processes
	ICHPLPPRO00	IPP. Chemical Pulp Processes
	IMCPLPPRO00	IPP. Mechanical Pulp Processes
	IRCYPLPPRO00	IPP. Recycled Paper Processes
Steel	IISHRPRO00	IIS. Hot Rolling Processes
	IISCCPRO00	IIS. Continuous Casting Processes
	IISSCMETPRO00	IIS. Secondary Metallurgy Processes
	IISBOXFURPRO00	IIS. Basic Oxygen Furnace Process
	IISBLAFURPRO00	IIS. Iron Blast Furnace Process
	IISSNTRPRO00	IIS. Sinter Production Process
	IISCOKOVPRO00	IIS. Coke Oven Process
	IISEARCFURPRO00	IIS. Electric Arc Furnace EAF Process

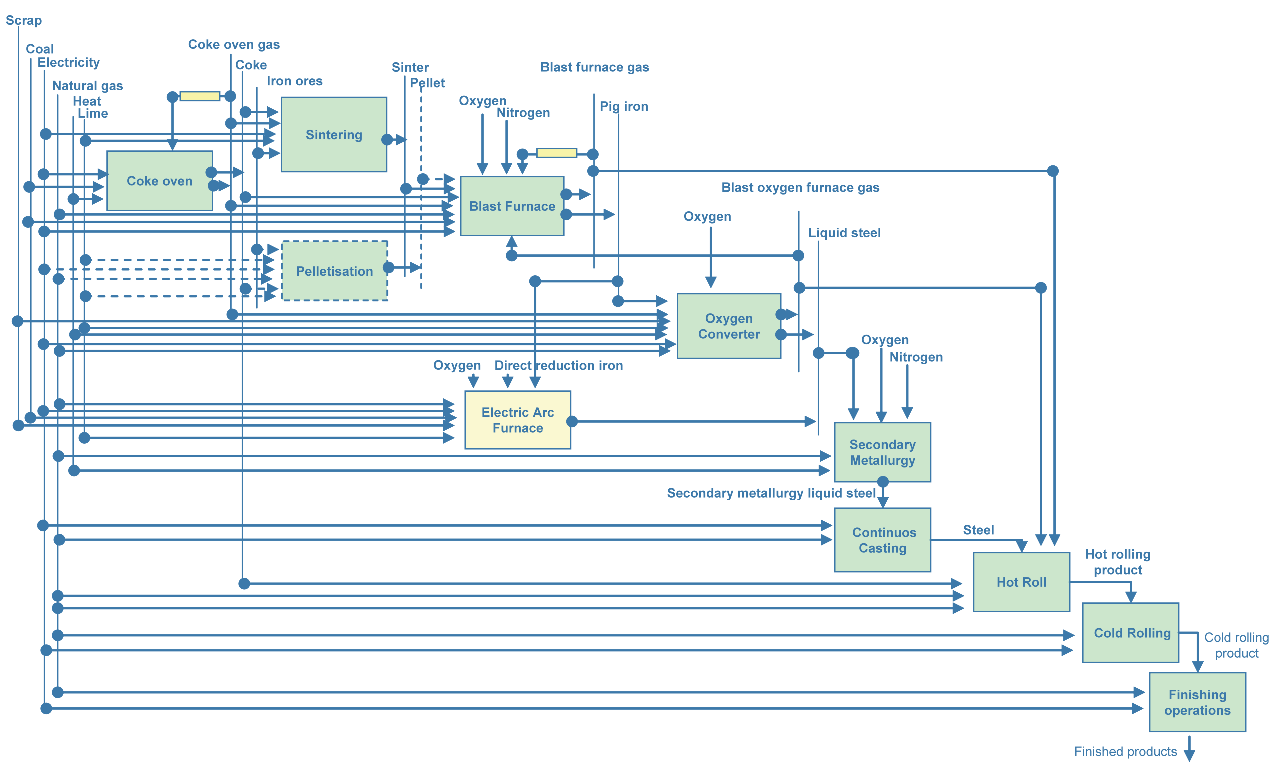


Figure 1: Iron and steel Reference Energy System

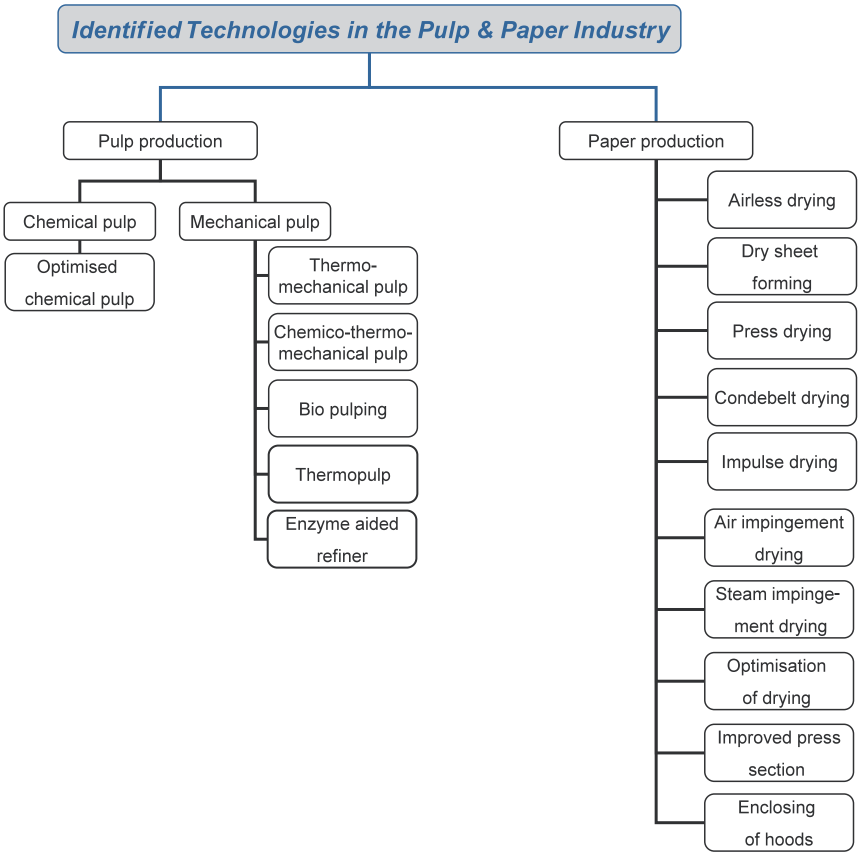


Figure 2: The saving options taken into account in the pulp and paper industry

see at what carbon price a change occurs, specially during the transition period.

2. Influence of CO2 mitigation obligations by a factor of 4
Factor 4 is a concept first introduced by Ernst Ultrich von Weizsäcker in a report of the Rome Club (1997). It refers to an increase by two of the well-being while dividing by two the use of natural resources. At the origin, it is a larger concept than only diminishing greenhouse gases. The expression, used within the framework of the greenhouse gas emissions, consists in stabilizing the atmospheric concentration of CO_2 at a 450 ppm level. To achieve this target in France, it is necessary to reduce the CO_2 emissions by a factor of 4 (2000-2050).

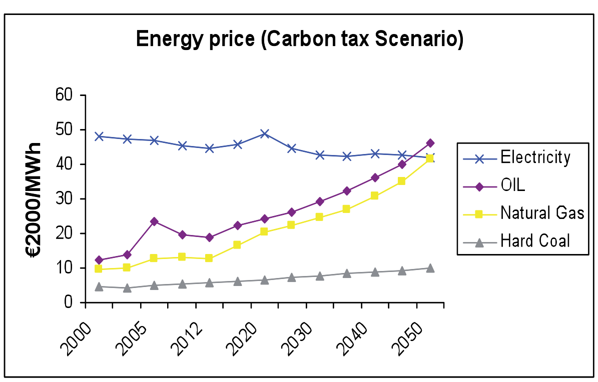
A factor of 4 is a real challenge; it implies huge efforts in all sectors. We postulate here its application to the large energy consuming industries.

ECONOMIC CONTEXT: BUSINESS AS USUAL

The "business as usual" scenario is a prospective scenario that assumes that economic actors are going to act like they used to do in the past, with no particular event. The "business as usual" scenario is used as a standard scenario, in order to see the additional effects of the tested environmental scenarios.

- **Energy prices**

The forecasted energy prices are coming from an external model, with exogeneous hypotheses but in accordance with the two environmental scenarios (Carbon tax and Factor 4). We used the POLES (Prospective Outlook on Long-term Energy Systems) model prices. This model has been developed by LEPII (Research Laboratory in Economy and Energy Policies of Grenoble [reference 7].



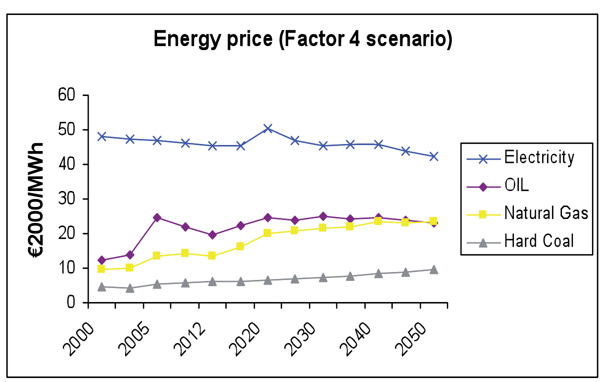


Figure 3: Energy price scenarios for France (from the POLES model)

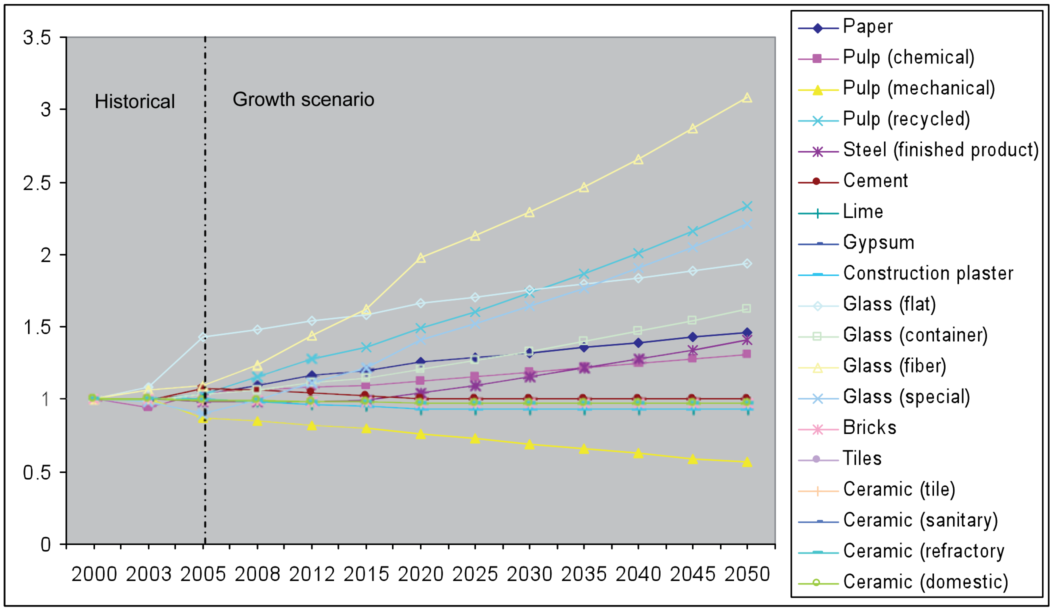


Figure 4: industrial growth scenario for France (reference year base in 2000-physical production)

The price of electricity is not impacted by the environmental constraints scenarios because French electricity comes mainly from nuclear energy. In a factor 4 scenario, fossil energies prices decrease as a result of the equilibrium offer-demand because the global demand for such energies becomes lower.

- **Industrial growth**

The industrial growth scenario for France is coming from our own assumptions, based on growth forecasts from the main industrial producers or specialized literature. We still suppose a “business as usual” economic scenario. The scenario was originally made at the beginning of 2008, before the world financial crisis. The forecasts were set up for 2030 and extrapolated to 2050 assuming a continuation of the economic development. It is considered that industrial growth is not affected by environmental constraint scenarios, so physical production is the same in all the scenarios. This enables a direct comparison of the results of energy consumptions in the different scenarios.

We believe that the industrial growth (in term of physical production, i.e. ton production) will be limited in France by a factor 1 to 2 in a 50 years period, except for some promising industrial products (fiber glass, recycled paper or special glass). Concerning steel production, we assumed that world steel production will double by 2050, mainly because of Asian growing demand. We supposed (in an optimistic way) that France would pick up a major part of the steel production growth, at the occasion of the steel plants renewal scheduled around 2030 and favoured by more advantageous production costs.

THE MODEL RESULTS FOR FRANCE (2050)

- **Carbon tax**

Concerning the energy consumption, we can observe:

- During the first period, from 2000 to 2035, in the “business as usual” scenario, there is a rather constant level of energy consumption, despite the low growth of industrial production. This means that industry has adopted “naturally” energy efficient processes, because they are competitive. After 2035, energy consumption increases because of the steel production growth (see figure 10 and industrial growth hypothesis). This may appears as a “strong” or “too optimistic” hypothesis, but this is a case study assumption, and the reader has to consider the differences between the scenario rather than the absolute level of energy consumption.
- No short term effects; there is no change before 2030 (comparing the two scenarios). Large energy consuming industries use long life time equipments (around 20 years for the main production structures[1]). The change is coming very slowly in accordance with the equipment change rhythm.
- Change in the energy mix after 2030. Coal is replaced by natural gas. With a medium carbon tax (50 Euro/t), it is cheaper to adopt low carbonated energy when possible (coal → natural gas → electricity). Steel industry replaces the traditional blast furnace (coal consuming) by a direct reduction process consuming natural gas, where natural gas acts as a reducing agent for the iron ore [reference 8].

Concerning energy efficiency, we observe

- An overall energy gain of around 19%. But this is mainly due to one industrial sector effort, steel industry. Steel industry represents more than 60% of the 2050 total energy consumed by energy-intensive industry. We found no additional significant effect for other industrial sectors. This means that the next energy efficiency options are no competitive with such a carbon price.

- **Factor 4**

The main questions in the Factor 4 scenario are: is it possible to reach the target and what are the technological solutions for satisfying this ambitious environmental constraint?

1. In steel industry, the lifetime for a blast furnace is longer, around 50 years, but with numerous revamping events during life.

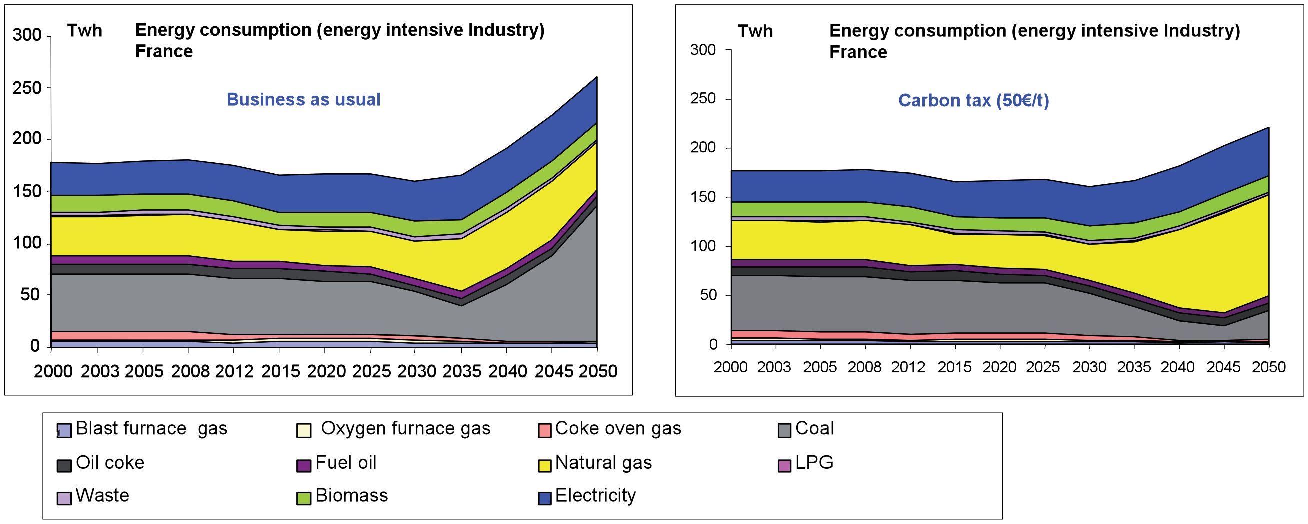


Figure 5: energy consumption, with or without a carbon tax

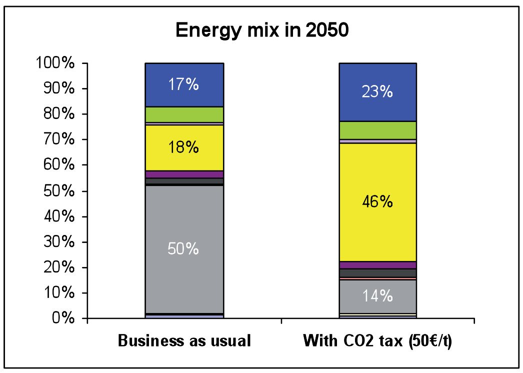


Figure 6: energy mix in 2050 (carbon tax scenario) – same notice as figure 5

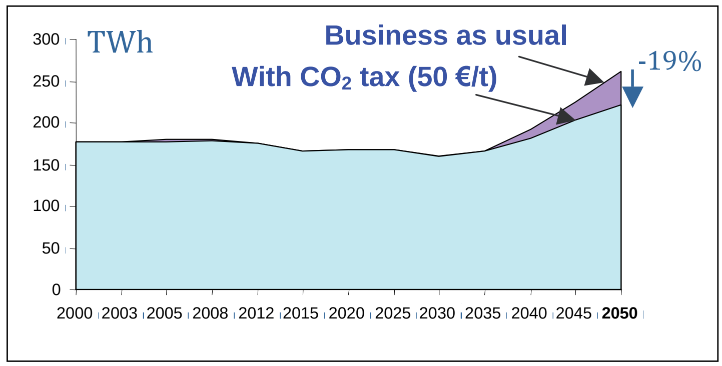


Figure 7: energy efficiency (carbon tax scenario)

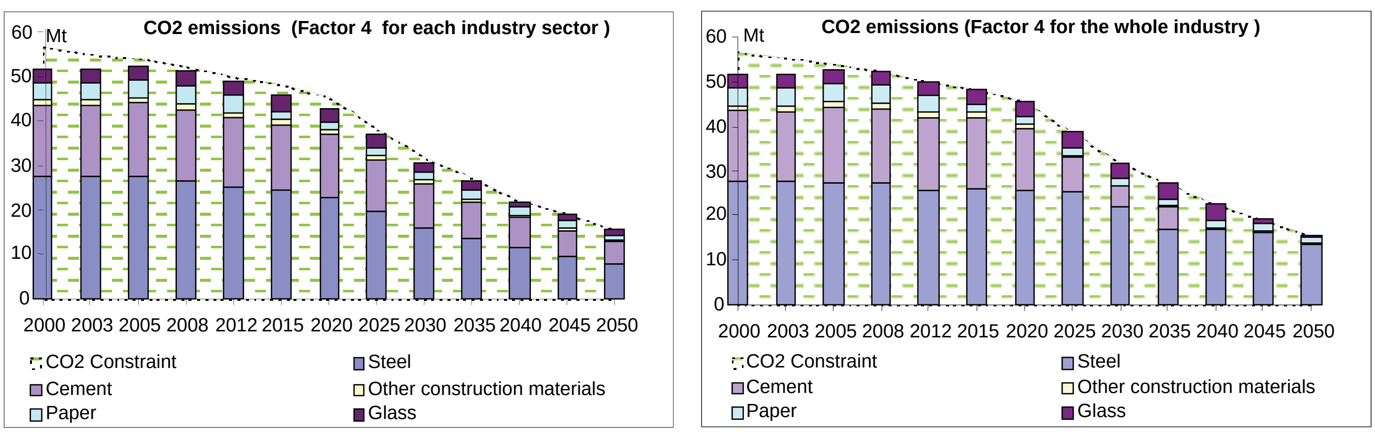


Figure 8: CO_2 emissions by industrial sectors, two case studies in the Factor 4 scenario (Factor 4 applied with a proportional constraint to each industrial sector, or applied to the whole industry)

Figure 8 shows the calculated CO_2 emissions and in which industrial sectors the CO_2 economies are made. It can be noticed that the "CO_2 constraint" curve is higher in 2005 than the real amount column because French industry finally emitted less CO_2 than allowed. Figure 9 shows that it is possible to reduce CO_2 emissions up to 79% in 2050 (comparison in 2050 between the Business as usual scenario and the Factor 4 scenario).

Figure 8 presents 2 case studies for the Factor 4 scenario; in a first case we have considered that the environmental constraint is applied for each industrial sector, that means that each sector must divide its own CO_2 emissions by a factor of 4 (Factor 4 by sector). In the second case, we have considered that the industry is concerned as unique entity, and it is up to the industry to find the best sectors (where it is cheaper) for the CO_2 reductions (Factor 4 for the whole national industry).

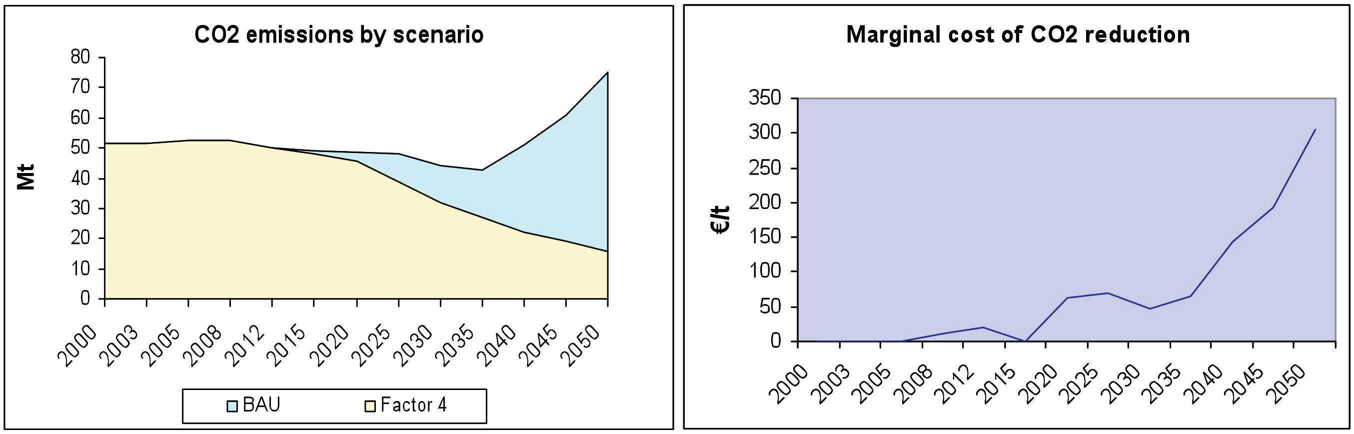


Figure 9: CO_2 emissions and CO_2 marginal reduction cost for large energy consuming industries in the Factor 4 scenario

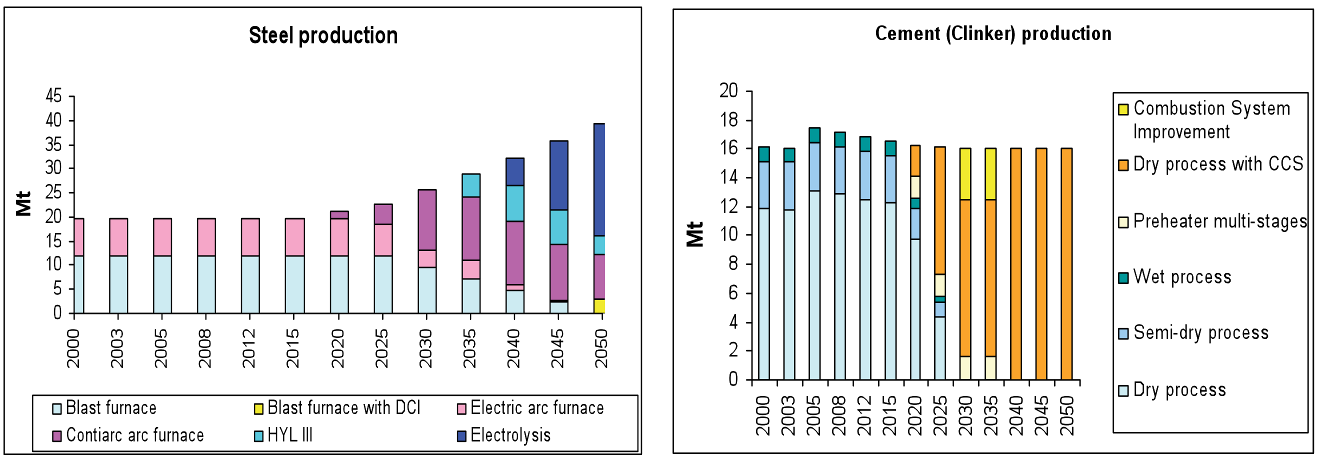


Figure 10: Steel and cement industry response to factor 4 (process change)

Figure 10 presents the technological solutions for two main industrial sectors. The solutions are different for each of the industrial sectors:

- Steel industry has changed for a mix of a natural gas process and an electrical solution. We find the appearance of the Direct Reduction process, like in the carbon tax scenario. But we find also the emergence of a radical process change towards the electrolysis of the iron ore.
- Cement industry needs CO_2 capture and storage (CCS).
- Glass industry is more balanced (both electricity, natural gas process and CCS)
- Paper industry adopts the airless drying process. This new technique allows a 70% reduction in steam use but with the use of more electricity (+15 to 20%).

The appearance of those new technologies, both low CO_2 emitting and high capital cost, is explained by the strong constraint in CO_2 emissions.

We postulate for CO_2 capture and storage a favourable set of conditions (limited cost for transport, no environmental problem, public acceptance, large volumes storage)

We find a 79% CO_2 emission decrease in 2050 (Factor 4 versus Business as usual). Consequently, the cost of the CO_2 constraint could reach 300 Euro/t in 2050. It represents the CO_2 price to make the energy system optimal. It can be noticed that, even with the availability of CCS technology, the model calculates a strong CO_2 price to oblige the industry to use all the technical possibilities (even at a high cost) to be able to reach the Factor 4 target.

The comparison between a Factor 4 for the whole industry and a Factor 4 by sector (figure 8) shows a different behaviour of the industry branches in response to the CO_2 constraint. The application of Factor 4 for the whole industry leads to a more drastic reduction of the CO_2 emissions in the cement industry, at the benefice of the other sectors. It is a result in agreement with the minimization of the overall industry cost. The model thus privileges the reduction of the CO_2 emissions in the sectors at lower costs. We found out that the cement industry has the lowest CO_2 reduction cost (figure 11).

With a high pressure on CO_2 emissions, coal nearly disappears in 2050. Natural gas becomes more important but it is electricity that becomes the first energy consumed.

CASE STUDIES – CONCLUSIONS

The large energy consumption in industry has a high inertia and a slow response. Because of the long life time of the industrial equipments, the changes are very slow in this industry. There are no visible effects on the short term. We find that the response to an environmental incentive made in 2010 only oc-

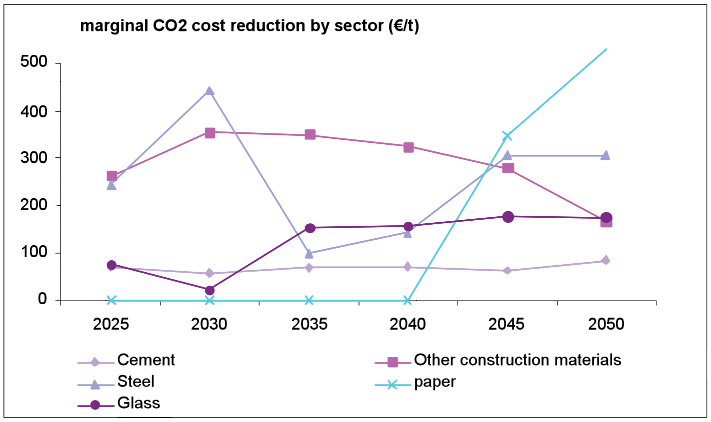


Figure 11: Marginal Cost of CO_2 (Factor 4 scenario)

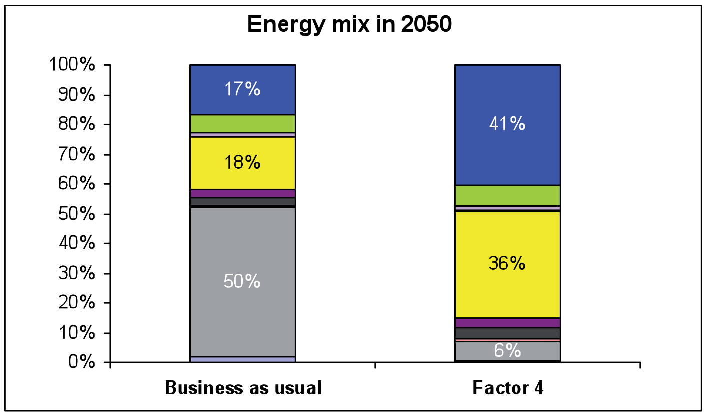


Figure 12: Energy mix in 2050 (Factor 4 scenario) – same notice as figure 5

curs in 2030, corresponding to the average life time period of industrial equipments.

A medium incentive carbon tax (50 Euro/t) has an impact on the energy mix. Natural gas would replace coal as the main energy use in industry (2050 horizon). But this is mainly due to one major change in the most energy consuming industry: the steel industry. This change (use of a Direct Reduction process instead of the traditional Blast Furnace) leads to a 19% drop in consumed energy by industry. This is a significant but unstable result because this is only due to one industrial sector. We found no significant effect of a 50 Euro/t carbon tax on the other industrial sectors.

To reach important gains in terms of CO_2 reduction, industry needs the CO_2 Capture and Storage technology. But some other technological break-through processes could also help, such as electrolysis in steel industry. Today these R&D processes are too expensive, but with a strong environmental constraint, they could become competitive.

Of course, these results have to be balanced because of the uncertainty of the future processes. To be chosen in 2040, a process must exist today in 2009, and its 2040 industrial cost production is extrapolated from 2009 laboratory's studies.

Conclusions

In a competing economic environment, industry seeks to reconcile energy efficiency, CO_2-reduction and economic profitability. Modeling makes it possible to take the economic aspect of energy efficiency into account and to choose the best couple (energy performances/economic profitability) of the processes in industry. Modeling allows to identify the particular industrial sectors presenting the highest potential in energy efficiency.

In industry, and especially for large energy consuming industries, the response times to an environmental policy are slow because of the long life time of industrial equipements. And it is also necessary to consider that the responses to energy efficiency are today in the laboratory phase. Break-trough processes and CCS technologies have still some development way to go before being available at a large industrial scale. There is a strong inertia of the industry energy system. Only a strong long-term signal can drive the R&D efforts on the industrial processes towards the way of energy efficiency and CO_2-reduction.

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