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# Prospective bottom-up modelling of industry: what place for electrification in a cost optimised trajectory ?

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**Abstract**—This paper focuses on evaluating the place of electricity in a cost-optimised trajectory of industrial emissions reduction in France, Germany, Belgium, Spain, Italy, and the United Kingdom (altogether called EU-5+1) for three key sectors: steel, chemistry, and cement. Authors used an open-source industry-centered bottom-up model and open-source data to achieve this goal. The results show that in the framework studied, the combined use of bioenergy, electricity and carbon capture is economically optimal for lowering emissions. Even in a higher electricity price scenario, electricity consumption increases by 185%. However, competitive electricity prices are associated with an increase in consumption of up to 366% (in the case of a fossil phase-out) as well as with a greater decrease in emissions. Finally, the associated connection capacity is also expected to increase in line with consumption according to minimum power estimates. At the scale of France (resp. EU-5+1), in this paper’s reference scenario, this could represent around to 14 GW (resp. 54 GW) of minimum additional capacity.

**Index Terms**—Industry, Bottom-up, Electrification

## I. INTRODUCTION

Industry generally accounts for more than 25% of global greenhouse gas emissions. In order to combat global warming the industry must take its part in the emissions reduction effort. In Europe, in heavy industry, three sectors stand out representing more than 50% of industrial emissions : steel, chemical and non-metallic minerals (i.e. cement, glass, ceramics, etc. manufacturing) industries.

Electrification of the industry is a highly considered pathway to tackle emissions. While not every industrial process can be electrified, the remaining prospective electricity consumption may be considered as massive and the question arises as to how much.

To model industry, associated energy-economy issues are to be considered. While top-down models, based on historical relationships, represent behavioural relations at an aggregated level, bottom-up models include a lot of details describing specific energy technologies with both technical and economic parameters [1]. Therefore, bottom-up modelling is the preferable approach for prospective energy consumption assessment.

For many years, industry modelling has been a subject of research and many models exist for this purpose, including FORECAST [2], MARKAL/TIMES [3] and PRIMES [4]. However, industry modelling is often only one block among others in these models. Moreover, the use of these models is almost systematically associated with limited or no sharing of the data used or even the model itself. This is a problem because it makes the results difficult to reproduce.

The aim of this paper is, while presenting an open-source industry-centred bottom-up model and open-source data, to evaluate the place of electricity in an optimised trajectory of industrial emissions reduction. Additionally, the case of a complete phase-out of fossil fuels will be studied. The focus of this paper will be on France, Germany, Belgium, Spain, Italy and the United-Kingdom (altogether called EU-5+1) and three key sectors: steel, chemistry, and cement.

## II. METHODOLOGY

### A. Linear optimisation model

The model was developed with Python 3.10 and the Pyomo library. Thanks to the latter, the equations of the model are easily accessible and modifiable. The model works by linear optimisation of the total cost.

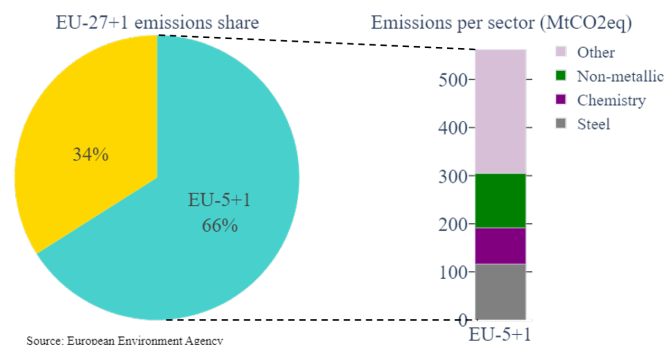


Fig. 1. Manufacturing industry CO<sub>2eq</sub> emissions in 2015 in EU-5+1 per sector

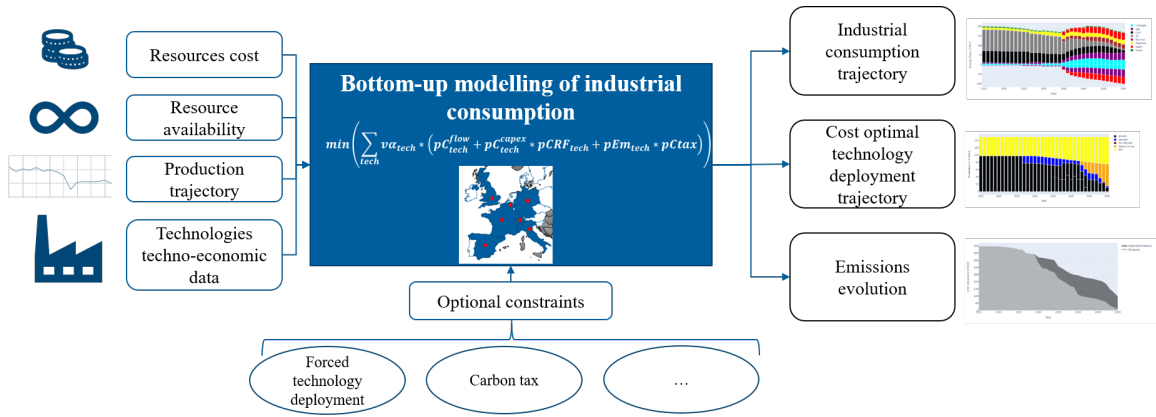


Fig. 2. Bottom-up industry model scheme

Input data includes resources cost, availability, production trajectories as well as techno-economic data for the considered production technologies. Then, for the given techno-economic scenario, the model shall give an cost optimised industrial consumption and technology deployment trajectory with associated emissions evolution. Therefore, the model optimises investments in technologies and chooses which resource/energy to consume in order to minimize overall costs.

The use/import of resources has a cost and associated emissions. Some resources such as biomass may be limited in quantity.

All the input data and code were made available on GitHub<sup>1</sup>.

### B. Main hypothesis

Nowadays production and future price trajectories were derived from existing literature and are specific for each country. Concerning electricity, the assumption was made that market zones' prices would converge significantly by 2050 (Figure 4) due to the growing interconnections between countries [5]. For bioenergy specifically, prices and availability/potential were mainly derived from the ENSPRESO database [6] and ENGIE's report on biomethane [7]. Regarding carbon tax evolution, similar values were taken from the transition plan for the cement industry of the French Ecological Transition Agency (ADEME) [8].

Although it is clear that there is a significant issue of relocation of heavy industry to other parts of the world where low-carbon energy will be cheaper and more plentiful (which will be the subject of further work), it has been assumed that there will be some retention of an industrial base. Production trajectories (see Figure 3) are therefore as follows:

- Steel: production is assumed to remain constant but with an increasing share of recycling (countries with less than 50% recycling in 2015 were linearly moved to that value from 2030 to 2050);
- Cement: the production trajectory is derived from the reference scenario of ADEME's transition plan for cement industry [8], which considers a 12.5% decrease in cement

production from 2015 to 2050 and types of cement with lower clinker rates;

- Methanol: base production is assumed to remain constant although the model will be able to produce more if necessary (for Methanol to Olefins process in particular);
- Ammonia: it has been assumed that nitrogen fertilisers production shall remain constant and thus ammonia production too (since almost all of the world's ammonia production is used for fertiliser production [9]). Ammonia has not been considered for other uses (carrier for hydrogen import, fuel etc.).
- Olefins: most olefins are used in the manufacture of plastics, which are used, among other things, to make packaging. It has been assumed that olefin production will decrease by 40% between 2015 and 2050.

Simulation starts in 2015 and it was imposed to the model a minimum 35% emissions reduction in 2035, 50% in 2040 and 80% in 2050 (in accordance with France's National Low Carbon Strategy). Thus, the model can further reduce emissions if economically relevant.

### C. Three scenarios

Combined with carbon capture, current production technologies, largely dependent on fossil fuels, can potentially continue to produce until 2050. Thus, a variant of the reference scenario was simulated with the constraint of a forced gradual exit from fossil fuels between 2035 and 2050. It has been assumed that electricity prices will converge around 70€/MWh in 2050. However, in its transition plan for cement [8], ADEME assumes a 65% increase in the price of electricity in France in 2050 compared to today. By maintaining the convergence of prices between countries, a variant of the reference scenario was simulated with an electricity price of 125€/MWh in 2050.

Overall the three scenarios have the following parameters :

- Reference: main hypothesis
- Fossil phase-out: main hypothesis + fossil phase-out between 2035 and 2050
- High Electricity Prices (HEP): main hypothesis + 125€/MWh electricity price in 2050

<sup>1</sup>[https://github.com/qraillard/Industry\\_prospective\\_bottom-up\\_modelling](https://github.com/qraillard/Industry_prospective_bottom-up_modelling)

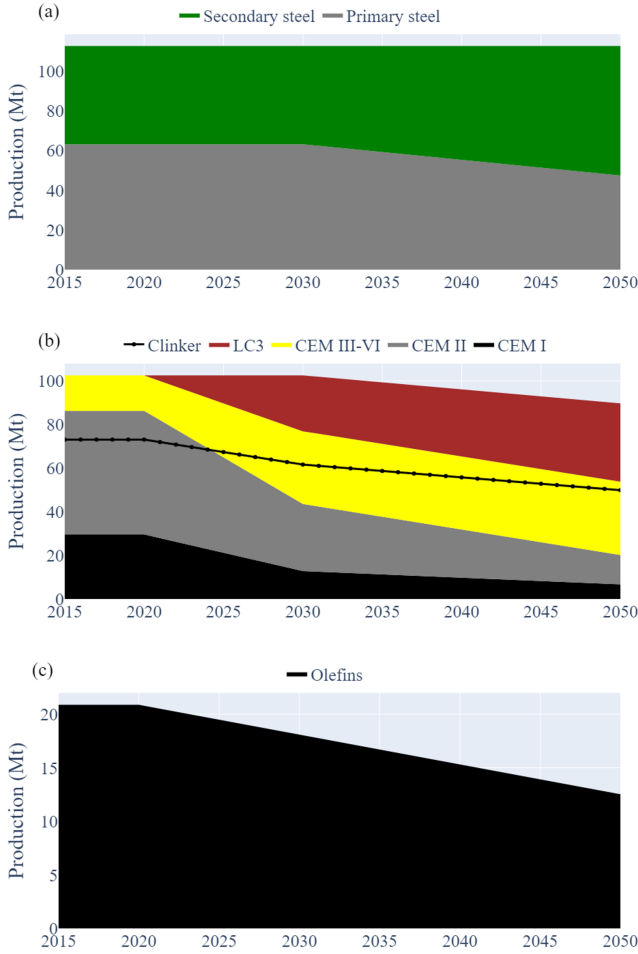


Fig. 3. Production trajectories for (a) Steel (b) Cement (c) Olefins

#### D. Specific case of hydrogen production modelling

The model works with annual values. Therefore, electricity price is constant and technologies such as electrolysers cannot steer production according to market prices. To allow electrolysers to reach for lower prices, two electricity sub-resources were created with lower load factors with a corresponding reduced price. Consequently, if the model chooses to use these sub-resources, installed capacity will be adapted to match the required production.

### III. RESULTS

The results show that in order to achieve at least an 80% reduction in emissions compared to 2015, the joint use of low-carbon electricity, bioenergy and carbon capture and storage (CCS) are necessary under the studied framework (Figure 5 and 6). While the bulk of the emission reduction can be associated with the first two, the use of CCS shall be economically relevant to achieve a more substantial emission reduction. CCS is especially needed in the cement sector, where natural CO<sub>2</sub> emissions from limestone decomposition

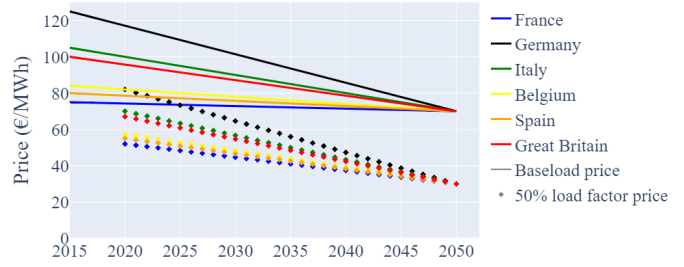


Fig. 4. Electricity price per country and load factor (reference price scenario)

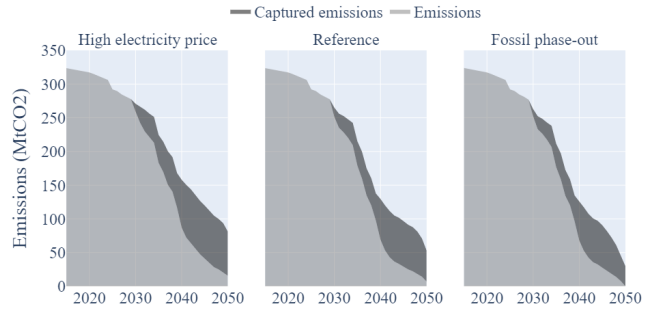


Fig. 5. EU-5+1 emissions per scenario

account for about two-thirds of the sector's emissions, and in blast furnaces for steel production.

Overall, given the uncertainties of a prospective approach, result differences between reference and zero fossil scenarios are rather small while high electricity prices show substantial result changes. This suggests energy transition shall be quite sensitive to energy prices.

Comparing the evolution of emissions in the scenarios (Figure 5), it appears that in the reference scenario a 97.8% emissions reduction from 2015 is achieved and that the exit from fossil fuels in the "fossil phase-out" scenario allows a lesser use of CCS. However, the high electricity prices in the HEP scenario lead to higher emissions and a greater use of CCS. This highlights the need for competitive electricity prices for the energy transition.

Indeed, while the exit from fossil fuels is partly compensated by electricity, high electricity prices lead to much less electrification (Figure 7). Similarly, a correlation between electricity prices and energy independence seems to be emerging (see Figure 8).

All this of course also has an impact on hydrogen production (Figure 9). While a phase-out of fossil fuels leads to significant increase in H<sub>2</sub> production compared to an optimised reference trajectory, high electricity prices negatively impact H<sub>2</sub> production. This also makes local hydrogen production less competitive than imports. As a result, a peak H<sub>2</sub> import of 138TWh is observed in 2041-2042 against 58TWh in the

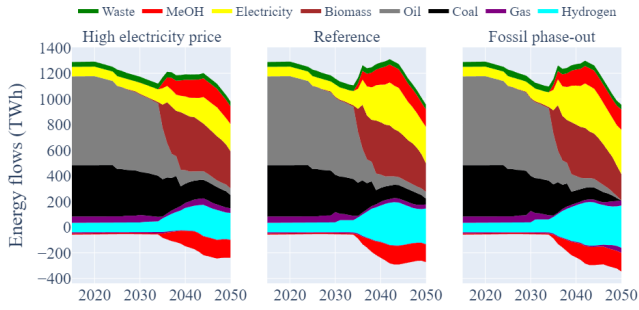


Fig. 6. EU-5+1 energy flows per scenario — positive flows = consumption, negative flows = production

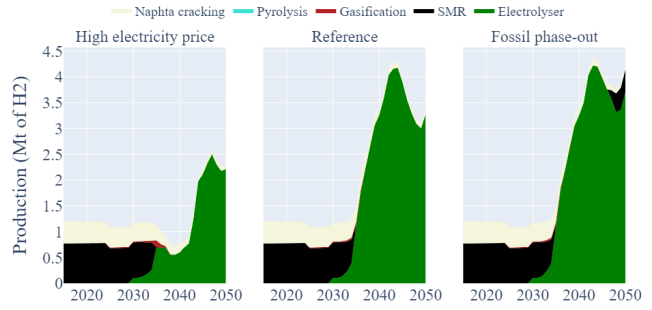


Fig. 9. EU-5+1 hydrogen production per scenario

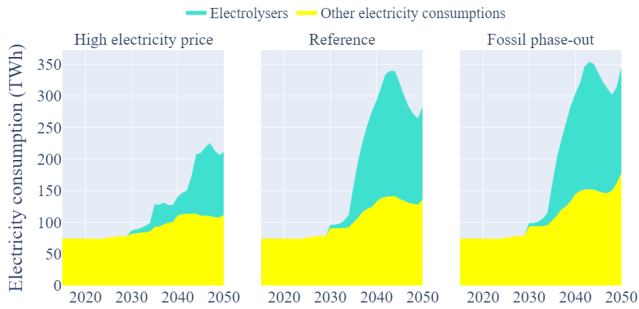


Fig. 7. Electricity consumption with and without electrolyzers per scenario

reference trajectory.

### A. Focus on olefins production

In terms of energy flows, we can see a decrease in the use of oil (Figure 6) due to the decrease in the use of naphtha for the production of olefins. Although naphtha cracking remains, more than two thirds of olefin production in 2050 is from methanol. Results show that for the remaining naphtha consumption, bio-naphtha takes a large part (Figure 10).

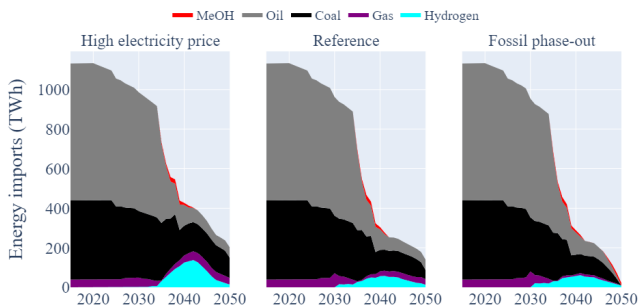


Fig. 8. EU-5+1 energy imports per scenario

### B. Focus on steel production

In the reference scenario, blast furnaces, although marginal and mainly using biomass, remain in 2050. As biomass cannot entirely replace coal in blast furnaces [10], the fossil phase-out scenario brings blast furnace production down to zero in 2050. Nonetheless, with high electricity prices, hydrogen for direct reduction of iron is far less competitive and blast furnaces with biomass can therefore thrive (Figure 11).

## IV. DISCUSSION

### A. Electrification potential and impact

Electrification seems to be linked in the results to a more significant decrease in emissions. Only for three sectors (steel, chemistry and cement), for an initial electricity consumption

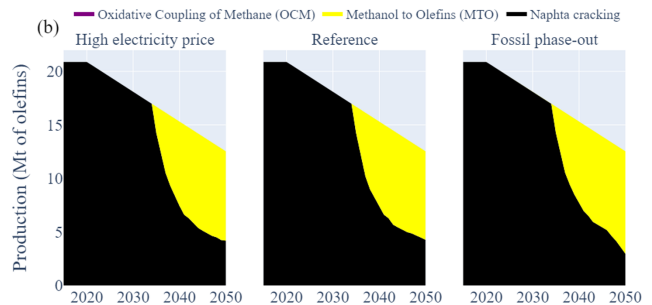
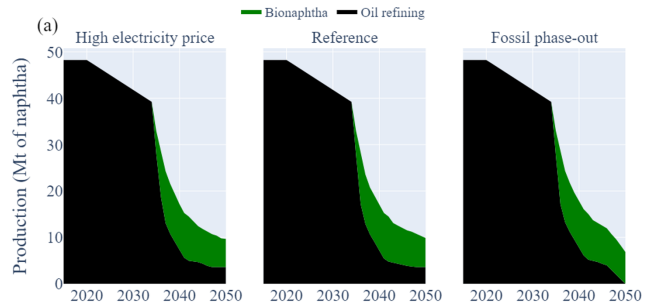


Fig. 10. EU-5+1 (a) naphtha and (b) olefins production per technology and scenario

## V. CONCLUSION

For the three sectors and six countries simulated, a 97.8% emissions reduction from 2015 is achieved in the case of a scenario with an optimised consumption and technology deployment pathway. For this, the model developed uses bioenergy, carbon capture and electrification together. Electricity consumption in 2050 is estimated at 284TWh (compared to 74TWh in 2015), including 148TWh for hydrogen production by electrolysis.

A fossil phase-out scenario and a scenario with higher electricity prices were simulated. While the former leads to a consumption of 345TWh, the latter foresees a much lower electrification (211TWh) even if consequent. Moreover, the high electricity price scenario leads to higher emissions in 2050.

Thus, the price of electricity is a key component to make electrification competitive and thus achieve carbon neutrality. However, the use of bioenergy and carbon capture should not be neglected as all scenarios also rely on these.

## ACKNOWLEDGMENT

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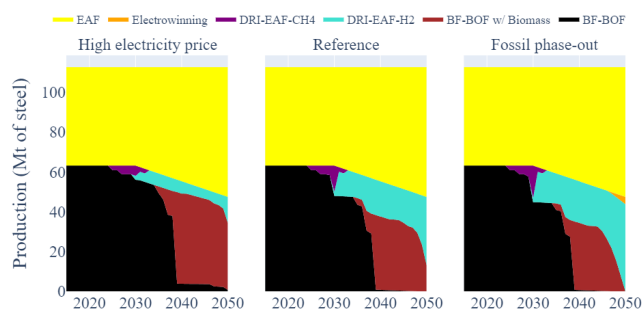


Fig. 11. EU-5+1 steel production per technology and scenario — EAF: Electric Arc Furnace (for recycling), DRI: Direct Reduction of Iron, BF: Blast Furnace, BOF: Basic Oxygen Furnace

of 74TWh, depending on the level of electrification, the simulated scenarios give a consumption in 2050 between 211 and 345TWh (Figure 7). This is equivalent to an increase of between 185% and 366%.

Future electricity consumption is in part strongly linked to the production of green hydrogen. However, even without counting the latter, the fossil phase-out scenario reaches a consumption of 178TWh in 2050 (versus 112TWh with the HEP scenario).

Heavy industries generally have a base production pace. Considering this and the foreseen electricity consumption, power connection requirement can be estimated. Table I shows power requirement different per country and scenario.

TABLE I

STEEL, CHEMISTRY AND CEMENT INDUSTRIES SIMULATED MAXIMUM POWER REQUIREMENT (GW) FOR BASE PRODUCTION BETWEEN 2040 AND 2050

	France	Germany	Italy	United-Kingdom	Spain	Belgium	EU-5+1
Initial (2015)	1.1	2.8	2.1	0.5	1.4	0.5	8.5
High electricity prices	13.7	17.7	3.5	4.4	8.7	7.8	49.4
Reference	15.4	22.7	6.0	9.2	12.2	10.2	62.9
Fossil phase-out	15.8	29.2	7.9	9.2	12.1	9.7	72.2

The question then arises as to the capacity of future electrical systems to meet this future demand. This question, although outside the scope of this study, will have to be addressed when designing the electricity system in the framework of the energy policies chosen by each country.

This question will be especially important as these political choices will eventually determine the price of electricity and therefore the competitiveness of electrification.

### B. Limitations and model improvement

Changes in technology and energy consumption can occur abruptly, and their effects can be seen in the results. Although constraints were implemented to control technology deployment speed, these were applied uniformly across all countries without considering each country’s unique characteristics. Consequently, the implementation of new technologies, such as carbon capture, may be happening too fast for some countries to realistically keep up with. Such a matter shall be addressed in future model improvement.