Arbitrage between energy efficiency and carbon management: an industry sectorial study

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Abstract

Following the Copenhagen Climate Conference in 2009, some countries have adopted carbon abatement pledges. As energy savings are a source of indirect carbon reduction, those pledges will impact the development of Energy Efficiency solutions. This study aims to quantify those impacts and determine their sensitivity to COP15 pledges within the competition with other cleaner technologies, especially on the supply-side.

The study relies on the TIAM-FR model, which is a 15-region world version of the MARKAL/TIMES model family, where an Energy Efficiency-dedicated module was implemented. A focus is given on Europe, United States and China; and only the implementation of the Energy Efficiency solutions in the industrial sector is considered.

On the supply side, the level of power generation is weakly changed with the carbon mitigation constraint while the power mix has a strong sensitivity for pledges more strict than COP15. On the demand side, Energy Efficiency implementation appears as the only lever in mature countries to achieve COP15 variant pledges, whereas a competition with cleaner generation technologies is pointed out according to the stringency of the pledge adopted by China.

Introduction

With the rise of energy prices and the development of carbon markets, Energy Efficiency and carbon emissions are two key decision variables for industrial actors. Those two variables are closely related, but the following question remains open: Does Energy Efficiency consist in the best allocation to reduce carbon emissions? This is not a general rule: if we consider, for instance, a nuclear power plant, it has a low carbon footprint but can be poorly efficient. The future development of Carbon Capture and Sequestration (CCS) technology will break even more this correlation. Thus, carbon management and energy efficiency management are different business models. The goal of this study is to evaluate the arbitrage between carbon management and energy efficiency implementation for industrial actors.

The study is organized as follow:

- In a first section the TIAM-FR model, which is a 15-region world version of the MARKAL/TIMES model family, is described. It is a bottom-up "Energy – Environment – Economy"-dedicated model which optimizes energy systems under constraints by using a partial equilibrium. This model is used for mid-term to long-term energy and carbon prospective (Loulou and Labriet, 2007; Loulou and Labriet, 2005).
- In order to compare energy efficiency and carbon policies, an extension giving access for each energy vector to:
  - the primary equivalent and carbon content, along with
  - their evolution through time for each region,

  is implemented.
- Primary equivalent and carbon content of commodities will depend on various parameters (climate policies, processes availability, costs of technologies, demands, etc.). Attention

is paid on the definition of variant scenarios based on the COP15 pledges.

- Results are finally inspected in order to assess the arbitrage between energy efficiency and carbon management.

The TIMES formalism for energy modelling

With the research on energy modeling thriving, many different visions emerged, embodied in dozens of different modeling paradigms. They are often categorized in two major families, namely "bottom-up" and "top-down" models.

- **The "top-down" models** are said to be "economy-rich", and use economy and econometrics theory to derive evolution scenarios from a general equilibrium along with a set of macro- and microeconomics indicators (GDP, energy intensity, demography, growth effects, etc.);
- **The "bottom-up" models** are technology-rich models building general tendencies by piling up extremely disaggregated technology data (energy prices, investment costs, technology specific efficiencies), thus acting in a bottom-up way;
- **The IAM** (Integrated Assessment Models), which combine a top-down or bottom-up module with a climate or impact evaluation module, are a more all-inclusive (but often less precise) way to look at the problem.

The TIMES (The MarkAl-EFOM Integrated System) paradigm is a bottom-up representation, relying on highly disaggregated technology-rich data. It inherits the characteristics of two former modelling paradigms (MarkAl and EFOM), which had been developed from the early 80s to 2005 by the Energy Technology Systems Analysis Programme (ETSAP, 2007) under the aegis of International Energy Agency (IEA, 2006).

The analyses carried out in this work are derived from the ETSAP/TIAM-FR (the French version of the TIMES Integrated Assessment Model) bottom-up model developed by the Centre of Applied Mathematics of MINES ParisTech.

THE ETSAP TIMES INTEGRATED ASSESSMENT MODEL

TIAM-FR depicts the world energy system with a detailed description of different energy forms, resources, processes/technologies and end-uses. The link between the commodities and the technologies is described via a Reference Energy System (Figure 1). More precisely, the RES is a network of interlinked commodities (an energy form, an emission, a material, or an energy service) and technologies (anything that produces and/or consumes commodities).

The main features are given below (Loulou and Labriet, 2007):

- TIAM-FR includes several thousand technologies in all sectors of the energy system (energy procurement, conversion, processing, transmission, and end-uses). The description of the technologies includes data on investment and operation costs, efficiencies and, sometimes, market potentials. Figure 2 gives a synthetic description of the RES covering the whole energy chain. In order to satisfy the demands, energy sources are extracted and in series number of steps, transformed into the end-use demand commodities.
- In TIAM-FR, end-use demands (*i.e.* energy services) are based on socio-economic assumptions and are specified exogenously by the user in physical units (number of houses, commercial area, industrial production, vehicle-kilometers, etc.) over the planning horizon. However, contrary to traditional bottom-up models, TIAM acknowledges that demands are elastic to their own prices. This feature insures the endogenous variation of the demands in constrained runs (on emission or concentrations), thus capturing the vast majority of the macroeconomic feedback of the energy system. Thereby, the energy consumption in TIAM-FR is based on external projections of the growth of regional GDP as well as population and volume of various economic sectors (transport, residential, industry, etc.). These drivers and IEA statistics for a given base year – in this case 2000 – are the basis for future projections of the consumption of different energy such as road passenger transportation, steel demand, residential heating, etc.
- TIAM-FR is a global multiregional model. It is geographically integrated and offers a representation of the global energy system in 15 regions covering the entire world: Africa, Australia-New Zealand, Canada, China (includes Hong Kong, excludes Chinese Taipei), Central and South America, Eastern Europe, Former Soviet Union (includes the Baltic states), India, Japan, Mexico, Middle-East (includes Turkey), Other Developing Asia (includes Chinese Taipei and Pacific Islands), South Korea, United States of America and Western Europe (EU-15, Iceland, Malta, Norway and Switzerland). The regions are linked by energy, material, and emission permit trading variables, if desired. The trade variables transform the set of regional modules into a single multiregional (possibly global) energy model, where actions taken in one region may affect all other regions. This feature is essential when global as well as regional energy and emission policies are simulated.
- The model also consists of a number of other elements, such as user-defined constraints, *e.g.* on emission or technology limitation and a climate module (Loulou and Labriet, 2005).

TIAM-FR is the global multiregional version of the TIMES model generator, a linear programming model that estimates an inter-temporal partial economic equilibrium on integrated energy markets. The model assumes perfect markets and unlimited foresight for the calculation period, the described economic sectors, and commodities. In other words, the model minimizes, under environmental and technical constraints, the total discounted cost of the energy system over the whole studied time horizon, typically 2000-2100. Cost of the energy system includes investment costs, operation and maintenance costs, costs of imported fuels, incomes of exported fuels, the residual value of technologies at the end of the horizon, and welfare loss due to endogenous demand reductions. The model computes both the flows of commodities (energy forms, materials, and environmental), as well as their prices. The prices of the commodities are computed in such that at the prices computed by the model, the suppliers of energy produce exactly the

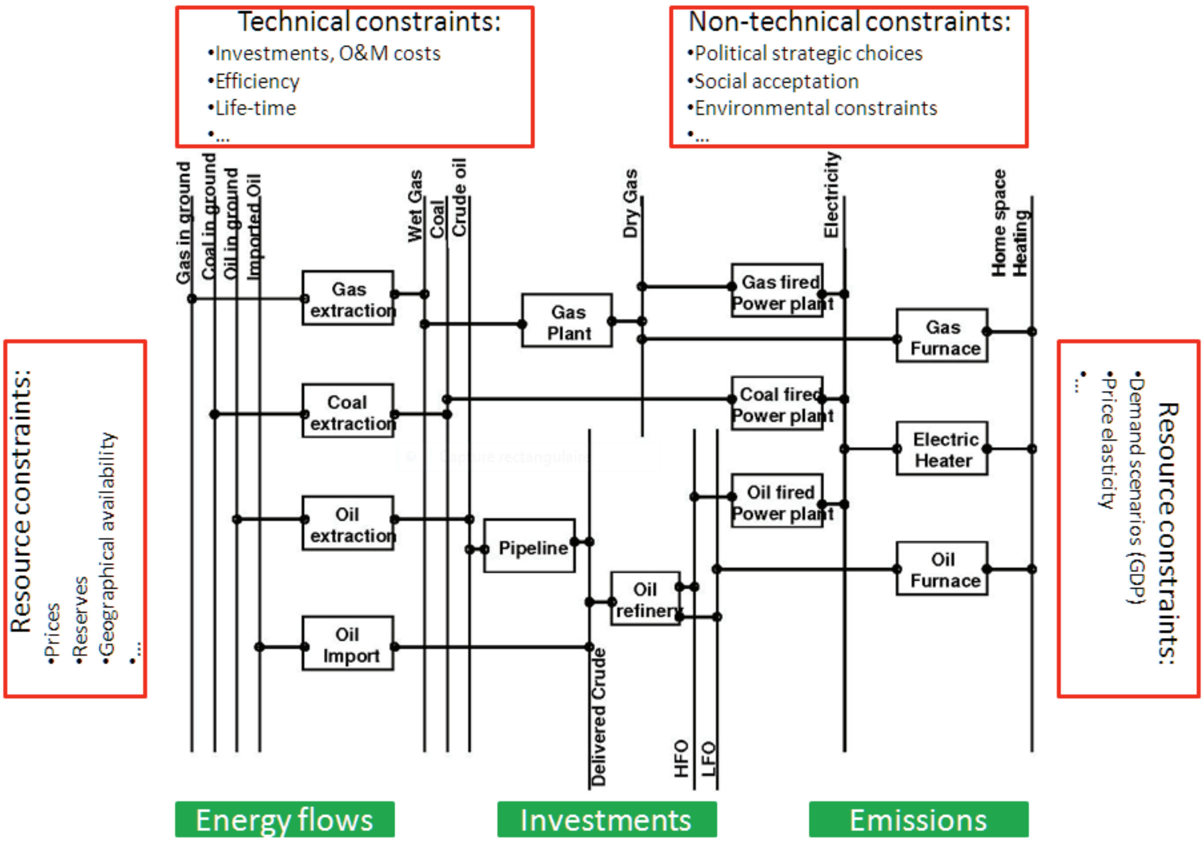

Figure 1. Simplified view of the Reference Energy System within the TIMES formalism framework:

- *In the middle, a simplified topology of the Reference Energy System for one demand, respecting the representation codes used by TIMES modelers: the vertical lines are the energy carriers (commodities), and the boxes are the technologies (processes in the TIMES language). Each process is described by its investment, operation and maintenance costs, its life, and its efficiency, thus defining a linear relationship between its inputs and its outputs.*
- *In red boxes, the other constraints that the user must provide to complete the model;*
- *In green, the outputs of the calculations.*

See Figure 2 for a synthetic representation of the Reference Energy System.

amounts that the consumers are willing to buy. The equilibrium feature is present at every stage of the energy system: primary energy forms, secondary energy forms, and energy services. TIAM-FR aims to supply energy services at minimum global cost by simultaneously making decisions on equipment investment, equipment operation, primary energy supply, and energy trade.

The main outputs of the model are future investments and activities of technologies for each time period. Furthermore, the structure of the energy system is given as an output, *i.e.* type and capacity of the energy technologies, energy consumption by fuel, emissions, energy trade flows between regions, transport capacities, a detailed energy system costs, and marginal costs of environmental measures as GHG reduction targets. The model tracks emissions of CO_2, CH_4, and N_2O from fuel combustion and processes. Emission reduction is brought about by endogenous demand reductions, technology and fuel substitutions (leading to efficiency improvements and process changes in all sectors), carbon sequestration (including CO_2 capture at the power plant and hydrogen plant level, sequestration by forests, and storage in oil/gas fields, oceans, aquifers, etc.) An additional output of the model is the implicit price, or opportunity cost (shadow price), of each energy form, material and emission.

ENERGY EFFICIENCY MODELLING IN TIAM-FR

Generally, the percentage of Energy Efficiency is an input in energy models, used for assessing its impact on the energy and climate system. Aiming to consider arbitrage between Energy Efficiency and other Carbon abatement solutions especially at the demand side (Renewables, Nuclear, Carbon Capture and Sequestration, Cleaner conventional power plants …), the optimal Energy Efficiency percentage need to be derived as an output of the model.

The basic idea would be to represent an Energy Efficiency technology as an energy service amplifier, *i.e.* $\eta>1$ (Figure 3), and modify the Reference Energy System (Figure 2) according to its technical and economical characteristics.

However, the huge list of Energy Efficiency-dedicated technologies involved in the industry sector – and their use of multiple commodities – could provide significant changes in the

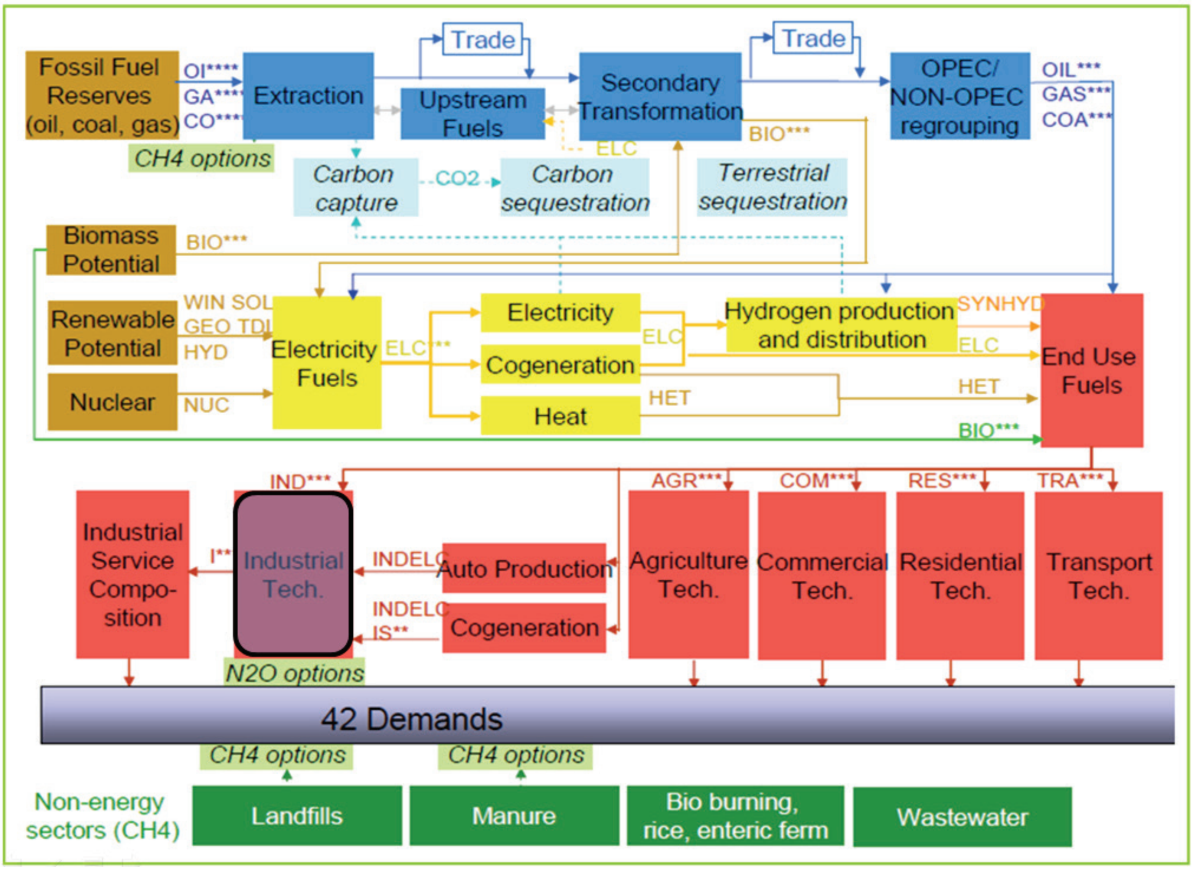

Figure 2. Global Reference Energy System, including more than:

- *3,000 technologies;*
- *500 commodities;*
- *15 regional areas.*

The shadowed box denotes the altered part in order to implement Energy Efficiency potentials in the industry sector (see Figure 3).

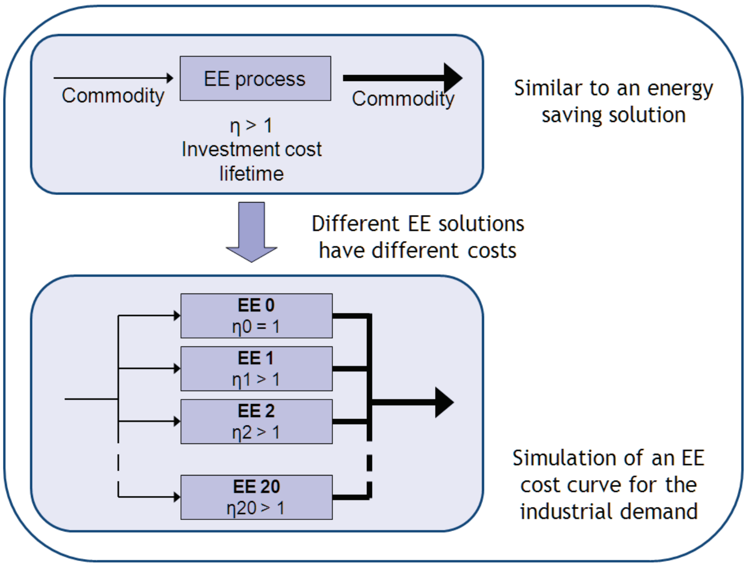

Figure 3. Energy Efficiency disaggregation for the industry sector.

- *Above: classical Energy Efficiency technology connecting input and output commodities;*
- *Below: disaggregation of the Energy Efficiency potential in several steps. Cost curves are given in Figure 4.*

Note that the system has the possibility not to implement Energy Efficiency solution (η0=1) in order to compete with other clean(er) generation technologies.

topology of the RES. The task of describing all of them appears to be huge, cumbersome and endless. Moreover, due to the lack of a homogeneous set of data or the risk of double-counting, this approach could lead to a distorted model.

However, the purpose of this work is not to provide a sectorial roadmap for short-term implementation of Energy Efficiency solutions in industry, but to challenge the link between energy efficiency and carbon emission mitigation.

Hence, a cost/efficiency approach has been adopted (Figure 3). It consists in disaggregating the energy efficiency potential in several steps (here refined to 20) with the following basics (Figure 4):

- Each potential of Energy Efficiency checks a saturation cap opening the possibility to implement the next level;
- The residual potentials of Energy Efficiency are more expensive than the first steps. In other words, countries involved for a long time in EE policies should implement more capital-intensive solutions.

As a result, the cost curves were calibrated for different regions, according to their maturity in experiencing energy efficiency, and exponential step-wise cost curves were adopted. With this aggregated implementation of Energy Efficiency, the model has the possibility to determine the most cost-effective allocation of Energy Efficiency processes (*i.e.* the optimal percentage for a given region, a given sector and a given year) in a competition with other clean(er) technologies, especially on the supply-side, in order to achieve carbon mitigation pledges.

Climatic scenarios for 2020–2030

The international community appears to converge on its long-term objectives, particularly to reduce GHG emissions by 80 % in 2050, compared to 1990 or 2005 depending the reference year adopted by the regions (Remme and Blesl, 2008; Syri at al., 2008). In the mid-term, international negotiations occurring within the Conference of the Parties (COP) under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC), try to set up targets. The last attempt to fix global objectives occurred in the Copenhagen Conference (COP15 in 2009).

A key feature of the post-Kyoto agreement was the participation of non-Annex-1 countries, especially China, and United States as they represent a large share of global CO_2 emissions (Den Elzen and Höhne, 2008). Various kinds of pledges were expressed in COP15:

- While Europe and Japan pledge for a CO_2 emission mitigation of respectively 20 % and 25 % to 2020, compared to 1990 level, other regions consider 2005 as reference year.
- A more pessimistic view was expressed by United States due to their late acceptation of a global mitigation process. Australia and Canada are expected to align themselves with the US commitment.
- For China, the commitment is not on the emission level but on the carbon intensity. This means that China's GDP will pursue its rise but carbon emissions will have to increase at a lower rate due to greater energy efficiency and investment in greener technologies.

An important and well-known observation to note concerns the choice of reference year. This induces of course an important impact on the target to reach. More precisely, if these pledges are translated on the same reference year, it means (Selosse et al., 2010):

- For China, reducing CO_2 by 40 % to 2020 (resp. 80 % to 2050) its carbon intensity compared to 2005 level is equivalent to limiting the increase of its CO_2 emission at 292 % in 2020 (resp. 485 % to 2050) compared to 1990 level for its COP15 pledge. Conversely, a pledge aiming to reduce its CO_2 emission level by 10 % to 2020 compared to 2005 level is equivalent to limit the increase of its CO_2 emission

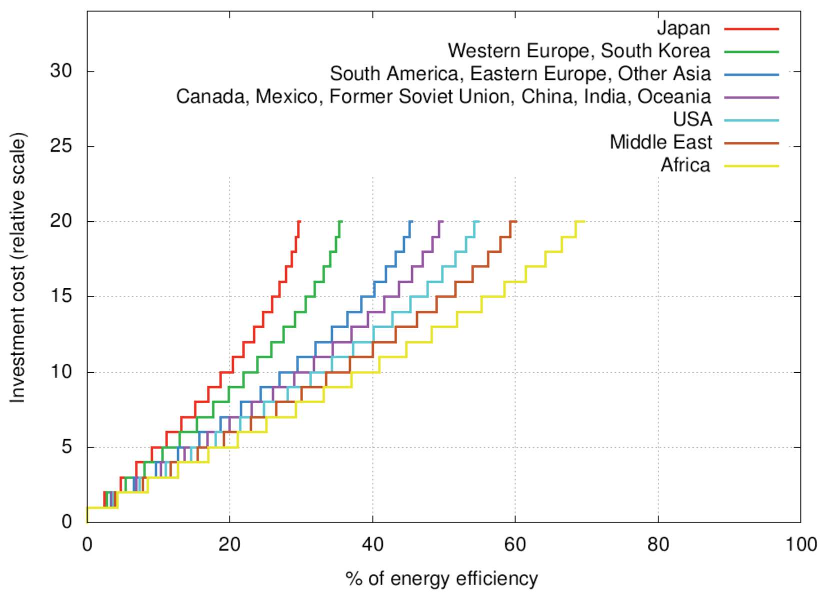

Figure 4. Regional Costs vs. Energy Efficiency potentials (relative scale).

Table 1. COP15 pledges.

Region	Reference year	COP15 targets		Post-COP15 targets	
		2020	2050	2020	2050
Australia	2005	No	No	34 %	80 %
Canada	2005	No	No	34 %	80 %
China	2005	40 % on carbon intensity	80 % on carbon intensity	60 % on carbon intensity	80 % on carbon intensity
Japan	1990	25 %	80 %	25 %	80 %
United States	2005	17 %	80 %	34 %	80 %
Western Europe	1990	20 %	80 %	30 %	80 %

Table 2. Carbon constraints scenarios centered on the COP15 pledges.

Reduction pledge (with reference year)	Europe	USA	China
COP15 – 80 %	more constrained by 20 % than the COP15 scenario		
COP15 – 85 %	more constrained by 15 % than the COP15 scenario		
COP15 – 90 %	more constrained by 10 % than the COP15 scenario		
COP15 – 95 %	more constrained by 5 % than the COP15 scenario		
COP15	20 % of emissions (1990)	17 % of emissions (2005)	40 % of Carbon intensity (2005)
COP15 – 105 %	less constrained by 5 % than the COP15 scenario		
COP15 – 110 %	less constrained by 10 % than the COP15 scenario		
COP15 – 115 %	less constrained by 15 % than the COP15 scenario		
COP15 – 120 %	less constrained by 20 % than the COP15 scenario		
COP15 – 125 %	less constrained by 25 % than the COP15 scenario		
COP15 – 130 %	less constrained by 30 % than the COP15 scenario		
Business As Usual	/	/	/

at 109 % in 2020 compared to 1990 level. Therefore, due to wide variation in GDP projections, it is obvious that China cannot reasonably pledge neither an emission reduction, nor 1990 as a base year. Indeed, the annual average growth rate of the China GDP for the period 2000–2050 is 6.37 %, with a GDP which reaches US$30,000 billion in 2050.

- For the United States, reducing its CO_2 emission by 17 % to 2020 (resp. 80 % to 2050) compared to 2005 levels, is equivalent to reducing by 0.33 % to 2020 (resp. 76 % to 2050) its CO_2 emission compared to 1990 level. So, it appears clearly the lesser effort committed by United States in the mid-term, notably compared to the European Union, whereas they have emitted a larger share of CO_2 emissions. In other words, the United States are unlikely willing to pledge on a constrained short-term target, while they have ratified the agreement.

So, through the different targets, the level of commitments announced by the regions, particularly the lesser efforts of China and United States can be underlined.

To analyze possible alternative development paths of the system, a variety of environmental target scenarios on different regions of the world over the period 2000–2030 was investigated.

A baseline Business As Usual (BAU) scenario without any emission constraints was first calculated. In the reference scenario, no climate policy and thus no post-Kyoto policy are assumed. The BAU scenario outlined some key patterns in the evolution of the energy system, and served as the starting point for the analysis. Besides, eleven Carbon constraints scenarios centered on the COP15 pledges (Table 2), allowed investigating the changes induced by stronger environmental policy, and determining the sensitivity of the implementation of Energy Efficiency solutions within a competition with other abatement technologies.

In the following, the impact of these environmental measures on the energy system is analyzed for the three regions: Western Europe, USA and China.

Results

The variant scenarios are used to discuss the level of implementation of Energy Efficiency solutions in the industry sector under the climate-dedicated commitment. Both sectorial analysis and global investment to consider on the horizon are studied for the three studied regions. To analyze the influence of the climatic constraint on the generation mix, the competition with the supply side is then investigated. A focus on the Carbon Capture and Sequestration (CCS) technology is finally given, as an example of decarbonized technology.

SENSITIVITY OF ENERGY EFFICIENCY POLICIES TO COP15 PLEDGES

A first set of graphs (Figure 5) represent the percentage of EE in 2020 in different industry sectors for different climate scenarios. Besides a lack of Energy Efficiency implementation within the BAU scenario:

- Energy Efficiency is increasingly used as carbon emissions becomes more constrained; but
- The development of Energy Efficiency solutions is more sensitive to carbon abatement pledges in the USA and Europe than in China.

This behaviour is also observed in term of cumulated energy efficiency market for the period 2010–2020 (Figure 6). Obviously, this trend is due to the lesser ambitious indicator on Carbon intensity adopted by the China. However, although Energy Efficiency solutions remain a powerful lever to reduce CO_2 emissions in the industry sector, high-valued steps of Energy Efficiency (Figure 4) appear less cost-effective in China than cleaner generation units for highly constrained scenarios. In other word, China provides opportunities to challenge supply- and demand-sides within the same carbon abatement framework. Conversely, for mature economical countries, the opportunity to implement generation capacities is very weak, and Energy Efficiency remains the only vector to achieve CO_2 emission mitigation.

POWER GENERATION MIX

As a general result, constraints on carbon emissions have a limited effect on the global generation level, compared to the BAU scenario (Figure 7). However, the structure of the energy mix is changed for pledges more strict than COP15, whereas a weak sensitivity is observed for lower constrained scenarios:

- In China, the BAU structure is kept till COP15 pledge. Hence, coal is partially replaced by gas for stronger constraints on emissions;
- In USA, the share of coal is progressively substituted by gas, nuke or renewable, from 40 % for COP15 pledge to 20 % for the strongest investigated scenario;
- In Europe, a coal substitution by nuclear, gas and geothermy is noticed; and a coal phase-out is observed for the COP15-80 % pledge.

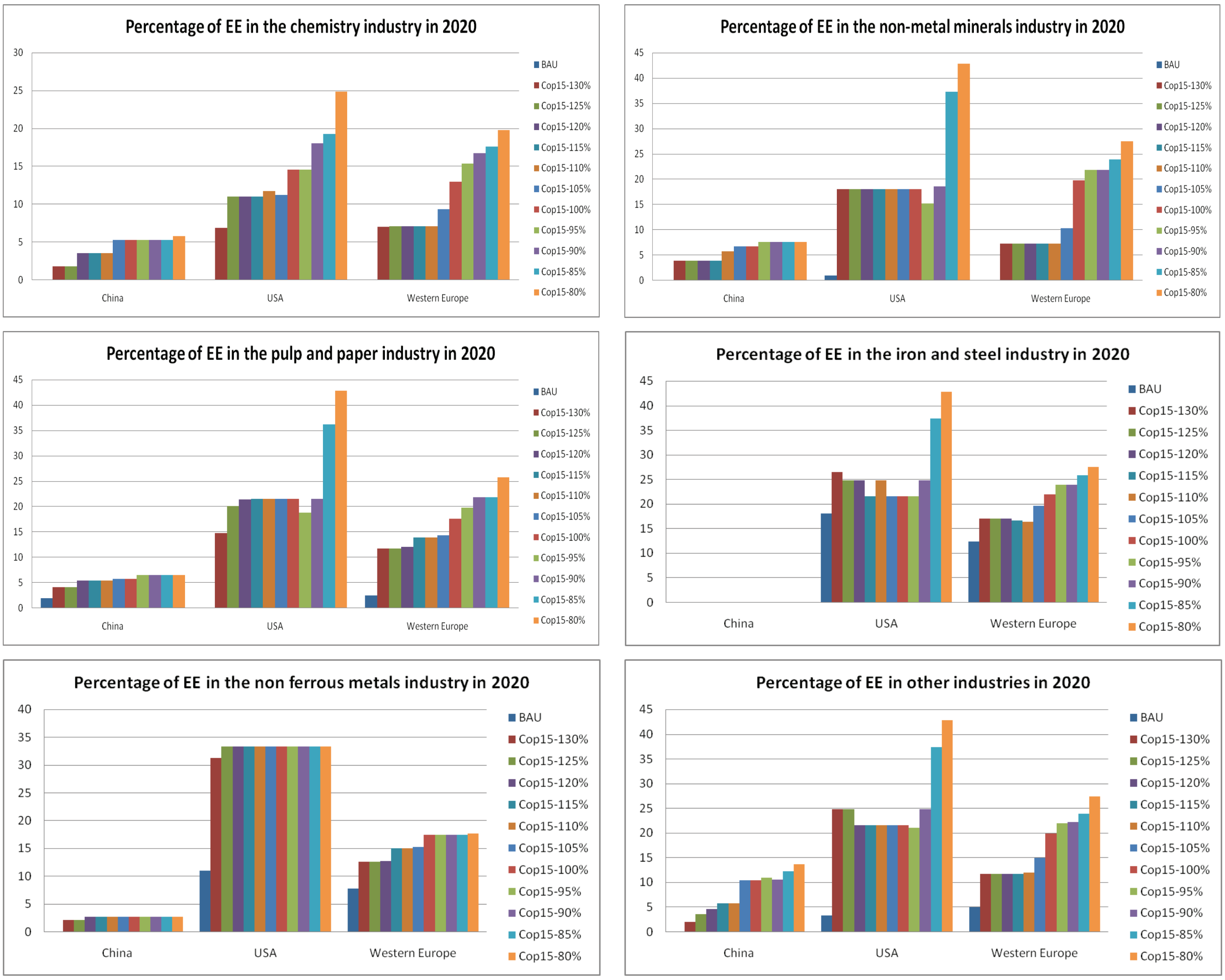

Figure 5. Sectorial sensitivity of Energy efficiency levels to COP15 pledges.

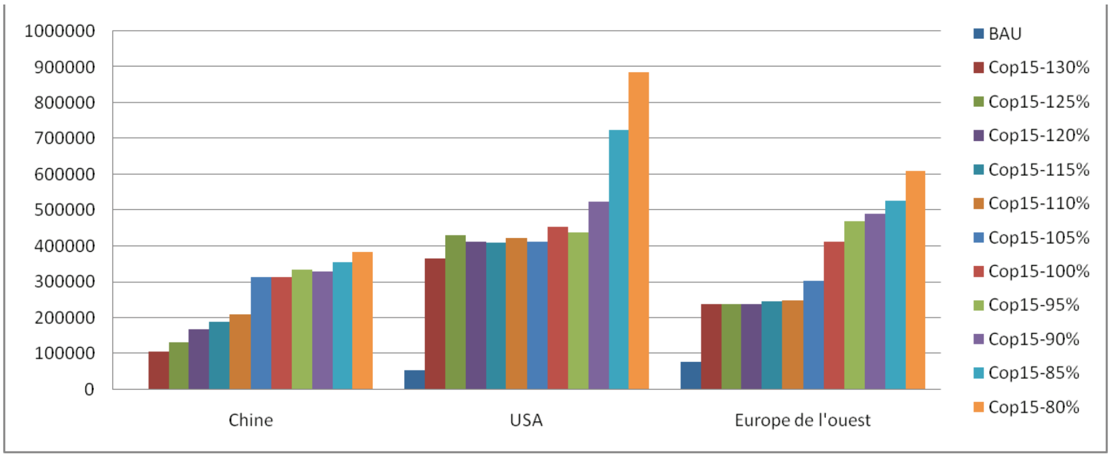

Figure 6. Sensitivity of the Energy Efficiency market to COP15 pledges. Cumulated investment over the horizon 2010–2020 in Million USD.

CARBON CAPTURE AND SEQUESTRATION IMPLEMENTATION

As is presented in Figure 8, only more constrained pledges than COP15 lead to significant level of Carbon Capture and sequestration technologies. Even though CCS appears as a long term solution, its significantly higher level and earlier implementation in Europe reflects the saturation of Energy Efficiency potentials, subsequent to a longer implementation in the past, and a more ambitious commitment. Conversely, CCS implementation is a marker of the stringency of the climate policy, following the exhaustion of the Energy Efficiency potential.

Conclusion

The implementation of the Energy Efficiency concept in the TIAM-FR energy model makes it possible to determine the optimal Energy Efficiency allocation for each region, each industrial sector and each year. To our knowledge, it is the first time an aggregated approach of EE is deployed in an optimization energy model within this methodology (Figure 4).

Because Energy Efficiency plays an important role in the fight against climate change, this promising approach is of key importance when studying the arbitrage between carbon abatement solutions.

In order to improve the relevance and the reliability of our model, further calibration work is probably necessary, especially to derive cost curves, and the approach deserves to include other sectors like transport, residential, commercial, agriculture, oil & gas and electricity.

Let us note that the quite high investment levels in Energy Efficiency displayed by the model represent optimal economic potential, without any restrictions on the speed of the market penetration (industrial deployment, investment mechanism) or government incentives (subsidies, taxes …). This should be also considered to influence a global Energy Efficiency policy.

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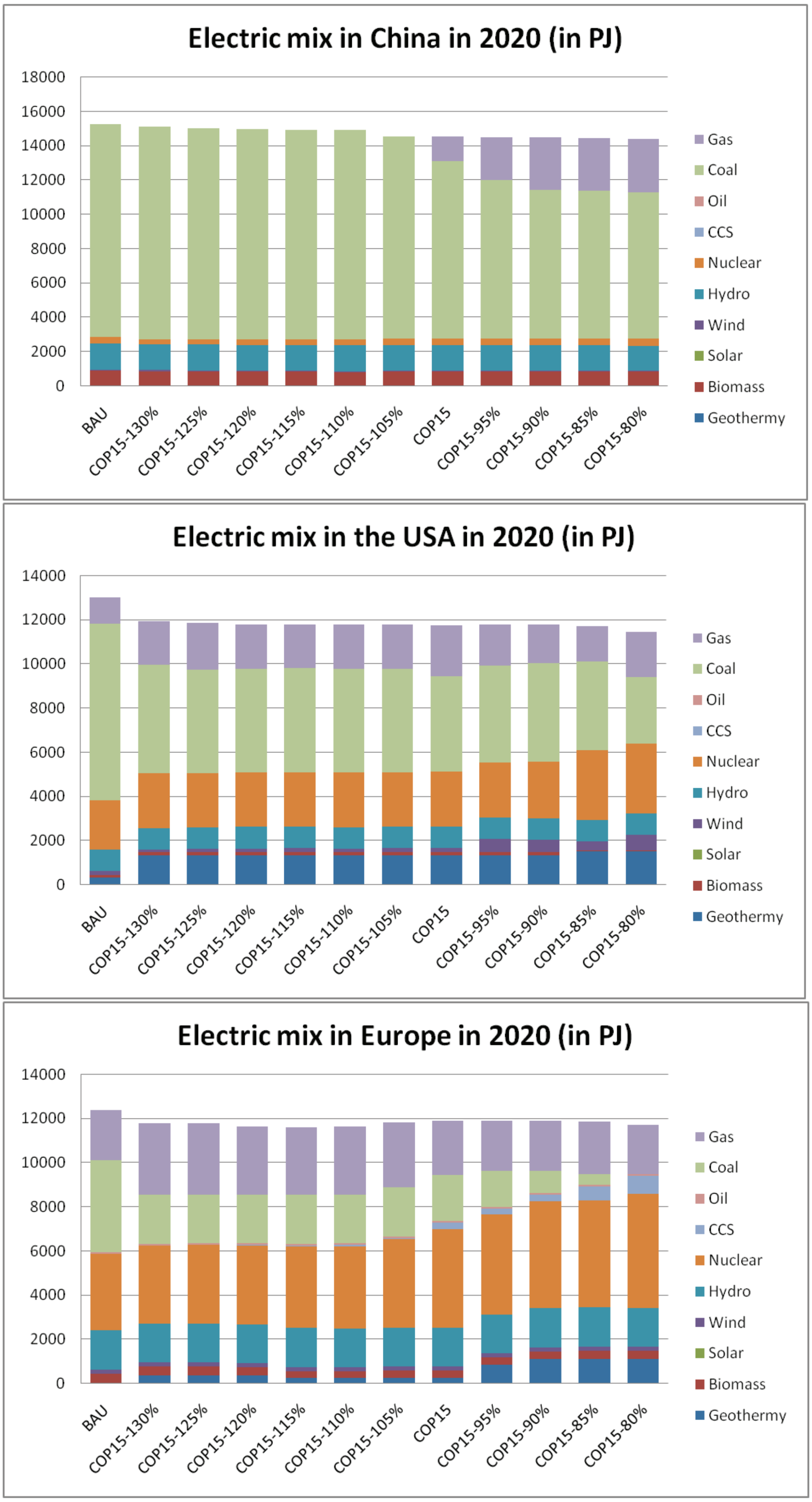

Figure 7. Power generation mix.

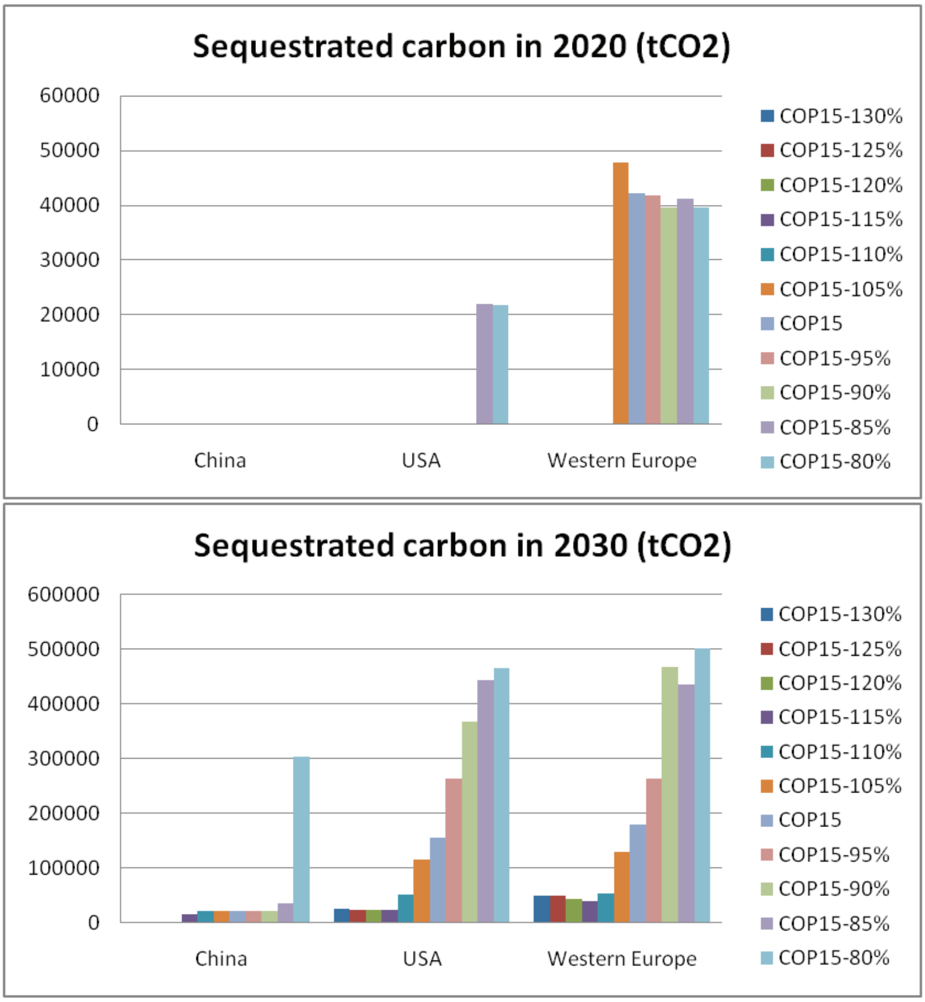

Figure 8. Carbon Capture and Sequestration technology implementation. Notice the cumulated level in 2030 is ten times higher than in 2020.