Will climate policy improve European energy security?

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Introduction

Energy security and climate policy are strange bedfellows. Energy security concerns were one of the main motivations of the G7 in 1990, held in Houston, the United States energy capital, and hosted by George H. Bush, for putting a Climate Convention on the international agenda (Kirton, 2007). At that time, there was a hope that climate change could be used to convince the American public to accept the discipline necessary to reduce oil dependence (Schlesinger, 1989). As a trick of history, energy security has experienced a recent revival of interest, triggered by high oil prices but also linked to the difficulties in establishing an international climate architecture. The hope now is that some support to climate policies would be won by invoking their co-benefits in terms of energy security.

In one way or the other, energy security and climate policy are thus frequently presented as two aspects of the same issue. Tony Blair declared in a speech in the United States on October 20, 2006 that "*we must treat energy security and climate security as two sides of the same coin*" — which has become a frequently repeated refrain. EU is especially involved in such an approach treating climate policy and energy security jointly: both the Climate and Energy Package (EU, 2007) and the Energy Roadmap 2050 (EU, 2011) endorse the goals of reducing greenhouse gases emissions while at the same time ensuring security of energy supply.

But are climate policy and energy security actually two sides of the same coin? They undeniably share a common root cause - the humanity increasing demand for energy. But the solutions to improving energy security and reducing greenhouse gases are not necessarily the same, and may imply synergies or trade-offs. For example, energy efficiency and renewable technologies have been recognized as options to promote both goals simultaneously (EC, 2001). On the contrary, limiting coal use to reduce CO_2 emissions could have negative impacts on the energy security of the many countries that have abundant coal reserves. Similarly, restricting the uptake of emission-intensive unconventional oil would increase the world's dependence on oil from the Middle East (Hartley, 2008). Therefore it is not obvious whether climate policies would improve energy security or not, and this issue deserves a close scrutiny.

The aim of this paper is to propose a methdology to investigate whether climate policies improve energy security or not. It also provides some insights resulting from the application of this methodology, focusing on the European case.

The article first reviews the small but growing literature examining the links between climate policies and energy security (Section 1.1). This literature gives evidences of both synergies and trade-offs between climate policies and energy security. But the differing results in the existing studies seem to primarily come from differing indicators chosen to measure energy security. This difficulty calls for an examination of the definition of energy security and of indicators to measure this concept, which is done in Section 1.2. This section builds on the literature exploring the concept of energy security to identify the various dimensions involved in this polysemic concept, and to develop a set of indicators to measure these dimensions.

A second difficulty arises when studying the effect of climate policy on energy security due to pervasive uncertainties on the determinants of the energy systems' future evolutions — for instance population and economic growth, costs and potential of technologies such as electric vehicles, renewable energies or synthetic fuels and energy-services consumption behaviours. This difficulty calls for an investigation of the uncertainty space to test the robustness or sensitivity of the results. Section 1.3 describes a methodology to build a large database of scenarios exploring the uncertainty space with an energy-economy-environment model, IMACLIM-R, to account for this second difficulty.

In the second section, the set of indicators developed is used to analyze the database of scenarios, focusing on Europe. It shows that the effect of climate policy on energy security indicators is very different depending on the time horizon considered. It also shows that there is no case of improvement of all energy security indicators, traded-offs are always involved.

1 Context and Methodology

1.1 Literature review

There is a small but growing literature examining the issue of the links between climate policies and energy security. Evidences of both synergies and trade-offs are given.

On the synergy side, Rozenberg et al. (2010) show that climate policies reduce the world vulnerability to peak oil (measured as the difference between the discounted summed Gross World Product between two scenarios with more or less oil scarcity). Climate policies, therefore, appear as a hedging strategy against the uncertainty on oil resources, in addition to their main aim of avoiding dangerous climate change. Similarly, Maisonnave et al. (2012) conclude that unilateral EU climate policy offers a protection against oil price rise (measured by lower GDP losses inferred by an exogenous scenario of oil price rise in the case when climate policies are implemented than in the absence of climate policy).

On the trade-offs side, Kuik (2003) shows that there is a trade-off between economic efficiency of climate policies and energy security for the EU.

Other studies highlight synergies for some cases, and trade-offs in others. For instance, Turton and Barreto (2006) conclude that stringent climate policies offer synergies with respect to security of oil supply (measured by the resource to consumption ratio), but trade-offs with respect to security of gas supply. IEA (2007) choses two indicators for energy security: a measure of the market concentration in each international fossil fuel market weighed by the exposure of the country considered to each fuel (ESIprice), and a country's share of total energy demand met by oil-indexed, pipe-based gas imports (ESIvolume). Its analysis shows that different measures aimed at reducing CO_2 emissions can have either positive or negative impacts on these two indicators. For instance, end-use efficiency improvements have positive impacts on both indicators, while switching to boifuels in transport improves the ESIprice indicator but worsens the ESIvolume indicator. Brown and Huntington (2008) acknowledge that complementarity between CO_2 emissions reduction and energy security improvement exists at the level of individual technologies, but trade-off arise when selecting the mix of technologies to pursue both goals. Optimal policy could result in the adoption of a suite of technologies in which each contributes more to a single policy objective than to the heavy reliance on a few technologies, each of which contributes to both objectives. van Vliet et al. (2012) shows that in stringent climate change mitigation scenarios, the diversity of the primary energy supply mix increases in the emerging Asian regions, while the effect on the imported share of total primary energy supply depends on the region (it increases in Centrally Planned Asia, mainly China, and decreases in South Asia, dominated by India).

This brief literature review highlights a difficulty in answering the question of the impact of climate policy on energy security due to a lack of clarity and commun understanding of the definition of energy security and of indicators to measure this concept. Indeed, the differing results in the aforementionned studies seem to primarily come from differing measure choices. This difficulty calls for an examination of the definition of energy security and of indicators to measure this concept.

1.2 Indicators to measure energy security

If energy security is high on the policy agenda and pervasive in the discourse, it is seldom accompanied by a clear definition of the notion or a discussion how to measure it.

A broad definition of energy security can be given by the negative, i.e. by defining its opposite: energy insecurity. Energy insecurity is the risk of welfare impact of either the physical unavailability of energy, or prices that are unaffordable or overly volatile (IEA, 2007). Energy security is about limiting this risk. Short-term energy security considers risks of energy supply disruption ue to strikes, extreme climate events, accidents, political unrest, etc., while long-term energy security considers risks due to the depletion of fossil fuels and the unequal distribution of resources in the world. We focus in this article on long-term energy security.

Translating this broad definition into operational ways to measure energy security is a difficult endeavour. But without clear measures, the analyze of the concept is bound to be vague and blurr. Three recent contributions — Sovacool and Brown (2010); Kruyt et al. (2009); Chester (2010) — have advanced significantly in this endeavour. All three emphasize the polysemic nature of the energy security concept, and all three propose a 4-dimensional grid of analysis. Two dimensions are common to the three contributions: the availability axis and the affordability axis. The availability axis regroups elements relating to the physical or geological existence of energy. The affordability axis includes the elements of costs for energy consumers. The other two dimensions differ between the three studies, but can be grouped into acceptability and sustainability on one side, and accessiblity, dependency and diversity on the other side. The acceptability and sustainability axis regoups the elements on the environmental impacts and societal acceptability of energy extraction and transformation technologies. The last axis refers to elements measuring an economy's dependency on energy. Due to the spatial discrepancy between the extraction and consumption of energy, these elements encompass measures of the accessibity of energy to an economy and the diversity of an economy's energy sources.

Table 1 summarizes these four dimensions of the energy security concept, and gives a selection of indicators to measure them that will be used in this article. The indicators are chosen such that an increase (respectively

Table 1: Axes of the energy security concept and a selection of corresponding indicators to measure them

Axes of the energy security concept	Selection of indicators
Availability	Production/Resource (oil)
Accessibility/Dependence and Diversity	TPES/GDP Imports/TPES Diversity of imports (oil)
Affordability	Households energy budget Energy import bill/GDP
Sustainability and Acceptability	Carbon content of TPES Installed nuclear capacity

decrease) of their value indicates a worsening (respectively improvement) of the dimension of energy security they measure. For the availability dimension, we focus on oil, and propose to use the production over resources ratio. For the dependence dimension, the energy intensity of GDP (the ratio of Total Primary Energy Supply (TPES) over GDP) measures the dependance of the economy on energy, and the share of imports in TPES measures the dependence of the energy supply on imports. The diversity of oil imports adds an element of diversity in the second dimension of energy security. It is measured by the Herfindahl-Hirschmann index, calculated as the sum of squared market shares of oil producers. For the affordability dimension, instead of the absolute prices of energy types (that do not account for the fact that some energy types might become expensive over time but also less used), we focus on the share of households' consumption budget devoted to energy and the energy import bill as a share of GDP. In the sustainability and acceptability dimension, two indicators are chosen: the carbon content of TPES and the installed nuclear capacity.

This selection of indicators rests necessarily on a number of arbitrary choices, and many other indicators are proposed in the literature and could be relevant. The selection presented here results in a trade-off to propose (i) a limited number of indicators, (ii) a variety of indicators covering the four axes of the energy security concept, (iii) indicators that can be calculated with the modeling results we will use in this article.

1.3 Building a scenarios database

1.3.1 The IMACLIM-R model

IMACLIM-R is a hybrid simulation model of the world economy (Rozenberg et al., 2010; Waisman et al., in press) which represents in a consistent framework the macro-economic and technological world evolutions. It is disaggregated into 12 regions and 12 sectors, including 5 energy sectors: coal, oil, gas, refined products and electricity. It is calibrated on the 2001 base year by modifying the input-output tables provided by the GTAP-6 dataset (Dimaranan and McDougall, 2006) to make them fully compatible with 2001 IEA energy balances (in Mtoe) and data on passengers' mobility (in passenger-km) from Schafer and Victor (2000). The model was tested against historic data up to 2006 (Guivarch et al., 2009) and covers the period 2001-2100 in yearly steps through the recursive succession of static equilibria and dynamic modules.

The static equilibrium represents short-run macroeconomic interactions at each date t under technology and capacity constraints. It is calculated assuming Leontief production functions with fixed intermediate consumption and labor inputs, decreasing static returns caused by higher labor costs at high utilization rate of production capacities (Corrado and Mattey, 1997) and fixed mark-up in non-energy sectors. Households maximize their utility through a tradeoff between consumption goods, mobility services and residential energy uses considering fixed end-use equipments. Market clearing conditions can lead to a partial utilization of production capacities given the fixed mark-up pricing and the stickiness of labor markets. This equilibrium provides a snapshot of the economy at date t in terms of relative prices, wages, employment, production levels and trade flows.

Dynamic sub-modules are reduced forms of bottom-up models that represent the evolution of households' equipment and of productive capacities technical characteristics between t and t+1. They include technology explicit descriptions of the energy system (power generation, vehicles...) and endogenous technical change mechanisms (learning-by-doing, induced energy efficiency). As an example, the dynamic sub-modules that describes the determinants of oil markets includes lessons from partial equilibrium analyses of supply/demand adjustments on oil markets. It includes the technical constraints (including geology) on the short-term adaptability of oil supply; the influence of Middle-East countries on production decisions; technical inertias on the deployment of oil substitutes; and consumers' short-term trade-offs in a set of technical and economic conditions. A full description of these sub-modules is available in (Waisman et al., in press).

The model represents international trade between the 12 regions in both energy and non-energy goods. For each good, exports from all world regions are blended into an international variety, which is then imported by each region based on its specific terms-of-trade with it.

The competition between domestic and imported varieties of each good is settled in an aggregate manner, based on terms-of-trade measured between the price of the aggregate international variety, and the production price of the domestic good. In order to prevent the cheaper goods to systematically win market shares over the more expensive ones, it is assumed, following Armington (1969), that the domestic and imported varieties of the same good aggregate in a common quantity index, but in an imperfectly substitutable way.

This Armington specification has the major drawback of introducing aggregate volumes that do not sum up the volumes of imported and domestic varieties. While this shortcoming can be ignored for 'composite' goods, it is not compatible with the need to track energy balances expressed in real physical units. Competition between energy goods is thus settled through simplified specifications: the international market buys energy exports at different prices and sells at a single average world price to importers; shares of exporters on the international market and regional shares of domestic vs. imported energy goods depend on relative prices, export and import taxes, and market fragmentation parameters that are calibrated to reproduce the existing markets structure.

1.3.2 The scenarios database

Investigating the impact of climate policies on energy security requires building long-term scenarios for the world economy. But the potential determinants of this impact are numerous and highly uncertain. They include *inter alia* the future evolution of population, energy markets, low-carbon technologies, trade liberalization, consumption preferences and industrial policies. In order to account for the large uncertainties surrounding the potential determinants of future energy security, we build a database of scenarios combining hypotheses on a large number of model parameters, following methodology proposed by Rozenberg et al. (2012).

We briefly describe the alternatives below, and a full description of the parameters choices is available in the appendix (A).

- **Natural growth**: in the IMACLIM-R model, economic growth is endogenous but is driven by natural growth, that is the sum of population growth and labor productivity growth (Solow, 1956). We build nine combinations of population growth and labor productivity convergence in line with O'Neill et al. (2011) and the quantifications of these SSPs (Shared Socio-economic Pathways) that are being done by the OECD.[1]
- **Induced energy efficiency**: in the IMACLIM-R model, energy efficiency is driven by energy prices. We introduce three alternatives for the parameters describing its maximum annual improvement in the leading country and the catch-up speed of the others.
- **Behaviors**: We make two assumptions (i.e. two groups of hypotheses affecting many different parameters) regarding behaviors and energy sobriety:
  - Development patterns: We introduce two assumptions on the evolution of households' preferences in transportation and housing (evolution of the number of cars per capita, maximum dwelling surface per capita in developing countries) as well as on the saturation level of households' industrial goods consumption.
  - Production choices: We introduce two alternatives on the freight content of economic growth through alternative evolutions of the input-output coefficient representing the transportation requirement per unit of good produced.
- **Availability of low carbon technologies**: We build two assumptions for parameters describing the market penetration of nuclear energy, renewable resources, carbon capture and storage, and electric vehicles. These parameters include learning rates and maximum market shares throughout the simulation period.
- **Coal market and availability of coal-to-liquids**: For fossil fuel markets, we focus on the uncertainty surrounding oil substitutes. We thus build two alternatives combining hypotheses on the elasticities of coal price growth to demand changes and on the availability of coal-to-liquids (CTL).
- **Labor rigidities**: In IMACLIM-R, we represent labour market imperfections through a wage-curve that links real wage levels to the unemployment rate. For developing countries, we make two assumptions on the elasticity of this wage curve to account for the uncertainty surrounding future rigidities of their labor markets.

Combining those assumptions we build $(9 * 2 * 3 * 2 * 2 * 2 = 432)$ baseline scenarios.

The same number of climate policy scenarios are built, adding for each baseline an exogenous constraint on global CO_2 emission trajectory. The trajectory is chosen to be consistent with a stabilization of CO_2 concentration in the atmosphere at 450 ppm CO_2 : global emissions peak in 2020, and are decreased by 25% and 75% with respect to 2000 level in 2050 and 2100, respectively. As a working hypothesis, we assume an international climate regime imposing a global carbon tax (or a corresponding global cap-and-trade system) so as to reach the objective emission trajectory. If it is unrealistic that this hypothesis would be achieved in the short-term, we may assume an such an international climate regime would unfold over this century.

[1] The first quantifications are available on a IIASA database: https://secure.iiasa.ac.at/web-apps/ene/SspDb

Figure 1: Effects of climate policy on the set of energy security indicators, for Europe, at three time horizon: short-term (mean effect over 2020-2030), medium-term (mean effect over 2045-2055) and long-term (mean effect over 2085-2095). The effect is calculated as the ratio between the value of the indicator in a climate policy scenario and its value in the corresponding baseline, at the same date. The bold line materializes the average effect across scenarios; red dots correspond to the 5^{th} and 95^{th} percentile. The dashed line shows the point where the ratio would be equal to 1, i.e. where climate policies would not change the value of the energy security indicator. Results outside of this line correspond to a worsening of the energy security indicator due to climate policy, while results inside this line correspond to an improvement of the energy security indicator.

2 Results

2.1 The indicator and the time horizon matter

The result section focuses soly on results for Europe, which is one of the regions represented in the IMACLIM-R model. Figure 2.1 shows the effects, for Europe, of climate policy on the set of energy security indicators chosen at three time horizon: short-term (mean effect over 2020-2030), medium-term (mean effect over 2045-2055) and long-term (mean effect over 2085-2095). Before analysing these results, a few warnings should be given. First, it should be noted that the effect is calculted as the ratio between the value of the indicator in a climate policy scenario and its value in the corresponding baseline, at the same date. This is therefore a comparison between two future values of the indicator (the value that it would take at a given date in a world where climate policy would be implemented vs. the value that it would take at that same future date in a world with no climate policy), out of which at least one will not be realized. This makes the comparison somewhat virtual. Comparing with the value of the indicator today (instead of with the value it would take in a baseline scenario at a future date) would give a different picture. See Annex B for the time trends of energy security indicators in baseline and climate policy scenarios. Second, the axes in Figure 2.1 are not comparable, *i.e.* the variation of one indicator cannot be compared to that of another indicator (*e.g.* it would not make sense to try and compare a 20% worsening of the household energy budget with a 20% worsening of the Imports/TPES ratio).

Two striking messages emerge from Figure 2.1. First, time matters: the effects of climate policy on the set of energy security indicators is very different depending on the time horizon considered. Then, it appears that for several indicators there are trade-offs (climate policy makes some indicators worse). The short-term picture implies some trade-offs. The medium-term shows only one or two indicators that deteriorate. And on the long-term trade-offs reappear but on different indicators than in the short-term, and with large uncertainty ranges.

In more details, it can be seen that:

1. Three indicators experience in all cases and at all time horizons an improvement when climate policies are implemented: the oil Production/Resources ratio, the energy intensity of GDP and the carbon content of energy.

   This is not a surprising result. By putting a price on carbon, the climate policy triggers substitution away from carbon intensive energy sources, which reduces the carbon content of the energy mix. In particular, it triggers substitution away from oil, and also reduces economic activity in fossil-intensive (oil-intensive in particular) sectors; therefore the oil production/resources ratio is improved. The price on carbon makes energy more expensive (at least on the short-term before technical change and learning mechanisms have had time to transform the installed productive capacities and equipment), which triggers energy efficiency improvement and structural change reducing the energy intensity of GDP.

2. Two indicators are worsened by climate policy in all cases over the short and medium terms, and on average over the long-term (but with some cases of improvement over the long-term): the Imports/TPES ratio and the diversity of oil imports.

   The share of imports in European TPES is increased on the short-term because the price of carbon triggers first subsitution away from (mainly domestic) coal towards (mainly imported) gas in power generation and end-use efficiency. The substitution is towards gas mainly and less towards renewable because at low carbon prices renewable are less competitive than gas for power generation. The myopic anticipation of the carbon prices in the IMACLIM-R framework exacerbates this result. Considering perfect anticipation of future carbon prices, would moderate this result and trigger more renewable and less gas penetration on the short-term. Over the medium and long terms, the effect that dominates to explain the worsening of the Imports/TPES ratio is the fact that climate policy restricts the use of European domestic coal that happens largely in baselines (in particular for coal-to-liquids). Note that the improvement of the energy intensity of GDP always outweighs the worsening of the Imports/TPES ratio, such that the ratio of Imports over GDP is always improved by climate policy.

   Climate policy restricts the extraction of unconventional oil due to lower demand, which limits diversity of producers. This result was already mentioned in Kruyt et al. (2009).

3. One indicator, the households' energy budget, is worsened by climate policy over the short term, but improves on average over the medium and long terms, with some cases of persistant deteriation. The short-term deterioration of households' energy budget is due to higher energy prices (due to the carbon price) and inertia in adapting energy-consuming equipment stocks to these higher prices. But learning mecanisms and end-use efficiency improvements explain that the worsening is only transitory. Similarly, learning and evolution of the generation mix explain that electricity prices increases due to the carbon prices can be only transitory; therefore households' do not necessary face higher energy prices for the whole time horizon. Cases of persistant deterioration of the households' energy budget correspond to scenarios with low availability of low carbon technologies (see Annex B), such as the electric vehicle.

4. Two indicators, the energy import bill as a share of GDP and the installed nuclear capacities, follow more complex time trends, with, on average, a deterioration on the short term, then an improvement on the medium term and again a deterioration on the long term. The effect of climate polilcy on the energy import bill exhibits a large range of results across scenarios, and cases of improvement or worsening can be found at all time scales.

   The installed nuclear capacities are increased by climate policy over the short-term due to substitution effects, but decrease over the medium-term due to lower electricity demand (end-use efficiency). The effect on the long-term is more ambiguous and depends on the relative weighs of conflicting forces that tend to reduce electricity demand (end-use efficiency) on one hand but tend to increase electricity demand (deployment of electric vehicles) on the other hand, and subtitution effects between power generation technologies (fossil-powered plants, fossil-powered plants with carbon capture and storage, renewable, nuclear).

   The energy import bill as a share of GDP is a complex indicator whose variation depends on the interplay between climate policy effects on (i) energy imports volumes and structure between energy types, (ii) international energy prices, (iii) GDP (macroeconomic cost of climate policy). On the short-term climate policy increases the gas import volume and reduces the coal and oil import volumes, increases the international gas price and reduces the oil and coal international prices, and reduces GDP compared to baseline values. The effect on gas tends to dominate, which explains the increase of the energy import bill as a share of GDP on average over the short-term. On the medium term, the reduction of international energy prices (due to less demand) dominates to explain the reduction of the energy import bill. Over the long-term, the uncertainty range is very wide. The major effect is that of the assumption on coal market and coal-to-liquids availability (see Annex B). Indeed, it has two additive effects on the energy import bill, through the role of domestic coal on energy imports volumes and through the role of coal-to-liquids on liquid fuels prices. In the cases of high availability of coal and coal-to-liquid technologies, in baseline scenarios energy import volumes are moderated by the use of European domestic coal resources and liquid fuels import prices are moderated by coal-to-liquids large deployment. Climate policy restrict both, thus increases both import voumes and import prices compared to baseline situation.

2.2 Uncertainty matters

The full analysis of the effects of uncertainties on the different sets of model parameters on the results is beyond the possiblity of a single article. Annex B shows the average effect of alternative assumptions on the four groups of model parameters that matter most for the results: the assumption of induced energy efficiency, the assumption on the availability of low carbon technology, the assumption on coal market and coal-to-liquids availability, the assumption on the leader productivity growth. The study here is therefore restricted to the analyze of four notable results:

- Alternative assumptions on one set of parameters do not necessarily have a similar effect on energy security indicators through time. For instance, it can be noted that the assumption on low carbon technologies availability has conflicting effect on oil production/resources ratio over the short-term and over the medium or long-term. Low availability of low carbon technologies over the short-term forces a larger share of emissions reduction to go through economic activity reduction than in the case of high availability of low carbon technologies. More precisely, in the cases of high availability of low carbon technologies, on the short-term a large share of emissions reductions are realized in the power generation sector thanks to these technologies, while less reduction occur in the transport sector. In the cases of low availability of low carbon technology, relatively more emission reductions occur in the transport sector. Oil consumption is thus more reduced by climate policy in cases with low availability of low carbon technologies. Over the medium and long-term the effect is reversed due to larger penetration of electric vehicles in the vehicles fleets in cases of high availability of low carbon technologies.
- Alternative assumptions on one set of parameters do not either necessarily have a similar effect on all energy security indicators. For example, the assumption on coal and coal-to-liquids has conflicting effects on the carbon content of TPES and the energy intensity of GDP on one side, and on the share of imports in TPES and the energy import bill on the other side. High availability of coal and coal-to-liquids results in more energy intensive and more carbonated baselines than baselines with low availability of coal. Climate policy therefore improve more these two indicators in the case of high availability of coal. But, by restricting the use of (domestic) coal and of coal-to-liquids, climate policy also influences the share of imports in TPES and the energy import bill, in a less favorable way in cases of high availability of coal.
- The fast induced energy efficiency cases exhibit on average a negative effect compared to the slow induced energy efficiency cases for several indicators: the oil production/resources ratio, the carbon content of TPES, as well as the imports share of TPES and the energy import bill on the medium and long-terms. On the long-term, it even appears that in cases with slow induced energy efficiency these last two indicators are improved by climate policy, while they are deteriorated in cases with fast induced energy efficiency. This somehow surprising negative effect of fast induced energy efficiency can in fact be easily explained. Indeed, since climate policy is modeled with an fixed objective of emission trajectory, the faster the indiced energy efficiency (on end-uses), the less the emission reduction efforts fall on supply, hence the negative effect on indicators of energy security with respect to the supply side.
- The assumptions on natural growth (population, leader productivity growth and convergence speeds) are second order determinants in general, except in the long-term for the energy import bill indicator, as well as for the households' energy budget. This means that in general the scale of the economies does not matter so much. This result is due to positive feedbacks between the size of the economies and the possibilities of energy efficiency improvement and technical change in general (due to faster turn-over of installed productive capacities and equipement when economies are larger, and faster technical change thanks to cummulative effects such as learning mechanisms). In the long-run, the scale of the economies become important for the affordability dimension of energy security. Indeed, in baselines, larger global economies tend to resort more to unconventional oil and coal-to-liquids than smaller economies. Climate policy restrict the use of these fuels. The effect of this restriction depends of the extend of its use in baseline. In other words, it is more an issue for large economies to do without unconventional oil and coal-to-liquids.

3 Conclusion

This article proposed a methodology to investigate whether climate policy would improve energy security, accounting for the difficulties entailed by the polysemic nature of energy security concept and the large uncertainties on the determinants of the energy systems' future evolutions. To do so, it uses a set of indicators in a four-dimension grid of analysis of the energy security concept, and a database of scenarios exploring the uncertainty space.

Focusing on Europe, the results highlight two messages. First, time matters: the effect of climate policy on energy security indicators depends on the time horizon considered. Then, for several indicators there are trade-offs, *i.e.* climate policy makes some energy security indicators worse. This allows allows identifying the risks of contradiction between climate objective and energy security, and indicates when complementary policies may be necessary to reconcile the two objectives. Decision makers should recognize that energy security has several dimensions, some of which can be worsened by climate policy. Therefore policy objectives have to be defined clearly with respect to the energy security concept (which dimension/indicator the policy aims at improving), trade-offs have to be acknowledges, and accompanying measures have to be designed and implemented if trade-offs are to be moderated. In particular, our results highlight the risk of deterioration of the affordability dimension of energy security on the short-term. Targetted measures for modest households for instance should therefore be considered. Moreover, our results showed that gas plays an important role on the short-term, which risks to deteriorate the share of imports in TPES and the energy import bill in particular. This importance of gas is link to the fact that low carbon prices trigger subsitution towards gas, and not so much towards zero-carbon technologies. This has two types of policy implications. First, that might be a reason to consider complementary policies in favour of zero-carbon technologies to limit the role of gas. Second, the potential critical role of gas calls for measure to securize its supply.

Any analysis based on the use of indicators rests necessarily on a number of simplifications. This article does not depart from this rule, and obviously other indicators would also be relevant to analyze, such as the production/resources ratio and the diversity of producers for other fuels than oil, indicators measuring the diversity of TPES etc. Furthermore, the climate policy considered in this article is extremely stylized. Further research could investigate more detailed policy designs, and test different levels of climate policy ambitious. Also, the effect of unilateral climate policy on energy security could be tested. Finally, the comparison of results for other regions would bring additional insights.

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A Description of the scenario database

A.1 Natural growth drivers

The natural growth rate of the economy defines the growth rate that the economy would follow if it produced a composite good at full employment, like in standard neoclassical models developed after Solow (1956).

Equation 1 represents labor productivity growth through the decrease of unitary labor input l in each region j and at each time step t.

$$\dot{l}(t,j) = e^{-\frac{t}{\tau_1}} \cdot l(t_0,j) + \left(1 - e^{-\frac{t}{\tau_1}}\right) \cdot \left[\frac{t}{\tau_2}\left(l(t,j) - l(t,leader) + \dot{l}(t,leader)\right)\right] \tag{1}$$

In line with the SSP quantifications, we build assumptions combining hypotheses on population growth, on the leader productivity growth, and on catch-up speed for two groups of regions: high income and low income countries (see Tables 2 and 3).

	Option 1	Option 2	Option 3
leader productivity growth	low	middle	high
high income population growth	ssp_3	ssp_2	ssp_5

Table 2: Parameters options for leader growth and high income population growth. Data for population is available at https://secure.iiasa.ac.at/web-apps/ene/SspDb

	Option 1	Option 2	Option 3
low income catch-up time (τ_2 in eq. 1, in years)	300	200	150
low income population growth	ssp_3	ssp_2	ssp_5

Table 3: Parameters options for low income catch-up speed and population growth. Data for population is available at https://secure.iiasa.ac.at/web-apps/ene/SspDb

A.2 Induced energy efficiency

In each sector, the country with the lowest energy intensity is the leader and its energy efficiency is triggered by energy prices. The other countries catch-up with the leader after a delay. We build three hypotheses (see Table 4) using the following parameters: maximum annual improvement in the leader's energy efficiency, other countries' speed of convergence (% of the initial gap after 50 years) and asymptotic level of catch-up (% of the leader's energy efficiency).

A.3 Behaviors

Historically, the literature on the decoupling between energy and growth has focused on autonomous energy efficiency improvements (implicitly encompassing end-use energy efficiency and structural changes) and on the energy efficiency gap, i.e. the difference between the most energy efficient technologies available and those actually in use.

However important it may be, energy efficiency is not the only driver of energy demand. Indeed, the rate and direction of technical progress and its energy content depend, not only on the transformation of the set of available techniques, but also on the structure of households' demand. This is why IMACLIM-R endogenizes both energy efficiency strict sensu, and the structural change resulting from the interplay between consumption, technology and localization patterns. This enables us to capture the effect of non-energy determinants of energy demand, such as the prices of land and real estate, and political bargaining (set exogenously) over urban infrastructure to be represented. This endogenization of technical change is made for both stationary uses (industry and services, buildings) and non-stationnary uses (freight and passenger transportation).

For behaviors, we build two assumptions using parameters which describe (a) development patterns in transport, housing and industrial goods consumption and (b) localization patterns.

A.3.1 Development patterns

Transport

Passenger mobility needs and their modal breakdown across four travel modes (ground-based public transport, air transport, private vehicles and non-motorized modes) result from the maximization of households' utility under the assumption of constant travel time (Zahavi and Talvitie, 1980) and budget constraints. This helps to represent two crucial determinants of the demand for passenger transportation, namely the induction of mobility demand by infrastructure and the conventional rebound effect consecutive to energy efficiency gains on vehicles (A. Greening et al., 2000).

	Option 1	Option 2	Option 3
maximum annual improvement in the leader's energy efficiency (%)	1.5	0.7	1.5 for OECD countries 0.7 for other countries
other countries' speed of convergence (% of the initial gap after 50 years)	10	50	10 for OECD countries 50 for other countries
asymptotic level of catch-up (% of the leader's energy efficiency)	95	60	95 for OECD countries 60 for other countries

Table 4: Parameters options for energy efficiency

In addition to the availability of transportation infrastructure and energy efficiency, mobility needs are dependent upon agents' localization choices (Grazi et al., 2008). This is captured by differences in regional households' motorization rates, everything else being equal (income, energy prices), with dispersed spatial organizations implying a higher dependence on private transport. In each region, the motorization rates increase with disposable per capita income through variable income-elasticity η_{mot}: (a) low for very poor people whose access to motorized mobility relies on non-motorized and public modes; (b) high for households with a medium per capita income with access to private motorized mobility (c) low again, because of saturation effects, for per capita income level comparable to that of the OECD. We make two hypotheses on this parameter for developing countries, representing the evolution of preferences (see Table 5).

Buildings

The 'Housing and Buildings' module represents the dynamics of energy consumption as a function of the energy service level per housing square meter (heating, cooling, etc.) and the total housing surface. The former is represented by coefficients encompassing the technical characteristics of the existing stock of end-use equipment and buildings and the increase in demand for energy services: heating, cooking, hot water, lighting, air conditioning, refrigeration and freezing and electrical appliances. Housing surface per capita has an income elasticity of η_H, and region-specific asymptotes for the floor area per capita, h_{max}. This limit reflects spatial constraints, cultural habits as well as assumptions about future development styles (including the lifestyles in emerging countries vis-à-vis the US, European or Japanese way of life). To account for different development patterns, we make two hypotheses on h_{max} in developing countries (see Table 5).

Industrial goods

The industrial and services sectors are represented in an aggregated manner, each of them covering a large variety of economic sub-sectors and products. Technical change then covers not only changes and technical progress in each sub-sector but also the structural effects across sectors. In addition to autonomous energy efficiency gains, the IMACLIM-R model represent the structural drop in energy intensity due to a progressive transition from energy-intensive heavy industries to manufacturing industries, and the choice of new techniques which results in both energy efficiency gains and changes in the energy mix. The progressive switch from industry to services is controlled by saturation levels of per capita consumption of industrial goods (in physical terms, not necessarily in value terms), via an asymptote at κ_{ind} multiplied by its level in 2001. For developing countries, these saturation levels represent various types of catch-up to the consumption style in developed countries. We thus make two hypotheses on this parameter (see Table 5).

A.3.2 Localisation choices: freight content of economic growth

In the freight sector, total energy demand is then driven by freight mobility needs, in turn depending on the level of economic activities and their freight content. Even though the share of transportation in total costs is currently low, decoupling freight mobility demand and economic growth is an important determinant of long-term mitigation costs. In the absence of such a decoupling (constant input-output coefficient), and once efficiency potentials in freight transportation have been exhausted, constraining sectoral carbon emissions from freight transportation would amount to constraining economic activity. We thus build two alternative evolutions of the input-output coefficient representing the transportation requirement per unit of good produced (see Table 5).

A.4 Availability of low carbon technologies

In the IMACLIM-R model technologies penetrate the markets according to their profitability, but are constrained by a maximum market share which follows a 'S-shaped curve' (Grübler et al., 1999) and of which parameters are described in Table 6.

A.5 Coal market and availability of coal-to-liquids

Unlike oil and gas markets, cumulated coal production has a weak influence on coal prices because of large world resources. Coal prices then depend on current production through an elasticity coefficient η_{coal}: tight coal markets exhibit a high value of η_{coal} (i.e the coal price strongly increases if production rises). For this sector, we make two hypotheses for η_{coal} (see Table 7).

A.6 Labor rigidities

In IMACLIM-R, we consider an imperfect labour market. Indeed, friction arises in the labour markets due to *e.g.* geographic immobility, the time-consuming job search process, and the specific skills required for a specific job sector. Moreover wages are not fully flexible: wage rigidities are linked to work contracts, the power of unions, and laws on minimum wage *etc.*

The labour market imperfections are represented through a **wage-curve** that links real wage levels to the unemployment rate. This representation is based on theories developed in the 1980s and early 1990s,

		Option 1	Option 2
Transport	Motorization rate growth with GDP per capita (η_{mot})	Values from IEA data (Fulton and Eads, 2004)	50% increase w.r.t Option 1 value
Buildings	Income elasticity of buildings stock growth (η_H)	0.7	1
	Asymptote to surface per capita in China and India (h_{max})	40	60
	Start year and fuel price for a forced decline of oil consumption in this sector	2010/1000$/tep	2020/1300$/tep
Industrial goods	Households industrial goods consumption saturation level [min-max] (κ_{ind})	[1-2]	[1.5-3]
Freight content of economic growth	Input-output coefficient of transportation requirement per unit of good produced	decreases along with labor productivity growth in the composite sector and along with energy efficiency in the industry sector	Constant in all sectors

Table 5: Parameters options for behaviors

	Nuclear (new generation)		Renewables		CCS		Electric vehicles	
	Option 1	Option 2	Option 1	Option 2	Option 1	Option 2	Option 1	Option 2
Start date	2001		2001	2001	2010	2014	2010	2010
Bottleneck phase (years)	15		2	3	13	17	6	6
Growth phase (years)	75		20	65	8	8	40	40
Maturation phase (years)	25		15	25	8	8	16	16
Maximum market share at the end of the maturation phase (%)	30	0	60	50	80	30	80	25

Table 6: Parameters options for low carbon technologies

		Option 1	Option 2
Coal	Price growth elasticity to production variations (η_{coal})	2	1.5
CTL	margin applied to the production cost in the price equation	0.4	0.3
	ratio between capital cost and coal cost in the calibration year	1.5	1
	ratioOMcoalCTL	1.7	1.5
	aCTL	0.05	0.3

Table 7: Parameters options for coal and CTL

in which an aggregate wage curve, *wage setting curve* or *surrogate employment supply curve*, *wage curve* ou *wage setting curve*, replaced the usual labour supply curve.

In the model, the real hourly wage $\frac{w}{p}$ is linked to the unemployment level z by the following equation:

$$\frac{w}{p} = a \cdot z^{-\alpha} \tag{2}$$

where α is the wage-curve elasticity.

The unemployment level z, or more precisely the level of under-utilization of the labour force, is given by:

$$z = 1 - \frac{l \cdot Q}{L} \tag{3}$$

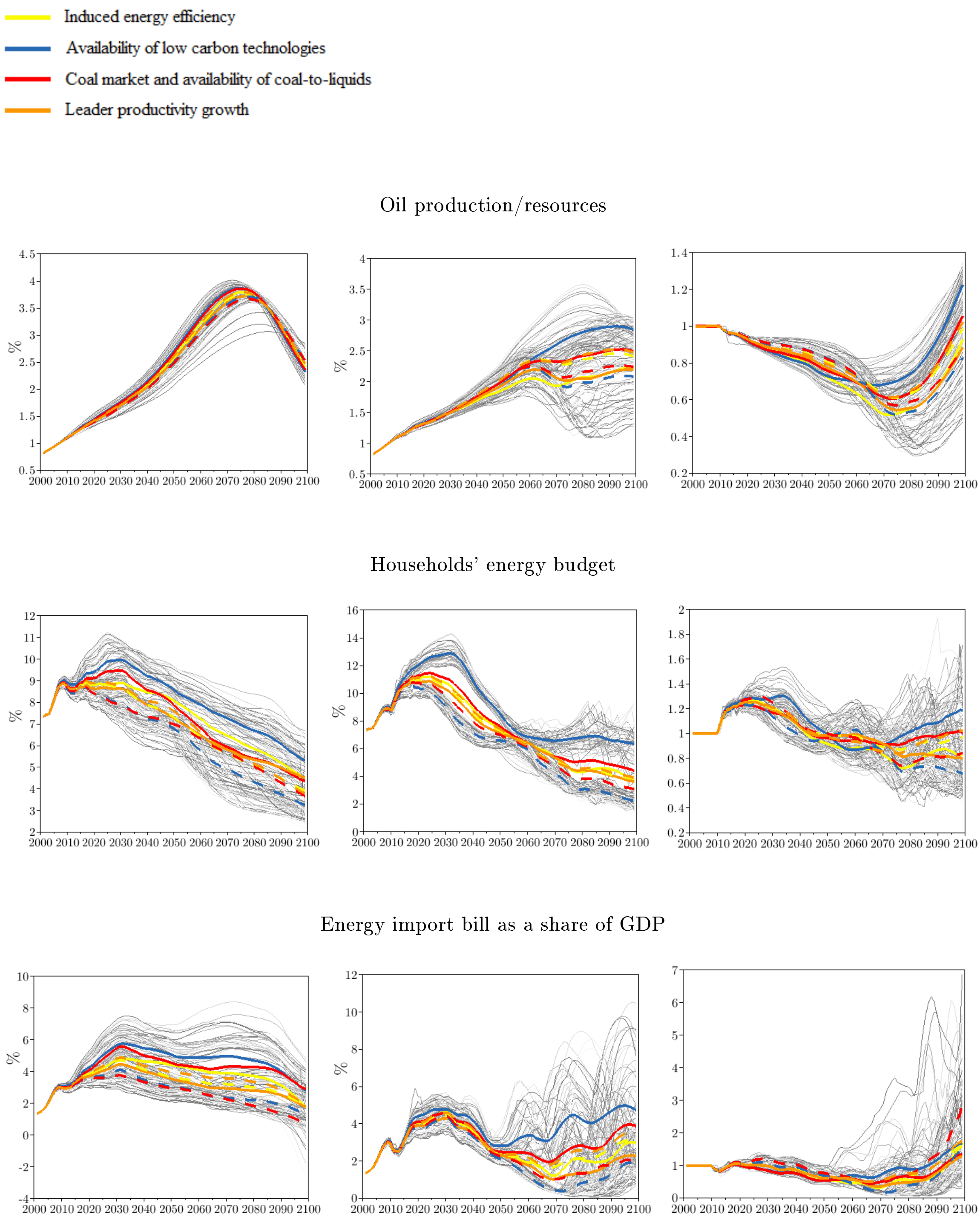
where Q is total production and L the total labour is all active population is fully employed.

The wage-curve elasticity is important in the response of economies to an increase in energy prices, since it determines the balance between the adjustment of the economy in prices (high elasticity) or in quantities (low elasticity). In other words, the elasticity of the wage-curve represents the ability to moderate the production price increase following an energy price increase, transferring part of this increase on a decrease of wages. Faced with falling demand and rising energy costs, a firm can lower its prices if it can pay less its employees, but it will have to cut its production to reach a higher level of productivity in the case of downward-rigid wages (see Guivarch (2010) for more details).

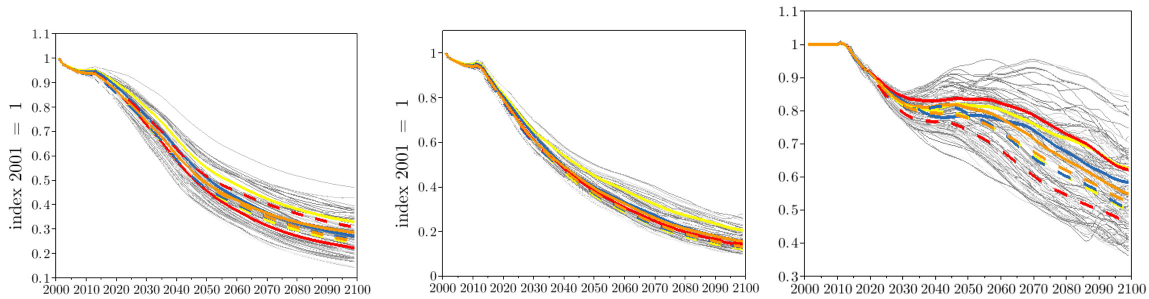
To account for the uncertainty surrounding the evolution of labor markets in developing countries, we build two assumptions on the wage-curve elasticity in these countries: it is either 0.55 or 2.

B Time trends for energy security indicators

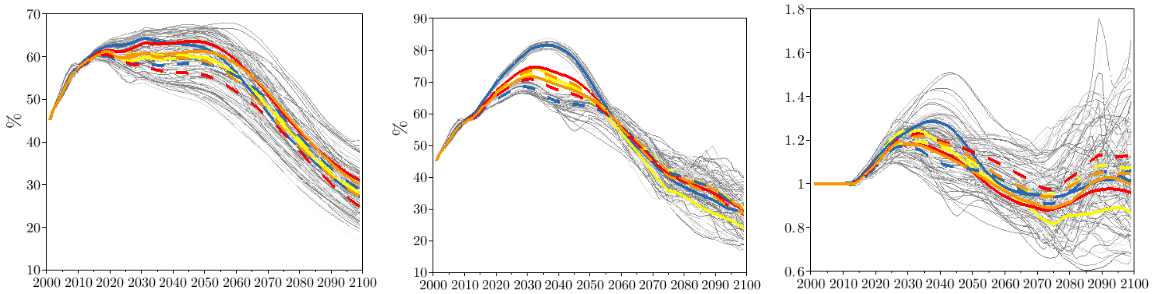
Figure 2: Time trends for energy security indicators in baselines scenarios (left panel), in climate policy scenarios (middle panel), and the ratio between the value of the indicator climate policy scenarios and its value in the corresponding baseline scenarios (right panel). Each grey line correspond to one scenario. Bold coloured lines correspond to average values across scenarios sharing the same assumption for a given set of parameters: blue plain lines correspond to the average values across scenarios with low availability of low carbon technologies, blue dashed lines to the average values across scenarios with high availability of low carbon technologies, yellow plain lines to the average values across scenarios with slow induced energy efficiency, yellow dashed lines to the average values across scenarios with fast induced energy efficiency, red plain lines to the average values across scenarios with low availability of coal and coal-to-liquids, red dashed lines to the average values across scenarios with high availability of coal and coal-to-liquids, orange plain lines to the average values across scenarios with slow leader productivity growth and orange dashed lines to the average values across scenarios with fast leader productivity growth. The other sets of parameters have less influence on the results, and are thus not represented in the graphs for clarity.



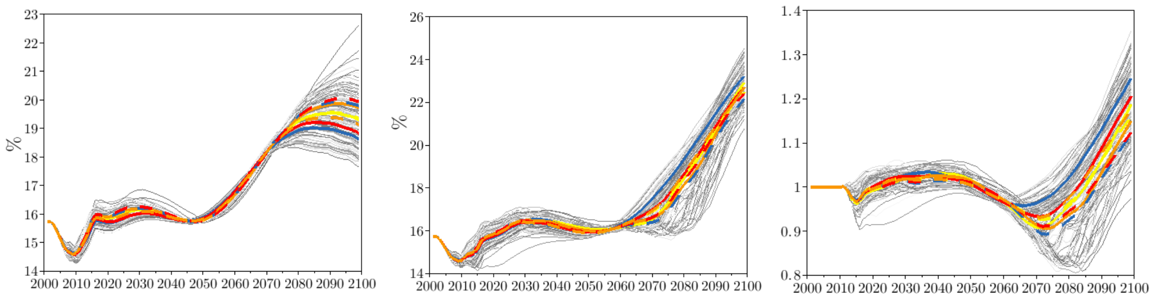
Energy intensity of GDP



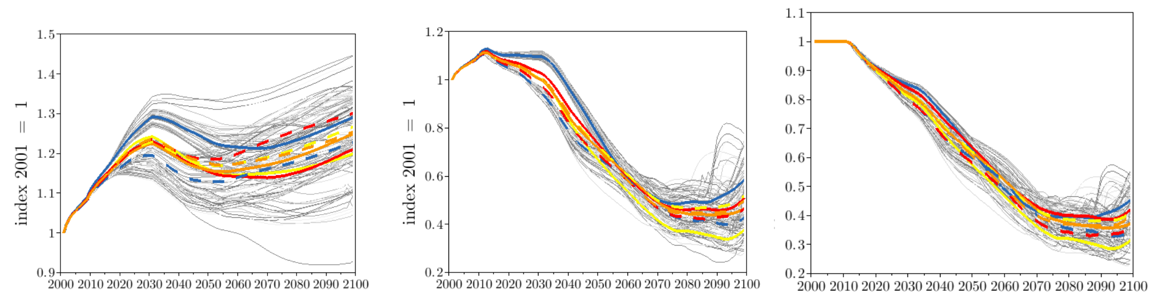
Imports share of Total Primary Energy Supply



Diversity of oil production



Carbon content of Total Primary Energy Supply



Installed nuclear capacity