Energy security in a low-carbon world:
Identifying the main uncertain drivers of energy security in Europe

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Abstract

This analysis contributes to recent efforts to better understand better the evolution of energy security in a low-carbon world. Its objective is to assess how energy security may evolve over the century, and to what extent these changes depend on the uncertainty in the factors that drive the evolution of energy systems, such as future technologies, improved energy efficiency, fossil fuel resources and markets, and economic growth. To examine this issue, we focused on Europe and on a set of energy security indicators based on three perspectives: sovereignty, robustness and resilience. A database of scenarios allowed us to account for the large uncertainties surrounding the determinants of future energy systems. It was then possible to analyze the way energy security indicators evolve over time, and how their trajectories vary across scenarios. We identified the indicators that vary the most between scenarios, i.e. the indicators whose future evolution is the most uncertain. For those indicators, we performed an analysis of variance to estimate the contribution of each driver to their uncertainty. This made it possible to identify levers which could limit the degradation of energy security when ambitious climate policies are implemented.

Keywords: Climate policy, energy security, Europe, scenarios database, sovereignty, robustness, resilience.

JEL Classification: Q43, Q47, Q54

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1. Introduction

In 2008, the Lisbon Treaty launched new climate and energy policies in the European Union with the aim of significantly decreasing CO_2 emissions, while increasing the security of the supply of energy in the Union, at reasonable costs in order to maintain competitiveness. Since then, climate policy and energy security policy have been closely linked in the EU, as developed in the European Energy Roadmap 2050 (European Commission, 2011).

Today it is obvious that the two issues are intertwined. They share a common root cause, the demand for energy, but the solutions for improving energy security and reducing greenhouse gases (GHG) are not necessarily the same, and may involve some contradictions. For instance, the deployment of renewable energies led to greater dependency on natural gas for peak load and back-up, especially on Russian gas. Recent geopolitical crises between Russia and Ukraine revealed the European energy vulnerability on this issue.

Energy security does not only refer to geopolitical risks or dependency on primary fuels but is multi-faceted. Several recent contributions proposed an analytical framework to evaluate the concept by incorporating different dimensions or perspectives of the energy security (APERC, 2007; Cherp et al., 2012; Winzer, 2012). In this paper, we use the framework developed by the Global Energy Assessment (Cherp et al., 2012). The starting point of this approach is to work with a definition of the energy security which incorporates the likely radical transformations of energy systems in the long term. Energy security is defined as the low vulnerability of vital energy systems. Even if the security of oil supplies remains important, contemporary energy security policies must address other energy systems as well. This point is crucial in the current context in which many stakeholders call for speeding up energy transition. Vital energy systems thus also refer to different energy carriers (electricity, hydrogen, liquid and synthetic fuels), or to the total energy supply.

Several papers recently used this framework to explore the consequences of climate policies for energy security from a long-term perspective (Cherp et al., 2013; Jewell et al., 2013, 2014; Guivarch et al., 2015). These analyses show that the implementation of ambitious climate policies affects vital energy systems differently. They also emphasize the importance of the time dimension. For instance, Guivarch et al. (2015) show that the impact of climate policies is mixed in the short term and globally good in the medium term, whereas in the long term, there is a risk of degradation of energy security, especially related to the electricity system.

The objective of this paper is to highlight possible levers that could improve energy security, or limit its degradation, when ambitious climate policies are implemented. This is a companion paper to that of Guivarch et al. (2015). In the present paper, we take up the same series of energy security indicators and analyze their dynamics over the century in a low-carbon world. We aim to identify the main drivers of these dynamics among those of key technologies, the evolution of energy efficiency, fossil fuel resources and markets and economic growth. The positive or negative impact of ambitious energy security policies may depend on the evolution of some uncertain drivers of future energy systems.[4] For instance, the

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[4] The term uncertainty is used here as in Saltelli (2002) where it is defined as *"Sensitivity analysis is the study of how the uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input"*.

availability and affordability of carbon capture and storage (CCS) technologies would make the use of coal possible in a low-carbon world, while improving energy security for coal-producing countries. Without being sure of succeeding in developing low-carbon technologies, public policies will play a crucial role in their future availability and cost. This is also true for energy efficiency and for economic growth.

The paper proposes an original methodology to investigate these issues. Using the energy-economy-environment model, Imaclim-R, we created a database of long-term scenarios in which different determinants of the future energy systems, on both the supply and demand side, are considered. Each scenario describes a possible future in terms of economic growth, fossil fuel availability, energy efficiency and the cost of different low-carbon technologies. For each possible future, we imposed a global CO_2 emission trajectory leading to the stabilization of the concentration of CO_2in the atmosphere at 550 ppm CO_2-eq. A set of indicators that capture the multi-faceted aspect of the energy security concept were assessed in each scenario, enabling us to analyze the evolution of the indicators in all possible future worlds, and their dispersion over the course of the century. By focusing on the indicators with the largest dispersion, and by applying a multi-factor analysis of variance (ANOVA), we identified the main explanatory factors. The analysis was applied to Europe and identified the most important drivers of energy security indicators in a low-carbon world. The method identified some levers to improve energy security if ambitious climate policies are implemented.

In Section 2, we report a brief review of the literature exploring the impacts of climate policies on energy security from a long-term perspective. In Section 3, we explain our contribution and detail the method we used. We present the series of indicators used for the analysis and the energy-economy-environment model, Imaclim-R, used for the simulations. We explain how we built our database of scenarios and the tools we used to analyze the results of the simulations. In Section 4, we present the results: first, the dynamics of the indicators in all the scenarios over the century and the assessment of their dispersion; second, the contributions of the different drivers to this dispersion with an analysis of variance. In section 5 we discuss the results and conclude.

2. Climate policy and energy security: recent advances

Although the issue of energy security is high on the policy agenda and pervasive in the discourse, it is seldom accompanied by a clear definition of the term. As explained in Winzer (2012), the concept of energy security is "blurred", "elusive" or "slippery". This is partly due to its multi-faceted nature. The assessment of energy security thus implies developing an analytical framework to identify the different dimensions of the concept. Several recent contributions proposed different frameworks (APERC, 2007; Cherp et al., 2012; Winzer, 2012).

In this paper, we use the framework developed by the Global Energy Assessment (GEA) in a series of recent papers that specifically examined the effect of climate policies on energy security worldwide and in different regions (Cherp et al., 2013; Jewell et al., 2013, 2014; Guivarch et al., 2015). The aim of the analytical framework is to assess the "new" energy security dealing with tensions in the supply of natural gas in Europe, the rising energy demand in Asia, and the transition towards low-carbon societies that began in the 2000s. The analysis framework is based on a definition of the energy security that is sufficiently flexible to include the likely future evolution of energy systems in the long term. Energy security refers to the low vulnerability of vital energy systems. These systems refer not only to primary fossil fuels but also to different energy carriers (electricity, hydrogen, liquid and synthetic fuels), which will play an increasing role in a low-carbon world. The GEA approach aims to identify the vulnerabilities of these systems, from three perspectives: sovereignty, robustness and resilience. The sovereignty perspective refers to threats posed by external actors and the exposure of a region/country to such threats (Cherp and Jewell, 2011). It is related to historic events such as energy embargoes or price manipulations and to foreign control of energy resources. The robustness perspective deals with technological and natural risks to energy systems. Historically, it is related to major accidents, electricity blackouts and resource scarcity. The resilience perspective focuses on the ability of the energy systems to resist diverse disruptions due to social and economic factors that are difficult to predict and control (political instability, price volatility, etc). With the resilience perspective, the future is considered as unpredictable. This future uncertainty may be related to markets, technologies and societies. From this perspective, the energy security can be apprehended in terms of the range of energy options. The risks apprehended by the framework refer not only to traditional ones, like geopolitical risks, but also to new challenges, for instance those posed by the development of electricity systems.

Cherp et al. (2013) envisage different levels of ambition in terms of reducing GHG emissions at the world level and introduce uncertainties by considering different levels of GDP growth and of the availability of fossil resources. These different scenarios were simulated in two different Integrated Assessment Models. They found that climate mitigation policies will increase the resilience of energy systems as reflected in their diversity, and will improve sovereignty around the middle of the century when low-carbon and fossil energy source co-exist. Climate policies will lead to a deep penetration of solar energy in the electric sector and of bio-fuels in the liquid fuel sectors, which will reduce diversity by the end of the century.

Jewell et al. (2013) examine future evolution of energy security in major economies: China, India, the European Union and the United States of America. Their analysis is based on results of six integrated assessment models. In each model, two temperature limitation targets are considered: an increase of 3 °C, and an increase of 2 °C. The results conclude that the different regions share common trends. For instance, climate policies reduce energy imports and increase the diversity of energy options. But the major economies would also be exposed to specific evolutions. For instance, in the EU, climate policies would decrease dependency on imports, while increasing the diversity of energy options in the transport sector. With climate policies, China would not completely exhaust its oil and gas reserves, allowing it to avoid being totally dependent on imports of these products.

Jewell et al. (2014) explore low-carbon scenarios to limit the global mean temperature increase to 2 °C above the pre-industrial level by 2100. Three elements differ among the scenarios: availability of some low carbon energy sources (solar and wind, biomass, nuclear energy etc.), improvement of energy efficiency, and the availability of advanced transport technologies. The sovereignty perspective is evaluated by global trade in energy, some regional energy balances, and trade in individual fuels. The resilience perspective is evaluated by world energy intensity and the diversity of the primary energy supply at international and regional levels. These authors found that low-carbon scenarios are associated with lower trade in energy and increased diversity of energy options than in the baseline scenario, but that a few risks emerge in the second half of the century due to high trade in natural gas and hydrogen and limited diversity of sources of electricity. Indeed, in some low-carbon scenarios, levels of gas trade are equivalent to levels of oil trade today. However, gas would not dominate a given sector as oil dominates the transport sector today. Other indicators rather suggest an improvement in energy security in the low-carbon scenarios.

Guivarch et al. (2015) investigate the effect of climate policies on energy security indicators at three specific time horizons, 2025, 2050 and 2075. Their analysis focuses on the relative variation in energy security indicators between a case with climate policies and a case without climate policies. Their results show that very few indicators of energy security, e.g. the ratio of oil production to resources and energy intensity, are unambiguously improved by climate policies. Others are degraded either at a certain time horizon, or in certain scenarios. For instance, indicators of the sovereignty perspective, which are all improved, on average, from the medium term on, may be degraded in some scenarios. Moreover, tensions concerning some aspects of energy security could emerge around 2025, which is a critical period for international climate negotiations. The paper also shows that there is a risk of degradation of energy security in the long term, due to the greater use of electricity carriers and greater concentration of primary sources for the generation of power. Lastly, the paper notes that the dispersion of the indicators tends to increase with the time horizon and briefly explores the issue in the medium term.

3. Contribution and method

The aim of this paper is to contribute to recent efforts to improve our understanding of the impact of climate policies on energy security. More precisely, our objective is to assess how energy security indicators could evolve in a low-carbon world, and to what extent these evolutions depend on the uncertainty surrounding the factors that drive the evolution of energy systems, such as future technologies, improved energy efficiency, fossil fuel resources and markets, and economic growth.[5] To our knowledge, this issue has not been explored to date.

To examine the evolution of energy security in a low-carbon world, we focused on Europe and on a small number of energy security indicators in the recent literature. We evaluated the evolution of these indicators until 2075 in a database of long-term scenarios built with the energy-economy-environment model, Imaclim-R. To explore the relevant uncertain factors, we constructed a large set of scenarios, following a method previously described in Rozenberg et al. (2014). We identified the main driving forces (or main uncertain drivers) that affect the future outcomes of the systems, e.g. learning potentials and costs of key technologies. We translated these driving forces into model parameters, and combined them to build a large number of model runs. This process led us to build what we call a "scenario database". In all the scenarios, we imposed a global CO_2 emission trajectory leading to the stabilization of CO_2 concentration in the atmosphere at 550 ppm CO_2-eq. It was then possible to analyze the way energy security indicators evolve over time in each scenario, and how their trajectories differ among the scenarios. We identified the indicators that vary the most between scenarios, i.e. the indicators that have

[5] We are interested in the absolute values of energy security indicators, and not in their variations compared to a reference scenario.

the most uncertain evolution. For those indicators, we analyzed the contribution of each (uncertain) driver to their uncertainty, with an analysis of variance. In this part, we present the indicators, the model Imaclim-R, and the uncertain drivers on which the database of scenarios is based. We then explain the tools we used to analyze the dispersion of the indicators.

The indicators

As explained above, we used the GEA's analytical framework based on three perspectives. Even within this framework, the choice of indicators can be difficult. Often different indicators can be used to inform on a perspective of a specific energy system. Although they used the same assessment framework, Cherp et al. (2013), Jewell et al. (2013) and Jewell et al. (2014) selected somewhat different indicators depending on the models or the objective targeted. We used indicators similar to those used in Guivarch et al. (2015), see Table 1 for a summary.

Table 1 – Vulnerabilities of vital energy systems and related indicators

Vital energy systems	Sovereignty perspective	Robustness perspective	Resilience perspective
Total primary energy supply	Share of imports in TPES	/	Energy intensity of GDP
Primary fuels: oil, coal, gas	Regional import dependence	Production/Resource ratio[6]	Concentration of markets[7]
Electricity carrier	Share of imports for generating power[8]	Existing nuclear capacities	Concentration of primary energy sources used for electricity production

The total primary energy supply (TPES) is the first vital energy system we analyzed. The sovereignty perspective is apprehended by the share of TPES imports that measures the dependence of the energy supply on imports. From a resilience perspective, the energy intensity of GDP (the ratio of TPES to GDP) measures the dependence of the economy on energy.

Primary fuels (oil, gas and coal) are the second vital energy system we examined. The sovereignty perspective is evaluated by net imports of oil, gas and coal into the region. The robustness perspective is apprehended by the ratio of oil production to oil resources.[9] The resilience perspective is measured by the global concentration of suppliers of oil. A Herfindahl-Hirschmann index, calculated as the sum of

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[6] The model only evaluates this indicator for oil.

[7] The model only evaluates this indicator for oil.

[8] When assessing the rate of energy independence, uranium is conventionally not included in imported fuels. We applied the same rule.

[9] It is more common to present the inverse ratio, i.e. the ratio of resources to production, expressed in years of reserves remaining at the current rate of extraction. However, we use the ratio of production to resources, so that the value of the indicator increases when availability decreases.

squared market shares of oil producers, was used. Note that this index increases when the market is dominated by a small number of producers. These two indicators are global and not specific to Europe.[10]

The last vital energy system we analyzed is the electricity carrier. The vulnerability of European electricity production is evaluated by the reliance on imported fuels as primary sources for the generation of power (sovereignty perspective). The robustness perspective is apprehended by existing nuclear capacity, a technology that may be strongly contested in the case of a major accident.[11] The concentration of primary energy sources, measured by the Herfindahl-Hirschmann index of the shares of the different primary sources, informs on the resilience of the electricity generation capacity. This index increases when a smaller number of sources are responsible for a large share of the generation, i.e. when the diversity of the mix decreases.

All the indicators were calculated such that an increase (respectively a decrease) in their value indicates a worsening (respectively an improvement) of the dimension of energy security they measure.

The model[12]

Imaclim-R model (Waisman et al., 2012) is a multi-region and multi-sector model of the world economy that represents the intertwined evolution of technical systems, energy demand behavior and economic growth. It combines a Computable General Equilibrium (CGE) framework with bottom-up sectoral modules in a hybrid and recursive dynamic architecture. In addition, it describes growth patterns in second-best worlds with market imperfections, partial uses of production factors, and imperfect expectations. The model represents endogenous GDP and structural change, energy markets and induced technical change. The scope of GHG gases represented is restricted to CO_2 emissions from fossil fuel combustion.

It is disaggregated into 12 regions and 12 sectors, including five energy sectors: coal, oil, gas, refined products and electricity. Europe is one of the 12 regions. Details on the regional and sectoral disaggregation can be found in supplementary material. The model 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 simulates future trajectories through the recursive succession of static equilibria and dynamic modules with yearly steps.

The main exogenous assumptions are increased demography and labor productivity, the maximum potentials of technologies (renewable, nuclear, CCS, electrical vehicles, etc.), with learning rates decreasing the cost of technologies, fossil fuel reserves, the parameters of the functions representing energy-efficiency in end-uses.

The scenario database

In the long term, high uncertainty surrounds population growth, the growth and structure of the economy, energy markets, low-carbon technologies, or even energy efficiency. Following the methodology

[10] In our modeling framework, oil trade is not modeled bilaterally but via an international pool.

[11] The Fukushima Daiichi nuclear accident led Japanese authorities to temporarily shut down all the nuclear plants in Japan.

[12] A full description of the model is available at http://www.imaclim.centre-cired.fr/IMG/pdf/imaclim_v1.0.pdf. Details on the model structure and results with respect to various aspects (energy technologies, energy efficiency, fossil fuels, macro-economy) can be found in the publications listed in supplementary material.

proposed by Rozenberg et al. (2014), we constructed a database of scenarios combining hypotheses on a large number of model parameters. This methodology allowed us to consider many different types of uncertain drivers simultaneously.[13]

Here we briefly present the six different drivers analyzed and the alternatives considered. A full description of the choice of parameters is given in the Appendix. For each parameter, the alternatives considered are contrasted, but no extreme assumption is included.

• **Availability of different types of low carbon technologies:**

The availability and diffusion of some low carbon technologies will strongly impact the future of energy systems. We considered three different groups:

- Low carbon power generation technologies (nuclear energy and renewable resources);[14]
- Carbon capture and storage (CCS) technologies;
- Low carbon end-use technologies in the transport and residential sectors (electric and hybrid vehicles, efficient buildings and household equipment).

For each group of low carbon technologies, we built two sets of assumptions for parameters describing their costs, the learning rates on investment costs and maximum market shares over the entire simulation period. One alternative represents limited availability (high cost and low potential market share) of the technology concerned; the other corresponds to high availability (low cost and high potential market share).

• **Induced energy efficiency (IEE):**

Energy efficiency in end-use sectors (agriculture, industry, construction and services) is endogenous and is driven by energy prices.[15] We introduced two alternatives for the parameters describing its maximum annual improvement in the leading country and the catch-up speed of the other countries: one fast IEE and one slow IEE.

• **Fossil fuel resources and markets:**

This set describes assumptions concerning oil, gas and coal resources and markets. These parameters include: (1) the amount of ultimately recoverable resources; (2) the amount of investment by Middle Eastern countries required to sustain oil production at the scale of existing oil fields and to explore new fields; (3) inertia in the development of non-conventional production; (4) the indexation (or de-indexation) of gas prices to oil prices; and (5) changes in coal prices in response to fluctuations in demand. One assumption corresponds to relatively abundant fossil fuels, the other to relatively scarce fossil fuels.

• **Economic growth:**

In the Imaclim-R model, economic growth is endogenous but is driven by exogenous trends of population growth and labor productivity. We built three alternative combinations of population growth

[13] This method is frequently used to investigate the uncertainty space in integrated assessment models. Of course, only a portion of the full uncertainty space is investigated, and that results are conditional to the choices of sets of parameters to vary and of the alternative values tested. Obviously, the impact of an uncertain driver on the results depends on the numerical assumptions behind each state of the driver. This limitation is inherent to our methodology, as in all sensitivity analyses, but cannot be avoided when accounting for uncertainty in a large number of model input parameters.

[14] In the "low" assumption, it is assumed that the new generation of nuclear energy is not available at all.

[15] See Bibas et al. (2014) for a detailed description of how energy efficiency is modelled and how it impacts the model.

and labor productivity trends that correspond to the SSP (Shared socio-economic pathways) 1, 2 and 3. SSPs are the new generation of socioeconomic scenarios for climate change research (O'Neill et al., 2014). SSP1 can be described as a scenario with low population and high productivity growth, while SSP3 is a scenario with high population and slow productivity growth and SSP2 lies between the two[16].

Combining those assumptions led to 96 (3×2^5) scenarios with different trajectories of CO_2 emissions during the century. In each of these scenarios, we added an exogenous constraint on global CO_2 emission trajectories leading to 96 climate policy scenarios. The trajectory of emissions was chosen to be consistent with the stabilization of CO_2 concentrations in the atmosphere at 550 ppm CO_2-eq: global emissions peak in 2020, and are reduced by 30% and 75% with respect to 2010 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) designed to reach the target emission trajectory from 2011. The tax level is determined endogenously and changed each year to respect the global emissions constraint. Although extreme, this assumption has the advantage of avoiding the need to define an inevitably arbitrary share of the reduction in emissions among countries. Like Guivarch et al. (2015), we restrict our analysis to the period up to 2075, beyond which certain factors, notably technologies, are very uncertain.

Analysis of the indicators

Our aim is to identify the determinants of energy systems that play a crucial role in the evolution of energy security in a low carbon world. Guivarch et al. (2015) show that the effect of climate policies on energy security can differ significantly depending on the indicator or the time horizon considered. The first stage of the analysis was to evaluate the robustness or uncertainty of the simulated trajectories of the energy security indicators, with respect to the uncertainty in the driving forces. To do so, we calculated the relative standard deviation at each date, defined as the ratio of the standard deviation to the (arithmetic) mean value across all scenarios. This statistical tool reveals the extent of variability of a result in relation to its mean value.

The second stage of the analysis was to identify the factors that contribute most to this variability. The contributions of each uncertain driver over time result from an analysis of variance, ANOVA, based on the partitioning of the sum of squares in a linear regression. The total sum of squares (i.e. the variance of the results, multiplied by the number of scenarios minus one) can be partitioned into the explained sum of squares linked to each uncertain driver and the residual sum of squares (which corresponds to the non-linear interactions between drivers). This partitioning of the sum of squares is computed each year for the ensemble of scenarios. It gives the fraction of variance explained by each uncertain driver at each time step.

[16] The populations and GDP quantifications of SSPs are available on a IIASA database: https://secure.iiasa.ac.at/web-apps/ene/SspDb

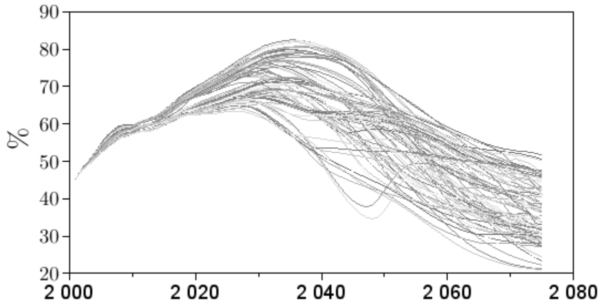
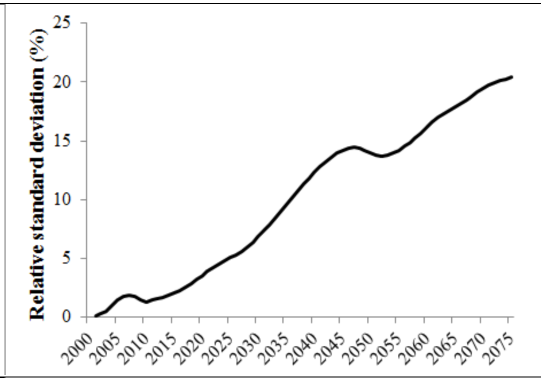
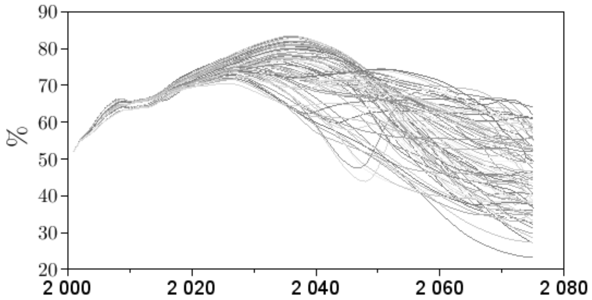
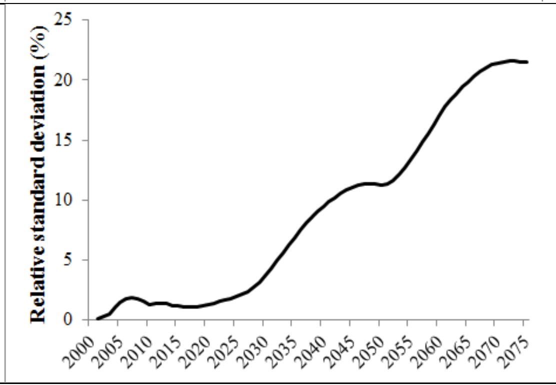
4. Results

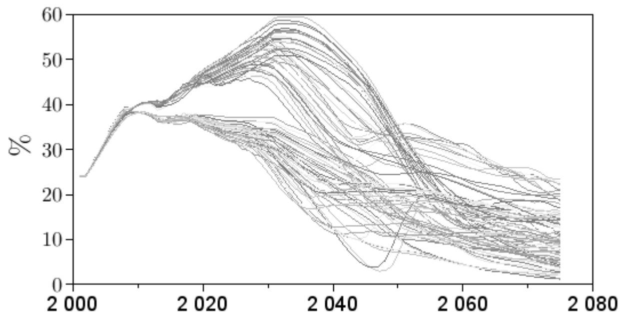
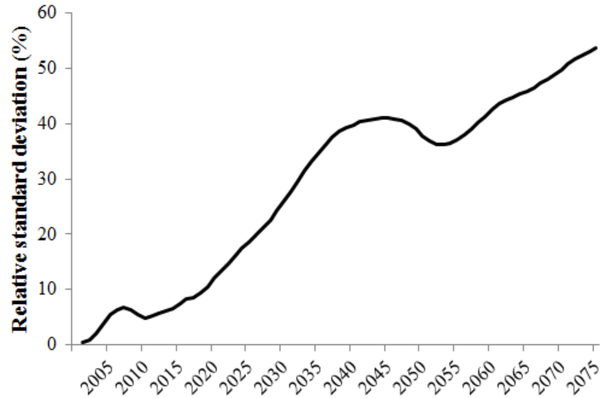
Here we present results for Europe, one of the regions represented in the Imaclim-R model. First, we describe the evolution of all the indicators over the century. Each line represents one scenario, i.e. one combination of the different assumptions under consideration. The dispersion of each indicator was evaluated by the relative standard deviation (RSD). This analysis revealed significant differences in the values of some indicators depending on the future considered. An indicator may even improve over time in some scenarios but deteriorate in other scenarios. Second, we focused on the most dispersed indicators for which more than one driver explains the variability. An analysis of variance was conducted to identify the uncertain drivers that contribute the most to this dispersion. We then discuss the results obtained.

4.1. The evolution and dispersion of the indicators

Here we analyze the different sets of indicators that highlight a specific energy security perspective. Figure 1 presents the indicators of the sovereignty perspective. All the indicators were calculated such that an increase (respectively a decrease) in their value indicates a worsening (respectively an improvement) in the dimension of energy security they measure. The RSD allowed us to assess whether an indicator varied a lot, or a little in the different scenarios. In other words, it evaluated the degree of uncertainty of the indicator across the scenarios considered. The variability can also evolve over time.

Figure 1: Evolution and dispersion of the indicators of the sovereignty perspective

<table>
<tr><th colspan="3">Sovereignty perspective</th></tr>
<tr><th></th><th>Evolution of the indicator</th><th>Relative standard deviations</th></tr>
<tr><td>TPES:
Share of imports in TPES</td><td>
</td><td>
</td></tr>
<tr><td>Primary fuels:
Regional import dependence</td><td>
</td><td>
</td></tr>
</table>

Electricity: *Share of imports for power generation*	 	

Note: The scale of the y-axis differs among the figures.

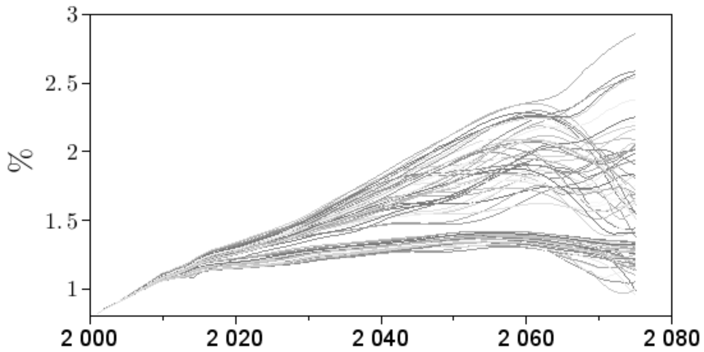
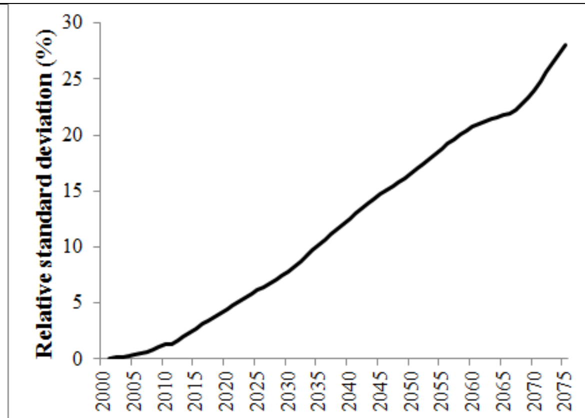
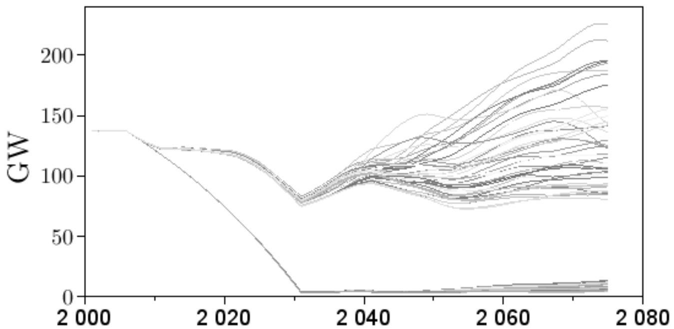
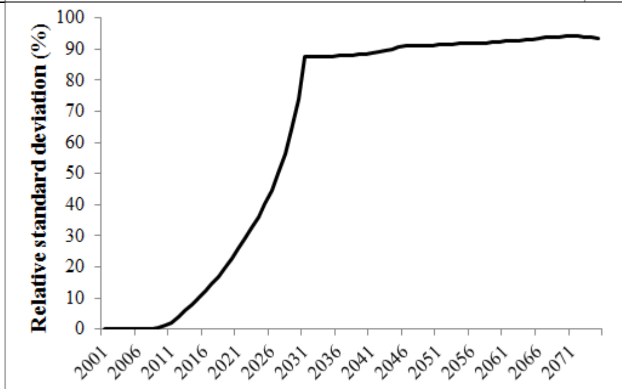
The sovereignty perspective refers to threats posed by external actors and the exposure of a region/ country to these threats (Cherp and Jewell, 2011). This is apprehended by different indicators based on the share of imports used for the functioning of the three energy systems analyzed. Figure 1 shows that the indicators of the sovereignty follow similar trends.

For TPES and primary fuels, in all scenarios there is a first phase of worsening of the indicator, then a trend reversal between 2025 and 2035, followed by an improvement of the indicator in the long term. The date of the trend reversal and the speed of the subsequent improvement vary across scenarios. The short-term worsening is due to carbon pricing triggering substitutions away from (mainly domestic) coal towards (mainly imported) gas. The long-term improvement is due to higher market penetration of renewables, as well as by the penetration of CCS technologies that enable the use of domestic coal with low emissions. These results reveal that the implementation of ambitious climate policies in Europe initially worsens these indicators compared to 2000, irrespective of the combination of assumptions envisaged. After around 2040, the indicators improve, with less reliance on imports in some scenarios, whereas the indicators are still worse in other scenarios. Moreover, in a few scenarios, the dependence on imports remains higher than in 2000 until the end of the study period, 2075. As shown by the RSD, the spread across scenarios increases over time. At the end of the simulation period, the ratio of the standard deviation to the mean is around 20% for both the systems.

For the electricity system, two groups of scenarios can be distinguished. One group follows the same trend as that described for TPES and primary fuels. The other group is not subject to the first phase of worsening of the indicator, but follows a relatively flat, or slightly improved, trajectory until 2030. The intensity of the use of renewables in the medium term explains this difference: when the use of renewables is high, market penetration by gas-powered plants limits associated imports of gas. The improvement of this indicator happens earlier than for the other systems studied. As early as 2030, in some scenarios, the reliance on imports to produce electricity in Europe is reduced, compared to the situation at the beginning of the century. Moreover, at the end of the simulation period, the indicator is improved in all the scenarios. Like the other systems, except for a short period around 2050, the variability of the indicator across scenarios increases over time. But the RSD of the simulated values is higher for this indicator than in the two other systems. This confirms the importance of understanding which drivers explain this variability.

Figure 2 presents the evolution and dispersion of the indicators of the robustness perspective.

Figure 2: Evolution and dispersion of the indicators of the robustness perspective

Robustness perspective		
	Evolution of the indicator	**Relative standard deviation**
Primary fuels: *Production/Resource ratio (oil)*		
Electricity : *Nuclear capacities installed*		

Note: The scale of the y-axis differs between the figures.

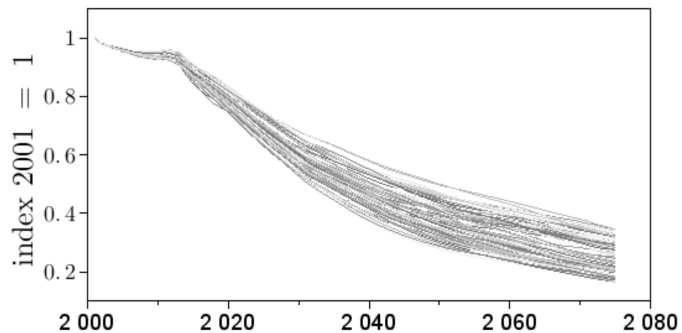
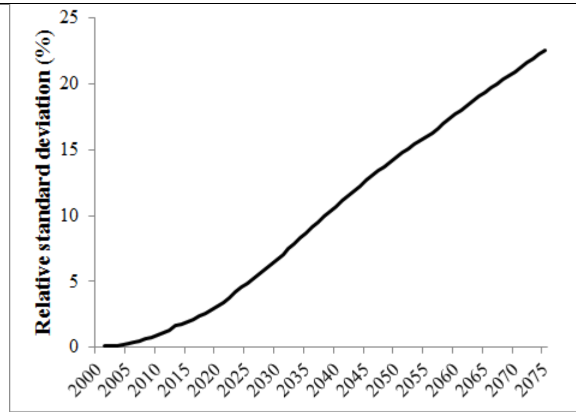
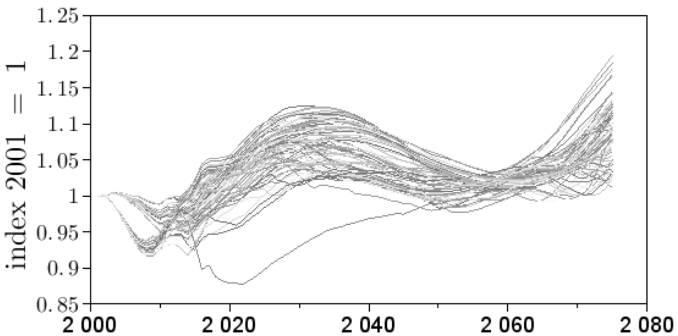
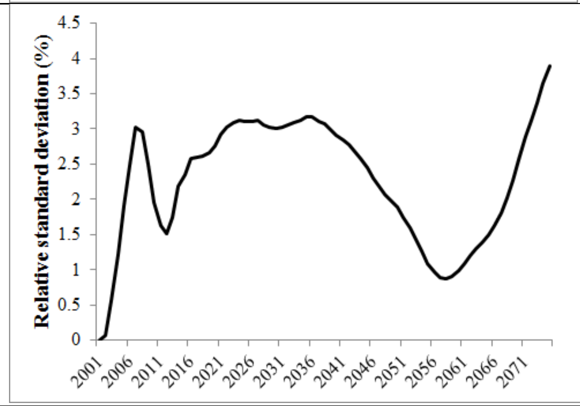
The robustness perspective refers to threats related to technical factors, such as scarcity of resources, aging of infrastructure or technical failures. The indicators selected to apprehend this perspective deal with the availability of the oil resource compared to production, and a technology used to produce electricity but regularly questioned, in particular given the risk of major accidents.

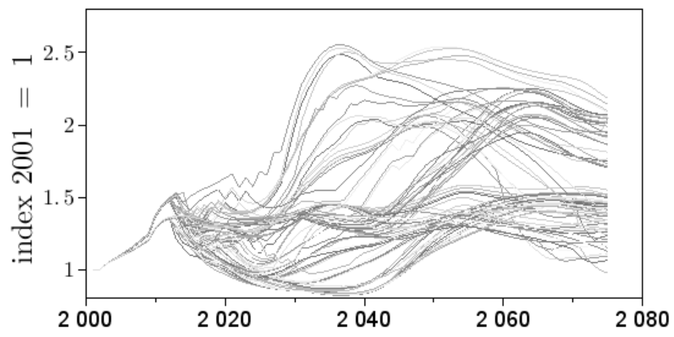
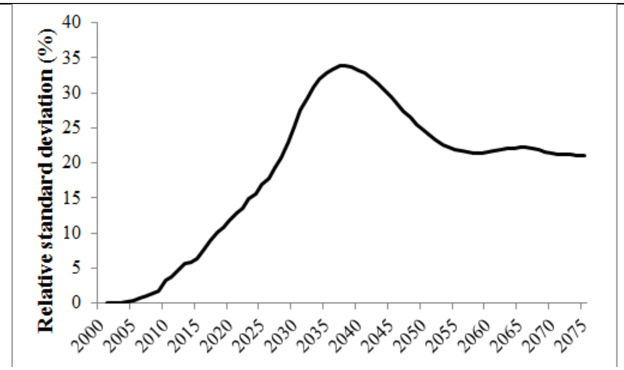
Figure 2 shows that the ratio of production to oil resources oil worsens continuously over time until around 2060 in all the scenarios. However, the speed of degradation varies across the scenarios. The indicator remains relatively flat in some scenarios, but increases substantially in others. This reveals that, although ambitious, the climate policies will not prevent the worsening of the ratio of oil production to oil resources for several decades. This indicator is not specific to Europe, the result applies to the whole world. After 2060, there is an improvement in some scenarios but the situation remains worse than at the beginning of the century. The improvement happens because, in some scenarios, extraction of oil is sufficiently slowed down by climate policy to counter-balance the effect of depletion. As shown by the RSD, the spread across scenarios increases over time. At the end of the simulation period, the ratio of the standard deviation to the mean is around 30%.

For electricity, two groups of scenarios can be distinguished, even though the indicator is improved in both. In one group, existing nuclear capacities are significantly reduced until they reach floor level, after which the indicator remains extremely low. This evolution is due to assumptions concerning nuclear technology, which assume no new nuclear capacities in the "low" alternative. In the other group of scenarios, the indicator also decreases up to 2030, but from this date on, depending on the scenario, the capacities may stabilize at the 2030 value or double between 2030 and 2075. In some scenarios in this group, existing nuclear capacities in 2075 will be significantly higher than at the beginning of the century. Due to these two subsets of scenarios, one with almost no existing nuclear capacities, the RSD grows to reach almost 100% in 2030 and afterwards.

Figure 3 presents the evolution and dispersion of the indicators of the resilience perspective.

Figure 3: Evolution and dispersion of the indicators of the resilience perspective

Resilience perspective		
	Evolution of the indicator	**Relative standard deviation**
TPES: *Energy intensity of GDP*		
Primary fuels: *Concentration of oil markets*		

<table>
<tr>
<td>Electricity:
Concentration of primary energy sources used in electricity production</td>
<td>
</td>
<td>
</td>
</tr>
</table>

Note: The scale of the y-axis differs between the figures.

With the resilience perspective, the future is considered to be unpredictable. This future uncertainty may be related to markets, technologies and societies. The indicators aim to characterize the exposure, adaptability, or diversity of energy systems with respect to different known and unknown threats (Cherp and Jewel, 2011).

Figure 3 shows that the trends followed by the indicators of the resilience perspective vary between vulnerable systems and among the scenarios.

For TPES, the energy intensity of GDP is improved over time in all the scenarios. Carbon pricing accelerates the historical trend of a decrease in energy intensity over time. The speed of the improvement varies between scenarios, and ranges from 1.6%/yr to 2.7%/yr decrease in energy intensity between 2015 and 2075. The RSD increases over time to reach almost 25% at the end of the study period.

For primary fuels, the concentration of oil markets follows approximately the same trajectory in most scenarios: first, the concentration increases until approximately 2030, then decreases for two to three decades before again undergoing a long-term increase. The short-term increase is due to carbon pricing which excludes unconventional oil producers from the market, after which the markets are diversified, partly because CCS allows some unconventional oil producers to enter the market, partly because depletion of conventional resources decreases the market shares of conventional producers. In the long-term, the oil markets again become concentrated because of the depletion of conventional resources. The trajectories are very similar in all the scenarios, and the RSD remains below 4% throughout the study period.

The evolution of the diversity of primary energy sources used in electricity production differs considerably among the scenarios. In some, the indicator improves from 2011 on, whereas in others it deteriorates. These differences remain high over time. The RSD reaches a peak of approximately 35% around 2040. From 2060 on, the trajectories are less chaotic but dispersion among the scenarios remains high.

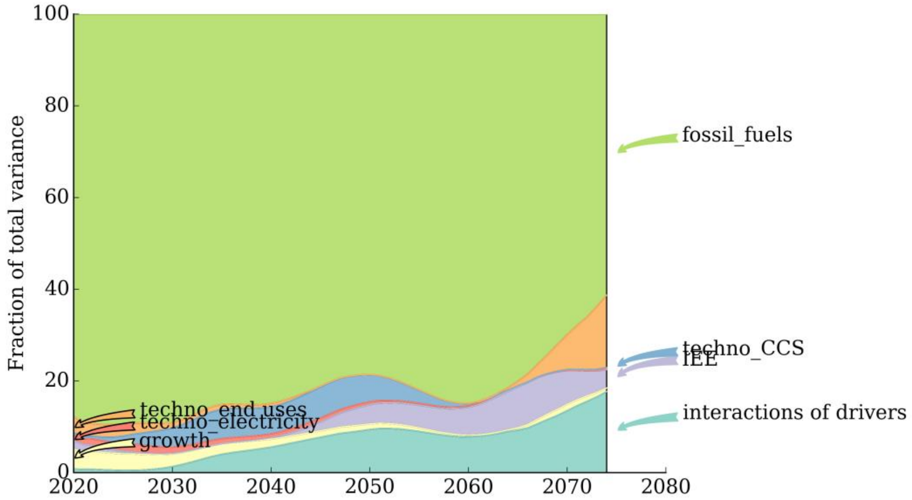
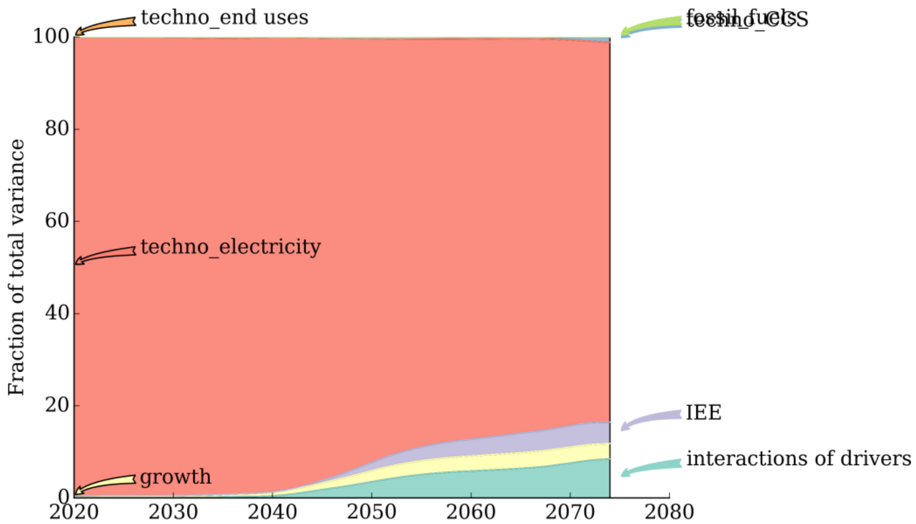
To sum up, the evolution of energy security dimensions in a low-carbon world are varied and complex. The conclusion depends on the indicator examined but also on the time horizon considered. Moreover, the dispersion of some indicators is substantially higher than that of others. In the following, we analyze which uncertain drivers explain this dispersion.

4.2. Contribution of the different determinants

Our objective was to identify the main factors behind the dispersion of the indicators. We focused on those characterized by the highest variability. Consequently we excluded the indicator of the resilience perspective for primary fuels whose RSD peaked at 4%.

The first group of indicators was characterized by a certain variation across the scenarios, but this variation is almost entirely explained by a single assumption. Figure 4 shows the result of the ANOVA for the ratio of production to oil resources and existing nuclear capacities. Both the indicators are related to the robustness perspective. A different color is used for each type of driver: red for low carbon power generation technologies, blue for CCS technologies, orange for low carbon end-use technologies in the transport and residential sectors; purple for induced energy efficiency (IEE), green for fossil fuel resources and markets, and yellow for economic growth.

Figure 4: Analysis of variance

<table>
<tr><th>Indicators of robustness perspective</th><th>Contributions of the six different potential drivers</th></tr>
<tr><td>Ratio of production over resources for oil</td><td>
</td></tr>
<tr><td>Nuclear capacities installed</td><td>
</td></tr>
</table>

Note: The graphs show the contributions of each driver to the total uncertainty of the energy security indicator over time

The dispersion of the ratio of oil production to resources is mainly explained by the assumption concerning the fossil fuel resources and markets. Logically, the indicators worsen over time in the scenarios with a "low" assumption for fossil fuels, but remain stable in the scenarios with the alternative assumption. In the second case, the climate policies reduce the production required to satisfy world demand.

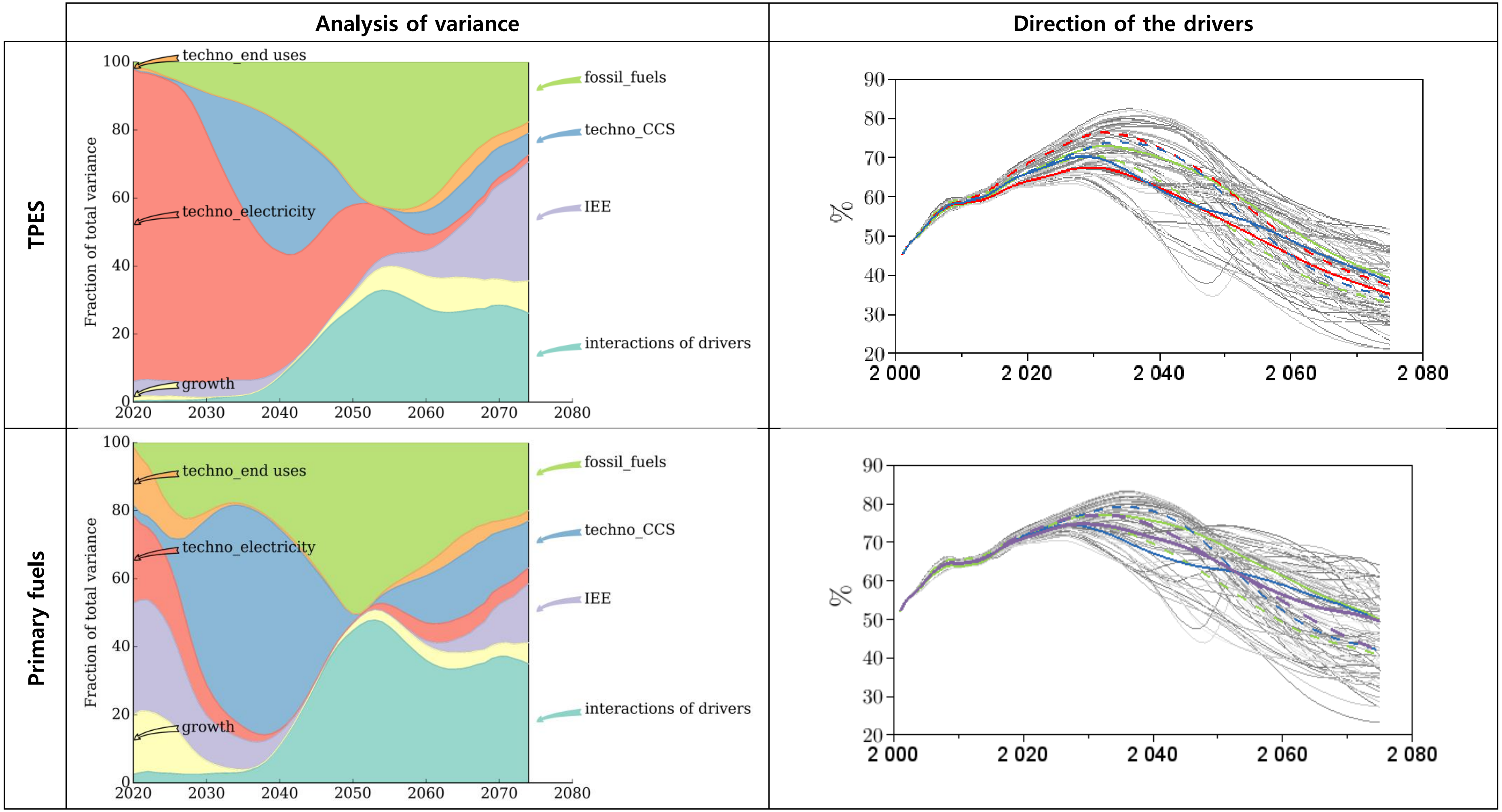
Concerning existing nuclear capacities, dispersion is mainly due to the assumption concerning the availability of the low carbon power generation technologies. Logically, the scenarios based on the "high" assumption, characterized by low cost and a high potential market share for nuclear technology, indicate greater existing capacity and hence the degradation of energy security.

Concerning the remaining indicators, we now analyze in more detail the factors that contribute to the variations between scenarios. Indicators of the robustness perspective are no longer included. Figures 5 and 6 present the contributions of each driver to the total uncertainty surrounding the energy security indicator (second column) over time. The evolution of the indicator is shown again in order to show the "direction" of the effect of each determinant. The same color code is used as in fig. 4. Only the three drivers that contribute most to the variance of the indicator are included. The solid line represents the average of the indicator across the subset of scenarios based on the "high" assumption; the dashed line represents the average of the indicator across the subset of scenarios based on the "low" assumption. Table 2 is a reminder of the meaning of the "low" and "high" assumptions with their corresponding color.

Table 2: The "low" and "high" assumptions for the six drivers considered

Determinants	Assumptions and corresponding color			
	Low	**Color code**	**High**	**Color code**
Power generation technologies	Low availability Slow learning	Dashed red	High availability Fast learning	Solid red
Carbon capture and sequestration	Low availability Slow learning	Dashed blue	High availability Fast learning	Solid blue
End-use technologies	Low availability Slow learning	Dashed orange	High availability Fast learning	Solid orange
IEE	Slow	Dashed purple	Fast learning	Solid purple
Fossil fuels resources and markets	Scarce/expensive	Dashed green	Abundant /cheap	Solid green
Economic growth	Slow leader productivity growth Slow productivity catch-up	Dashed yellow	Rapid leader productivity growth Rapid productivity catch-up	Solid yellow

Figure 5: Analysis of the dispersion of the indicators of the sovereignty perspective



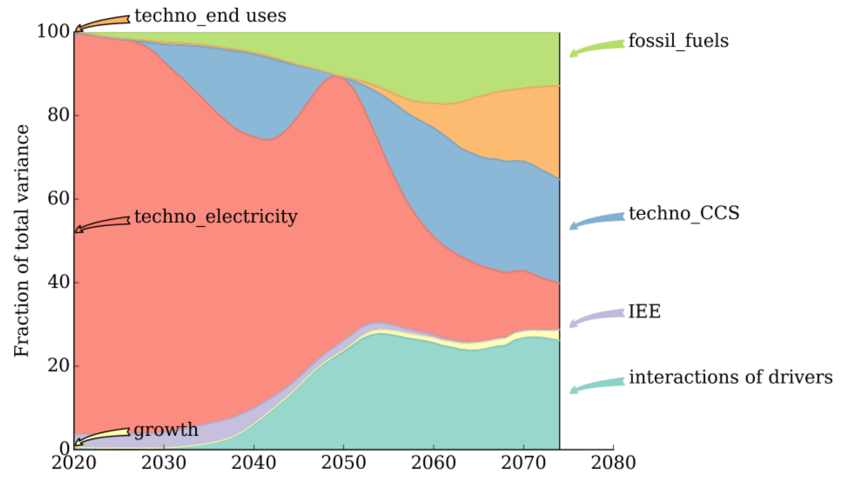
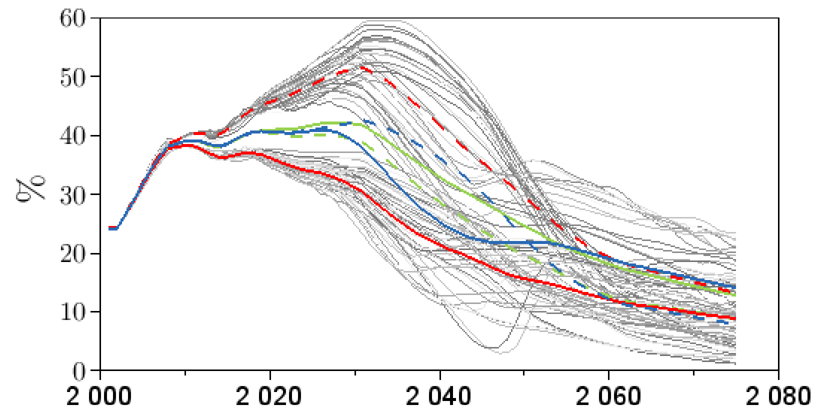
Electricity		

Figure 5 shows the results for the three indicators of the sovereignty perspective. They reveal that, for this perspective, the three indicators share almost the same main drivers. Indeed, the assumptions concerning CCS technologies and fossil fuels have a significant effect on all three indicators. The third determinant is the assumption concerning power generation technologies for the indicators on TPES and electricity, whereas the determinant is the assumption concerning IEE for the indicator on primary fuels.

For the share of imports in TPES and in power generation, the assumption concerning power generation technologies explains a large proportion of the variation between scenarios. This driver is particularly important in the short and medium term, but its importance declines in the long term, especially the share of imports in TPES. For both indicators, the "high" assumption leads to a significant improvement in energy security. The explanation for this result is that "high" availability of low-carbon power generation technologies leads to a faster penetration of renewables, which limits the imports of gas and diversifies the power generation mix. From around 2050 on, this assumption explains the dispersion of the results for the share of imports in TPES to a lesser extent, whereas the assumptions concerning fossil fuels and IEE play a bigger role.

The assumption concerning CCS technologies is also an important driver of the uncertainty in the results of the two previous energy systems but also of primary fuels. Nevertheless, the "direction" of its impact varies over time: around 2050, the blue dashed and solid lines intersect. In the short-/medium-term, a "high" assumption of CCS enables a lower share of imports in all the energy systems studied, because it uses relatively more (mainly domestic) coal and limits the penetration of gas and associated imports. In the long term, the "high" assumption concerning CCS allows more fossil fuel-powered generation to remain in the electricity generation mix, which has a negative impact on the share of imports.

The assumption concerning fossil fuels, not surprisingly, explains a large proportion of the dispersion of the results of the sovereignty perspective indicators, especially in the long term. For the three systems, (TPES, primary fuels and electricity), the "high" availability of fossil fuels has a negative effect: in this case gas prices are lower, which leads to higher imports of gas and more gas in the power generation mix.

The last significant determinant for the indicator on primary fuels is the assumption concerning IEE, which plays a role especially in the short term. After 2040, this assumption is no longer discriminating across the scenarios. After 2065, the assumption again plays a role, but less important than at the beginning of the century. The "high" assumption concerning IEE leads to scenarios with lower European dependence on imports because higher efficiency limits the overall energy demand, including for primary fuels.

In the long term, interactions between individual uncertain drivers explain a large proportion (up to 30% or 40%), of the variance of the indicators of the sovereignty perspective.

Figure 6: Analysis of the dispersion of the indicators of the resilience perspective

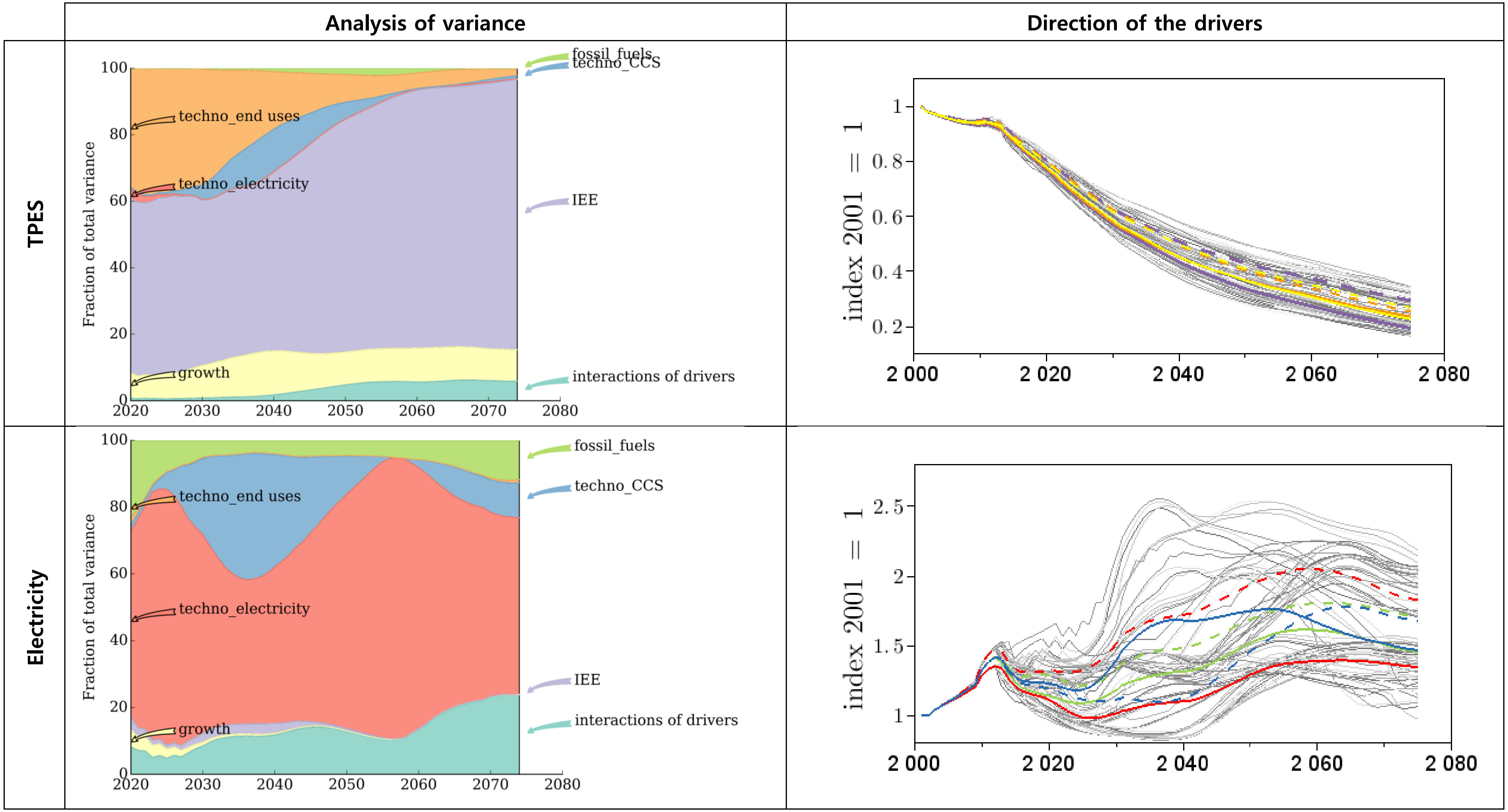


Figure 6 gives the results for two indicators, TPES and electricity, of the resilience perspective. Unlike the sovereignty perspective, the two indicators share no driver to explain their dispersion. Indeed, the assumptions concerning IEE, end-use technologies and economic growth are the main drivers of the uncertainty of the concentration of primary energies in power generation, whereas the assumptions concerning power generation technologies, CCS technologies and fossil fuels are discriminant for energy intensity across the scenarios.

The assumption concerning IEE is the main uncertain driver of the energy intensity of GDP. This discriminatory effect continues to the end of the century. The "high" assumption leads to a fast improvement of energy efficiency and thus significantly decreases energy consumption in the region. In the long term, this assumption also becomes important for the share of imports in TPES, an indicator of the sovereignty perspective, because higher efficiency limits overall energy demand, which can then be more easily satisfied with domestic resources.

The assumption concerning end-use technologies is important for the energy intensity of GDP in the short term. Logically, the "high" assumption reduces energy intensity faster.[17] The share of the variation across the scenarios is significantly due to end-use technologies, especially in the short term.

Although more modest, the assumption concerning economic growth also explains some of the variance of energy intensity. Although small, the discriminatory effect lasts over the whole period. Greater economic growth improves the energy intensity of GDP. This is because faster growth leads to faster capital turnover and hence more rapid improvement in energy intensity.

The dispersion of the resilience indicator for the electricity system is explained by completely different drivers. For the concentration of the power generation mix, the assumptions that play a discriminatory role are the same as for the sovereignty indicators for TPES and electricity. Nevertheless, the direction of some assumptions may differ.

The assumption concerning power generation technologies plays the most important role in explaining the dispersion between the scenarios during the entire century. This differs from the result concerning the share of imports in TPES and in power generation, for which the assumption shifts the evolution of the indictors especially in the short and medium terms. Here again, the "high" availability of low-carbon power generation technologies leads to faster penetration of renewables, which limits the imports of gas and diversifies the power generation mix.

The assumption concerning CCS technologies is a significant driver of the variation across the scenarios but there is a major difference in the results compared to the sovereignty indicators. Indeed, for the concentration of the power generation mix, the "high" assumption on CCS has a negative impact in the short and medium term because it limits the penetration of renewables, thus limiting the diversification of the mix. In the long term, the "high" assumption concerning CCS becomes positive for

[17] We note that, in the long term, "high" end-use technologies can have a negative effect on the share of imports for power generation, an indicator of sovereignty, because it leads to higher penetration of electrified vehicles and thus increases the demand for electricity, which is met by power generation technologies that require imports of fuel. This result might be moderated if "smart-grid" options were included in the modeling framework.

the diversity of the mix (i.e. it decreases the concentration of the power generation mix), because it allows more fossil fuel-powered generation to remain in the mix.

Lastly, the assumption concerning fossil fuels explains a rather modest proportion of the dispersion of the results for the concentration of the power generation mix. The assumption is most discriminatory in the short term. The effect of "high" availability of fossil fuels is negative, because it reduces the cost of generation of fossil fuels (including with CCS) and thus limits the penetration of renewables that diversify the generation mix.

5. Discussion and conclusion

This analysis focused on Europe contributes to recent efforts to better understand the evolution of energy security in a low-carbon world. We aimed to identify the uncertain drivers that explain the dispersion of the energy security indicators. As a result, we were able to identify levers that could limit the degradation of energy security when implementing ambitious climate policies.

Our results show that the evolution of some indicators can be highly contrasted across the scenarios and over the course of this century. The indicators for the electricity system exhibited the highest dispersion. Particular attention should be paid to this energy carrier so as not to damage European energy security too much when implementing significant reductions in CO_2 emissions. Our results show that several uncertain drivers play a crucial role in the evolution of these indicators. Logically, the cost and availability of the low carbon power generation technologies have a major effect on the dynamics of the indicators. If the "low" assumption concerning these technologies turns out to be true, European reliance on imported fuels for power generation and the concentration of primary energy sources in power generation would deteriorate significantly and rapidly, whereas the robustness of the system would be improved. Although less important, the cost and availability of the CCS technologies also affect the evolution of the indicators of the electricity system. Nevertheless, this driver plays a different role depending on the indicator concerned. If the "high" assumption on these technologies turns out to be true, the sovereignty of the system would be significantly improved, whereas its resilience would be degraded during the first half of the century. Indeed, the strong diffusion of the CCS technology would reduce the share of imports thanks to increased use of coal, but would limit the penetration of renewables. In the long term, the effect would be reversed. This last result reveals a possible contradiction between the deployment of CCS technologies and of renewables.

For the other energy systems, we also found significant, but lower, dispersion of the indicators. The results for TPES are the most interesting. The uncertain drivers that contribute strongly to the variance of the results for sovereignty are the same as those for the electricity system. On the other hand, the resilience of TPES depends on completely different drivers. The one that contributes the most is induced energy efficiency.

Finally, the paper shows that the European double target of significantly decreasing CO_2 emissions and increasing the security of the supply of energy can be difficult to reach. Nevertheless, some levers could facilitate the transition to a low-carbon society by improving energy security, or limiting its degradation. Indeed, our results emphasize the importance of policies in favor of low- or zero-carbon technologies in power generation, but also the differences in their contributions to the complete uncertainty of the indicators. Policies promoting energy efficiency also play a role but only for the sovereignty of TPES. These policies are thus important levers for mitigating the negative impacts of climate policies on energy security. This analysis could be completed interestingly by focusing on specific uncertain drivers and distinguishing between the different technologies (e.g. renewables and nuclear energy) or fossils fuels.

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Appendix - Description of the scenarios database

A.1. Drivers of economic growth

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 in unitary labor input l in each region j and at each time step t.

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

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 3 and 4).

Table 3: Parameters options for leader growth and high income population growth. Population data are available at https://secure.iiasa.ac.at/web-apps/ene/SspDb

	Slow growth	Intermediate growth	Rapid growth
Leader productivity growth	slow	medium	rapid
High income population growth	SSP3	SSP2	SSP1

Table 4: Parameters options for low income catch-up speed and population growth. Population data are available at https://secure.iiasa.ac.at/web-apps/ene/SspDb

	Slow growth	Intermediate growth	Rapid growth
Low income catch up time (τ_2 in eq. 1, in years)	300	200	150
Low income population growth	SSP3	SSP2	SSP1

A.2. Availability of different types 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 (Grubler et al., 1999). We consider two alternatives for each group of technologies. The high availability assumption corresponds to an earlier start date (only for Carbon Capture and Storage), a higher maximum market share, and faster diffusion than under the low availability assumption. Moreover, for some new technologies, there is an endogenous learning mechanism: the cost of the technology is reduced with the cumulative investment in that technology. This mechanism is governed by a learning rate, and two alternative values are considered for this learning rate.

• Low carbon power generation technologies

The technologies considered are nuclear and renewable energies. In the low availability assumption it is assumed that the new generation of nuclear energy is not available at all. The parameters are described in Table 5.

• Carbon Capture and Storage (CCS)

The parameters of each alternative are listed in Table 5.

• Low carbon end-uses technologies

The technologies considered are electric and hybrid vehicles, efficient buildings and household equipment. The parameters for electric and hybrid vehicles are described in Table 5.

Table 5: Parameters options for low carbon power generation, CCS and electric and hybrid vehicles

		Start date	Bottleneck phase (years)	Growth phase (years)	Maturation phase (years)	Maximum market share at the end of the maturation phase (%)	Learning rate
Nuclear (new generation)	High availability	2001	15	75	25	30	
	Low availability					0	
Renewables	High availability	2001	2	20	15	60	0.07
	Low availability	2001	3	65	25	50	0.05
CCS	High availability	2010	13	8	8	80	0.1
	Low availability	2014	17	8	8	30	0.05
Electric and hybrid vehicles	High availability	2010	6	40	16	80	0.2
	Low availability	2010	6	40	16	25	0.1

In the residential sector, the buildings stock is divided into two types of buildings: "classical" buildings and very low energy buildings (that consume 50 kWh per square meter and per year, 80% of which is electricity and 20% gas). The energy consumption of "classical" buildings is described by equation 2. The penetration of very low energy buildings depends on its extra investment cost that decreases following a learning rate. The parameters are listed in Table 6.

Housing energy expenditure of "classical" buildings:

$$H_{Exp} = \sum_{e} \left(\mu_h(t) \cdot \alpha_{m2}^{e} \cdot b_{stock} \cdot pFD_e \right) \qquad (2)$$

where H_{Exp} is the total energy expenditure in housing, for each country; α_{m2}^{e} is the energy consumption of buildings e per m^2, in each country (exogenous trend calibrated on POLES: see LEPII-EPE (2006)); $\mu_h(t)$ is a multiplier coefficient at year t; b_{stock} is the building stock in each country; pFD_e is the price of final demand for energy e in each country (which takes all taxes, including the carbon tax, into account).

Table 6: Parameters options for residential buildings and household equipment

	High availability	Low availability
Buildings energy consumption per	1	Trend starting at 1, reaching 1.2 in

m² (see μ_h in Equation 2)		2030 and staying at 1.2 after
Learning rate for very low energy buildings	0.08	0.03

A.3. 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. After a delay, the other countries catch up with the leader. We build two hypotheses (see Table 7) 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).

Table 7: Parameters options for energy efficiency

	Fast	Slow
Maximum annual improvement in the leader's energy efficiency	1.5	0.7
Other countries speed of convergence (% of the initial gap after 50 years)	10	50
Asymptotic level of catch-up (% of the leader's energy efficiency)	95	60

A.4. Fossil fuels - resources and markets

A.4.1. Oil

The modeling structure of oil supply in Imaclim-R is based on three general principles. First, a physical description of oil resources with an explicit differentiation according to the region and nature (conventional vs. non- conventional) is used in the dynamic submodel to describe changes in oil producing capacities (see Equation 3). Oil resource availability is based on data from USGS (2000); Greene et al. (2006) and Rogner (1997). Secondly, an explicit differentiation is made between fourteen (seven conventional and seven non-conventional) categories of resources in each region according to the cost of exploration and exploitation. As oil must be discovered before it is produced, the temporal availability for production of a given category of oil resources depends on the characteristics of the discovery process, which is subject to two main effects: the information effect (the more an oil slick is exploited, the more information about the localization of remaining resources is obtained) and the depletion effect (the more a slick is exploited, the less oil remains in the soil). Following Rehrl and Friedrich (2006), inertias in the deployment of oil producing capacities resulting from the combination of these technical constraints on the discovery process are captured through independent bell-shaped curves that determine the changes in the oil producing capacities over time for each category of oil in each region.

We distinguish the different categories of regional oil resources according to their production costs (i.e. including exploration and exploitation costs) and the nature of the resource (conventional or non-conventional). To this end, we associate a bell-shaped time profile of its production with each resource category:

$$\frac{Q_\infty \cdot b \cdot e^{-b(t-t_0)}}{\left(1+e^{-b(t-t_0)}\right)^2} \qquad (3)$$

where t is the current date, t_0 is the starting date of oil production for this category, Q_∞ is the amount of ultimate resources and b is a parameter that captures the intensity of constraints that slow down production growth.

Concerning the dynamics of production capacities, Imaclim-R distinguishes two types of oil producers according to their investment behaviors. All non-Middle-Eastern countries are assumed to be motivated by short-term returns on investments, which implies that they will bring a category of oil reserve into production as soon as it becomes profitable (that is when the selling price on world market exceeds the total cost of exploration and exploitation). From then on, the deployment of production capacities is limited by geological constraints and strictly follows the corresponding bell shaped curve. Producers who do not use any strategic behavior are referred to as "fatal producers" (Rehrl and Friedrich, 2006). The situation is different for Middle Eastern producers, as the amount of their oil resource gives them market power and allows them to choose a strategy to fulfill a specific objective (either a price or a market share target). For a given year, Middle Eastern production capacity is still bounded by a bell-shaped curve but its actual production may be below this limit if the chosen strategy requires a restriction on production. This "swing producer" (Rehrl and Friedrich, 2006) behavior is consistent with past OPEC production, which has not fitted the discovery trend since the oil shocks in the 1970s (Laherrere, 2002).

Middle Eastern countries can use their market power in two opposite ways (and any combination in between). The first is to secure high prices in the short run by limiting the expansion of their production capacities; but this strategy has the disadvantage of encouraging oil importing countries to accelerate their efforts to develop oil free technologies and to adopt energy-sober consumption patterns. The second one is a "market flooding" strategy to maintain rather low prices in the short-term to encourage oil consumption and discourage oil importing countries from continuing efforts to save oil. The trade-off is between low revenues in the coming decades and higher income in the long run, the lower price elasticity of the oil demand being due to the lack of large scale cheap substitutes for oil. The trade-off between these two assumptions does not depend only on the flows of export revenues, it also depends on geopolitical considerations and on the long term objectives of the Middle Eastern governments, including the way they prepare their "post-oil" era. The conduct of these strategies will depend on the internal agreement among OPEC members and Middle Eastern countries. When OPEC countries agree on policy, they may agree to cut back production so that oil prices are high; conversely, when they are divided, they tend to produce more individually, resulting in lower oil prices.

Within this oil supply module, we decided to explore the uncertainty on the components of three major parameters to describe different levels of oil scarcity: the amount of ultimately recoverable resources, the level of inertia that will shape the development of non-conventional production, and the OPEC target oil price (see Table 8).

A.4.2. Gas

In the model, gas world production capacities match demand growth until ultimately recoverable resources enter a depletion process. Variations in gas prices are indexed on variations in oil prices via an indexation coefficient (0.68, see Equation 5) calibrated on the World Energy Model (IEA, 2007). When oil prices increase by 1%, gas prices increase by 0.68%.

Two alternative assumptions are used in this price indexation. Under the assumption "relatively abundant and cheap" for the fossil fuel resources and market parameter set, this indexation disappears when oil prices reach 80$/bl: beyond this threshold, fluctuations in gas prices only depend on production costs and possibly on the depletion effect. When depletion is reached, price increases. Under the assumption "relatively scarce and expensive", gas prices remain indexed on oil prices regardless of fluctuations, but an additional price increase occurs when gas production enters its depletion phase.

The price of gas in each region at year *t* is:

$$p_{gas}(t) = p_{gas}^{ref} \cdot \tau_{gas}(t) \qquad (4)$$

where p_{gas}^{ref} is the gas price in this region at year 1.

As long as gas depletion has not started, $\tau_{gas}(t)$ in each region is:

$$\tau_{gas}(t) = 0.68 \cdot \left(\frac{1}{3} \cdot wp_{oil}(t) + \frac{2}{3} \cdot wp_{oil}(t-1) \right) \cdot \frac{1}{wp_{oil}^{ref}} \qquad (5)$$

Where $wp_{oil}(t)$ is the world oil price at year t; wp_{oil}^{ref} is the world oil price at year 1.

If depletion has started in this region, $\tau_{gas}(t)$ increases 5% each year, regardless of oil prices.

A.4.3. Coal

Coal is treated in a different way than oil and gas because more coal resources are available, which prevents coal production from entering a depletion process before the end of the 21st century.

We describe price formation on the world coal market in a reduced functional form linking variations in price to variations in production. This choice allows us to capture the cyclic behaviour of this commodity market. 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 price of coal increases if coal production increases). We make two assumptions for η_{coal} (see Table 8). Under the assumption of "relatively abundant and cheap" the sensitivity of an increase in coal price to an increase in coal production is quite low, so that the increase in coal production can be absorbed without price fluctuations. Conversely, the increase in coal price is very sensitive to any increase in coal production under the assumption "relatively scarce and expensive".

Table 8: Parameters options for fossil fuels

	Relatively abundant	Relatively scarce
Oil		
Amount of ultimately recoverable resources (Q_∞)	3.6 Tb	3.1 Tb
Inertia in the deployment of non-conventionals (spread of the bell-shaped curve *b*)	No inertia (*b*=0.061)	Inertia (*b*=0.041)
OPEC target oil price	80$/bl	120$/bl
Gas		
Indexation of gas price on oil price	$p_{oil/gas}$=80$/bl	No threshold
Coal		
Price growth elasticity to production variations (η_{coal})	1.5	2

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Supplementary material

Regional and sectoral aggregation of Imaclim-R model

Regions	Sectors
USA, Canada, Europe, Pacific OECD (Japan, Australia, New-Zealand, South Korea), Commonwealth of Independent States, China, India, Brazil, Middle East, Africa, Rest of Asia, Rest of Latin America.	Coal, Oil, Gas, Liquid fuel refinery, Power generation, Air transportation, Maritime and water transportation, Terrestrial transportation, Construction, Agriculture, Industry, Composite sector (services and light industry).

Publications where specific modules of the model Imaclim-R are explained

	Description of Imaclim-R structure and results	Models comparison (including Imaclim-R)
Technologies	Bibas and Méjean (2014) (bioenergy)	Kim et al. (2014) (nuclear) Koelbl et al. (2014) (CCS) Krey et al. (2014) Kriegler et al. (2014) Luderer et al. (2014) (renewables) Rose et al. (2014) (bioenergy) Tavoni et al. (2012)
Energy efficiency	Bibas et al. (2015)	Sugiyama et al. (2014)
Fossil fuels	Rozenberg et al. (2010) Waisman et al. (2012) Waisman et al. (2013a)	Bauer et al. (2015) MCCollum et al. (2014)
Transport	Waisman et al. (2013b)	
Macroeconomy	Crassous et al. (2006) (endogenous structural change) Guivarch et al. (2011) (labor	

	markets)	
Evaluation of model	Guivarch et al. (2009) (b ackcasting)	Kriegler et al. (2015b) (diagnostics)
Scenarios	Guivarch and Mathy (2012) Hamdi-Cherif et al. (2011) Mathy and Guivarch (2010) Rozenberg et al. (2014) Waisman et al. (2014)	Blanford et al. (2014) Kriegler et al. (2015) Luderer et al. (2012a) Luderer et al. (2012b) Riahi et al. (2015)

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