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1. Introduction

This deliverable aims at analyzing the energy and climate change aspects of AUGUR scenarios. To do so, we first map AUGUR scenarios into the framework of the new socioeconomic pathways for climate change research. Indeed, the climate change research community is pursuing development of a new framework for the creation and use of scenarios to improve interdisciplinary analysis and assessment of climate change, its impacts, and response options. It is important that the analysis of energy and climate change aspects of AUGUR scenarios is conducted within this framework, for relevance and comparability with other scenarios that will be described in the literature. Section 2 exposes the methodology used to map the scenarios.

Section 3 then analyses the scenarios results focusing on the climate change and energy security issues. It shows that both climate change and energy security issues are long-term issues, for which the main challenges may arise after the 2030 horizon. However, the two coming decades are crucial for these issues since the directions taken over this short-/medium-term risk to create lock-ins of the economies in carbon and/or oil dependency. And 2030 should then be seen as an intermediary point with respect to these issues. The question is therefore less that of the point reached in 2030 but more that of the legacy it represents for the decisions to be made at that time and of which options it preserves for them.

Section 4 concludes by giving quantified elements for the narratives of the energy and climate change aspects of AUGUR scenarios.

2. Mapping AUGUR scenarios into the framework of the new socioeconomic pathways for climate change research

2.1 The new socioeconomic pathways for climate change research

The climate change research community is pursuing development of a new framework for the creation and use of scenarios to improve interdisciplinary analysis and assessment of climate change, its impacts, and response options. It is important that the analysis of energy and climate change aspects of AUGUR scenarios is conducted within this framework, for relevance and comparability with other scenarios that will be described in the literature.

Within this new framework, the scientific community is now developing a new set of scenarios to replace the SRES (Moss et al., 2010; van Vuuren et al., 2010; Kriegler et al., 2010; Arnell et al.,2011; O'Neill et al., 2012).The new process will build climate and socioeconomic scenarios in parallel, starting from a set of four future paths for anthropogenic impact on the climate system, measured using "radiative forcings."[1]These four paths are known as representative concentration pathways (RCPs). Climate modelers are currently assessing the climate response to these RCPs. At the same time, Integrated Assessment Model (IAM) modelers will build socioeconomic scenarios, called Shared Socioeconomic Pathways (SSPs), consistent with the RCPs.

As with the earlier SRES scenarios, the new SSPs will describe different socioeconomic characteristics, different vulnerabilities, and different GHG emissions. To assist with the exploration of both adaptation and mitigation questions with the same set of scenarios, Arnell et al. (2011) propose to develop SSPs that are contrasted along two axes: the capacity to mitigate and the capacity to adapt (see Figure 1).

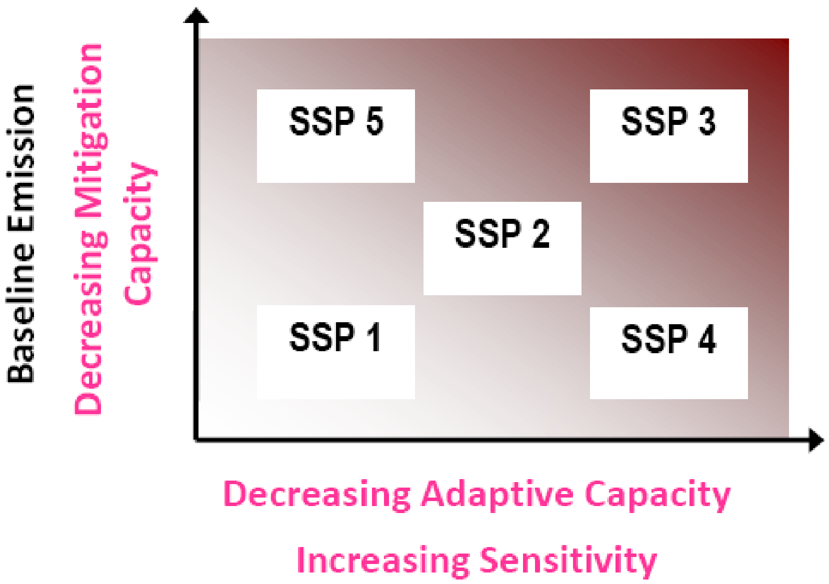


Figure 1: SSPs covering the space of possible futures in terms of capacity to mitigate and capacity to adapt.

[1] The radiative forcing is the change in net radiative flux at the top of troposphere (i.e., at the tropopause) that results from a change in atmospheric composition (including greenhouse gas [GHG] concentrations); this change takes into account all GHG and is calculated after the stratosphere reaches its equilibrium.

2.2 A scenario elicitation methodology to map the space of possible future mitigative and adaptative capacity

2.2.a Scenario elicitation methodology

To explore the space of capacity to mitigate and capacity to adapt, we develop here a "backward" approach. We start with a large set of model runs that span a wide range of capacities to adapt and to mitigate. We define SSPs in terms of different threshold values for capacity to adapt and to mitigate. We then determine which sets of drivers best determine those SSPs. In consequence, our methodology is based on (i) an identification of potential drivers of mitigation and adaptation capacity, (ii) a modeling exercise to explore the uncertainty space and select scenarios, and (iii) an *a posteriori* confirmation of which drivers matter and of the sign of their influence on adaptation and mitigation capacity.

To build a database of many cases, we first identify potential drivers of future capacity to adapt and mitigate, following, for instance, Hallegatte et al. (2011). Then, we translate some of our potential drivers of adaptation and mitigation capacity into different model parameters (e.g., the amount of oil resources ultimately recoverable). Others drivers cannot be accommodated in the model and are considered part of a quantitative (or qualitative) narrative, accompanying model parameters and results (e.g. quality of governance). Combining the different states of these drivers (e.g., the amount of oil is low, medium, or large; governance is efficient or not), we build a database of model runs. We obtain several hundreds of scenarios by combining these runs with the narrative components that cannot be included in the model.

Once we have constructed the database, we distinguish the scenarios using criteria measuring future ability to adapt (e.g., the share of people living below the poverty line) and future ability to mitigate (e.g., baseline CO_2 emissions). We can then choose a few scenarios according to their contrasting results in terms of these criteria. From this selection, we can identify (in a backward way) a set of drivers and model inputs that correspond to these scenarios and can be labeled SSPs.

We identify these drivers using an analytic "scenario discovery" method (Bryant and Lempert, 2010; Groves and Lempert, 2007), which applies statistical algorithms to databases on model results to find those combinations of input parameters most important towards generating model outputs with significant common characteristics. For example, one such scenario discovery analysis focused on mitigation strategies, evaluating the costs and benefits of a Renewable Energy Portfolio standard in the U.S. It found that the availability of low-cost biomass feedstock and low-cost sites for wind energy were the most important drivers for whether or not the policy produced high cost outcomes (Toman et al., 2008). Another analysis focused on adaptation options, evaluating the impact of climate change on the investment plans of a particular California water agency. It found that the most important scenarios to consider included both the severity of climate change and the agency's ability to implement specific components of its investment plan (Lempert and Groves, 2010).

In this study, the scenario discovery algorithms identify the common characteristics (e.g., the demographic changes, the extent of globalization) that best predict the scenarios where the capacity to adapt or to mitigate is high or low. They thus help us select a few SSPs that are contrasted along these criteria.

To summarize, we propose the following approach for developing SSPs:

(i) We first identify *a priori* the main driving forces of the world future capacity to mitigate and adapt to climate change, based on existing literature (Section 1.2.b).

(ii) We then translate these driving forces into model parameters for a global energy-economic model, and we combine these parameters to build a large number of model runs. We also combine model outputs with "narrative" information to create a large set of scenarios (Section 1.2.c).

(iii) We analyze the resulting database using indicators measuring future capacity to mitigate and adapt to climate change, and we identify *a posteriori* the main driving forces of the world future capacity to mitigate and adapt to climate change. Then we select five contrasting combinations of drivers to cover the range of possible capacities to adapt and mitigate. We propose these five driver combinations as SSPs (Section 1.2.d).

2.2.b The a priori drivers of capacity to adapt and mitigate

Hallegatte et al. (2011) propose three dimensions to explore climate change vulnerability and adaptation capacity, and it appears that these dimensions are also relevant for mitigation capacity. To map the space of possible futures and cover plausible capacities to mitigate, however, it is necessary to add a fourth one. The four resulting dimensions– globalization, equity, environmental stress, and carbon supply -- are presented in this section.

Globalization: a "converging" world vs. a "fragmented" world

In a converging world, the economic structure of developing countries converges rapidly toward the structure of industrialized countries. For instance, the share of agriculture in their economies decreases in terms of gross domestic product (GDP) and exports. Also, available technologies are similar in industrialized and developing countries; and urbanization rates converge around rich-country standards. Developing countries undergo a demographic transition so that population age structure converges and global population growth rates decrease. In a more fragmented world, conversely, developing-country economies catch up more slowly, and for an extended period of time they remain based on agriculture, raw-material extraction, and tourism. These countries remain largely rural. In such a world, developing countries depend more on rich countries for high-technology goods and can balance their imports only thanks to low-value-added goods and services. Population remains young in developing countries, with high fertility and mortality rates, and global population growth rates are higher than in a homogenous world.

This dimension is mainly about changes in economic structures and not trade and openness, even though a converging world has more international trade than a more fragmented one. Indeed, in a homogenous world, industrial and commercial policies seek export-led growth, whereas a fragmented world induces a more inward-oriented growth.

In such a world, globalization of financial markets is limited, whereas in a homogenous world, capital markets are integrated.

This dimension is important for IAV (Impacts, Adaptation, and Vulnerability) analysis for two main reasons. First, agriculture in developing countries is likely one of the sectors most negatively affected by climate change (Lobell et al., 2008). In a more homogenous world, these countries would be less vulnerable because agriculture becomes less important in their economy. They would also be at reduced risk of food insecurity because of better access to world food markets, thanks to alternative non agricultural exports (Chen and Kates, 1994). Second, the future of urbanization matters because urban and rural areas have different main vulnerabilities (e.g., floods in urban areas vs. droughts in rural areas). Population matters because it has important impacts on food security, flood risks, or housing.

This dimension is relevant for MP (Mitigation Policies) analysis because the economic structure of developing countries will determine their energy consumption and production. In a fragmented world, developing countries remain mainly rural and based on agriculture, so their future patterns of energy consumption are similar to those today, i.e., much lower than in developed countries. In a converging world, developing countries' energy consumption will depend on the other dimensions, for instance, the type of technologies available and the magnitude of urban sprawl. Population growth rates are important for MP analysis, because higher population growth rates imply higher energy consumption. Even though it is not very well understood yet, population aging is important as wellit might be accompanied by a decline in the number of people per household (a process already observed in industrialized countries). As small households consume more energy per person than large households (Ironmonger et al., 1995), CO_2 emissions might increase with increased aging (MacKellar et al., 1995).

Equity: inclusive development vs. "growth and poverty" development

In an inclusive world, the poorest communities have a voice in political choices, national governance takes poverty reduction into account as an important policy goal, and policies successfully reduce the share of people in extreme poverty. Social protection is reinforced so that almost everybody gets access to basic services, such as health care, education, energy and transport, drinking water and sanitation, financial services, secured land tenure, and risk management practices.

In a more "poverty and development" oriented world, a fraction of poor-country population is excluded from these services.

This dimension is partly independent of the previous one because extreme poverty may either disappear or increase in countries, regardless of their aggregate economic growth.

This dimension can also include differences in terms of governance efficiency. In particular, in an inclusive world, environmental policies are likely to be more efficient than in a "poverty and growth" world. Conversely, a non inclusive world can include a lack of government regulation that often implies the existence of a huge informal sector (Gerxhani, 2004). Indeed, in such a world, informal market labor is likely to be widely developed (undeclared labor, lack of social benefits, subminimum wages, poor working conditions, etc.) (Palmer, 2008).

It is important for IAV analysis to take into account this dimension because poor communities are considered the most vulnerable to climate change (Smit and Wandel, 2006). They are more exposed to environmental conditions (e.g., their access to natural resources, such as water, is not mediated by infrastructure). They also have to cope with multiple stressors (O'Brien et al., 2004) and have less capacity to adapt due to lower financial capacity, education and health, institutional capacity, or political weight, for instance (Yohe and Tol, 2001).

This dimension also has consequences for MP analysis because today, 20% of the global population lack access to electricity and 40% rely on traditional use of biomass for cooking (IEA, 2010). The burning of biomass in inefficient stoves emits black carbon, which plays a large role in global and regional warming (Luoma, 2010). In a "strong governance world," households can more easily climb the "energy ladder" (Reddy, 2000; Reddy and Balachandra, 2006). An "inclusive development" world implies universal electricity access and an expansion of household access to modern fuels. This would increase global energy consumption – and global GHG emissions – more than in a "poverty and development" world, even though improved stoves and greater conversion efficiency would reduce its black carbon content (IEA, 2010).

Environmental stress: an "environment-oriented" world vs. an "environmentally-stressed" world

In an environment-oriented world, policies, technologies, management practices, and lifestyles lead to an efficient use of natural resources and reduce environmental stresses. There is a differentiation in consumption behaviors, each region yearning – or being enforced – to follow a more energy-sober development style.

In an environmentally stressed world, water use is inefficient and energy and mobility demands are growing. Soil depletion and degradation are accelerated and reduce agricultural productivity and increase natural risks (e.g., floods). Biodiversity losses are large. In this world, the use of natural resource is already creating environmental stresses, even without climate change, and climate change impacts affect already vulnerable environments.

This dimension is partly independent of the previous ones, since economic development and poverty reduction may be accomplished– temporarily – with or without efficient use of natural resources.

Environmental stress matters for IAV analysis, because ecosystems' ability to cope with climate change depends on the other stresses with which they have to cope (Noble et al., 2005) and additional resource scarcity from climate change can have different consequences depending on how they are managed. For instance, reduced rainfall has larger economic consequences if existing resources are already stretched by inappropriate agriculture production and if groundwater is not usable because of pollution or salinization (Arnell, 2004).

This dimension is important for MP analysis, because mobility preferences and spatial organization determine the energy content of economic growth through the populations' need for energy services. Accordingly, an "environment oriented" world has a larger capacity to mitigate climate change than an "environmentally-stressed" world.

Carbon dependence: a "high carbon dependence" world vs. a "low carbon dependence" world

To analyze mitigation, it is important to consider other drivers. In particular, the dependency to fossil fuel will play a critical role, justifying the introduction of a fourth axis in our framework.

In a "low-carbon dependence" world, the availability of fossil energy is low. World oil resources are scarce, with oil production reaching its maximum level before 2020, and gas and coal are expensive to extract. The potential for new technologies is high, and it is easy to orient technical change toward mitigation. Low-carbon technologies, such as electric cars, biofuels, CCS (Carbon Capture and Sequestration), and renewable energy sources are easy to develop, because of a low inertia in the renewal of equipments and fast technical progress.

In a "high-carbon dependence" world, fossil fuels are largely available and fossil energy prices thus remain low for a few decades. The pace and direction of technical change favors carbon-intensive technologies and carbon alternative liquid fuels (e.g., Coal-To-Liquids).

This dimension is partly independent from the previous one because it is driven by geological parameters and some technical parameters independent from the agents' choices (the pace and direction of technical change is partly exogenous and partly endogenous, since it depends on learning-by-doing mechanisms and investments in R&D).

Carbon supply matters for IAV analysis because carbon dependence will determine the potential for developing adaptation-friendly technologies (e.g., use of desalinization and air conditioning).

It is important for MP analysis because, everything else being equal, mitigation policies will be cheaper if fossil energy prices are high and low-carbon technologies are easy to develop. In a world locked into a carbon-intensive pathway because fossil energy is cheap, mitigation potential is very thin. Indeed, economy sectors are characterized by significant inertia in installed capital, infrastructure, and behaviors that cannot be changed overnight. In some sectors, productive capacities and infrastructures have lifetimes of several decades (IEA, 2000; Worrell and Biermans, 2005; Davis et al, 2010; Guivarch and Hallegatte, 2011). For instance, most industrial installations have lifetimes spanning more than 30 years, whereas urban infrastructure, transport infrastructure, and some buildings have lifetimes lasting over a century. It is likely that urban forms imply an even larger inertia than that suggested by physical capital lifetime (Gusdorf and Hallegatte, 2007; Gusdorf et al., 2008). This inertia constrains the pace of possible decarbonisation of the sectors, and a lock-in of the transportation and residential sectors in carbon-intensive pathways can have very important consequences on mitigation costs.

The resulting four dimensions are shown in Figure 2, giving an idea of which parameters can be included in each dimension. The figure suggests that some of these parameters can be included in different dimensions (e.g., urbanization can be included in the environmental/lifestyle dimension or in the convergence dimension), showing that there will always be some flexibility and subjectivity in how our approach is applied.

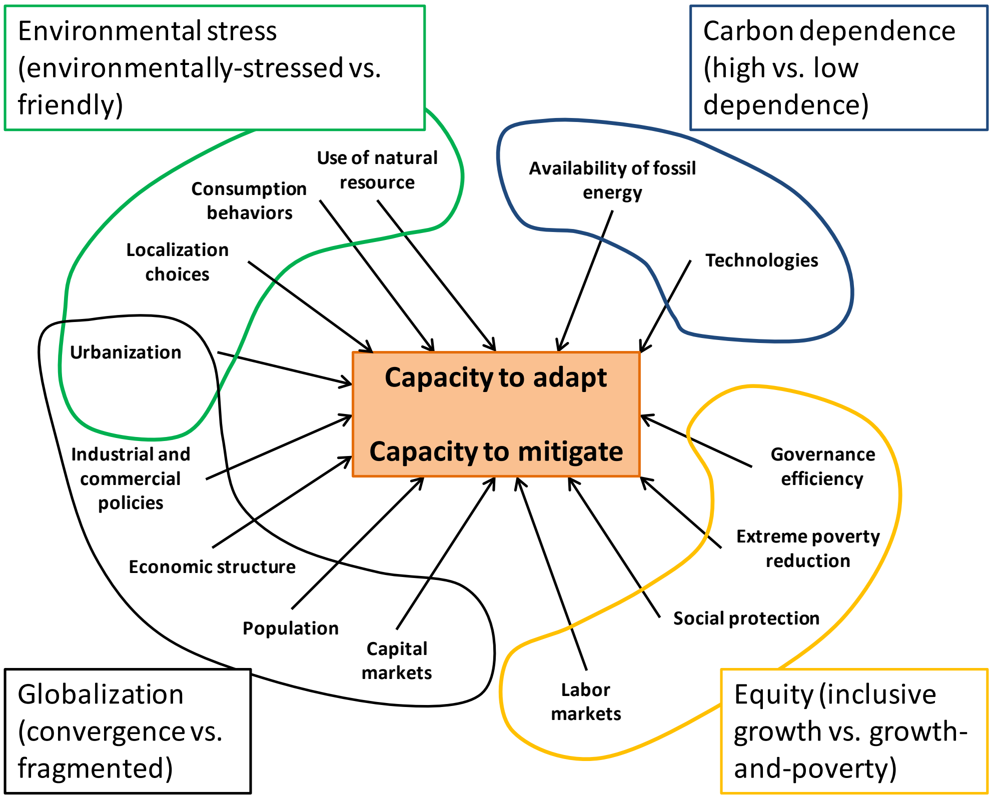


Figure 2: Identified drivers of the capacity to mitigate and adapt, in the four main dimensions.

2.2.c How to build scenarios

There are good reasons to think that these factors will be the major drivers of the ability to adapt and to mitigate, but this is only an informed guess. Complex mechanisms, interactions, and feedbacks can act on these drivers, and a more sophisticated analysis is possible. To test whether these drivers are well chosen, we translated some of them into model parameters.

To do so, we used the IMACLIM-R model (see the box below for a brief description and AUGUR WP5 deliverable 1 for details), which projects the long-term evolution of the world economy and allows us to explore the uncertainty that arises from unknown exogenous trends (e.g., future population) and parameter values that are debated.

Description of the IMACLIM-R model.
IMACLIM-R is a hybrid simulation model of the world economy (Rozenberg et al., 2010; Waisman et al, 2012) which represents in a consistent framework the macro-economic and technological world evolutions.
The growth engine is composed of exogenous demographic trends and of technical progress that increases labor productivity, as in Solow's neoclassical model of economic growth (Solow, 1956). The two sets of assumptions on demography and labor productivity only prescribe potential growth. Actual economic growth then results endogenously from the interaction of these driving forces with short-term constraints: (i) available capital flows for investments and (ii) under-utilization of production factors (labor and capital) due to the inadequacy between flexible relative prices (including wages) and inert capital vintages characteristics. Importantly, the model is not based on perfect expectations, but on adaptive expectations reacting on current price signals and past trends. IMACLIM-R, therefore, represents a second-best economy, i.e a suboptimal economy in which resources can be under-utilized. Actual economic growth can thus be constrained by resource availability if resource scarcity was not well anticipated.
Dynamic sub-modules in the model represent the evolution of households' equipment and productive capacities technical characteristics, including technology explicit descriptions of the main elements of the energy system (power generation, vehicles…) and endogenous technical change mechanisms (learning-by-doing, induced energy efficiency).

For this exercise, we selected the following drivers to be translated into input parameters of the IMACLIM-R model and consider several alternative values for these parameters to reflect uncertainty about future conditions:

Dimension1: Globalization

Population. We use the three UN scenarios (low, median, and high).

Economic structure. Even though this driver is an output of the IMACLIM-R model, we influence it by introducing three assumptions on the speed of labor productivity convergence (see A1 in Annex 1).

Capital markets. The IMACLIM-R model treats capital balances as exogenous, so we consider two assumptions about global financial imbalances reduction: In the first assumption financial imbalances are phased out exponentially in two decades, whereas in the second assumption they remain constant for the whole simulation period.

Dimension2: Environmental stress

Energy sobriety. We make two assumptions (i.e. two groups of hypotheses affecting many different variables) regarding 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 (see A2 in Annex 1).
- 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 (see A2 in Annex 1).
- Induced energy efficiency: Even though energy efficiency is driven by energy prices, we introduce two alternatives for the parameters describing its maximum annual

improvement in the leading country and the catch-up speed of the others (see A2 in Annex 1).

Dimension3: Carbon supply

Availability of fossil energy. We introduce two assumptions about oil resources (parameters include the amount of ultimately recoverable resources, inertia in the deployment of non conventional oil, the maximum growth rate of Middle-East production capacities), the gas price indexation on the oil price, and the elasticities of coal price growth to demand changes (see A3 in Annex 1). Each of these variables can take two different values depending on the assumption.

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. (More details are given for each technology in A4 in Annex 1.)

Dimension4: Equity

Dimension 4 has to be treated differently, because its drivers (inequality within countries) cannot be included in the model in its current form. Since the model is based on a representative consumer-worker, distribution aspects cannot be taken into account. Considering the importance of this driver, it cannot be disregarded, and we introduce it in a "quantitative narrative," i.e., in numerical information that accompanies model results to build a scenario.

In the current case, therefore, we add to the model outputs a qualitative/quantitative narrative information (an "equity" driver). Some of the scenarios are built assuming a global reduction of within-country inequality (an "inclusive growth" set of scenarios), in which the share of income of the 20% poorest in countries increases by 33% by 2090 (e.g., in a country where the 20% poorest receive an income corresponding to 6% of total GDP in 2010, this share increases to 8% in 2090). Others are built assuming a global increase in within-country inequality (a "growth and poverty" world), with a share of income of the 20% poorest that decreases by 33% by 2090. To the model outputs, therefore, we add an additional variable, namely, the income of the 20% poorest, which is built from model outputs (GDP per capita in less developed countries) and from "narrative" information.

Resulting scenarios database

The result is a set of 286 scenarios[2] (see Figures 3 and 4), each being the combination of (1) a set of model parameters describing the drivers, (2) a model run with these parameters, and (3) additional quantitative and qualitative information that cannot be accommodated in the model but are relevant for adaptation and mitigation capacity (e.g., in our case, inequalities within countries).

[2] Combining all assumptions creates 288 model runs,but one baseline did not run until the end of the simulation period.Thus, two scenarios are excluded from the database (derived from this model run and the two hypotheses on equity).

2.2.d How to select relevant scenarios

To select scenarios that cover the capacity to mitigate and adapt, the first step is to define indicators for these capacities. This is a very important (and difficult) endeavor. Much work has been devoted to this task, but there is little agreement on how to proceed. Taking the example of the capacity to adapt, Füssel (2009) reviews the many indicators that have been proposed and shows that they lead to very different prescriptions and vulnerability hot spots. Also, he shows that vulnerability and adaptive capacity cannot be identified in isolation from political considerations and value and ethical judgments. Our analysis is thus developed and illustrated using very simple indicators, taking into account the fact that more work on this issue needs to be done, and that the methodology needs to be able to accommodate a fairly large set of indicators.

For mitigation, we chose baseline CO_2 emissions as an indicator. We are well aware that this measure does not include all components of the ability to mitigate. For instance, good governance and reduced inequalities are likely to make it easier to implement mitigation policies, regardless of CO_2 emissions. But as a first-step analysis, we use this indicator.

For adaptation, no natural indicator is available. Still well aware of the limits, we decided to use the income of the 20% poorest in a selection of developing countries (African countries, India, South America [except Brazil] and South East Asia). Of course, this is a very partial indicator, and it is well known that the ability to adapt will depend on many other factors, such as governance and technologies (see the review in Section 1.2.b and in Hallegatte et al., 2011). In the current analysis, we use this very simple indicator only to illustrate our methodology and make a first proposal for SSPs.

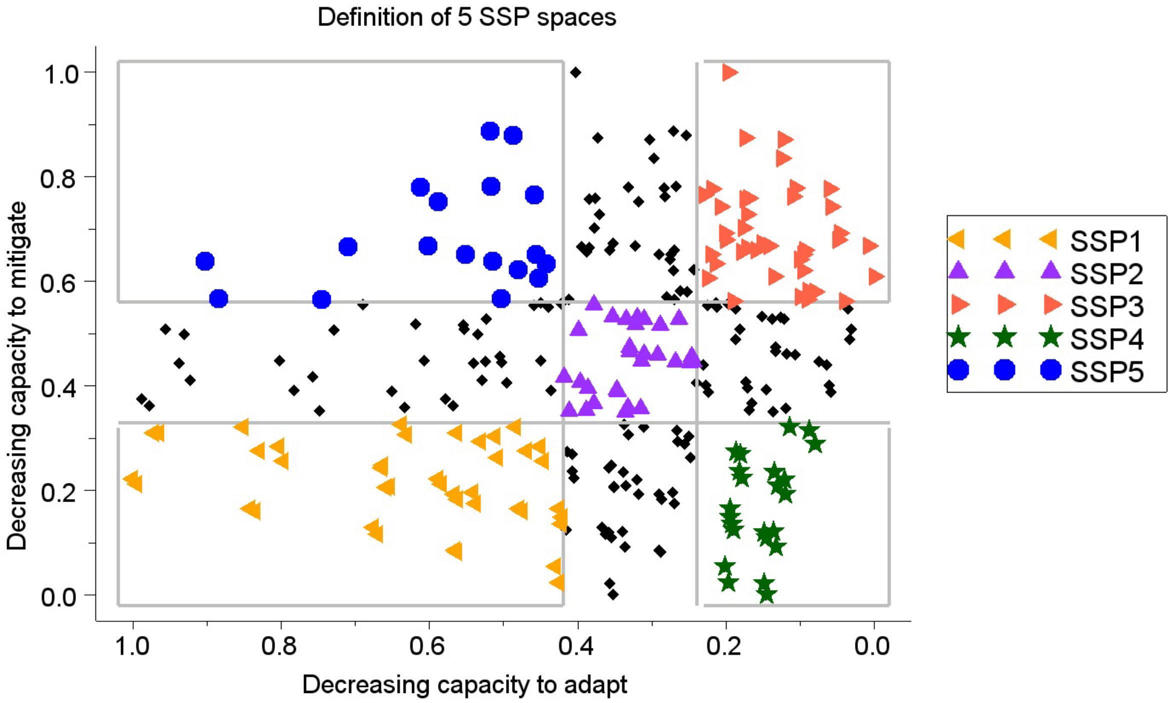


Figure 3: Capacities to adapt and to mitigate that define the five SSP spaces and the results of our 286 model runs arrayed in this space.

We next normalize our two indicators (the sum of global emissions over the 2011-2090 period for mitigation capacity and the discounted income, over the same period, of the 20% poorest in developing countries) for adaptive capacity and map our 286 scenarios over the resulting space. As shown in Figure 3, the scenarios span most combinations of capacity to mitigate and adapt as defined by these indicators. We then define five regions in this space that correspond to the five SSPs.

In the selection of SSP spaces, we emphasize contrast, i.e., on having scenarios with different capacities to mitigate and adapt. We do not focus on the "probability," or even the plausibility, of these scenarios. The "plausibility" is supposed to be ensured in the first phase of this analysis, when the determinants have been chosen and transformed into model parameters. We do not want to focus on probabilities because the ability to assess them appears out of reach and because focusing on the most likely scenarios would lead to disregarding low-probability high-impact scenarios, which might be the most relevant in a risk-management approach. Since we think that the analysis of climate policies is an analysis of climate risks more than anything else, the inclusion of low-probability scenarios in SSPs appears essential.

In practice, to select the five SSP boxes, we define numerical thresholds for the capacity to mitigate and the capacity to adapt indicators that characterize each SSP. These thresholds are defined such that one-third of the scenarios are below the first threshold and one-third of the scenarios are above the second one (see Figure 3).

We can now use a "scenario discovery" cluster analysis to identify the main drivers of each scenario group. "Scenario discovery," often used to support robust decision making (Robert Lempert and Kalra, 2011; R J Lempert et al., 2003), provides a computer-assisted method of scenario development that applies statistical or data-mining algorithms to databases of simulation model results to characterize the combinations of uncertain inputs parameter values most predictive of specified classes of results. Importantly, scenario discovery also suggests which uncertain input parameters have less influence.

We apply a modified version of the PRIM (Patient Rule Induction Method) (Friedman and Fisher, 1999) to the 286 scenarios spanning the range of adaptation and mitigation indicators shown in Figure 3. PRIM searches for a combination of a small number of drivers that best explain the conditions that place a case in each of the SSP's.

In fact, an SSP is defined by a set of drivers, and we want to maximize the matching between the drivers and the fact that the scenarios belong to one of these boxes. For instance, for SSP5, we want to find the drivers such that a scenario with these drivers has a high likelihood of being in the upper-left-hand corner and such that a scenario is in the upper-left-hand corner has a high likelihood of having these drivers. To measure this match, we use three criteria (see Bryant and Lempert, 2010). *Density* is the fraction of scenarios that are in the box and associated with the SSP drivers. *Coverage* is the fraction of all scenarios with the SSP drivers and contained in the box. And *interpretability* is measured by having a small number of drivers.

Since these three measures are generally in tension with one another, PRIM provides the user a set of options representing different tradeoffs among density, coverage, and interpretability. Bryant and Lempert (2010) also provide two tests of the statistical significance of each driving force proposed by the PRIM algorithm.

Table 1 shows our results. Each row shows an SSP and the middle eight columns list its potential drivers. A cell filled with black text indicates that a driver plays a significant role in that SSP whereas grey text indicates that the driver plays a partial role. We distinguish the former from the latter using the resampling test described in Bryant and Lempert (2010). This test runs PRIM on multiple subsamples of the original dataset and notes the fraction of subsamples for which each parameter emerges as an important driver of the scenario definition. We consider a driver that scores greater than 50% in the test as significant and less significant otherwise.

The final column shows the explanatory power of these combinations of drivers, as measured by their coverage and density. For instance, low equity, slow convergence, and high energy sobriety contribute most significantly to SSP4. Ninety percent of the cases in the region of Figure 3 noted as SSP4 meet these conditions (coverage). Eight-five percent of the cases that meet these conditions are SSP4 (density).

Some drivers, such as equity, contribute strongly to all the SSPs. Indeed, this driver has a direct impact on the capacity to adapt axis, since it was used to calculate the indicator (see Section 4); this driver splits the income of the 20% poorest into two groups, with a compression to the right as GDP per capita decreases. In the same way, the "energy sobriety" driver has a strong impact on the capacity to mitigate, since it directly influences CO_2 emissions in the baseline. It also influences the capacity to adapt because energy sobriety leads to higher GDP, i.e. to less poverty.[3]

The impact of population on the indicators is ambiguous and not always significant. Indeed, a higher population growth rate implies higher potential economic growth in the model, so that adaptation capacity might increase. Moreover, higher economic growth accelerates capital turnover and increases the share of low-carbon technologies, thus increasing mitigation capacity. The results show, however, that a high population is inconsistent with SSP1 and that a low population is inconsistent with SSP3.

Other drivers, such as fossil fuel availability and capital markets, contribute to few if any SSPs. The non significant impact of fossil fuel availability is due to two contradictory effects: On the one hand, a constrained oil supply induces substitution toward coal, which emits more CO_2 for the same energy service. On the other hand, it also induces higher energy prices, which trigger faster energy efficiency. In the same way, low-carbon technologies contribute to only two SSPs because they tend to slow down energy efficiency through lower energy prices, which lessens their effect on carbon emissions.

[3] The "energy sobriety" driver contains hypotheses on behaviors, localization choices, and the potential for energy efficiency (energy efficiency is endogenous and driven by energy prices). In scenarios with high energy sobriety, energy prices are lower, accelerating GDP growth. This result warns against the use of exogenous GDP scenarios, developed independently from natural resources and energy modeling.

	Equity (2 options)	Conver-gence (3 options)	Energy sobriety (2 options)	Availability of low C technologies (2 options)	Availability of fossil fuels (2 options)	Population (3 options)	Capital markets (2 options)	Coverage/ Density
SSP1 (15% of cases)	improved	Fast or medium	high	high		Medium or low		50% / 80%
SSP2 (10% of cases)	improved	Medium or slow	low			low		30% / 60%
SSP3 (14% of cases)	worsen		low	low		High or medium		55% / 90%
SSP4 (8% of cases)	worsen	slow	high					90% / 85%
SSP5 (6% of cases)	improved	fast	low				Reduced imbalances	60% / 45%

Table 1: Combinations of future capacity to adapt and mitigate in our five SSP spaces as identified by the scenario discovery analysis described in the text. Black/grey text indicates more/less statistically significant drivers. Coverage and density measure the explanatory power of the drivers for each SSP.

2.3 Mapping AUGUR scenarios into the SSP framework

Since we want AUGUR scenarios to span the uncertainty of future energy and climate change aspects of the world evolution, we want to make sure AUGUR scenarios are contrasted in terms of challenges for mitigation and challenges for mitigation and span the SSP domain. We therefore build a correspondence between AUGUR scenarios and the SSP framework (Table 2).

AUGUR scenarios	SSP framework
S1 Reduced government	SSP4 – challenge for adaptation dominate
S2 China and US intervention	SSP3 – high challenges for mitigation and adaptation
S3 Regionalisation	SSP5 – challenges for mitigation dominate
S4 Multipolar collaboration	SSP1 – low challenges for mitigation and adaptation

Table 2: Correspondence between AUGUR scenarios and the SSP framework.

To be consistent with the narratives of AUGUR scenarios on the aspects covered by the other working groups (in particular on the issues of convergence and trade (WP1), financial imbalances (WP2), innovation (WP3)), we chose scenarios such as:

- S1 Reduced government scenario is an SSP4 with slow convergence, energy intensive behaviors, low availability of low carbon technologies and continued imbalances in the global capital market.

- S2 China and US intervention is an SSP3 with medium convergence, energy intensive behaviors, high availability of low carbon technologies and reduced imbalances in the global capital market.

- S3 Regionalisation is an SSP5 with fast convergence, energy intensive behaviors, high availability of low carbon technologies and reduced imbalances in the global capital market.

- S4 Multipolar collaboration is an SSP1 with fast convergence, energy sober behaviors and high availability of low carbon technologies.

Moreover, we assume that an international regime of climate policies can be implemented only in S4 scenario. No climate policies are implemented in the other three scenarios, while in S4 we assume policies are implemented in order to meet the Copenhagen pledges (see Table below). Europe maintains its objective of 20% CO_2 emissions reduction in 2020 compared to 1990 levels.

Country	**2020 Target under Copenhagen Accord**
Europe	20% reduction compared to 1990 level
USA	17% reduction compared to 2005 level
Japan	25% reduction compared to 1990 level
New Zealand	10% reduction compared to 1990 level
Russia	15% reduction compared to 1990 level
China	40-45% reduction in emission intensity of GDP relative to 2005
India	20-25% reduction in emission intensity of GDP relative to 2005
Brazil	36% reduction in emissions relative to BAU *(10% reduction in energy-related emissions)*
Mexico	30% reduction in emissions relative to BAU
South Africa	34% reduction in emissions relative to BAU
Indonesia	26% reduction in emissions relative to BAU

3. Analysis of the energy and climate change aspects of AUGUR scenarios

3.1 Climate change: the future legacy of the two coming decades and the 2°C target

Figure 4 gives the four global total CO_2 emissions pathways over the two coming decades corresponding to AUGUR scenarios. The first three scenarios ("Reduced government", "China and US intervention" and "Regionalization") exhibit continuous trends of fast increasing emissions (at the mean annual rates of 2.5%, 2.9% and 3.2% respectively). The difference between the three scenarios comes mainly from a difference in GDP, while all are characterized by roughly the same trend of carbon intensity of GDP. The climate policies implemented in the multipolar scenario lead to a peak of emissions in 2020, at a level just 10% above 2010.

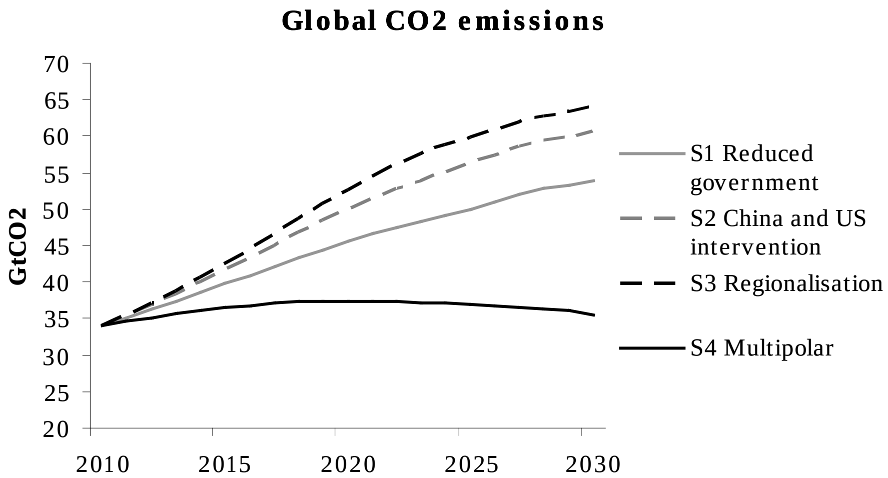


Figure 4: Global CO_2 emissions pathways over 2010-2030 in the four AUGUR scenarios.

Figure 5 shows the corresponding evolutions of CO_2 concentration in the atmosphere. It is important to note that the difference between the four scenarios is a lot smaller for concentrations (that are stocks of CO2 in the atmosphere) than for emissions (that are fluxes): there is 45% difference in emission level in 2030 between the highest and lowest level, but only 7% difference in concentration level. This is simply due to the inertia of the carbon cycle. Since what ultimately matters for climate change is the radiative forcing due to greenhouse gases concentration in the atmosphere, it is important to keep in mind that the room for manoeuvre for the coming two decades is small.

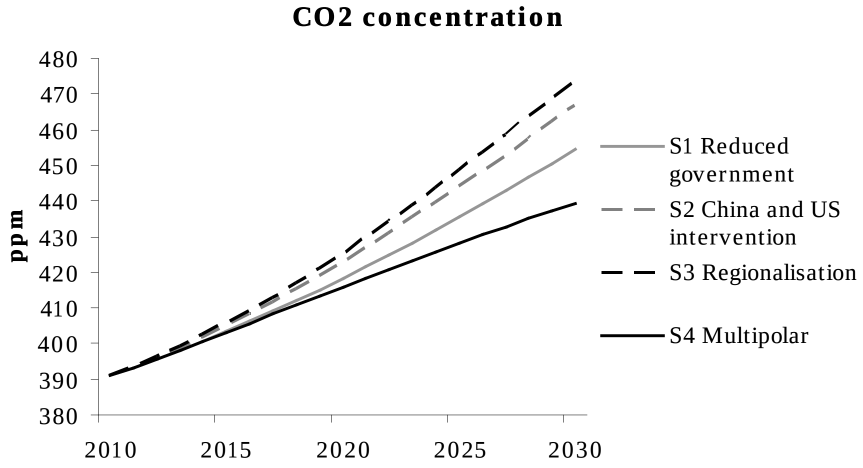


Figure 5: Atmospheric CO_2 concentration pathways over 2010-2030 in the four AUGUR scenarios.

Figure 6 gives the associated mean global temperature increase above pre-industrial temperature over 2010-2030. It shows that the difference between the four scenarios is also small. Even if emissions are stabilized as in the multipolar scenario, the world is committed to increasing mean global temperature increase due to the inertia in the carbon cycle and in the climate system.

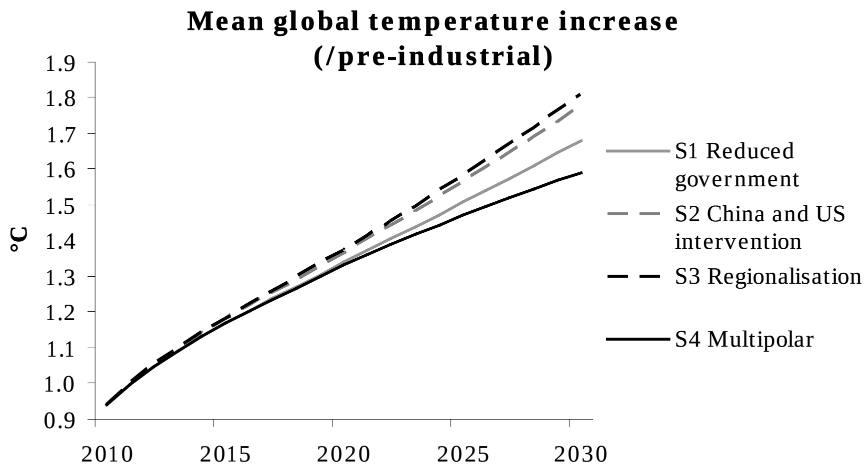


Figure 6 : Mean global temperature increase above pre-industrial temperature over 2010-2030 in the four AUGUR scenarios.

However, precisely due to these inertias, the issue of climate change is a longer-term issue. And 2030 should then be seen as an intermediary point with respect to this issue. The question is therefore less that of the point reached in 2030 but more that of the legacy it represents for the decisions to be made at that time and of which options it preserves for them. Table 3 explores the legacy of the coming two decades for the feasibility of the 2°C target. It gives the remaining carbon budget[4] admissible for 2031-

[4] Following Meinshausen et al (2009), we assume the 2000-2049 carbon budget to have 50% chances to remain below the 2°C target is equal to 1500 $GtCO_2$ approximately.

2049 if we want 50% chances to remain below the 2°C target. It shows that this admissible carbon budget would be exhausted in only a few years of emissions equal to 2030 level for the "Reduced government", "China and US intervention" and "Regionalization" scenarios. Alternatively, we may express the mean annual emissions decrease that would be necessary over 2030-2050 to reach the 2°C target. For the multipolar scenario, it is equal to 3%, while for the three over, it is above 15%.

	2010-2030 carbon budget	remaining budget to have 50% chances to reach the 2°C target		annual decrease of emissions over 2030-2050 to reach the 2°C target
		in GtCO2	in number of years of 2030 emissions	
S1 Reduced government	912	318	6	16%
S2 China and US intervention	1005	225	4	26%
S3 Regionalisation	1077	153	2	42%
S4 Multipolar	722	508	15	3%

Table 3: Carbon budget over 2010-2030 and remaining carbon budget for 2031-2049 to have 50% chances to remain under the 2°C target for the four AUGUR scenarios.

These numbers are to be compared to a few points of reference.

First, historical experience provides useful point of comparison. For instance, a 4.6 percent per year rate of mean annual CO_2 emissions reductions from 1980 to 1985 in France corresponds to the country's most rapid phase of nuclear plant deployment. According to WRI-CAIT data, it is the highest rate of CO_2 emissions reductions historically observed in any industrialized country over a five-year period, excluding the countries of the Commonwealth of Independent States during the years of economic recession that followed the collapse of the former Soviet Union. The French example is informative because it represents an important effort to shift away from fossil fuel energy and to decarbonize electricity production through the introduction of carbon-free technologies (in this case, the nuclear energy) and of energy efficiency measures. Even though motivations were different – reducing energy costs vs. reducing GHG emissions – and if future climate policies will likely be based on newer technologies and different economic instruments, this period provides an illustration of an energy transition similar in nature to what is needed to reduce GHG emissions.

Second, these numbers are also to be discussed in the light of the inertia of technical systems, behaviors and institutions. Indeed, economy sectors are characterized by significant inertia in installed capital, infrastructure, and behaviors that cannot be changed overnight. In some sectors, productive capacities and infrastructures have lifetimes of several decades (IEA, 2000; Worrell and Biermans, 2005). For instance, most industrial installations have lifetimes spanning more than 30 years, whereas urban infrastructure, transport infrastructure, and some buildings have lifetimes lasting over a century. It is likely that urban forms imply an even larger inertia than that suggested by physical capital lifetime (Gusdorf and Hallegatte, 2007; Gusdorf et al., 2008). This inertia constrains the pace of possible decarbonisation of the sectors, and a lock-in of the transportation and residential sectors in carbon-intensive pathways can have very important consequences on mitigation costs. Behaviors and institutions are also characterized by large inertias, and it may be inferred that they constrain the pace at which emissions pathways can be bent. From Davis *et al.* (2010), it can be calculated that committed emissions from existing energy infrastructure lead to a mean emission reduction pace of 5.7 percent per year during 2010–50 (middle scenario) and 4.3 percent (pessimistic scenario) if early capital retirement is avoided. In a comparable analysis that also takes the inertia in transport demand into account, Guivarch and Hallegatte (2011) find a mean decrease in committed emissions of 3.8 percent per year during 2010–50 (middle scenario) and 3.2 percent (pessimistic scenario). To go beyond this emission reduction rate, policies affecting new capital would not be sufficient, and early capital retirement or retrofitting would be necessary. Doing so would increase the cost of climate policy. Moreover, the limits to what is achievable in terms of emission reduction do not only depend on technical or economic criteria; political and social acceptability – linked in particular to the redistributive effects of climate policies – will also play a major role (Parry et al., 2005; Fullerton, 2008).

From this analysis, we may conclude that, even if the 2°C threshold is not crossed during the coming two decades in any of the four AUGUR scenario, only the multipolar scenario legacy in 2030 would leave open the possibility to reach this target. Other scenarios would be committed to larger climate change over the course of the 21st century.

Figure 7 gives the global CO_2 emissions on a study horizon extended to 2050, keeping the same assumptions for each of the four scenarios. In particular, in the multipolar scenario climate policies continue to be in place, while no climate policies are implemented in the other scenarios. The trend of emissions curbs down after 2030 nonetheless in the “China and US intervention” and “Regionalization” scenarios, and even start to decrease after 2040, but this is due to steep rise of energy prices (see next section). Emissions in the “Reduced government” scenario continue to rise, but remain below the other two scenarios. As we will see, this is due to very different oil prices pathways (see section below). Indeed, in the “Reduced government” scenario oil prices are high, and therefore tend to trigger energy efficiency improvements, which limits emissions growth; but these high oil prices also induce substitution towards coal (in the absence of concern for CO_2 emissions), when coal to liquids technology becomes economic, which in turns pushes emissions up. Figure 8 reports the associated mean global temperature increase. Only the multipolar scenario stays below the 2°C target, while this threshold is crossed in 2040, 2036 and 2035 in the “Reduced government”, “China and US intervention” and “Regionalization” scenarios, respectively.

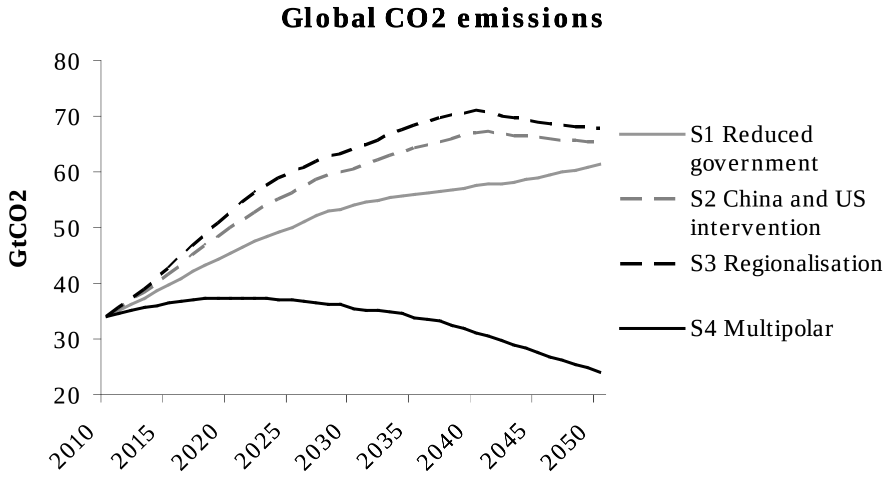


Figure 7 : Global CO_2 emissions pathways extended over 2010-2050 in the four AUGUR scenarios.

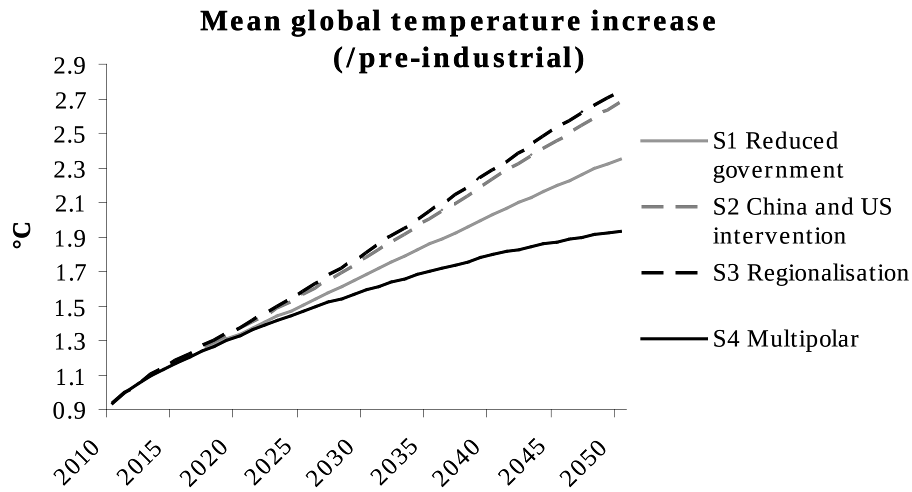


Figure 8 : Mean global temperature increase above pre-industrial temperature extended over 2010-2050 in the four AUGUR scenarios.

It is likely that the three scenarios "Reduced government", "China and US intervention" and "Regionalization" would experience warming above 3°C in the 21st century. This would have very severe consequences: a sea level rise of up to 2 meters, and changes to rainfall patterns, drought, flood, and heat-wave incidence that would severely affect human settlements, food production, human health and economies and ecosystems functioning. So, in these scenarios, societies, economies and institutions should be prepared to adapt to these consequences or bear their impacts.

It is important to keep in mind here that climate change is a highly non-linear phenomena, with positive feedbacks and irreversibilities once thresholds are crossed. Of course, there is some uncertainty on at which level are these thresholds. But some research suggests there may be one such threshold close to 2°C. For example, drying of the Amazon would release CO2 that would then lead to further warming (Lewis et al., 2011) and rising arctic temperatures would lead to extra emissions from melting permafrost (Schaefer et al., 2011). These feedbacks have not yet been characterised with certainty, but they are expected to be triggered by temperature rises between 2°C and 5°C (Smith et al., 2009). The threshold for larges scale sea level rise may be similar, between 1.8°C and 2.8°C (Lenton et al., 2008; Hansen et al., 2008). That is why, from a policy perspective, the 2°C appears as a target to pursue.

3.2 Energy security

3.2.a Oil prices pathways: when the bad surprise comes after 2030

Figure 9 shows the evolution of international oil prices in the four AUGUR scenarios. For the "multipolar" scenario there is a short period of oil prices decrease or stagnation between 2010 and 2015. The implementation of climate policies moderates the oil demand and therefore also releases the tensions on the oil markets, leading to a slight price decrease. However, after 2015, and since 2010 for the other three scenarios, oil prices follow an upward trend driven by the increase of demand (to various extents depending on the scenario) and depletion of reserves (in all scenarios) leading to the extraction of more expansive categories of oil. The highest prices over the first 15 years are in the "Reduced government". Although demand increase is relatively moderate in this scenario compared to the "China and US intervention" and "Regionalization" cases, high prices arise due to the strategic behavior of OPEC countries. In this world Middle-East oil companies act as profit maximizing firms independent of any political influence, so they try to maximize their discounted cumulated oil revenues. Given the high internal rates of returns demanded by private oil companies (17.26% to 21.97%, according to the Texas Comptroller's Property Tax Division[5]), maximizing their discounted cumulated oil revenues implies to refrain from investing in new capacity and to maintain the medium term oil price above 120$/bl, even if doing so might reduce future profits by fostering a fast penetration of oil substitutes and triggering energy efficiency abroad. Just before the end of the study period, oil prices levels in the "Regionalization" scenario exceed those of the "Reduced government", mainly due to high demand that creates tensions on the oil markets. Except for the first years and the very last years of the study horizon, oil prices trends are very similar in the "multipolar" and the "US and China intervention" scenario. But the driving forces are very different. In the multipolar scenario, oil prices rise are moderated by the fact climate policies induce energy efficiency improvement and substitutions away from fossil fuel use. In the "US and China intervention" scenario, USA and China impose their leadership on oil producers so that oil prices are moderated for as long as possible, and there is no significant progress made in energy efficiency, and an energy-intensive lifestyle spreads throughout the world.

[5] Determination of 2002 Discount Rate Range for Petroleum and Hard Mineral (*available at*: *http://www.window.state.tx.us/taxinfo/proptax/drs02/)*

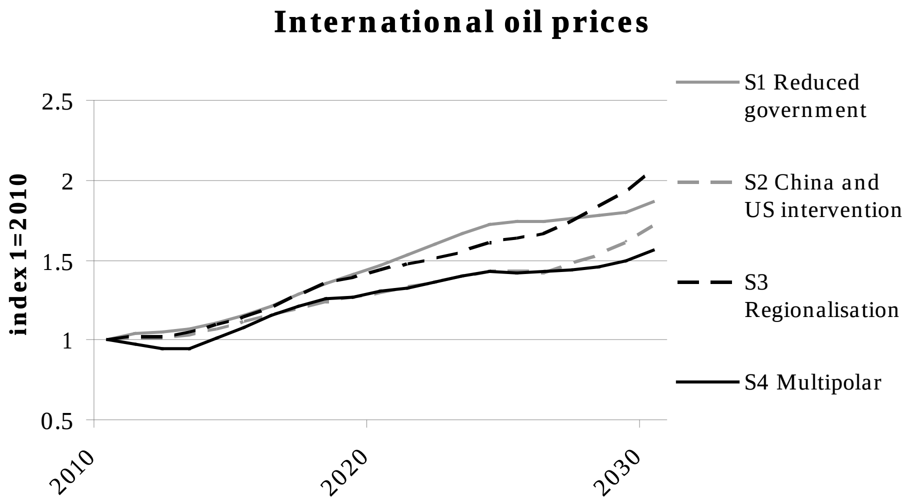


Figure 9 : International oil prices pathways over 2010-2030 in the four AUGUR scenarios.

If the oil prices evolutions are not so different from one scenario to the other on the 2010-2030 horizon, the picture is very different if we extend the study horizon to 2050 (Figure 10). The scenarios “China and US intervention” and “Regionalization” experience very steep increase of oil prices around 2040, when producers become constraint by depletion of the resources. This effect is less pronounced in the “Multipolar” scenario, because the oil demand is less increasing in this scenario; in the second because of climate policies that make economies move away from oil consumption, improve energy efficiency and make substitutions to low carbon energy. In the “Reduced government” scenario, oil prices do not exhibit steep increase before 2050. Since oil prices have been high from the beginning of the period, they have triggered energy efficiency improvement and substitution away from oil (but mainly towards coal). Moreover, growth is rather slow, so overall oil demand is moderate.

These oil price steep increases, in “China and US intervention” and “Regionalization” scenarios and to a lesser extent in the other two scenarios, may pose a threat on energy security and on growth ultimately, depending on how vulnerable or resilient the economies would be at the time of the price shock. Next section explores this issue.

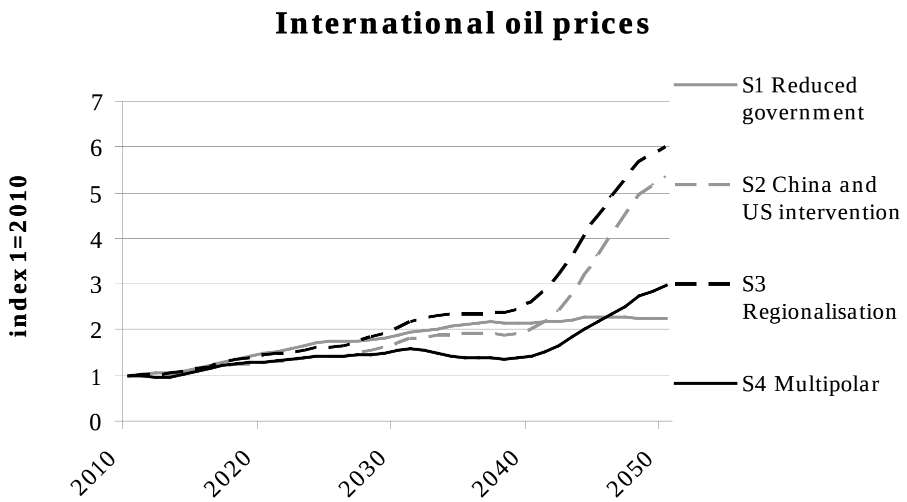
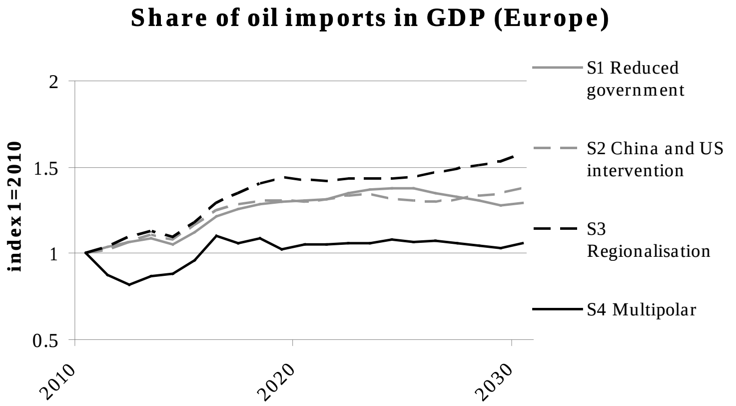


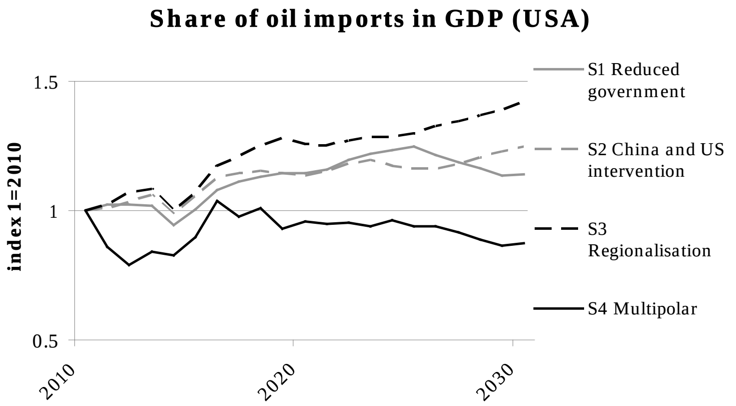
Figure 10 : International oil prices pathways extended over 2010-2050 in the four AUGUR scenarios.

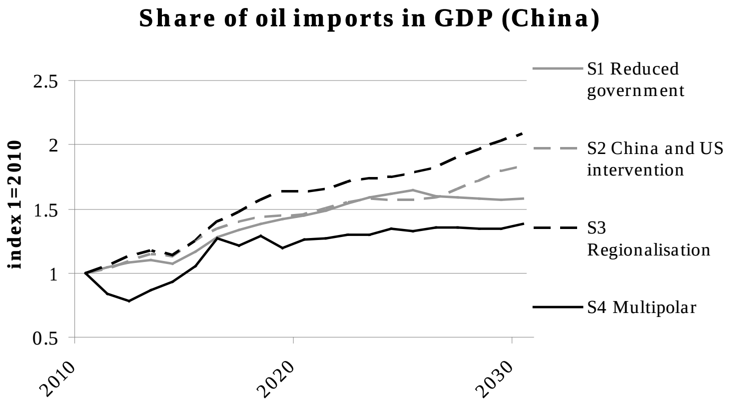
3.2.b The risks of carbon / oil lock-ins of our economies

The vulnerability of economies to oil price increase depends on the steepness of the price increase (which was analyzed in previous section) and on the dependence of the economy on oil. This second element can be measured by the share of the oil imports bill in GDP. Figure 11 gives the evolution of this share over the next two decades for Europe, USA, China and India. For Europe, this share is on a rising trend in the three scenarios “Reduced government”, “China and US intervention” and “Regionalization”, which indicates a worsening of the energy security situation. In the “multipolar” scenario, the energy security indicator remains rather stable. For the USA, the worsening of the energy security situation in the first three scenarios is less pronounced than for Europe. This is mainly explained by the fact the USA are oil producers. The energy security issue for China appears a major issue, since the share of oil imports bill in GDP is increase fast (multiplied by 2 in two decades) in the “Reduced government”, “China and US intervention” and “Regionalization” scenarios. The increase is slightly slower in the “multipolar” scenario, but the trend remains upwards. For India, the evolution of the share of oil imports bill in GDP is not very pronounced, but it should be noted that this share is already very high today (around 10%), which makes energy security an important issue for India. It can be seen that the “multipolar” scenario improves the energy security situation for India.

The study horizon is extended to 2050 in order to analyze how the increase of oil prices around 2040 in the scenarios affects energy security (Figure 12). The notable point is that for all four regions, the share of oil imports bill in GDP increases steeply over 2040-2050 in the two scenarios, “China and US intervention” and “Regionalization”, while it does not in the “Multipolar” scenario. In previous section, we saw that all three scenario experience a fast increasing trend of international oil prices (though less steep in the “multipolar” scenario than in the “China and US intervention” and “Regionalization” scenarios) over 2040-2050. However, the impact of this increase is very different in the three scenarios: it leads to a steep increase of the oil imports share in GDP in the “China and US intervention” and “Regionalization”, while the associated increase is not significant in the “Multipolar” scenario. In the same way as the pathways create “carbon lock-in” in all scenarios but the “Multipolar”, there is here a “oil lock-in”. In the “China and US intervention” and “Regionalization” scenarios, development styles, production technologies and consumption behaviors heavily rely on the use of oil, and when oil prices rise steeply, inertias of the technical systems and behaviors prevent from moving away from oil use, which makes the economies vulnerable to oil price shocks. In the “Reduced government” scenario, energy security indicator improves at the end of the period, but at the expense of high share of oil imports bill in GDP the first decades.







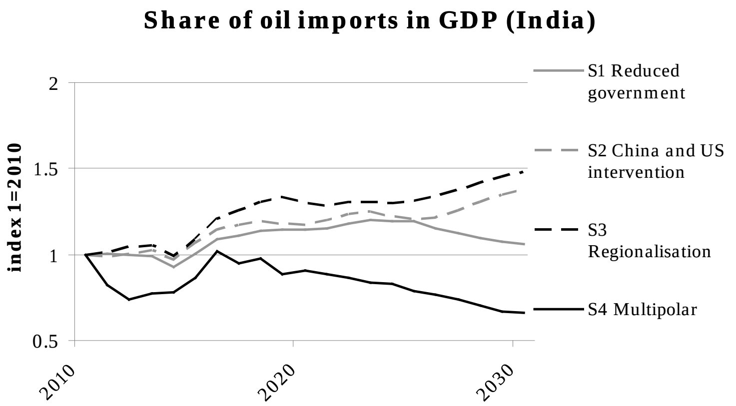


Figure 11: Oil imports as a share of GDP for Europe, USA, China and India over 2010-2030 in the four AUGUR scenarios.

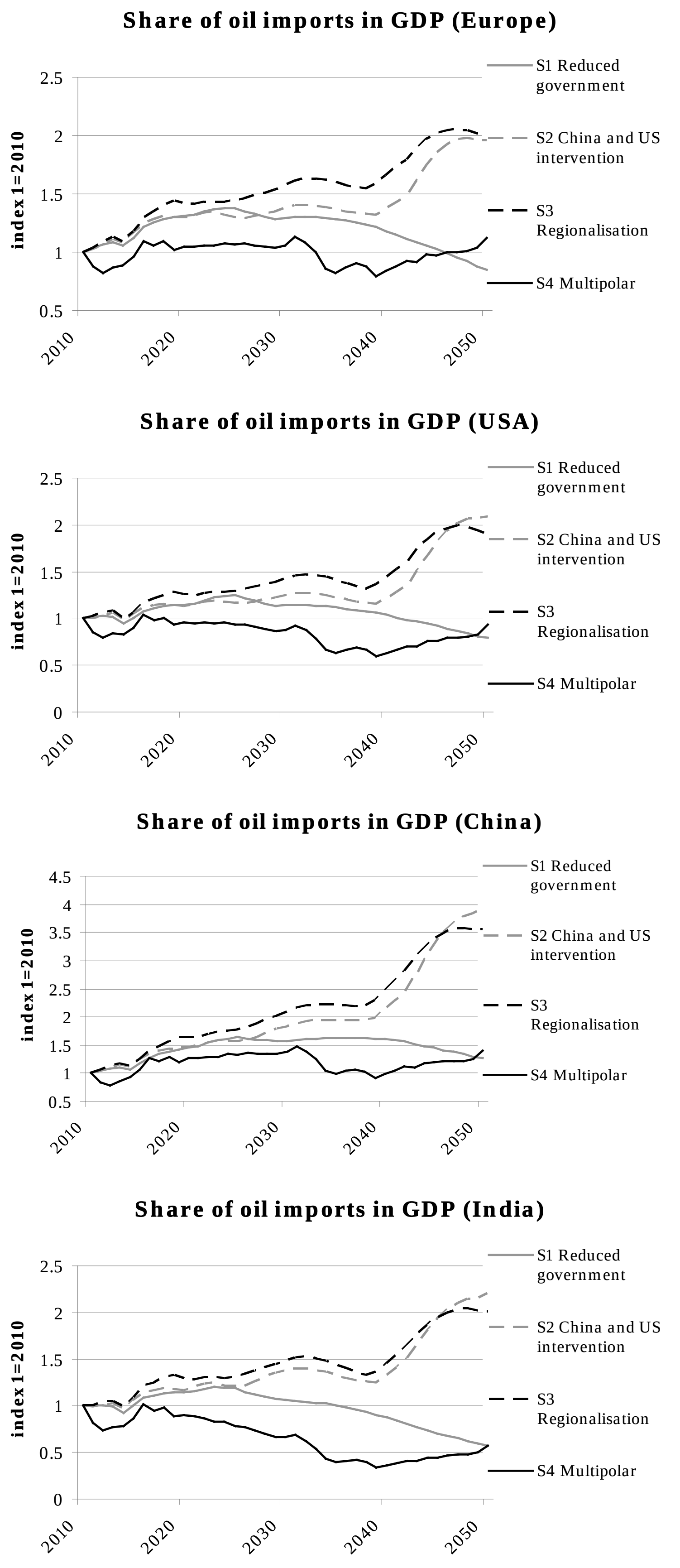


Figure 12: Oil imports as a share of GDP for Europe, USA, China and India over 2010-2050 in the four AUGUR scenarios.

3.3 Discussion

In the previous sections, we showed that both climate change and energy security issues are long-term issues, for which the main challenges may arise after the 2030 horizon. However, the two coming decades are crucial for these issues since the directions taken over this short-/medium-term risk to create lock-ins of the economies in carbon and/or oil dependency. Indeed, inertias in the technical systems, the behaviors and the institutions make the transformations away from oil consumption and/or away from carbon intensive economies a slow process. If these transformations are not started early, during the coming two decades, it creates the risks that (i) economies are vulnerable to oil prices shocks that may happen when producers reach depletion constraints (possibly after 2030, as in our scenarios), (ii) it would be unfeasible or extremely costly to limit climate change to the 2°C target.

One important point here is that the two issues of climate change and energy security are actually linked. Indeed, climate policies, by putting a price on carbon, give the signal increasing the price of fossil fuels, including oil. Therefore they trigger technical change, structural change and changes in behaviors that improve energy efficiency and leads to substitutions away from fossil fuel, including oil. If policies are implemented early, they may be able to avoid the "carbon lock-in", as well as the "oil lock-in" of the economies. The improvement of the energy security can thus be seen as a co-benefit of climate policies (For details on this point, see Rozenberg et al., 2010).

Another point to discuss is the links to other environmental issues (local air pollution, ocean acidification, biodiversity, water scarcity) that are not explicitly represented in our modeling framework, but have strong links to the mechanisms represented and have potentially important consequences.

Ocean acidification is due to CO_2 emissions, therefore it will evolve in the same direction as radiative forcing in the scenarios.

Local air pollutants often have the same sources as greenhouse gases, e.g. black carbon from coal combustion, particles from gasoline combustion in thermal engine vehicles. Therefore, it is likely that local air pollution co-varies with CO_2 emissions. And improvement of local air quality may be a co-benefit of climate policies in the "multipolar" scenario. However, there exists relatively cheap technologies to scrub local air pollutants, therefore it may happen than in some scenarios, if there is a focus on local environmental quality, local air quality is improved but CO_2 emissions are not reduced; one could think this could happen in the "regionalization" scenario. In the "reduced government" scenario, the is large use of coal due to high oil prices, therefore it is likely that local air quality is low in this scenario.

Water and biodiversity issues have two linking elements with climate change. First, climate change impacts will affect water availability, with changing rainfall patterns depending on the regions, which could lead to water scarcity issues in regions where the occurrence and severity of droughts would increase. Similarly, changing climate would affect ecosystems functioning, with potentially biodiversity loss. However, these effects will mostly happen on a longer time scale than 2030. A second linking element is bioenergy. Indeed, biofuel production can be seen as an option to mitigate emissions from fossil fuel burning and/or an option to hedge against fossil fuel scarcity. Depending on the extent of biofuel production and its sustainability, it may have significant negative impacts on water scarcity and biodiversity. This question of bioenergy is especially relevant to scenarios in which climate change mitigation would occur late, while short-term emissions would be high (as in our "Reduced government", "China and US intervention" and "Regionalization" scenarios). Indeed, one of the main options to still reach the 2°C target with high short-term emission would be to exploit the possibility to produce negative net global emissions.Negative emissions scenarios require large-scale combinations of bio-energy and carbon capture and storage (BECCS) (van Vuuren et al., 2010a; Edenhofer *et al., 2010;* van Vuuren et al., 2010b). For instance, Azar et al. (2010) show that two of the three models they consider cannot reach stabilization levels below 400 parts per million of CO_2 equivalent if BECCS is not available. However, BECCS is not currently a commercially proven technology and its potential remains contentious. Being so dependent on BECCS is a dangerous gamble considering the uncertainty with respect to this technology and the feasibility of its large-scale deployment, and the risks associated with leakage, food security, water scarcity, and biodiversity protection. For instance the low stabilization scenario "Representative Concentration Pathway 3 Peak&Decline" (RCP3-PD), which relies on large development of BECCS, has the second largest primary land area conversion to secondary land (harvested forest), cropland or pasture among the four Representative Concentration Pathways (Hurtt et al., 2011). In that scenario, low stabilization is achieved at the expense of biodiversity protection. And without negative emissions, the only solutions would rely on even more uncertain technologies, such as geo-engineering and radiative-forcing management strategies, with their unknown feasibility, risks, and local effects (Schneider, 2008).

4. Summary of the resulting quantified elements for the narratives of the energy and climate change aspects of AUGUR scenarios

4.1 S1 - Reduced government

This scenario depicts a consolidation of the influence and active role of financial institutions and business corporations at the expense of governments. Governments, trapped by the high level of public indebtedness caused by the 2008 crisis, are forced to reduce spending. In this world the process of trade liberalization goes on and also implies further financial liberalization. This benefits big emerging countries but prevents other developing countries from catching-up. The decrease in the role of states increases income inequalities. The main objective is economic growth, but it is founded on inequalities, and must be driven by the richest.

In this scenario social cohesion is low: there is hope for mass to become member of the elite. Governance faces regulatory capture, and government is for the elite, by the elite. A large diffusion of the US consumption style is ambitioned, with an increasing demand for energy and mobility, mostly in big emerging countries. Management practises and lifestyles lead to an inefficient use of natural resources, which increases environmental stresses. The access to such a lifestyle is however limited by the inequalities, and only rich people have access to it.

The population is thus divided in two groups (both between countries and within countries): small rich global elite is responsible for much of the emissions and can mitigate at low cost if necessary. A large poor group does not emit much and is vulnerable to impacts of climate change (also in industrialized regions).

In this world Middle-East oil companies act as profit maximizing firms independent of any political influence, so they try to maximize their discounted cumulated oil revenues. Given the high internal rates of returns demanded by private oil companies (17.26% to 21.97%, according to the Texas Comptroller's Property Tax Division[6]), maximizing their discounted cumulated oil revenues implies to refrain from investing in new capacity and to maintain the medium term oil price above 120$/bl, even if doing so might reduce future profits by fostering a fast penetration of oil substitutes and triggering energy efficiency abroad.

No climate policy is ambitioned and environmental policies are only reactive, but the challenges to mitigation can be low for two reasons: (i) emissions are relatively low because only produced by the richest, and (ii) there is a high capacity to mitigate.

Indeed, energy security considerations drive investments in energy efficiency improvements by big energy companies and lower the energy intensity of world production (for example big companies push for bio-energy, allocate land-resources). However this reduces options for adaptation for local communities and nature conservation. Energy security considerations might also lead to the choice for fossil

[6] Determination of 2002 Discount Rate Range for Petroleum and Hard Mineral (*available at*: *http://www.window.state.tx.us/taxinfo/proptax/drs02/)*

technologies that can relatively easy be combined with mitigation measures (for example, energy corporation "conspiracy": they buy the technology and patents and can deploy them quickly in case of climate policy).

Here the potential for mitigation is high but will not be used in the short-run because of a lack of global governance. Investments in innovative or very low-carbon energy production such as nuclear and renewable energy are not increased in the short run because they require subventions from the state to be profitable. However, in the longer run this scenario could be a technology breakthrough scenario, for instance for geo-engineering.

4.2 S2 - China and US intervention

This scenario is based on the hypothesis of increased coordination between China and the USA, who impose their leadership on other countries. In this scenario, government interventions are increased.

As in the consolidation scenario, social cohesion is low: there is hope for mass to become member of the elite. A large diffusion of the US consumption style is ambitioned, with an increasing demand for energy and mobility, mostly in China and a few big emerging countries. Management practises and lifestyles lead to an inefficient use of natural resources, which increases environmental stresses. The access to such a lifestyle is however limited by the inequalities, and only rich people have access to it.

The population is thus divided in two groups (both between countries and within countries): small rich global elite is responsible for much of the emissions. A large poor group does not emit much and is vulnerable to impacts of climate change (also in industrialized regions).

In this scenario, USA and China impose their leadership on oil producers so that oil prices are moderated for as long as possible. As a consequence there is no significant progress made in energy efficiency, and an energy-intensive lifestyle spreads throughout the world, leading to an "environmentally-stressed" world in which energy and mobility demand are growing. This world may be locked in oil-intensive pathways, and may be very vulnerable to peak oil.

China and the USA thus seek energy diversification and energy security, so they increase investments in nuclear power and renewable energy. They do not worry for CO_2 emissions, and clean air in big cities is not their top priority, so they disregard carbon capture and storage and electric vehicles, favoring synthetic fuels such as Coal-to-liquids or biofuels instead. China urbanizes rapidly and saturates at very high urbanization rates. City planning includes significant urban sprawl.

No climate policy is ambitioned and environmental policies are only reactive. Emissions levels reach 60 $GtCO_2$ in 2030.

In other regions development proceeds slowly, inequality remains high, and economies are relatively isolated, leaving these regions highly vulnerable to climate change with limited adaptive capacity.

4.3 S3 – Regionalisation

In this scenario the emphasis is on regional development, thanks to local steering and deepened regional institutions and markets. It is a fragmented world with inclusive growth, which implies intermediate levels of economic development, and relatively rapid and diverse technological change. Policies are focused on local solutions to economic, social, and environmental sustainability. There are no proactive climate policies.

In this scenario oil-producing countries seek maximization of local households' welfare. This comes down to assuming that oil companies and sovereign funds consider broader government objectives, such as calming short term social tensions or building infrastructure capable of ensuring sustainable development beyond the 'oil era'. To do so, oil producers maintain low prices for as long as possible, so that oil-importing regions do not shift away from oil too quickly. However, high demand maintains tensions on oil markets and oil prices follow upward trends. This period of oil prices rise moderation will likely be followed by a steep and lasting surge in oil prices which will begin just before Peak Oil, due to the inertia of technical systems and behaviors. This surge will be triggered by tensions between high demand, which cannot be reduced overnight, and the constraints on the deployment of oil and oil substitutes' production capacities. With this strategy, short-term inflows of oil revenues come at a pace compatible with the absorption capacity of the local economy, and the high post-Peak Oil inflows fall into a more mature industrial structure.

The world is thus developing rapidly powered by fossil energy. There is a strong push for development in developing countries which follow the fossil and resource intensive development model of the industrialized countries. This is aided by high levels of international trade allowing for specialization of countries. A global "development first" agenda is enforced leading to the achievement of the MDGs before 2030. Development policies emphasize education and health, leading to a strong build up of human and social capacity in developing countries. As a result, per capita incomes in developing countries increase rapidly with strong convergence of inter- and intra-regional income distributions.

At the same time industrialized countries continue their focus on economic growth aided by consumerism and resource intensive status consumptions, including – inter alia – a preference for individual mobility, meat rich diets, and tourism and recreation. Developing countries rapidly adopt these consumption patterns. The gross world product increases rapidly, with a continued large role of the manufacturing sector.

Labor markets are freed, allowing for large international mobility that buffers the effect of aging populations in industrialized countries. All regions urbanize rapidly and saturate at very high urbanization rates. City planning includes significant urban sprawl, which contributes to the carbon and oil lock-in by inducing high mobility needs.
Emissions in 2030 reach more than 60 GtCO_2.

Investments in technological innovation are very high, with a focus on increasing labor productivity, fossil energy supply, and managing the natural environment. With the help of technological progress, fossil resource extraction is being maximized at low costs, and local externalities of fossil energy production (e.g. health effects) are well controlled. Due to the strong reliance on fossil energy, alternative energy sources are not actively pursued. This is re-enforced by high discount rates posing additional barriers on capital intensive investments in the energy supply and end use sectors.

Massive infrastructure investments are undertaken to strengthen resistance against environmental perturbations including climate variability and climate change. This is complemented by high disaster preparedness. Environmental consciousness is strong on the local scale, and focused on end-of-pipe engineering solutions for local environmental problems. Agro-ecosystems are highly managed building on strong technological progress in the agricultural sector. Land use management is generally very resource intensive including water system management. Action on global environmental problems is hampered by high discount rates and a development first paradigm that believes in high opportunity costs of global environmental action.

4.4 S4 - Multipolar collaboration

In this scenario, strong global governance, increased regulation of the world economy and stronger cooperation policies benefit low income countries. Development policies emphasize education and health, leading to a strong build up of human and social capacity in developing countries. As a result, per capita incomes in developing countries increase rapidly with strong convergence of inter- and intra-regional income distributions.

In this convergent world, development proceeds at a reasonably high pace, with rapid changes in economic structures toward a service and information economy, and with reductions in material intensity. Inequalities are lessened, technological change is rapid and directed toward environmentally friendly processes, with the introduction of clean and resource-efficient technologies including lower carbon energy sources and high productivity of land. Technological transfers are high, and urbanization is planned and controlled. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity.

In this scenario environmental policies are proactive. In order to encourage environment-oriented ways of life, governments implement proactive environmental policies, including climate policies in order to meet the Copenhagen pledges (see Table below). Europe maintains its objective of 20% CO_2 emissions reduction in 2020 compared to 1990 levels.

Country	2020 Target under Copenhagen Accord
Europe	20% reduction compared to 1990 level
USA	17% reduction compared to 2005 level
Japan	25% reduction compared to 1990 level
New Zealand	10% reduction compared to 1990 level
Russia	15% reduction compared to 1990 level
China	40-45% reduction in emission intensity of GDP relative to 2005
India	20-25% reduction in emission intensity of GDP relative to 2005
Brazil	36% reduction in emissions relative to BAU *(10% reduction in energy-related emissions)*
Mexico	30% reduction in emissions relative to BAU
South Africa	34% reduction in emissions relative to BAU
Indonesia	26% reduction in emissions relative to BAU

In this scenario oil-producing countries participate in the climate coalition, so they refrain from investing in new capacity in order to maintain the medium term oil price between

80$/bl and 100$/bl. This price level is consensual as it is sufficient to trigger technical change and energy efficiency without hurting too much oil-importing countries during the transition phase to the 'post oil era', while providing sufficient revenues to oil-producers. There is a global reluctance to develop non-conventional fossil fuels.

The trend is towards maximum reduction of CO2 emissions, through investments in low-carbon technologies in all economic sectors. The electric sector is decarbonised first, thanks to investments in adequate technologies, such as renewable energy, biomass, nuclear and in carbon capture and storage. Vehicle electrification is quick because of high oil prices and benefits from electricity decarbonisation and the carbon prices. Large efforts are made to improve energy efficiency in productive sectors as well as in the dwelling sector with Very Low Energy buildings. Global emissions peak in 2020, at a level just 10% above 2010 level.

4.5 Discussion

To conclude, we identify areas for further work, in the connections with other AUGUR working packages:

- In connection with WP1, the links between energy prices and growth should be investigated for AUGUR scenarios;
- In connection with WP2, the question of the finance of "green" investments in the "multipolar" scenario would be interesting to explore;
- In connection with WP3, the influence of technology R&D and technology transfer on the energy intensity and carbon intensity pathways should be investigated;
- In connection with WP4, it could be interesting to analyze the issue of environmental migration, although this might be a longer-term issue;
- In connection with WP6, it should be analyzed which type of international governance could be put in place to go to a "multipolar-like" world, and what are the incentives to do so as well as the barriers;
- In connection with WP7, the environmental impacts on well-being could be analyzed, although this might also be a longer-term issue;
- In connection with WP8, it should be analyzed which type of political background evolutions could lead to a "multipolar-like" world, and what are the incentives to do so as well as the barriers.

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6. Annex 1: description of the alternatives

A1. 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). In the IMALCIM-R model, it is given by exogenous assumptions on active population and labor productivity growth. We build three alternatives for population, using demographic data on active population derived from UN scenarios (low, medium and high).

We also define three alternatives on labor productivity growth. Equation A-1 represents labor productivity growth through the decrease of unitary labor input *l* in each region *j* and at each time step *t*. In this equation, τ_2 can be equal to 55, 120 or 250 years depending on the assumption on convergence.

$$l(t,j) = e^{-\frac{t}{\tau_1}}.l(t_0,j) + \left(1 - e^{-\frac{t}{\tau_1}}\right).\left[\frac{1}{\tau_2}.\left(l(t,j) - l(t,leader)\right) + l(t,leader)\right] \qquad \text{(A-1)}$$

A2. Energy sobriety

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 energy sobriety, we build three assumptions using parameters which describe (a) energy efficiency, (b) development patterns in transport, housing and industrial goods consumption and (c) localization patterns. All assumptions are summed-up in Table 2.

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 two hypotheses using the following parameters (see Table 2): 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).

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 (Greening et al, 2000).

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 2).

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 2).

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 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 2).

		Assumption 1	Assumption 2
Energy efficiency	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%
Transport	Motorization rate growth with GDP per capita (η_{mot})	Values from IEA data (Fulton and Eads, 2004)	50% increase w.r.t As-sumption 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]
Localisation choices: 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 2: parameters of the two assumptions on energy sobriety

A3. Availability of fossil energy

Oil supply

The modeling structure of oil supply in IMACLIM-R embarks three crucial specificities of oil supply:

(a) a small group of suppliers benefits from a market power.

(b) the geological nature of oil reserves imposes a limited adaptability of oil supply.

(c) uncertainties on the technical, geopolitical and economical determinants of oil markets alter agents' expectations. The assumption of perfectly optimizing atomistic agents, which remains a useful analytical benchmark, fails to provide a good proxy for the oil economy.

We distinguish seven categories of conventional and five categories of non-conventional oil resources in each region. Each category *i* is characterized by the amount of ultimate resources[7] $Q_{\infty,i}$ and by a threshold selling price above which producers initiate production, $p^{(0)}(i)$. This price is a proxy for production costs and accessibility.

Each oil category is submitted to geological constraints (inertias in the exploration process and depletion effects), which limit the pace of expansion of their production capacity. In line with Rehrl and Friedrich (2006), who combine analyzes of discovery processes (Uhler, 1976) and of the "mineral economy" (Reynolds, 1999), we impose, at each date *t*, an upper bound $\Delta Cap_{\max}(t,i)$ on the increase of production capacity for an oil category *i:*

$$\frac{\Delta Cap_{\max}(t,i)}{Cap(t,i)} = \frac{b_i \cdot \left(e^{-b_i(t-t_{0,i})}-1\right)}{\left(1+e^{-b_i(t-t_{0,i})}\right)} \quad \text{(A-2)}$$

The parameter b_i (in t^{-1}) controls the intensity of constraints on production growth: a small (high) b_i means a flat (sloping) production profile to represent slow (fast) deployment of production capacities. The parameter $t_{0,i}$ represents the date at which production capacities of the concerned oil category are expected to start their decline due to depletion effects. It is endogenous and varies in time since it depends on the amount of oil remaining in the soil given past exploitation decisions.

The production decisions of non-Middle-East producers are those of 'fatal producers' who do not act strategically on oil markets and invest in new production capacity if an oil category becomes profitable given the selling oil price p_{oil}. They develop production capacities at their maximum rate of increase in eq (A-2) for least-cost categories ($p_{oil} > p^{(0)}(i)$) but stop investments in high-cost categories ($p_{oil} < p^{(0)}(i)$). If prices continuously increase, production capacities of a given oil category follow a bell-shape trend, whereas their deployment profile passes through a plateau if prices decrease below the profitability threshold.

Middle-East producers are 'swing producers' who fill the gap between fatal producers' supply and global oil demand. The stagnation and decline of conventional oil in the rest of the world temporarily reinforces their market power and they can control the time profile of oil prices through the utilization rate of production capacities (Kaufmann et al, 2004). They can decide to slow the development of production capacities down (below

[7] Ultimate resource of a given category is the sum of resources extracted before 2001 and recoverable resources.

the maximum increase given by eq (A-2)) in order to adjust the oil price according to their rent-seeking objective.

Total oil production capacity at date *t* is given by the sum over oil categories with different production costs (captured by different $p^{(0)}(i)$ threshold). This means that projects of various merit orders coexist at a given point in time, consistently with the observed evidence[8] and theoretical justifications[9].

For this sector, we build two assumptions using the following parameters: amount of ultimately recoverable resources (Q_∞), inertia in the deployment of non conventionals (spread of the bell-shaped curve *b*), maximum growth rate of Middle-East capacities and OPEC target oil price (see Table 3).

Gas supply

The evolution of worldwide natural gas production capacities meets demand increase until available reserves enter a depletion process. Distribution of regional production capacities in the 'gas supply' module is made using an exogenous distribution key calibrated on the output of the POLES energy model (LEPII-EPE, 2006), which captures reserve availability and regional production facilities. Gas markets follow oil markets with a 0.68 elasticity of gas to oil price. This behavior is calibrated on the World Energy Model (IEA, 2007) and is valid as long as oil prices remain below a threshold $p_{oil/gas}$. At high price levels reflecting tensions due to depletion of reserves, gas prices are driven by production costs and the increased margin for the possessors of the remaining reserves. We make two hypotheses on $p_{oil/gas}$ (see Table 3).

Coal markets

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 elasticity coefficients. To represent the asymmetry in coal price response to production variations, we consider two different values of this elasticity, η^+_{coal} and η^-_{coal} , the former (latter) corresponding to a price reaction to a production increase (decrease). Tight coal markets exhibit a high value of η^+_{coal} (i.e the coal price strongly increases if production rises) and low value of η^-_{coal} (the price decreases only slightly if production drops). For this sector, we make two hypotheses for η^+_{coal} and η^-_{coal} (see Table 3).

	Assumption 1	Assumption 2
Amount of ultimately recoverable resources (see Q_∞ in equation A-1)	3.6 Tb	3.1 Tb
Inertia in the deployment of non conventionals (spread of the bell-shaped curve: see *b* in Equation A-1)	No inertia (b=0.061)	No inertia (b=0.041)
Maximum growth rate of Middle-East capacities	1.1Mbd/yr	0.7 Mbd/yr
OPEC target oil price	80$/bl	120$/bl
Indexation of gas price on oil price	$p_{oil/gas}$ = 80$/bl	No threshold
Price growth elasticity to production decrease (η^-_{coal})	1.5	1
Price growth elasticity to production increase (η^+_{coal})	1	4

Table 3: parameter choices for the two assumptions on fossil fuels.

[8]For example, low-cost fields in Saudi Arabia and high-cost non-conventional production in Canada are simultaneously active on oil markets

[9]Kemp and Van Long (1980) have indeed demonstrated that, in a general equilibrium context, the lowest-cost deposits are not necessarily exploited first. Holland (2003) even demonstrates that least-cost-first extraction rule does not hold in partial equilibrium under capacity constraints, like those envisaged for geological reasons here.

A4. 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 4.

	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 4: parameter choices for the two assumptions on low carbon technologies.

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