MAY 2022

RESEARCH PAPER

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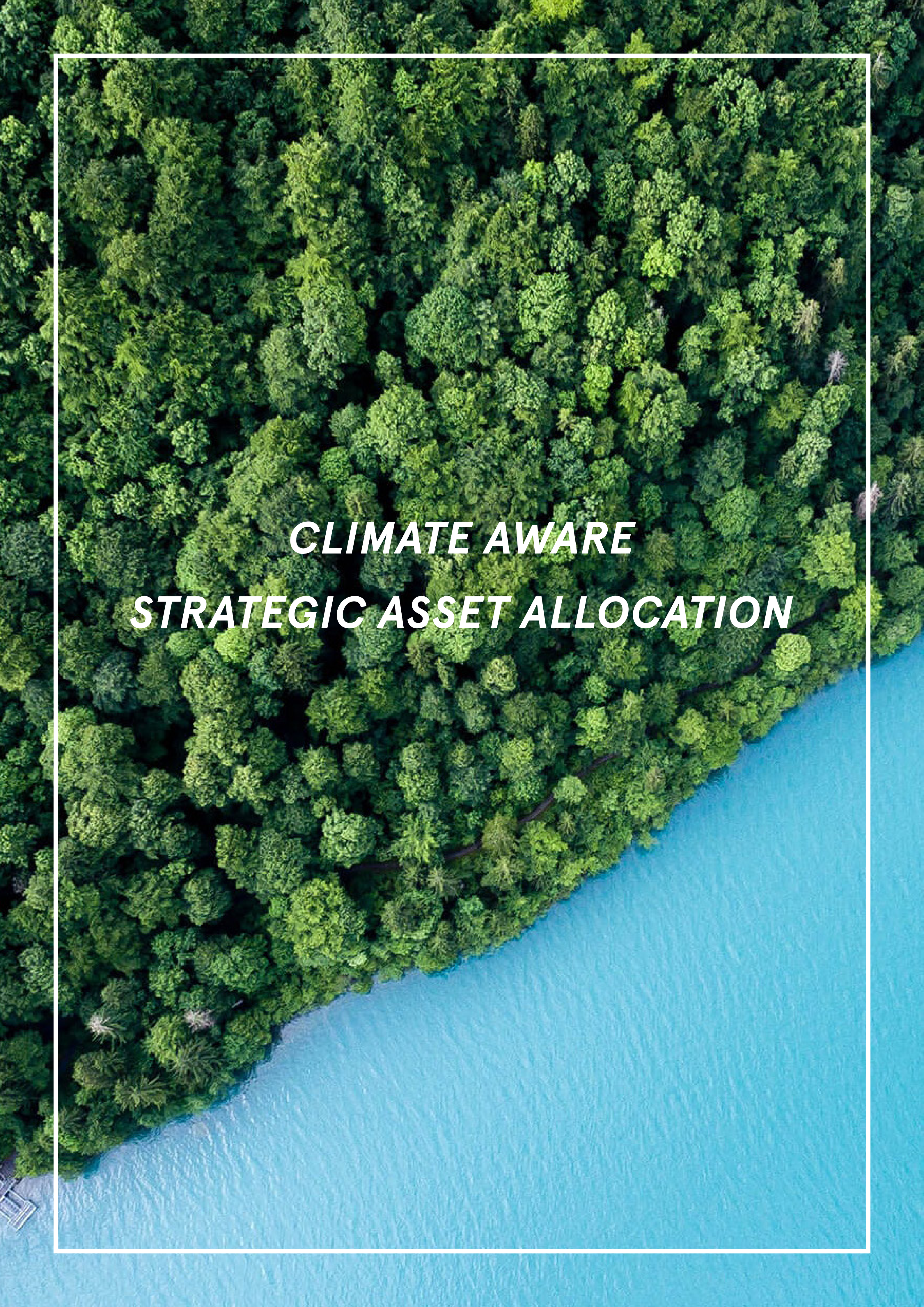

CLIMATE AWARE
STRATEGIC ASSET ALLOCATION

CONTENTS

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INTRODUCTION

The need to take climate change into account as a structural factor of performance

Academic research, as well as the lessons of experience, demonstrate that long-term asset allocation is the main source of performance, far ahead of tactical allocation or investment selection (Hoermann and al. 2005, Brinson and al. 1991, Ibbotson and al. 2000). However, with the problem of global warming linked to greenhouse gas emissions, the concept of "Tragedy of the horizon" (Mark Carney 2015) has highlighted the necessary consideration in the construction of portfolio of a very long duration event, of the order of 80 years, time necessary for the associated damage to materialize fully. Simultaneously, the community of central banks acknowledges that climate change poses potentially systemic risks to financial stability that could materialize in "green swan" events (Bank of International Settlements, 2020). The risks are of two different natures: physical and transitional. Physical risks refer to the financial losses that could result from the increase in frequency and severity of climate-related weather events and the effects of long-term changes in climate patterns. Transition risks relate to the financial impacts that could result from a rapid low-carbon transition, including policy changes (inevitable policy response), technological breakthroughs or shifts in individual preferences or social norms. A rapid and significant reassessment of the value of high-carbon assets could spark a pro-cyclical crystallization of losses and lead to Climate Minsky Moments (Minsky 1986).

Moreover, central banks broadly acknowledge that climate-related risks are not fully priced by financial players. The existence of a specific carbon factor in asset performance, through carbon footprints, alignment on temperature trajectories or other measures related to greenhouse gas emissions, has only been documented since 2016. Nevertheless, the signal is still weak, and hindsight is not enough to ensure the robustness of this factor and to build an approach to asset allocation based on historical data alone. The absence of a climate-related risk premium could be a consequence of the lack of transparency on climate-related risk disclosure. More fundamentally asset prices do not reflect climate-related risks simply because of the radical uncertainty related to climate change. Standard risk measurement relies on estimates of probability distributions for underlying variables derived from historical data. Uncertainty refers to a situation where no probabilities can be estimated. Consequently, traditional backward-looking probabilistic approaches would not be able to assess climate-related risks properly. Historical data are certainly not sufficient to define a long-term asset allocation. They are even partially counterproductive, because they are supported by irrelevant economic and monetary fundamentals. Alternative approaches based on a green taxonomy may also prove insufficient as they only offer a static view of the reality they depict. New forward-looking approaches are therefore needed. Such scenario-based methodologies seek to set up plausible hypotheses for the future without attributing a probability of occurrence to each of them.

The Solvency II regulation for life insurance, non-life insurance and reinsurance in Europe is now considering the issue of climate change. In 2019, the European Commission asked EIOPA (the European Insurance and Occupational Pensions Authority) to review this regulation introduced in 2016. Based on EIOPA's recommendations, the European Commission issued its final proposed wording in September 2021. In this text, the European Commission decided to introduce a requirement to conduct climate change scenario analyses to assess the impact of climate change on their activities and financial results. This will be part of Pillar 2 of the ORSA (Own Risk and Solvency Assessment) regulation. The analysis will be based on two long-term climate change scenarios (1) where the global temperature increase remains below 2°C, and (2) where the global temperature increase is equal to or higher than 2°C. Another element of the review was to analyse whether the regulation could be amended to introduce differentiated capital requirement treatments for "green" versus "brown" assets. At this stage, no decision has been taken but the European

Commission has mandated EIOPA to make an assessment for June 2023. The new text now awaits approval by the European Parliament and Council and could yet be modified as a result of the negotiations. Final passage into local law is therefore not expected before 2024.

Climate Aware Investing and Investing in Climate are the two sides of a coin to consider. Strategic asset allocation must take into account the transition of economies to a decarbonized economy, the only scenario capable of avoiding devastating global warming, by positioning itself on investments that generate performance and lower risk (Principles of Responsible Investment 2019). But other, less positive, scenarios have to be considered too. This is the subject that the Climate Aware Strategic Allocation aims to cover. In addition, this transition may be induced and accelerated by promoting the financing of of traditional industries, the development of transitional facilitating activities or of disruptive innovations. This is the subject of Investing in Climate by selecting ad-hoc investments within each asset class once the allocation has been completed. This approach is now at the heart of pension funds' concerns as declared in March 2020 in a joint statement by California State Teachers' Retirement System, Japan Government Pension Investment Fund and USS Investment Management Ltd: "As asset owners, our ultimate responsibility is to provide for the best post-retirement financial security of millions of families across multiple generations. Since our commitment to providing financial security spans decades, we do not have the luxury of limiting our efforts to maximizing investment returns merely over the next few years".

Prioritizing the environmental dimension over social, societal or governance dimensions might seem restrictive in a global ESG approach. However, if land becoms unlivable, income inequality and poor governance will no longer be top concerns. Hence there is reason to believe that the transition to a decarbonized economy can only be achieved by developing the circular economy, collaborative and inclusive, all in a spirit of transparency and stakeholder consideration.

A new Kondratieff cycle

The global financial crisis of 2008 exacerbated a number of economic and monetary disorders that show the depletion of a growth model mobilizing more and more money supply, and therefore financial debt, to maintain the activity and cohesion of society, while generating more and more environmental nuisances. The concept of Kondratieff's structural cycles is interesting to apply, because the current period corresponds to the end of a 50-year cycle fueled by carbon-based fossil energy initiated at the end of the Second World War. The end of a Kondratieff cycle is witnessed by a period of decline in inflation and interest rates. Following a phase of creative destruction and the purging of the debt accumulated by the old cycle, a new cycle supported by decarbonized renewable energies can begin, requiring colossal investments in physical infrastructure as well as human capital, and accompanied by significant political and societal changes. The fact that carbon-based fossil fuels are unevenly distributed on the earth's surface creates the condition for geopolitical struggles which do not promote price stability. In contrast, decarbonized renewable energy is present almost everywhere, bringing sustainable growth. The sanitary crisis of 2020 has further amplified the process by considerably accelerating the digitalization of production, uses and consumption.

Proposition for a Climate Aware Strategic Asset Allocation

Strategic asset allocation is based on three pillars: expected returns derived from a consistent economic scenario, risk measures, volatility and correlations, and an algorithm for optimizing risk-adjusted returns. The idea is to use an essentially forward-looking scenario-based approach to implement the strategic asset allocation.

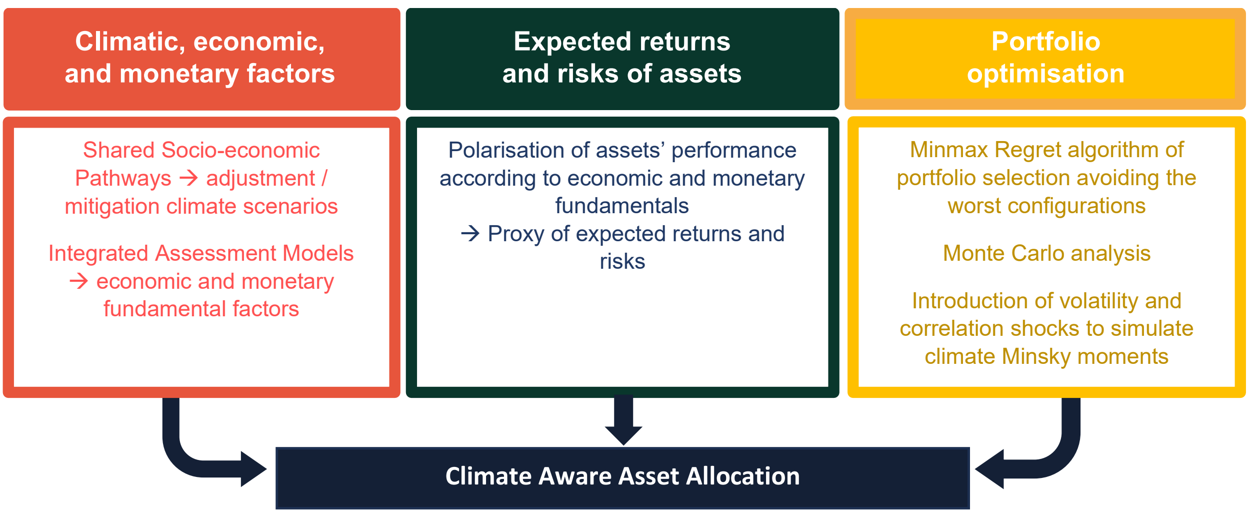
The scenarios translate the more or less intense efforts of the global economy to mitigate carbon emissions and adapt economic structures to warming while taking into consideration productivity, demographic trends, the relative energy intensity of the economy and the carbon content of energy production. The economic and scientific community agrees on five so-called Shared Socioeconomic Pathways (SSP), determined by the degree of mitigation and adaptation. They range from a virtuous scenario corresponding to the compliance with the United Nations Sustainable Development Goals in the context of enhanced international cooperation to an extreme scenario of regional rivalries abandoning any ambition in the field of climate. The purpose of this study is to deduce what strategic asset allocation is optimal for each SSP.

The approach is based on three steps. The first step is to deduce from each SSP the changes in economic and monetary fundamentals: growth, inflation and money supply that may explain asset class performance. This is done by means of an integrated economy-energy climate model, so-called Integrated Assessment Model (IAM). This type of model endogenizes the externality of carbon emissions, through a damage parameter of global warming on the economy, and the associated carbon price which enables the model to incorporate the laws of thermodynamics (Grandjean & al. 2017). The calibration of the damage function and of the carbon price is complex, because it poses the problem of determining an intergenerational discount rate to calculate the present value of damages that may occur in a distant future, which poses complex problems of moral hazard (Gollier 2019).

The second step is to implement a factor financial model of polarization of asset performance according to economic and monetary fundamentals to determine trajectories of the assets' expected returns. Expected risk measures, volatilities and correlations are derived from these trajectories. The factors are fitted to long-term historical records, as it is assumed that the organic link between economic and monetary fundamentals and the performance of assets, built on the legal basis of contracts, remains relevant. The polarization of asset performance according to historically calibrated economic and monetary fundamentals therefore has every chance to remain valid as whatever the cycle, dividends constitute compensation for shareholders, coupons for bondholders and rents for landlords. In fact, and in a very schematic way, equities outperform other assets in times of deflationary growth, real estate in times of inflationary growth, bonds in times of deflationary recession and cash in times of inflationary recession.

The third step is to choose a robust algorithm for optimizing risk-adjusted return. An algorithm, for decision-making in uncertain environments, such as the MinMax Regret makes it possible to select the asset allocation to avoid the worst configurations from a financial perspective. Minimizing the risk of regret, that is, the opportunity cost of a bad decision, is the syndrome of the bad loser in behavioral finance. The algorithm is built on Monte-Carlo simulations based on expected returns and risk measures which make it possible to integrate random shocks of volatility and recorrelation, characteristic of financial crises that return on average every 10 years. The irruption of such Minsky moments is consistent with economic and financial disruptions caused by a likely intensification of extreme natural events and transition break-ups.

Climate Aware Asset Allocation Principles



1 – SHARED SOCIOECONOMIC PATHWAYS AND REPRESENTATIVE CONCENTRATION PATHWAYS

1 – Shared socioeconomic pathways (SSPs)

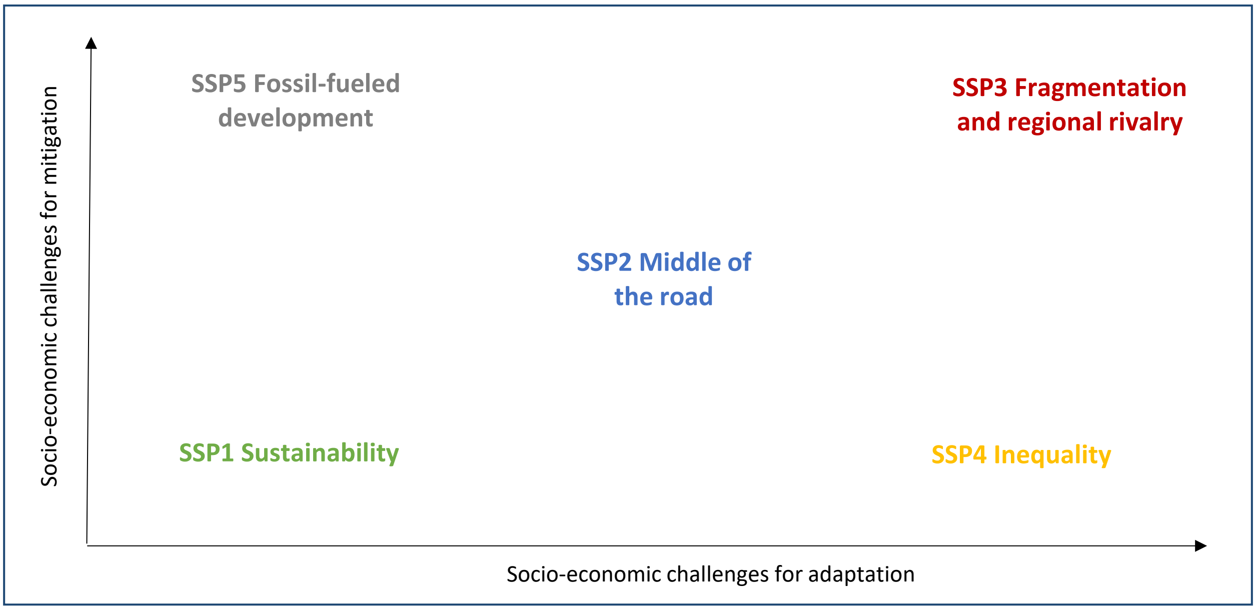
SSPs are narrative scenarios design by an international team of climate scientists to explore possible future pathways for demographics, economics and climate change (Moss & al. 2010, Arnell & al. 2011, Kriegler & al. 2012 and O`Neill & al. 2015). They are used to understand how socio-economic choices will affect the climate and how Paris Agreement Climate targets could be reached. They will be used to help produce the IPCC 6th Assessment Report on climate change.

The scenarios are :
- SSP1 : Sustainability
- SSP2: Middle of the road, an average of SSP1, SSP3, SSP4 and SSP5
- SSP3: Fragmentation and regional rivalry
- SSP4: Inequality
- SSP5: Conventional fossil-fueled development

These scenarios can be mapped on challenges to adaptation and challenge to mitigation:

SCENARIO	NARRATIVE	CHALLENGE FOR MITIGATION	CHALLENGE FOR ADAPTATION
SSP1	Strong international cooperation, priority given to sustainable development, improvement in living conditions and consumer preferences for environmentally friendly goods and services with lower resource and energy intensity.	Low	Low
SSP2	Current social, economic and technological trends continue, development and growth proceed unevenly depending on the country and region. National and international institutions work towards achieving sustainable development goals that progress slowly. The environment experiences degradation despite development that is less resource and energy intensive.	Medium	Medium
SSP3	Resurgent nationalism, slow economic development, persistence of inequalities and regional conflicts. Countries are guided by concerns about security and competitiveness. They focus on national or regional problems and on food and energy security issues. Low international priority is given to environmental protection, leading to strong environmental degradation in some regions.	High	High
SSP4	Development marked by wide disparities between and within countries. Degradation of social cohesion and multiplication of conflicts. A growing gap between an internationally connected elite, responsible for the majority of GHG emissions, and a fragmented collection of low income, poorly educated people who are vulnerable to climate change. The energy sector diversifies between carbon intensive and low carbon energy sources. Environmental policies focus on local issues.	Low	High
SSP5	Development based on heavy use of fossil fuels and marked by high investments in health, education and new technologies. Adoption of resource and energy intensive lifestyles around the world. High economic growth and rapid technological progress. Local pollution problems are successfully managed, and adaptation is facilitated by the reduction in poverty.	High	Low

Which may be summarized in the following chart.



For this study, all SSP data are collected from the International Institute for Applied Systems Analysis.
Carbon capture and storage through bioenergy, direct air capture or other technologies plays an important role in most SSPs by reducing CO2 emissions sufficiently fast to keep global warming under control (Collins & al. 2013, Rockström & al. 2016, Rogelj & al. 2016).

2 – Representative concentration pathways

Representative concentration pathways (RCPs) are greenhouse gas concentration trajectories adopted by the IPCC 5th Assessment Report on climate change in 2014.
The RCPs are labelled after a possible increase of radiative forcing extending up to 2100. The range of RCPs stretched from 2.6 to 8.5 W/m2[1]. Each level of radiative forcing leads to specific increases in temperature from 2.0°C for 2.6 W/m2 to 4.2°C for 8.5 W/m2.

SSPs are combined with RCPs that define different levels of climate change mitigation. They are named by the figure of the SSP and the radiative forcing level (ex: SSP1–60 for SP1 combined with an RCP of 6.0 W/m2). Combinations of SSPs and RCPs are not always compatible as mitigation efforts are more important when the targeted RCPs are low. SSPs baseline may be defined in combination with specific RCPs that might occur in the absence of any concerted international effort to address climate change beyond those already adopted by countries, they are SSP1-60, SSP2-70, SSP3-70, SSP4-60 and SSP5-85.

(1) Radiative forcing expressed in W/m2 is the net difference of the power of the infrared radiation emitted by the earth at the surface into the atmosphere and the power of the infrared radiation emitted by the atmosphere at the tropopause back to space. The radiative forcing is currently equal to 155 W/m2, responsible for a 30°C warming of the earth surface. Around 2.3 W/m2 have been added since the industrial revolution by anthropic greenhouse emissions

2 - INTEGRATED ASSESSMENT MODEL

1 - Overall presentation

IAMs are tools that bring together social issues (demographic, political), economic variables and physical climate systems in a coherent framework that is usable by researchers, decision makers and of course asset managers.

The Kaya identity (Kaya & Yokobori 1997) provides a simple conceptual introduction to the issue, splitting gross industrial carbon emissions into four components: population, GDP per capita, energy intensity (energy per unit of GDP), and carbon intensity (emissions per unit of produced energy).

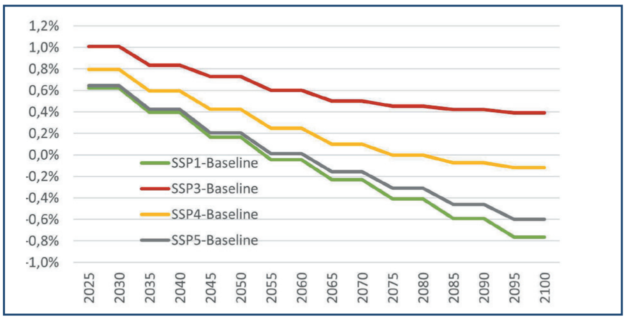
$$E = Pop \times \frac{GDP}{Pop} \times \frac{Energy}{GDP} \times \frac{CO_2eq}{Energy}$$

One of the first and the most famous IAMs is DICE which stands for Dynamic Integrated Climate-Economy model (Nordhaus 1992). The DICE model is a neoclassical long-term macro-economic model that integrates a carbon cycle and climate science with physical concepts such as radiative forcing and a Planck feedback parameter(2). The model estimates cost of climate change as a physical risk through a damage function and transition risk through a carbon tax concept. The physical risk is related to the economic damages on real assets caused by climate change. A wide range of events will be temperature related: tropical cyclones and coastal floods, the combined impact of droughts and heat stress on agricultural productivity, etc. The transition risk captures the more or less orderly transition towards carbon neutrality. It will be caused by a wide range of shocks: climate policy, shifts in market preferences and technological innovation. It may appear presumptuous to forecast such complex systems as the climate and the economy with a very limited set of equations, but the aim is really to focus on long-term trends, not on cyclical events.

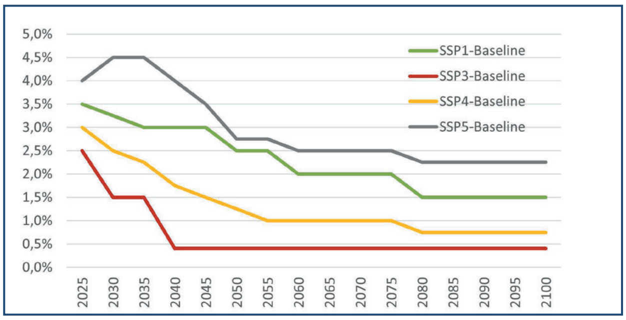
In response to a call from the IPCC, the Integrated Assessment Modeling Consortium (IAMC) was created in 2007 as a research organization to lead the integrated assessment modeling community in the development of SSP scenarios that could be employed by climate modelers. The models of five international teams models have participated so far in the development of the SSP scenarios: PBL Netherlands Environmental Assessment Agency, National Institute for Environmental Studies Japan, International Institute for Applied Systems Analysis Austria, Pacific Northwest National Laboratory USA and Postdam Institute for Climate Impact Research Germany.

As input data, the IAMC has adopted the SSP world population and GDP projections by the World Bank, the OECD and the IMF(3), from which the total factor productivity of growth is deduced.

Population Growth



Factor Productivity Growth



(2) The Planck feedback refers to the fact that the higher the temperature of a radiating body, the more energy it radiates which creates negative feedback

(3) Projections of GDP levels are determined for 176 countries, representing 98.5% of global GDP in 2010. The projections replicate short-term economic projections of the World Bank (2011), OECD (2011) and the IMF (2011) up to 2016. The model then follows a gradual process of convergence towards a balanced growth path along the lines of the Solow growth model.

2 - La Française IAM

The model is derived from the GEMMES Model (Bovari, Giraux & Mc Issac 2018), one of the most advanced IAMs used by Agence Francaise de Développement, which has the advantage of including the financial sphere in addition to the real sphere. The period covered runs to 2100 in five-year time steps.

The world carbon is represented cycle through a three-layer model: the deep ocean, the biosphere and the atmosphere. The carbon cycle is based upon a three-reservoir model calibrated to existing carbon-cycle models and historical data. Carbon flows in both directions between adjacent reservoirs. The accumulation of CO2 due to the use of fossil fuels leads to an increase in the radiative forcing and the increase in radiative forcing leads to a change in the atmospheric temperature.

The physical climate risk is modeled through a damage function adopting a polynomial form to capture de nonlinear effect of climate change on the economy. Total damage is split into damage on the GDP and damage on the capital. It is calibrated is such a manner that 50% of the output is lost if the temperature increase reaches 4°C (Dietz & Stern 2015).

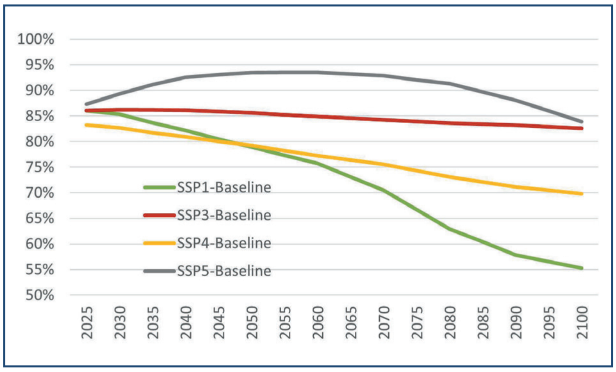
The transition risk is modeled through a climate policy aimed at curbing carbon emissions within a relatively short period of time. The abatement cost for the economy is expressed through a carbon tax equal to the net carbon emissions multiplied by the price of carbon.

The economic modelization is a long-run equilibrium model inspired by the Ramsay-Cass-Koopmans growth model assessing further the role of private debt dynamics in the intrinsic instability of a monetary market economy (Keen 1995) and where damage function and abatement costs are introduced. The climate, the energy system of the economy and a few economic variables are modelized but not interest rates and money quantity, that are fundamental factors for assets performance. The model is therefore broadened by financial and monetary equations: Taylor rule for interest rates and Fisher equation for broad money supply[(4)].

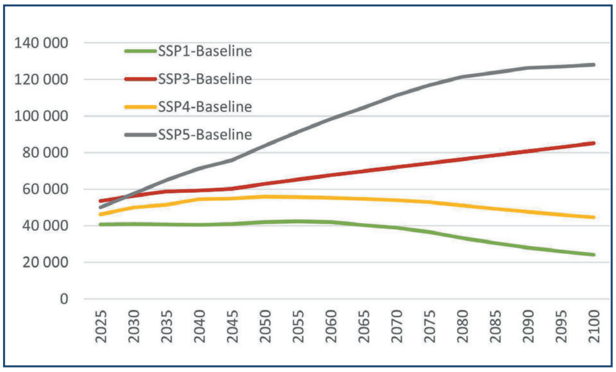
As a result, the energy, climate, economic and financial diffusions for SSP1, SSP3, SSP4 and SSP5 are disclosed in the charts below.

(4) In this equation the velocity of money is defined as a function of interest rates

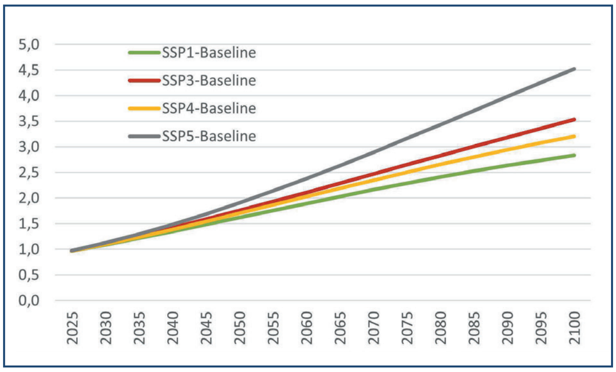
Share of Fossil Fuel in Energy Production



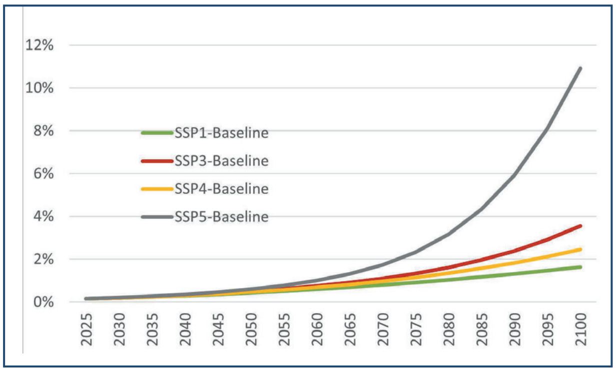
CO2 Emissions (million tons)



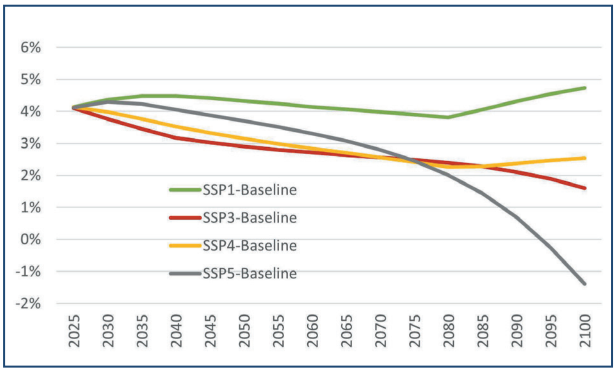
Temperature Increase



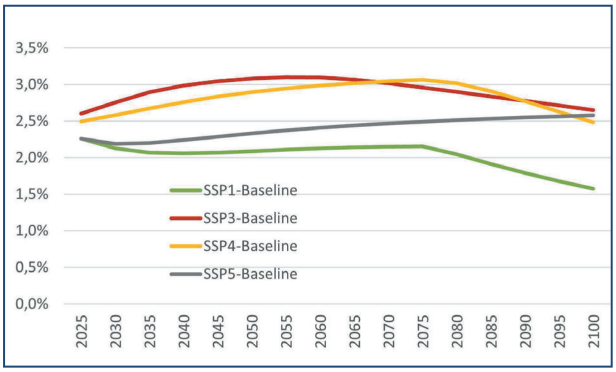
Climate Damage Output (% of GDP)



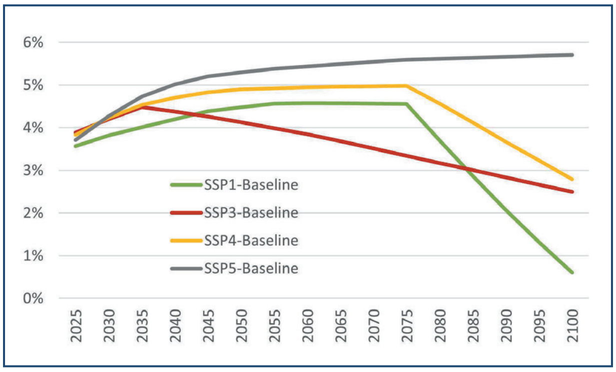
GDP Growth



Inflation



Interest Rate



3 – EXPECTED RETURNS AND RISKS OF ASSETS

1 - General Principles

The universe of assets considered in this study covers the main financial assets in France, the eurozone and the USA: government bonds, corporate bonds (investment grade and high yield), equities as well as two real estate sectors in France: residential and office, and lastly gold[5]. Their performance is measured in euros on a total return basis, asset performance in dollars is hedged against the euro.

La Française's IAM outputs a set of fundamental variables that describe the long-term behavior of economic and monetary factors for each SSP: GDP growth, inflation, and broad money supply. These factors are related to the total long-term returns of the assets thanks to a historical analysis of sensitivity covering thirty years on a quarterly basis[6].

A principal component analysis approach to cluster the assets has been excluded due to difficulties in interpretation of the principal components and the issue of consistency as results depend greatly on the universe of assets.

A first approach was implemented to measure the polarization of assets' total returns to a certain number of states of the fundamental factors which has yielded positive results. While the measure of polarization is useful to assess the strength of the difference in total return regimes, it does not provide any indication on the magnitude of this difference. A second and complementary regression-based approach was implemented.

The total return for a given asset is given by:

$$R_a=\beta_1 G + \beta_2 I + \beta_3 M$$

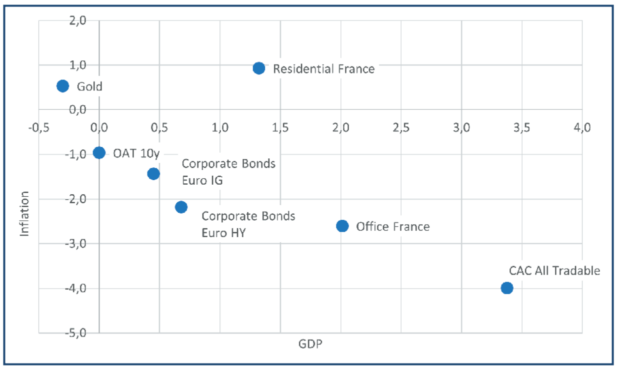
with
G: GDP growth
I: Inflation
M: Change in money supply
β: Beta coefficients - sensitivities

This model is extremely restrictive as the choice of dependent variables is a strong assumption. However, we believe that this approach is relevant given the historical depth of the analysis and the signal we are trying to capture. To maximize the explanation power of the regression, lags by 1 to 3 quarters in the time series of dependent variables are introduced, as the diffusion of a macroeconomic state in the assets' returns is often not instantaneous. The presence of lags greatly increases the explanation power of the model.

2 - Results

The chart below displays a selection of French and eurozone assets clustered in the 2-dimensional beta plan of GDP growth and inflation. Government bonds are neutral on growth, but have a negative beta to inflation, which shows that they tend to underperform when inflation rises. Corporate bonds also exhibit a negative beta to inflation, but are positively correlated to growth, which makes sense given the corporate nature of these issuers. Equities are the most sensitive to growth and inflation, with the highest betas in absolute value. The betas are positive for growth and negative for inflation. Real estate assets have a unique positionning in this space, in the higher-right part of the chart. While office property exhibits beta profiles somewhat between those of equities and corporate bonds, residential property is the only asset in the top right quadrant of the chart, benefiting in periods of growth and rising inflation. Gold is the only asset in the top left quadrant of the chart, performing well in periods of negative growth and rising inflation, which is an intuitive result and supports the definition of gold as a hedge asset.

Assets betas

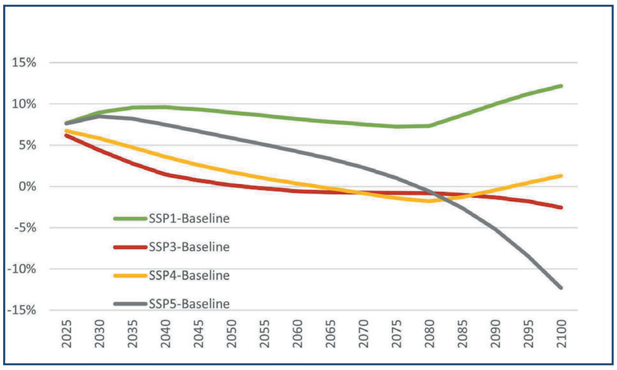


(5) Financial data sources: Agence France Trésor, MTS, Fed, BOFA, Barclays, Euronext, DJ STOXX, S&P, CBRE, LME
(6) Economic and monetary data sources: INSEE, Eurostat, BCE, Fed

Using the estimated time series of macroeconomic variables produced by the IAM and the betas estimated through the historical analysis, time series of expected returns of assets on different SSPs may be computed. From these time series, expected volatilities of assets' returns and expected correlations between assets' returns may in turn be computed.

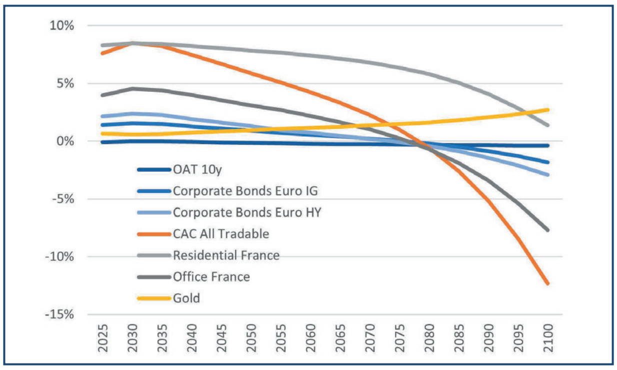
The chart below displays the expected return of the CAC All Tradable equity index for the different SSPs up to 2100. Equity returns remain strong until 2100 for the SSP1 scenario (Sustainability). On the other hand, equity returns for the SSP5 scenario (Conventional fossil-fueled development) start strong and collapse towards the end of the period. During the beginning of the period, the environmental damages inflicted on the economy remain low enough to be negligible compared to overall growth, but after several decades and the passing of a no-return point in environmental degradation, the damages outweigh growth as this path becomes unsustainable.

CAC All Tradable



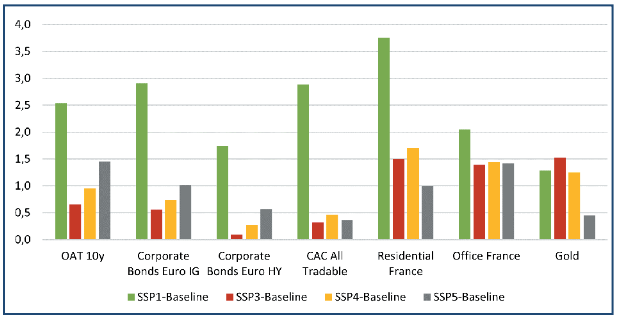
In a similar fashion, the returns of a group of assets for a given SSP may be estimated and compared. The chart below displays the expected returns of a selection of French and eurozone assets up to 2100 for SSP5 (Conventional fossil-fueled development). In this scenario, residential property is the only asset that survives the projected deterioration in macroeconomic conditions at the end of the period, while most assets experienced negative returns after 2080. Gold rebounds quite significantly after 2080, when the projected economic damages are too strong to be supported and the need for hedge is dominant.

SSP5 Baseline



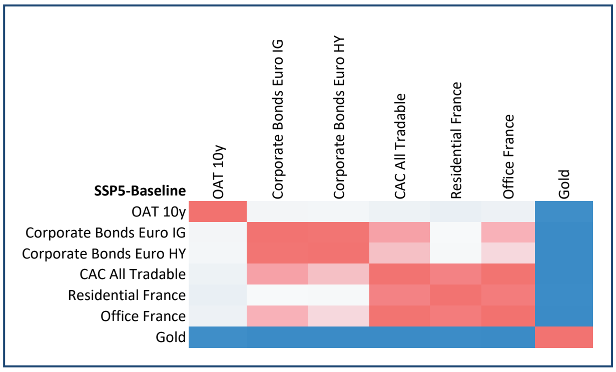
The chart below displays the ex-ante Sharpe ratio based on expected returns and volatilities of a selection of French and eurozone assets up to 2100 for the different SSPs. The Sharpe ratios are particularly high for SSP1 (Sustainability) and low for SSP3 (Fragmentation and regional rivalry) except for gold. Real estate assets exhibit a higher Sharpe ratio than financial assets. Government bonds' Sharpe ratios are particularly high for SPP5 (Conventional fossil-fueled development).

Sharpe ratios

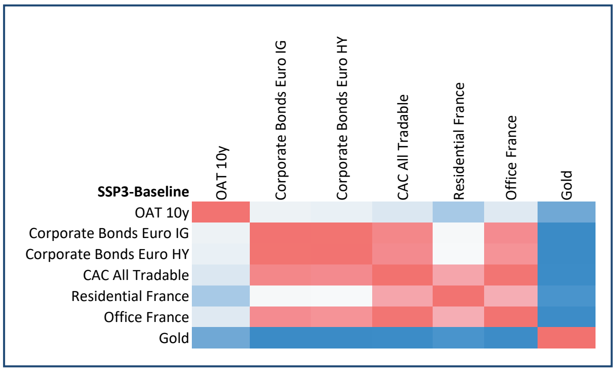


Finally expected correlations between French and eurozone assets' returns up to 2100 for the different SSPs are displayed in the following chart in a color scale mode: red for high correlation, blue for low correlation. The correlation patterns are very scattered across the SSPs. Gold and to a certain extend residential property have a strong diversification potential in relation to financial assets whatever the SSP. Diversification is particularly efficient in the SSP1 scenario (Sustainability).

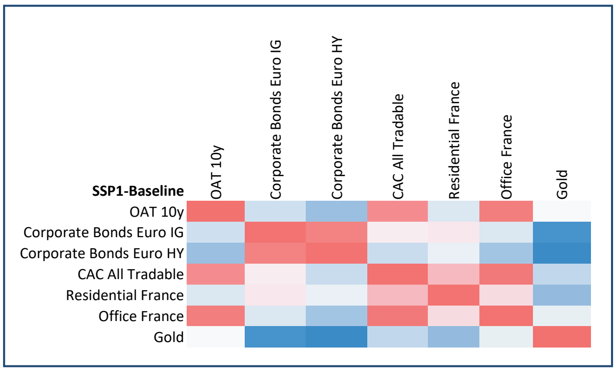
SSP5 correlation



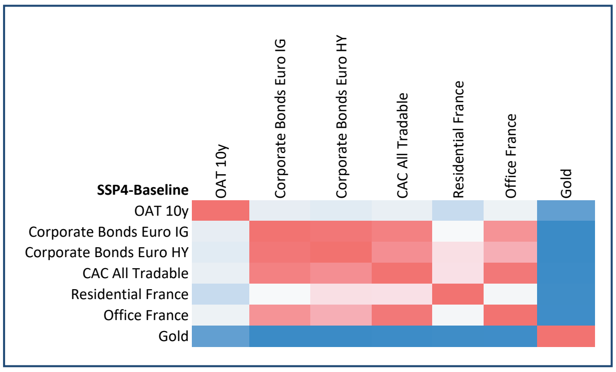
SSP3 correlation



SSP1 correlation



SSP4 correlation



4 – PORTFOLIO OPTIMIZATION: A MINMAX REGRET ALLOCATION ALGORITHM

1 - General Principles

Using expected returns and risks for each SSP, trajectories of asset's returns are modelized using a multidimensional gaussian diffusion process (Monte-Carlo simulation). From these trajectories, portfolio allocation returns are computed.

In broad terms, the minmax regret algorithm selects the best portfolio allocation to minimize the maximum regret experienced from such decision. Regret is defined as the deviation of the allocation return that is actually received from the maximum portfolio allocation return that could have been received. The higher the deviation, the higher the regret (Xidonas & al. 2017).

Instead of pure performance of each allocation, the objective function F_ω is defined as a utility function mixing expected return R, with weight (1-ω) and risk penalization σ, with weight ω. For a the allocation and S the scenario under consideration:

$$F_\omega(a,S) = (1-\omega)R(a,S) + \omega\sigma(a,S)$$

The example given in section 2 corresponds to ω=0.

It is not required that the user defines ω directly: all values will be tested, from 0 to 1 with a given step. Then, the results in terms of minimax regret for each ω enable to derive what the optimal ω value is. It can be interpreted as the optimal risk-aversion profile to adopt.

The minmax regret allocation may be regarded as a memory-heavy, or brute-force, optimization approach as no gradient descent is performed. Instead, all portfolio allocations are tested with respect to all the anticipated scenarios. Then, it is deduced that the portfolio allocation returning the lowest regret whatever the scenario is the optimal one.

Such approach has pros and cons:

PROS	CONS
- The algorithm works for any kind of constraints. As opposed to convex optimization, constraints can be path-dependent and non-convex. For example, it is possible to fix some limit for the Value-at-Risk or the maximum drawdown of the portfolio. - The assets do not need to have log normal or normal dynamics, as opposed to the Markowitz framework. Periods of stress can be easily added to the anticipated scenarios. - The optimization result adapts to either a buy & hold or frequently rebalanced portfolio strategies, whereas the Markowitz framework assumes constant rebalancing. - There is a 100% certainty to find the global optimum, even for complex cases.	- The computation takes much more time than its gradient descent equivalent. - The sensitivity of the optimization is the result of the number of portfolio allocations tested and the number of anticipated scenarios. As the memory of the computer is not limitless, there is a maximum number of allocations and scenarios that can be analyzed for a given number of assets.

From what precedes, it can be inferred that minimax regret shows inherent robustness. For financial applications, minimax regret is thus of prior interest, because it offers a simple-to-understand, risk versus reward decision rule.

2 - EXAMPLE

Assume five different portfolio allocations to choose from, and three future scenarios of performance: one scenario is pessimistic, one other is neutral and the last one is optimistic.

To ensure the realized performance remains good whatever scenario happens, none of the three scenarios is discriminated against the other two. In other words, no probability is allocated to any of the three scenarios. This is of particular importance: minmax regret allocation does not require any probability distribution of the anticipated scenarios.

The realized performances for each portfolio allocation and scenario are summarized in the table below:

	3 SCENARIOS		
5 ALLOCATIONS	Pessimistic	Most likely	Optimistic
portf1	3	10	17
portf2	5	9	15
portf3	5	6	12
portf4	**6**	**8**	**11**
portf5	4	7	16

Table 1: Performance of each allocation (% p.a.) depending on what scenario occurs.

Then, the regret is computed for each scenario. As previously defined, regret is the deviation of the realized performance of the portfolio allocation from the best performance that could have been obtained. For example, regret for each portfolio allocation in the neutral scenario is computed as follows:

$$\text{Regret}[i] = \max(10,9,6,8,7) - \text{portfolio}[i]$$

Note that the regret corresponding to the best performance is always zero-valued. All other regrets are strictly positive quantities.

All regrets are shown is the table below:

	Pessimistic	Most likely	Optimistic
portf1	3	0	0
portf2	**1**	**1**	**2**
portf3	1	4	5
portf4	0	2	6
portf5	2	3	1

Table 2: Regrets of each allocation, by scenario.

This table reads as follows: should the neutral scenario occur; the best portfolio allocation would be the first one (regret = 0). The worst would be the third one (regret = 4).

Then, the maximum regret of each portfolio allocation is computed. It is simply the maximum value by line in Table 2. The maximum regret by portfolio allocation is thus 3, 2, 4, 6 and 3, respectively.

The portfolio allocation with minimal value obtained from the previous step corresponds to the minimal regret portfolio allocation, i.e., the second portfolio allocation.

3 - Number of allocations

The minmax regret allocation is a memory-heavy approach. When the number n of assets is high (i.e., above 10 assets) and the allocation increment δ is low (i.e., 5 % or 1 %), the number of allocations to be tested becomes very high and may exceed a conventional computer memory capacity.

To ensure the workability of the computation, we develop an analytical formula of the number of portfolio allocations N_{tot} for n assets, such that:

- The portfolio is long-only: no negative weight in the allocation (short position) is allowed.
- No leverage is allowed: the sum of weights in the allocation is equal to 100 % exactly.
- The allocation increment is equal to δ for any asset: the investment in the asset is either equal to 0 %, δ %,2δ %, up to 100 %.
- The lower (resp. upper) bound investment for any asset is 0 % (resp. 100 %). Therefore 100 must be a multiple of δ, such that:

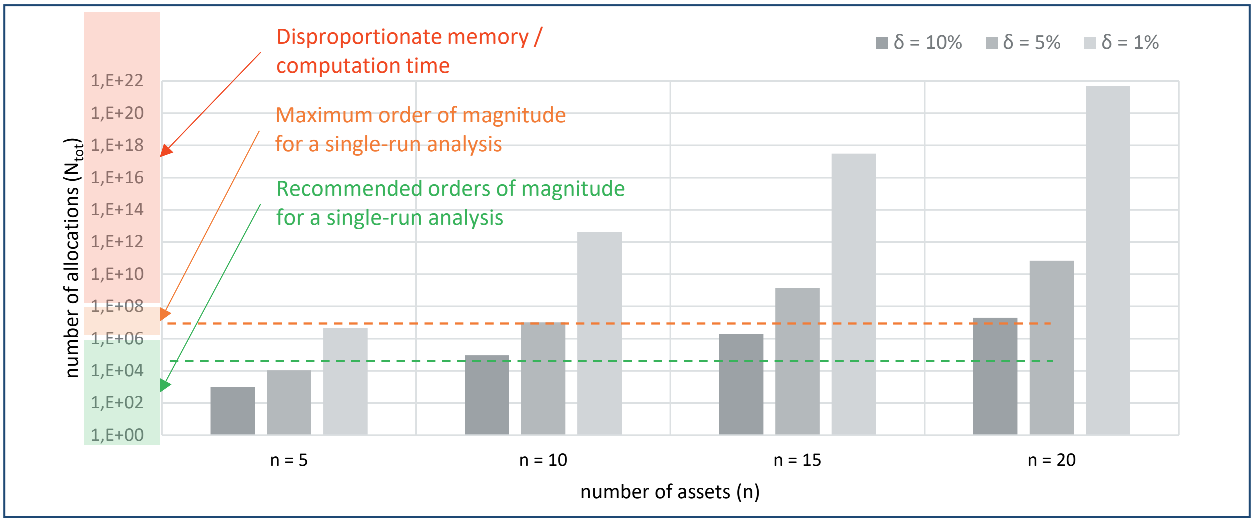
$$k = \frac{100}{\delta} \text{ is an integer.}$$

It can be proven easily that:

$$N_{tot} = \sum_{i=1}^{\min(n,k)} \binom{n}{i}\binom{k-1}{i-1}$$

The formula is used for several values of n and δ in the below chart. Note that the value of N_{tot} is displayed on a log axis.

Number of portfolio allocations N_{tot} with respect to the number of assets n and the allocation increment δ



When the order of magnitude for N_{tot} becomes too high, a specific computation strategy needs to be set. In that case, the following strategy is used:

- Perform a first run with allocation increment $m_0\delta, m_0 \geq 2$, such that $N_{tot,0}$ becomes acceptable, i.e., below, or equal to 10^4.
- Perform a second run with allocation increment $m_1\delta$, $m_0 \geq m_1$, such that $N_{tot,1}$ becomes acceptable. The lower (resp. upper) bound for any asset corresponds to the optimum value found in the first run, minus (resp. plus) $m_0\delta$.
- Proceed iteratively until the number of portfolio allocations becomes acceptable for allocation increment δ.

4 - Periods of stress, Climate Minsky Moments

As the time horizon is very long, the scenarios generated for the minmax regret allocation need to account for stressed market regimes, caused by rare, yet highly destabilizing events, so called Minsky moments. A Minsky moment is a sudden, major collapse of asset values which marks the end of the growth phase of a cycle in credit markets or business activity. The more general concept of a "Minsky cycle" consists of a repetitive chain of Minsky moments: a period of stability encourages risk taking, which leads to a period of instability when risks are realized as losses, which quickly exhausts participants into risk-averse trading (de-leveraging), restoring stability and setting up the next cycle. Typically, a Minsky cycle has a duration of 10 years corresponding to the periodicity of asset bubbles.

The occurrence of such events is highly likely as a consequence of global warming. Floods, heat waves, forest fires are expected to happen more often and may impact negatively and rapidly a given market, such as commodities. Other pandemics than covid may also occur due to deforestation, because it brings new wild species and affiliated viruses closer to humankind.

Their effects on financial markets are introduced according to a framework of distressed selling and endogenous correlation between assets' returns (Cont & Wagalath 2011). According to this framework, the dynamics of asset returns are twofold:

- First, market dynamics: this is the traditional model. Assets' returns follow a multidimensional gaussian diffusion process.
- Second, liquidity dynamics: if the value of an asset decreases below a given threshold, distressed sales are amplifying the trend (feedback effect). This effect is path dependent; it is controlled by a parameter λ denoting the depth of the market for the specific asset. For a certain level of λ, the feedback affect starts to operate and causes volatilities and correlations to increase sharply.

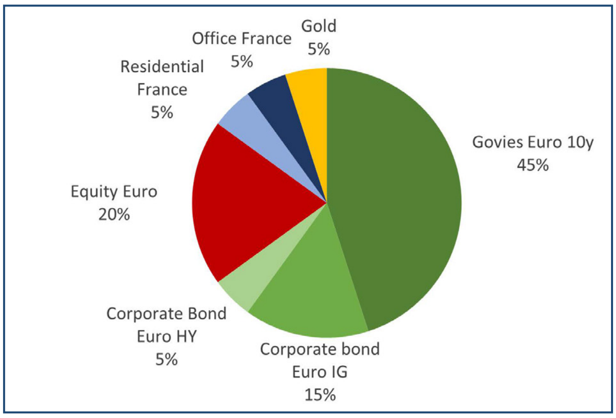
5 - Optimal allocations

The output of optimal allocations for the different SSPs considering a universe of French and euro assets up to 2100 is displayed in the chart below. Real estate exposure is subject to an upper limit of 20 % and gold to a limit of 10 %. Other time horizons may be considered but only beyond 2060 considering the need to have enough data to compute the expected risks.

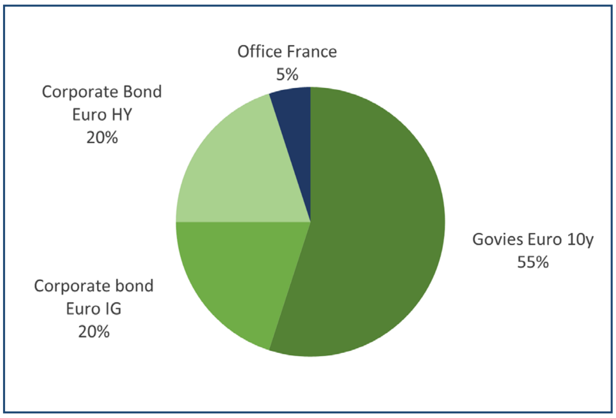
The exposure of the optimal allocation for SSP1(Sustainability) to risky assets (equity and high yield corporate bonds) is pretty high, counterbalanced by a substantial exposure in French residential property. The optimal allocation for SSP5 (Conventional fossil-fueled development) is in fact close to the current allocation of French institutional investors on average, which is reasonable to expect as the SSP5 reflects the historical and to a large extent current socio-economic conditions.

The equity exposure is high for SSP1 (Sustainability), lower for SSP5 (Conventional fossil-fueled development), inexistant for SSP3 (Fragmentation and regional rivalry) and SSP4 (Inequality). The optimal allocations for SSP2 and SSP3 are very close; they differ from the introduction of office property in SSP3 (fragmentation and regional rivalry).

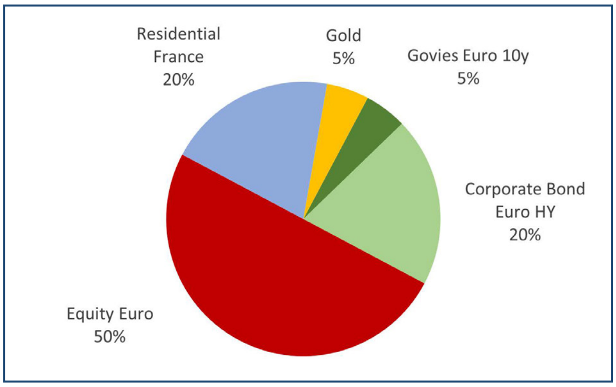
SSP5 baseline



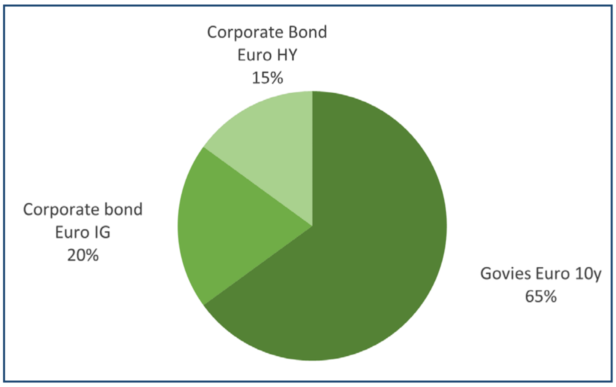
SSP3 baseline



SSP1 baseline



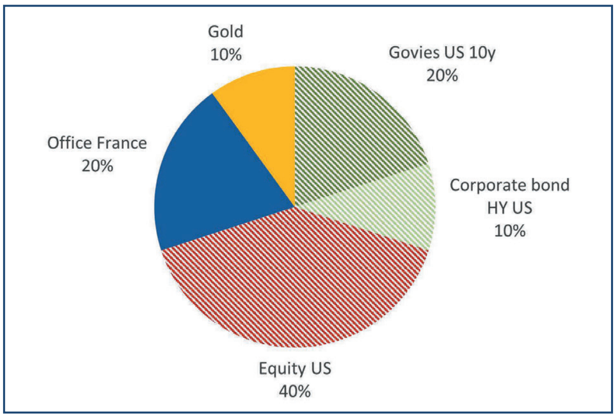
SSP4 baseline



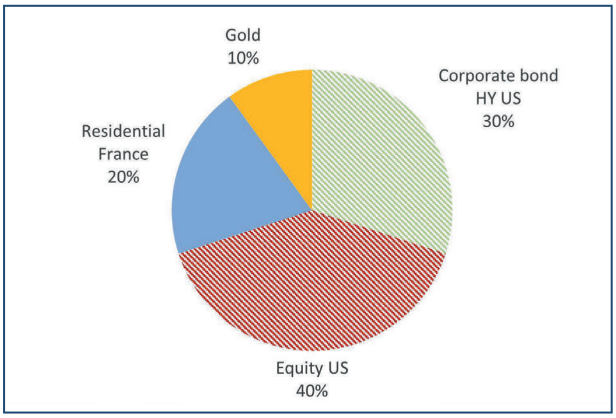
The chart below shows the output for the total universe of assets including US assets. In the optimal allocation for SSP1 (Sustainability), US equity becomes the largest exposure, taking part of the euro equity exposure and replacing entirely the euro high yield corporate bond exposure while keeping the French residential property exposure. The US assets replace the euro assets in the optimal allocation for SSP5 (Conventional fossil-fueled development) but with a reinforcement of French office property.

The optimal allocations for SSP3 (Fragmentation and regional rivalry) and SSP4 (Inequality) are completely upset compared with the allocations with French and euro assets only. The defensive stance is replaced by a much more offensive exposure in US assets balanced by French residential property. Clearly, US assets offer much better potential in these somewhat distressed scenarios.

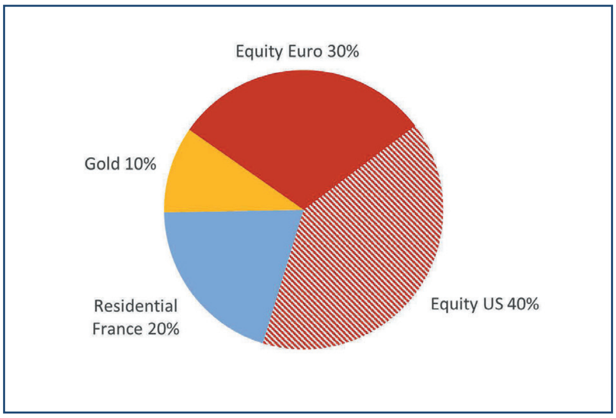
SSP5 baseline



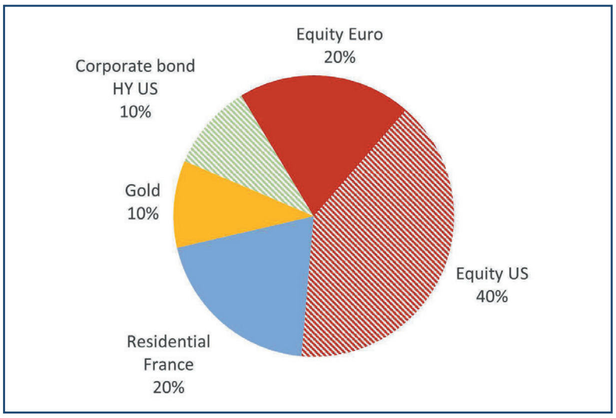
SSP3 baseline



SSP1 baseline



SSP4 baseline



CONCLUSION

The aim of this study is to determine as logically as possible what long-term strategic asset allocation is optimal for each SSP baseline scenario, keeping in mind that only a scenario-based forward-looking approach can cope with the inherent uncertainty surrounding climate change. To do that, an integrated assessment model including financial and monetary modules has been developed in order to deduct fundamental economic and monetary factors linked to each SSP as entry point. Then a factor model of explanation of assets' long-term performance was developed to deduce the long-term expected returns and risks of the assets from the fundamental economic and monetary factors. Finally, a robust optimization algorithm was implemented based on a minmax regret approach, including the simulation of financial crises.

The output of optimal portfolios for the different SSPs is very different. The optimal portfolio for SSP5 (Conventional fossil-fueled development) is close to the current portfolio of the French institutional investor on average, which is reasonable to expect as SSP5 reflects the historical and to a large extent current socio-economic conditions. The optimal portfolio for SSP1 (Sustainability) has a high-risk profile. The optimal portfolios for the distressed scenarios, SSP3 (Fragmentation and regional rivalry) and SSP4 (Inequality), are defensive if invested only in French and euro assets, offensive if US assets are introduced.

No matter how reckless the approach, the intent is to help institutional investors cope with climate change in their strategic allocation exercise and to build a climate aware strategic asset allocation. Each link in the chain is marred by hypotheses and approximations. The model risk is therefore important as a number of approximations that induce only second-order disturbances in the short run can lead to first-rate inconsistencies in the long run.

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