The opinions expressed in this presentation are those of the authors and are not meant to represent the opinions or official positions of Amundi Asset Management.
“There is no Plan B, because there is no Planet B“

Ban Ki-moon, UN Secretary-General, September 2014

Is it a question of climate-related issues?
In fact, it is more an economic growth issue

“The Golden Rule of Accumulation: A Fable for Growthmen“

Nobel Prize in Economics, 2006
Sustainable growth and climate change

Environmental, Social, and Governance (ESG)

Adam Smith (1776)
An Inquiry into the Nature and Causes of The Wealth of Nations
The Solow growth model

The model

- Production function:

\[ Y(t) = F(K(t), A(t) L(t)) \]

where \( K(t) \) is the capital, \( L(t) \) is the labor and \( A(t) \) is the knowledge factor.

- Law of motion for the capital per unit of effective labor

\[ k(t) = K(t) / (A(t) L(t)) \]

\[ \frac{dk(t)}{dt} = s f(k(t)) - (g_L + g_A + \delta_K) k(t) \]

where \( s \) is the saving rate, \( \delta_K \) is the depreciation rate of capital and \( g_A \) and \( g_L \) are the productivity and labor growth rates.
The golden rule

Golden rule with the Cobb-Douglas production and Hicks neutrality

The equilibrium to respect the ‘fairness’ between generations is:

\[ k^* = \left( \frac{s}{g_L + g_A + \delta_K} \right) \frac{1}{1 - \alpha} \]

“Each generation in a boundless golden age of natural growth will prefer the same investment ratio, which is to say the same natural growth path” (Phelps, 1961, page 640).

“By a golden age I shall mean a dynamic equilibrium in which output and capital grow exponentially at the same rate so that the capital-output ratio is stationary over time” (Phelps, 1961, page 639).
What is economic growth and what is the balanced growth path?

- There is a saving rate that maximizes consumption over time and between generations ("the fair rate to preserve future generations")
- Economic growth corresponds to the exponential growth of capital and output to answer the needs of the growing population
- Introducing human and natural capitals add constraints and therefore reduce growth!

Economic growth $\Rightarrow \{\text{productivity } \uparrow \text{ and labor } \uparrow \text{ maximization of consumption-based utility function}\}$
Extension to natural capital

What are the effects of environmental constraints on growth?

Introducing a decreasing natural capital (Romer, 2006)

The balanced growth path $g_Y^*$ is equal to:

$$g_Y^* = g_L + g_A - \frac{gL + gA + \delta N_c}{1 - \alpha} \vartheta$$

where $\delta N_c$ is the depreciation rate of natural capital and $\vartheta$ is the elasticity of output with respect to (normalized) natural capital $N_c(t)$

“*The static-equilibrium type of economic theory which is now so well developed is plainly inadequate for an industry in which the indefinite maintenance of a steady rate of production is a physical impossibility, and which is therefore bound to decline*” (Hotteling, 1931, page 138-139)

Accounting for environment... changes the definition of economic growth
Preferences modeling (Ramsey model)

- $\rho$ is the discount rate (time preference)
- $c(t)$ is the consumption per capita and $u$ is the CRRA utility function:

$$u(c(t)) = \begin{cases} 
\frac{1}{1-\theta} c(t)^{1-\theta} & \text{if } \theta > 0, \quad \theta \neq 1 \\
\ln c(t) & \text{if } \theta = 1
\end{cases}$$

where $\theta$ is the risk aversion parameter

- Maximization of the welfare function:

$$\int_{t}^{\infty} e^{-\rho t} u(c(t)) \, dt$$
The discounting issue

Does the golden rule of saving rates hold in a Keynesian approach with discounted maximization of consumption?

- “There is still time to avoid the worst impacts of climate change, if we take strong action now” (Stern, 2007)
- “I got it wrong on climate change – it’s far, far worse” (Stern, 2013)

The value of a loss in 100 years almost disappears... while it is only the next generation!

**Figure 1**: Discounted value of $100 loss
Does consumption maximization make sense?

How many planets do we need?

To achieve the current levels of consumption for the world population, we need:

- US: 5 planets
- France: 3 planets
- India: 0.6 planet

Fairness between generations

Keynes

“In the long run, we are all dead“

John Maynard Keynes\textsuperscript{a}, A Tract on Monetary Reform, 1923.

\textsuperscript{a}“Men will not always die quietly“, The Economic Consequences of the Peace, 1919.

Carney

“The Tragedy of the Horizon“

Mark Carney, Chairman of the Financial Stability Board, 2015

⇒ Back to the Golden Rule and the Fable for Growthmen...
Integrated assessment models (IAMs)

Main categories

- **Optimization models**
  The inputs of these models are parameters and assumptions about the structure of the relationships between variables. The outputs provided by optimization process are scenarios depending on a set of constraints.

- **Evaluation models**
  Based on exogenous scenarios, the outputs provide results from partial equilibriums between variables.

Three main components of IAMs

1. Economic growth relationships
2. Dynamics of climate emissions
3. Objective function
Figure 2: Economic models of climate risk

- **Production**: Industry and business generate CO\(_2\) emissions
- **Climate change**: Change in radiative warming; ocean currents; sea level rise; etc.
- **Impact and damages**: Losses on the entire economy
- **Objective**: Measures and tax policies to control CO\(_2\) emissions
Modeling framework

1. **Economic module**
   - Production function $\rightarrow$ GDP
   - Impact of the climate risk on GDP (damage losses, mitigation and adaptation costs)
   - The climate loss function depends on the temperature

2. **Climate module**
   - Dynamics of GHG emissions
   - Modeling of Atmospheric and lower ocean temperatures

3. **Optimal control problem**
   - Maximization of the utility function
   - We can test many variants
The most famous IAM is the **Dynamic Integrated model of Climate and the Economy** (or DICE) developed by William Nordhaus\(^2\)
The gross production $Y(t)$ is given by a Cobb-Douglas function:

$$Y(t) = A(t) K(t)^\gamma L(t)^{1-\gamma}$$

where:
- $A(t)$ is the total productivity factor
- $K(t)$ is the capital input
- $L(t)$ is the labor input
- $\gamma \in ]0, 1[$ measures the elasticity of the capital factor:

Climate change impacts the net output:

$$Q(t) = \Omega_{\text{climate}}(t) Y(t) \leq Y(t)$$

Classical identities $Q(t) = C(t) + I(t)$ and $I(t) = s(t) Q(t)$
The dynamics of the state variables are:

\[
\begin{align*}
A(t) &= (1 + g_A(t)) A(t - 1) \\
K(t) &= (1 - \delta_K) K(t - 1) + I(t) \\
L(t) &= (1 + g_L(t)) L(t - 1)
\end{align*}
\]

We have:

\[
\begin{align*}
g_A(t) &= \frac{1}{1 + \delta_A} g_A(t - 1) \\
g_L(t) &= \frac{1}{1 + \delta_L} g_L(t - 1)
\end{align*}
\]
Example #1

The world population was equal to 7.725 billion in 2019 and 7.805 billion in 2020. At the beginning of the 1970s, we estimate that the annual growth rate was equal to 2.045%. According to the United Nations, the global population could surpass 10 billion by 2100.
In 2020, the annual growth rate was equal to:

$$g_L(2020) = \frac{L(2020)}{L(2019)} - 1 = \frac{7.805}{7.725} - 1 = 1.036\%$$

Since we have $g_L(t) = \left(\frac{1}{1 + \delta_L}\right)^{t-t_0} g_L(t_0)$, we deduce that:

$$\delta_L = \left(\frac{g_L(t_0)}{g_L(t)}\right)^{1/(t-t_0)} - 1$$

An estimate of $\delta_L$ is then:

$$\delta_L = \left(\frac{g_L(1970)}{g_L(2020)}\right)^{1/30} - 1 = 2.292\%$$
**Figure 3: Evolution of the labor input $L(t)$**

- $\delta_L = 2.292\%$
- $\delta_L = 1.500\%$
- $\delta_L = 3.250\%$
Economic module

Labor input

Figure 4: Projection of the world population

Economic module

Labor input

- AR(1) model:

\[
g_L(t) = \phi g_L(t - 1) + \varepsilon(t)
\]

We have

\[
\hat{\delta}_L = \frac{(1 - \hat{\phi})}{\hat{\phi}}
\]

- Log-linear model:

\[
\ln g_L(t) = \beta_0 + \beta_1 (t - t_0) + \varepsilon(t)
\]

We have:

\[
\hat{\delta}_L = e^{-\hat{\beta}_1} - 1
\]
Figure 5: Population growth rate

### Table 1: Average productivity growth rate (in %)

<table>
<thead>
<tr>
<th></th>
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<th></th>
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<td>AUS</td>
<td>1.02</td>
<td>0.07</td>
<td>-0.23</td>
<td>1.02</td>
<td>0.36</td>
<td>0.13</td>
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<td>BRA</td>
<td>2.39</td>
<td>2.05</td>
<td>-1.04</td>
<td>-1.12</td>
<td>-0.17</td>
<td>-1.63</td>
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<td>0.21</td>
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<td>-0.04</td>
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<td>0.61</td>
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<td>0.02</td>
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<td>1.89</td>
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<td>1.66</td>
<td>-0.19</td>
<td>-0.20</td>
<td>-1.32</td>
<td>-0.34</td>
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<tr>
<td>JPN</td>
<td>4.05</td>
<td>0.77</td>
<td>1.09</td>
<td>-0.22</td>
<td>-0.15</td>
<td>0.69</td>
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<td>ZAF</td>
<td>2.37</td>
<td>0.30</td>
<td>-0.84</td>
<td>-1.11</td>
<td>0.50</td>
<td>-1.20</td>
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<tr>
<td>GBR</td>
<td>0.50</td>
<td>0.72</td>
<td>0.75</td>
<td>0.42</td>
<td>0.12</td>
<td>0.08</td>
</tr>
<tr>
<td>USA</td>
<td>1.00</td>
<td>0.42</td>
<td>0.46</td>
<td>0.73</td>
<td>0.65</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Source: Penn World Table 10.01 (Feenstra et al., 2015) & Author’s calculations.
Figure 6: Total factor productivity index (base 100 = 1960)

Source: Penn World Table 10.01 (Feenstra et al., 2015) & Author’s calculations.
Economic module
Total factor productivity

Figure 7: Dynamics of the TFP growth rate*

*We use the following calibration rule: $\delta_A = \sqrt[n]{d} - 1$
Penn World Table/IMF’s ICSD

In 2019, we obtain \( I(2019) = $30.625 \text{ tn}, \) \( K(2019) = $318.773 \text{ tn} \) and \( Y(2019) = $124.418 \text{ tn} \)

We also have:

\[
\delta_K(t) = \frac{K(t-1) - K(t) + I(t)}{K(t-1)}
\]

and we obtain \( \delta_K(2019) = 6.25\% \)

To calibrate the initial value of \( A(t) \), we inverse the Coob-Douglas function:

\[
A(2019) = \frac{Y(t)}{K(t)^\gamma L(t)^{1-\gamma}} = \frac{124.418}{318.773^{0.30} \times 7.725^{0.70}} = 5.276
\]

The saving rate \( s(t) \) is exogenous
**Figure 8:** Historical estimates of $I(t)$, $K(t)$, $Y(t)$ and $\delta K(t)$

**Source:** IMF Investment and Capital Stock Dataset (2021) & Author’s calculations.
Economic module

Figure 9: Simulation of the DICE macroeconomic module

\[ I(t) \text{ (in $\text{tn})} \]
\[ K(t) \text{ (in $\text{tn})} \]
\[ L(t) \text{ (in bn)} \]
\[ Y(t) \text{ (in $\text{tn})} \]

- \( s(t) = 25\% \)
- \( s(t) = 15\% \)
The survival function is given by:

\[ \Omega_{\text{climate}}(t) = \Omega_D(t) \Omega_\Lambda(t) = \frac{1}{1 + D(t)} (1 - \Lambda(t)) \]

where:
- \( D(t) \geq 0 \) is the climate damage function (physical risk)
- \( \Lambda(t) \geq 0 \) is the mitigation or abatement cost (transition risk)
The cost $D(t)$ resulting from natural disasters depends on the atmospheric temperature $T_{AT}(t)$:

$$D(t) = \psi_1 T_{AT}(t) + \psi_2 T_{AT}(t)^2$$

The abatement cost function depends on the control variable $\mu(t)$:

$$\Lambda(t) = \theta_1(t) \mu(t)^{\theta_2}$$

The global impact of climate change is equal to:

$$\Omega_{climate}(t) = \frac{1 - \theta_1(t) \mu(t)^{\theta_2}}{1 + \psi_1 T_{AT}(t) + \psi_2 T_{AT}(t)^2}$$
Figure 10: Loss function due to climate damage costs
Figure 11: Abatement cost function

\[ \Lambda(t) \text{ (in %)} \]

- Blue line: \( \mu(t) = 1 \)
- Red dashed line: \( \mu(t) = 0.75 \)
- Green dashed line: \( \mu(t) = 0.50 \)
- Pink dashed line: \( \mu(t) = 0 \)

\( t \) (in years): 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100

\( \Lambda(t) \) values: 0, 1, 2, 3, 4, 5, 6, 7
The total GHG emissions depends on the production $Y(t)$ and the land use emissions $CE_{\text{Land}}(t)$:

$$CE(t) = CE_{\text{Industry}}(t) + CE_{\text{Land}}(t) = (1 - \mu(t))\sigma(t)Y(t) + CE_{\text{Land}}(t)$$

$\sigma(t)$ is the anthropogenic carbon intensity of the economy:

$$\sigma(t) = (1 + g_\sigma(t))\sigma(t - 1)$$

where:

$$g_\sigma(t) = \frac{1}{1 + \delta_\sigma}g_\sigma(t - 1)$$
Figure 12: Physical carbon pump

Source: ocean-climate.org.
We have:

\[
\begin{align*}
CC_{AT}(t) &= \phi_{1,1}CC_{AT}(t - 1) + \phi_{1,2}CC_{UP}(t - 1) + \phi_1CE(t) \\
CC_{UP}(t) &= \phi_{2,1}CC_{AT}(t - 1) + \phi_{2,2}CC_{UP}(t - 1) + \phi_{2,3}CC_{LO}(t - 1) \\
CC_{LO}(t) &= \phi_{3,2}CC_{UP}(t - 1) + \phi_{3,3}CC_{LO}(t - 1)
\end{align*}
\]

The dynamics of \(CC = (CC_{AT}, CC_{UP}, CC_{LO})\) is a VAR(1) process:

\[
CC(t) = \Phi_{CC}CC(t - 1) + B_{CC}CE(t)
\]

---

**Carbon cycle diffusion matrix**

We have:

\[
\Phi_{CC} = \begin{pmatrix}
91.20\% & 3.83\% & 0 \\
8.80\% & 95.92\% & 0.03\% \\
0 & 0.25\% & 99.97\%
\end{pmatrix}
\]
Figure 13: Impulse response analysis ($\Delta C \mathcal{E} = -1 \text{ GtCO}_2\text{e}$)
We have:

\[ F_{RAD}(t) = \frac{\eta}{\ln 2} \ln \left( \frac{CC_{AT}(t)}{CC_{AT}(1750)} \right) + F_{EX}(t) \]

where:

- \( F_{RAD}(t) \) is the change in total radiative forcing of GHG emissions since 1750 (expressed in W/m²)
- \( \eta \) is the temperature forcing parameter
- \( F_{EX}(t) \) is the exogenous forcing (other GHG emissions)
The climate system for temperatures is characterized by a two-layer system:

\[
\begin{align*}
\mathcal{T}_{AT}(t) &= \mathcal{T}_{AT}(t-1) + \xi_1 (\mathcal{F}_{RAD}(t) - \xi_2 \mathcal{T}_{AT}(t-1) - \\
&\quad \xi_3 (\mathcal{T}_{AT}(t-1) - \mathcal{T}_{LO}(t-1))) \\
\mathcal{T}_{LO}(t) &= \mathcal{T}_{LO}(t-1) + \xi_4 (\mathcal{T}_{AT}(t-1) - \mathcal{T}_{LO}(t-1))
\end{align*}
\]

Let \(\mathcal{T} = (\mathcal{T}_{AT}, \mathcal{T}_{LO})\) be the temperature vector. We have:

\[
\mathcal{T}(t) = \Xi_T \mathcal{T}(t-1) + B_T \mathcal{F}_{RAD}(t)
\]
### Table 2: Output of the DICE climate module ($Y(t) = Y(t_0)$, $\mu(t) = \mu(t_0)$)

<table>
<thead>
<tr>
<th>Year</th>
<th>$CE(t)$</th>
<th>$\sigma(t)$</th>
<th>$CC_{AT}(t)$</th>
<th>$F_{RAD}(t)$</th>
<th>$T_{AT}(t)$</th>
<th>$T_{LO}(t)$</th>
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<tr>
<td>2010</td>
<td>36.91</td>
<td>0.55</td>
<td>830.4</td>
<td>2.14</td>
<td>0.800</td>
<td>0.007</td>
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<td>2015</td>
<td>36.25</td>
<td>0.55</td>
<td>825.7</td>
<td>2.14</td>
<td>0.900</td>
<td>0.027</td>
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<td>2020</td>
<td>36.06</td>
<td>0.56</td>
<td>821.9</td>
<td>2.14</td>
<td>0.986</td>
<td>0.048</td>
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<tr>
<td>2025</td>
<td>35.97</td>
<td>0.57</td>
<td>818.9</td>
<td>2.14</td>
<td>1.061</td>
<td>0.072</td>
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<tr>
<td>2030</td>
<td>35.98</td>
<td>0.57</td>
<td>816.6</td>
<td>2.15</td>
<td>1.127</td>
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<td>2035</td>
<td>36.05</td>
<td>0.58</td>
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<td>2.16</td>
<td>1.186</td>
<td>0.122</td>
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<tr>
<td>2040</td>
<td>36.18</td>
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<td>813.9</td>
<td>2.18</td>
<td>1.238</td>
<td>0.149</td>
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<td>2045</td>
<td>36.36</td>
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<td>2100</td>
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<td>2.59</td>
<td>1.677</td>
<td>0.494</td>
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Limits of economic models
Integrated assessment models
Scenarios
The DICE model
Social cost of carbon
Other IAMs

Climate module

Figure 14: Simulation of the DICE climate module

\[ Y(t) \text{ (in $\text{tn})} \]
\[ \mu(t) \]
\[ \mathcal{T}_A(t) \text{ (in °C)} \]
\[ \mathcal{T}_L(t) \text{ (in °C)} \]
Figure 15: The nightmare climate-economic scenario ($g_Y = 0\%, \mu(t) = 0$)
The optimal control problem

Optimization problem

- The social welfare function $W$ is equal to:

$$W(s(t), \mu(t)) = \sum_{t=t_0+1}^{T} \frac{L(t)U(c(t))}{(1+\rho)^{t-t_0}}$$

where $\rho$ is the (generational) discount rate and $c(t) = C(t)/L(t)$ is the consumption per capita.

- $U(c) = (c^{1-\alpha} - 1) / (1 - \alpha)$ is the CRRA utility function.

- The optimal control problem is then given by:

$$(s^*(t), \mu^*(t)) = \arg \max W(s(t), \mu(t))$$

subject to:

- DICE Equations
- $\mu(t) \in [0, 1]$
- $s(t) \in [0, 1]$
The important variables are:

- $T_{AT}(t)$ — Atmospheric temperature
- $\mu(t)$ — Control rate (mitigation policies)
- $CE(t)$ — Total emissions of GHG
- $SCC(t)$ — Social cost of carbon
“The most important single economic concept in the economics of climate change is the social cost of carbon (SCC). This term designates the economic cost caused by an additional tonne of carbon dioxide emissions or its equivalent. In a more precise definition, it is the change in the discounted value of economic welfare from an additional unit of COtwo-equivalent emissions. The SCC has become a central tool used in climate change policy, particularly in the determination of regulatory policies that involve greenhouse gas emissions.” (Nordhaus, 2017).
The social cost of carbon is then defined as:

$$
SCC(t) = \frac{\partial W(t)}{\partial CE(t)} = \frac{\partial C(t)}{\partial CE(t)}
$$

It is expressed in $/tCO_2$
Social cost of carbon (SCC)

**Figure 16:** Optimal welfare scenario (DICE 2013R)

![Graphs showing μ(t), T_AT(t), C(t), SCC(t)]

Social cost of carbon (SCC)

Figure 17: $2^\circ C$ scenario (DICE 2013R)

Figure 18: Optimal welfare scenario (DICE 2016R)

Figure 19: 2°C scenario (DICE 2016R)

The tragedy of the horizon

The Economist

SAY GOODBYE TO 1.5°C

Why climate policy is off target
Achieving the 2°C scenario

- In 2013, the DICE model suggested to reduce drastically CO$_2$ emissions...

- Since 2016, the 2°C trajectory is no longer feasible! (minimum $\approx 2.6$°C)

- For many models, we now have:

  $\mathbb{P}(\Delta T > 2$°C$) > 95\%$
Table 3: Global SCC under different scenario assumptions (in $/tCO_2$)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2050</th>
<th>CAGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>31.2</td>
<td>37.3</td>
<td>44.0</td>
<td>51.6</td>
<td>102.5</td>
<td>3.46%</td>
</tr>
<tr>
<td>Optimal</td>
<td>30.7</td>
<td>36.7</td>
<td>43.5</td>
<td>51.2</td>
<td>103.6</td>
<td>3.54%</td>
</tr>
<tr>
<td>2.5°C-max</td>
<td>184.4</td>
<td>229.1</td>
<td>284.1</td>
<td>351.0</td>
<td>1006.2</td>
<td>4.97%</td>
</tr>
<tr>
<td>2.5°C-mean</td>
<td>106.7</td>
<td>133.1</td>
<td>165.1</td>
<td>203.7</td>
<td>543.3</td>
<td>4.76%</td>
</tr>
</tbody>
</table>

In 2007, Nicholas Stern published a report called *The Economics of Climate Change: The Stern Review*

The Stern Review called for sharp and immediate action to stabilize greenhouse gases because:

“the benefits of strong, early action on climate change outweighs the costs”

The Stern Review proposes to use \( \rho = 0.10\% \)
Figure 20: Discounted value of $10
The time (or generational) discount rate $\rho$ is also called the pure rate of time preference.

It is related to the Ramsey rule:

$$r = \rho + \alpha g$$

where:

- $r$ is the real interest rate
- $g = \frac{\partial c(t)}{c(t)}$ is the growth rate of per capita consumption
- $\alpha$ is the consumption elasticity of the utility function
We report the computations done by Dasgupta (2008):

<table>
<thead>
<tr>
<th>Model</th>
<th>$\rho$</th>
<th>$\alpha$</th>
<th>$g_c$</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cline (1992)</td>
<td>0.0%</td>
<td>1.5</td>
<td>1.3%</td>
<td>2.05%</td>
</tr>
<tr>
<td>Nordhaus (2007)</td>
<td>3.0%</td>
<td>1.0</td>
<td>1.3%</td>
<td>4.30%</td>
</tr>
<tr>
<td>Stern (2007)</td>
<td>0.1%</td>
<td>1.0</td>
<td>1.3%</td>
<td>1.40%</td>
</tr>
</tbody>
</table>
### Table 4: Global SCC under different discount rate assumptions

<table>
<thead>
<tr>
<th>Discount rate</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2050</th>
<th>CAGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stern</td>
<td>197.4</td>
<td>266.5</td>
<td>324.6</td>
<td>376.2</td>
<td>629.2</td>
<td>3.37%</td>
</tr>
<tr>
<td>Nordhaus</td>
<td>30.7</td>
<td>36.7</td>
<td>43.5</td>
<td>51.2</td>
<td>103.6</td>
<td>3.54%</td>
</tr>
<tr>
<td>2.5%</td>
<td>128.5</td>
<td>140.0</td>
<td>152.0</td>
<td>164.6</td>
<td>235.7</td>
<td>1.75%</td>
</tr>
<tr>
<td>3%</td>
<td>79.1</td>
<td>87.3</td>
<td>95.9</td>
<td>104.9</td>
<td>156.6</td>
<td>1.97%</td>
</tr>
<tr>
<td>4%</td>
<td>36.3</td>
<td>40.9</td>
<td>45.8</td>
<td>51.1</td>
<td>81.7</td>
<td>2.34%</td>
</tr>
<tr>
<td>5%</td>
<td>19.7</td>
<td>22.6</td>
<td>25.7</td>
<td>29.1</td>
<td>49.2</td>
<td>2.65%</td>
</tr>
</tbody>
</table>

Some models

- AIM ____________________________ RCP 6.0
- DICE/RICE
- FUND
- GCAM
- IMACLIM (CIRED)
- IMAGE __________________________ RCP 2.6
- MESSAGE ________________________ RCP 8.5
- MiniCAM _________________________ RCP 4.5
- PAGE
- REMIND
- RESPONSE (CIRED)
- WITCH
Some models

Table 5: Main integrated assessment models

<table>
<thead>
<tr>
<th>Model</th>
<th>Reference</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stylized simple models</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DICE</td>
<td>Nordhaus and Sztorc (2013)</td>
<td>Dynamic Integrated Climate-Economy</td>
</tr>
<tr>
<td>FUND</td>
<td>Anthoff and Tol (2014)</td>
<td>Climate Framework for Uncertainty, Negotiation and Distribution</td>
</tr>
<tr>
<td>Complex models</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GCAM</td>
<td>Calvin et al. (2019)</td>
<td>Global Change Assessment Model</td>
</tr>
<tr>
<td>GLOBIOM</td>
<td>Havlik et al. (2018)</td>
<td>Global Biosphere Management Model</td>
</tr>
<tr>
<td>IMACLIM-R</td>
<td>Sassi et al. (2010)</td>
<td>Integrated Model to Assess Climate Change</td>
</tr>
<tr>
<td>IMAGE</td>
<td>Stehfest et al. (2014)</td>
<td>Integrated Model to Assess the Greenhouse Effect</td>
</tr>
<tr>
<td>MAGICC</td>
<td>Meinshausen et al. (2011)</td>
<td>Model for the Assessment of Greenhouse Gas Induced Climate Change</td>
</tr>
<tr>
<td>MAgPIE</td>
<td>Dietrich et al. (2019)</td>
<td>Model of Agricultural Production and its Impact on the Environment</td>
</tr>
<tr>
<td>REMIND</td>
<td>Aboumahboub et al. (2020)</td>
<td>REgional Model of INvestments and Development</td>
</tr>
<tr>
<td>WITCH</td>
<td>Bosetti et al. (2006)</td>
<td>World Induced Technical Change Hybrid</td>
</tr>
</tbody>
</table>

Source: Grubb et al. (2021) & Author’s research.
Stylized IAMs

The Leaders

- DICE
- FUND
- PAGE

⇒ SCC: PAGE ≻ DICE ≻ FUND
Figure 21: Histogram of the 150,000 US Government SCC estimates for 2020 with a 3% discount rate

Source: Rose et al. (2017).
Stylized IAMs
The liability/fairness question

Aristotle (384 BC – 322 BC)

Karl Marx and Friedrich Engels (1848)

The Communist Manifesto
Fairness

Du Contrat Social

Thierry Roncalli

Course 2022-2023 in Sustainable Finance
Three types of inequalities

- Spatial (or regional) inequalities
- Social (or intra-generation) inequalities
- Time (or inter-generation) inequalities

⇒ These issues are highly related to liability risks:

“[...] liability risks stemming from parties who have suffered loss from the effects of climate change seeking compensation from those they hold responsible” (Mark Carney, 2018)

- Regional inequalities ⇒ lack of cooperation between countries (e.g., Glasgow COP 26)
- Social inequalities ⇒ climate action postponing (e.g., carbon tax in France)
The Regional Integrated model of Climate and the Economy (RICE) model is a sub-regional neoclassical climate economy model (Nordhaus and Yang, 1996)

⇒ Sub-regional problem of welfare:

- Each region of the world has a different utility functions
- The big issue is how the most developed regions can finance the transition to a low-carbon economy of the less developed regions

Both spacial and time (inter-generation) inequalities
The Nested Inequalities Climate-Economy (NICE) model integrates distributional differences of income (Dennig et al., 2015)

“[…]. If the distribution of damage is less skewed to high income than the distribution of consumption, then weak or no climate policy will result in sufficiently large damages on the lower economic strata to eventually stop their welfare levels from improving, and instead cause them to decline” (Dennig et al., 2015)

Both social (intra-generation) and time (inter-generation) inequalities
Figure 22: Linkages between the major systems in GCAM

Source: Calvin et al. (2019).
Figure 23: The main land use sectors of GLOBIOM

Source: https://iiasa.github.io/GLOBIOM.
Figure 24: Overview of the IIASA IAM framework

Figure 25: The Remind-MAgPIE framework


---

Complex IAMs

Limits of economic models
Integrated assessment models
Scenarios
The DICE model
Social cost of carbon
Other IAMs

Macro-economics
- Drivers of economic growth and energy demand
- Capital accumulation and investment
- International trade
- Consumption and welfare impact

Energy system
- Primary energy resources
- Energy conversion technologies
- Technological change and learning
- Buildings, industry and transportation energy demand
- Greenhouse gases emissions
- Carbon sequestration

Climate system
- Greenhouse gases concentrations
- Radiative forcing
- Global mean temperature change

Land Use
- Agriculture and forestry
- Bioenergy supply
- Greenhouse gases emissions
- Carbon sequestration

MAG/CC
- Water demand
- Air pollution and health impacts
- Other environmental impacts
Criticisms of integrated assessment models

“IAM-based analyses of climate policy create a perception of knowledge and precision that is illusory and can fool policymakers into thinking that the forecasts the models generate have some kind of scientific legitimacy” (Pindyck, 2017)

- Certain inputs, such as the discount rate, are arbitrary
- There is a lot of uncertainty about climate sensitivity and the temperature trajectory
- Modeling damage functions is arbitrary
- IAMs are unable to consider tail risk
Figure 26: Scenario evaluation

- Climate scenario (input)
- Evaluation Process
- Economic scenario (output)
Climate scenarios

- The representative concentration pathways (RCPs) — IPCC AR5
- The IEA scenarios
- The 1.5°C scenarios — SR15
- The scenarios for the future published — IPCC AR6
Climate scenarios

The RCP scenarios

1. RCP 2.6: GHG emissions start declining by 2020 and go to zero by 2100 (IMAGE)
2. RCP 4.5: GHG emissions peak around 2040, and then decline (MiniCAM)
3. RCP 6.0: GHG emissions peak around 2080, and then decline (AIM)
4. RCP 8.5: GHG emissions continue to rise throughout the 21st century (MESSAGE)
Figure 27: Total radiative forcing (in W/m$^2$)

Source: https://tntcat.iiasa.ac.at/RcpDb.
Climate scenarios

The RCP scenarios

Figure 28: Greenhouse gas concentration trajectory

Source: https://tntcat.iiasa.ac.at/RcpDb.
Climate scenarios
The RCP scenarios

Figure 29: Greenhouse gas emissions trajectory

Source: https://tntcat.iiasa.ac.at/RcpDb.
Climate scenarios

The RCP scenarios

Figure 30: Total GHG emissions trajectory (in GtCO$_2$e)

Source: https://tntcat.iiasa.ac.at/RcpDb.
Figure 31: Direct CO₂ emissions (in Gt)

Figure 32: IPCC 1.5°C scenarios of CO₂ emissions

Source: https://data.ene.iiasa.ac.at/iamc-1.5c-explorer.
Climate scenarios

The 1.5°C scenarios

Figure 33: Confidence interval of the average IPCC 1.5°C scenario

Source: https://data.ene.iiasa.ac.at/iamc-1.5c-explorer.
Figure 34: IPCC 1.5°C scenarios of the global mean temperature

Source: https://data.ene.iiasa.ac.at/iamc-1.5c-explorer.
Figure 35: Confidence interval of the exceedance probability $\Pr \{ T > 1.5^\circ \text{C} \}$

Source: https://data.ene.iaas.ac.at/iamc-1.5c-explorer.
Figure 36: Confidence interval of the exceedance probability $\Pr \{T > 2^\circ C\}$

Source: https://data.ene.iiasa.ac.at/iamc-1.5c-explorer.
Climate scenarios
The AR6 scenarios

The new dataset contains 188 models, 1389 scenarios, 244 countries and regions, and 1791 variables, which can be split into six main categories:

- Agriculture: agricultural demand, crop, food, livestock, production, etc.
- Capital cost: coal, electricity, gas, hydro, hydrogen, nuclear, etc.
- Energy: capacity, efficiency, final energy, lifetime, OM cost, primary/secondary energy, etc.
- GHG impact: carbon sequestration, concentration, emissions, forcing, temperature, etc.
- Natural resources: biodiversity, land cover, water consumption, etc.
- Socio-economic variables: capital formation, capital stock, consumption, discount rate, employment, expenditure, export, food demand, GDP, Gini coefficient, import, inequality, interest rate, investment, labour supply, policy cost, population, prices, production, public debt, government revenue, taxes, trade, unemployment, value added, welfare, etc.
Figure 37: Histogram of some AR6 output variables by 2100

Source: https://data.ene.iiasa.ac.at/ar6.
Climate scenarios
The AR6 scenarios

Figure 38: Histogram of some AR6 output variables by 2100

- Agricultural demand (in GtCO$_2$e)
- Agricultural production (in $\text{tn}$)
- Land cover, cropland (in K$/\text{tCO}_2$)
- Water withdrawal, irrigation (in $\text{tn}$)

Source: https://data.ene.iiasa.ac.at/ar6.
“The SSP narratives [are] a set of five qualitative descriptions of future changes in demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources. [...] Development of the narratives drew on expert opinion to (1) identify key determinants of the challenges [to mitigation and adaptation] that were essential to incorporate in the narratives and (2) combine these elements in the narratives in a manner consistent with scholarship on their inter-relationships. The narratives are intended as a description of plausible future conditions at the level of large world regions that can serve as a basis for integrated scenarios of emissions and land use, as well as climate impact, adaptation and vulnerability analyses.” (O’Neill et al., 2017)
Figure 39: The shared socioeconomic pathways

Source: O’Neill et al. (2017).
Figure 40: The shared socioeconomic pathways

- **Sustainability (Taking the Green Road)**
  Low challenges for both mitigation and adaptation, rapid development

- **Middle of the Road**
  Moderate challenges for mitigation and adaptation

- **Regional Rivalry (A Rocky Road)**
  High challenges for both mitigation and adaptation — Concerns about competitiveness/security and regional conflicts pushing countries to focus on regional issues

- **Inequality (A Road Divided)**
  Low challenges for mitigation, high for adaptation — Unequal investment in human capital, concentration of power in a small business elite

- **Fossil-fueled Development (Taking the Highway)**
  High challenges for mitigation, low for adaptation

Source: O’Neill et al. (2017).
The mitigation/adaptation trade-off is obviously an environmental issue, but the SSPs encompass other environmental narratives, e.g. land use, energy efficiency and green economy.

The social dimension is the central theme of SSPs, and concerns demography, wealth, inequality & poverty, health, education, employment, and more generally the evolution of society. This explains that SSPs and SDGs are highly interconnected.

Finally, the governance dimension is present though two major themes: international fragmentation or cooperation, and the political/economic system, including corruption, stability, rule of law, etc.
Shared socioeconomic pathways

- SSP1: IMAGE (PBL)
- SSP2: MESSAGE-GLOBIOM (IIASA)
- SSP3: AIM/CGE (NIES)
- SSP4: GCAM (PNNL)
- SSP5: REMIND-MAGPIE (PIK) and WITCH-GLOBIOM (FEEM)
Figure 41: SSP demography projections

Source: https://tntcat.iiasa.ac.at/SspDb.
**Figure 42: SSP economic projections**

Source: [https://tntcat.iiasa.ac.at/SspDb](https://tntcat.iiasa.ac.at/SspDb).
Figure 43: SSP environmental projections

- Temperature (in °C)
- CO₂ emissions (in Gt)
- Solar electricity (in TW)
- Wind electricity (in TW)

Source: https://tntcat.iiasa.ac.at/SspDb.
Figure 44: SSP land use projections

Source: https://tntcat.iiasa.ac.at/SspDb.
Shared socioeconomic pathways

**Figure 45:** Example of SSP regional differences

- **Africa Population (in bn)**
- **Asia Population (in bn)**
- **Africa GDP/Capita growth (in %)**
- **Asia GDP/Capita growth (in %)**

Source: https://tntcat.iiasa.ac.at/SspDb.
Figure 46: Gini coefficient projections by 2100

Source: https://tntcat.iiasa.ac.at/SspDb.
Figure 47: Network of Central Banks and Supervisors for Greening the Financial System (NGFS)
Figure 48: NGFS scenarios framework
Orderly scenarios

#1 Net zero 2050 (NZ)
#2 Below $2^\circ$C (B2D)

Disorderly scenarios

#3 Divergent net zero (DNZ)
#4 Delayed transition (DT)

Hot house world scenarios

#5 Nationally determined contributions (NDC)
#6 Current policies (CP)
Scenarios at a glance

Scenarios are characterised by their overall level of physical and transition risk. This is driven by the level of policy ambition, policy timing, coordination and technology levers.

* See slide 18 for more details.

- The impact of CDR on transition risk is twofold: on the one hand, low levels of CDR imply an increase in transition ... in gross emissions should be obtained in a different way; on the other hand, high reliance on CDR is also a risk if the technology does not become more widely available in the coming years.

+ Risks will be higher in the countries and regions that have stronger policy. For example in Net Zero 2050, various countries and regions reach net zero GHG by 2050, while many others have emission of several Gt of CO2eq.

^ This assessment is based on expert judgment based on how changing this assumption affects key drivers of physical and transition risk. For example, higher temperatures are correlated with higher impacts on physical assets and the economy.

On the transition side economic and financial impacts increase with: a) strong, sudden and/or divergent policy, b) fast technological change even if carbon price changes are modest, c) limited availability of carbon dioxide removal meaning the transition must be more abrupt in other parts of the economy, d) stronger policy in those particular countries and/or regions.

### Figure 49: Physical and transition risk level of NGFS scenarios

<table>
<thead>
<tr>
<th>Category</th>
<th>Scenario</th>
<th>Physical risk</th>
<th>Transition risk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Policy ambition</td>
<td>Policy reaction</td>
</tr>
<tr>
<td>Orderly</td>
<td>Net Zero 2050</td>
<td>1.4°C</td>
<td>Immediate and smooth</td>
</tr>
<tr>
<td>Below 2°C</td>
<td></td>
<td>1.6°C</td>
<td>Immediate and smooth</td>
</tr>
<tr>
<td>Disorderly</td>
<td>Divergent Net Zero</td>
<td>1.4°C</td>
<td>Immediate but divergent across sectors</td>
</tr>
<tr>
<td></td>
<td>Delayed Transition</td>
<td>1.6°C</td>
<td>Delayed</td>
</tr>
<tr>
<td>Hot house world</td>
<td>Nationally Determined Contributions (NDCs)</td>
<td>2.6°C</td>
<td>NDCs</td>
</tr>
<tr>
<td></td>
<td>Current Policies</td>
<td>3°C +</td>
<td>Non-currente policies</td>
</tr>
</tbody>
</table>
**NGFS scenarios**

### Variables (economic)
- Central bank intervention rate
- Domestic demand
- Effective exchange rate
- Exchange rate
- Exports (goods and services)
- Gross Domestic Product (GDP)
- Gross domestic income
- Imports (goods and services)
- Inflation rate
- Long term & real interest rates
- Trend output for capacity utilisation
- Unemployment

### Variables (energy)
- Coal price
- Gas price
- Oil price
- Quarterly consumption of coal
- Quarterly consumption of gas
- Quarterly consumption of oil
- Quarterly consumption of renewables
- Total energy consumption

### Models (IPCC)
- Meta-model: NiGEM 1.21
- Sub-models:
  - GCAM 5.3
  - MESSAGE-GLOBIOM 1.1
  - REMIND-MAgPIE 2.1-4.2

### 6 scenarios
- Net Zero 2050 (NZ)
- Below 2°C (B2D)
- Divergent Net Zero (DNZ)
- Delayed Transition (DT)
- Notionally Determined Contribution (NDC)
- Current Policies (CP)
### Table 6: Impact of climate change on the GDP loss by 2050 (GCAM)

<table>
<thead>
<tr>
<th>Risk</th>
<th>B2D</th>
<th>CP</th>
<th>DNZ</th>
<th>DT</th>
<th>NDC</th>
<th>NZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chronic physical risk</td>
<td>−3.09</td>
<td>−5.64</td>
<td>−2.35</td>
<td>−3.28</td>
<td>−5.15</td>
<td>−2.56</td>
</tr>
<tr>
<td>Transition risk</td>
<td>−0.75</td>
<td>−3.66</td>
<td>−1.78</td>
<td>−0.89</td>
<td>−0.88</td>
<td></td>
</tr>
<tr>
<td>Combined risk</td>
<td>−3.84</td>
<td>−5.64</td>
<td>−6.00</td>
<td>−5.05</td>
<td>−6.03</td>
<td>−3.44</td>
</tr>
<tr>
<td>Combined + business confidence</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>−6.03</td>
<td>−5.09</td>
</tr>
</tbody>
</table>
Table 7: Impact of climate change on the GDP loss by 2050 (MESSAGEix-GLOBIOM)

<table>
<thead>
<tr>
<th>Risk</th>
<th>B2D</th>
<th>CP</th>
<th>DNZ</th>
<th>DT</th>
<th>NDC</th>
<th>NZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chronic physical risk</td>
<td>−2.05</td>
<td>−5.26</td>
<td>−1.55</td>
<td>−2.64</td>
<td>−4.78</td>
<td>−1.59</td>
</tr>
<tr>
<td>Transition risk</td>
<td>−1.46</td>
<td>−10.00</td>
<td>−10.77</td>
<td>−1.39</td>
<td>−3.26</td>
<td></td>
</tr>
<tr>
<td>Combined risk</td>
<td>−3.51</td>
<td>−5.26</td>
<td>−11.53</td>
<td>−13.37</td>
<td>−6.16</td>
<td>−4.84</td>
</tr>
<tr>
<td>Combined + business confidence</td>
<td></td>
<td></td>
<td>−11.57</td>
<td>−13.40</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 8: Impact of climate change on the GDP loss by 2050 (REMIND-MAgPIE)

<table>
<thead>
<tr>
<th>Risk</th>
<th>B2D</th>
<th>CP</th>
<th>DNZ</th>
<th>DT</th>
<th>NDC</th>
<th>NZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chronic physical risk</td>
<td>−2.24</td>
<td>−6.05</td>
<td>−1.67</td>
<td>−2.65</td>
<td>−5.41</td>
<td>−1.76</td>
</tr>
<tr>
<td>Transition risk</td>
<td>−0.78</td>
<td>−3.01</td>
<td>−1.95</td>
<td>−0.33</td>
<td>−1.46</td>
<td></td>
</tr>
<tr>
<td>Combined risk</td>
<td>−3.02</td>
<td>−6.05</td>
<td>−4.68</td>
<td>−4.59</td>
<td>−5.73</td>
<td>−3.21</td>
</tr>
<tr>
<td>Combined + business confidence</td>
<td>−4.70</td>
<td>−4.63</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### NGFS scenarios

**Table 9: Impact of climate change on the GDP loss by 2050 (MESSAGEix-GLOBIOM)**

<table>
<thead>
<tr>
<th>Risk</th>
<th>B2D</th>
<th>CP</th>
<th>DNZ</th>
<th>DT</th>
<th>NDC</th>
<th>NZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td>−13.58</td>
<td>−7.50</td>
<td>−27.35</td>
<td>−29.37</td>
<td>−11.78</td>
<td>−18.36</td>
</tr>
<tr>
<td>Asia</td>
<td>−1.50</td>
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NGFS scenarios

Figure 50: GDP impact by 2050 (% change from baseline) — Delayed transition scenario
**NGFS scenarios**

**Figure 51:** GDP impact by 2050 (% change from baseline) — Net zero 2050 scenario
Figure 52: Impact of climate scenarios on economics (% change from baseline) — China
NGFS scenarios

Figure 53: Impact of climate scenarios on economics (% change from baseline) — United States
Figure 54: Impact of climate scenarios on economics (% change from baseline) — France

Limits of economic models
Integrated assessment models
Scenarios
Climate scenarios
Shared socioeconomic pathways
NGFS scenarios

NGFS scenarios

Thierry Roncalli
Course 2022-2023 in Sustainable Finance

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Figure 55: Impact of climate scenarios on economics (% change from baseline) — United Kingdom