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Climate Change and Degrowth: a Nordhaus' DICE Model Set of Simulations based on Endogenous Discounting

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Abstract

This article introduces a new way of computing the social discount rate (SDR), taking into account a new class of consumers whose political or philosophical opinion of "degrowth" will endogenously decrease economic growth, within the DICE Model. For these Deep Green Consumers (DGCs) a new utility function is proposed, using the Ramsey equation.

New paths of consumption and greenhouse gas (GHG) emissions are thus modeled for both this social-rate time of pure preference, as well as the intertemporal value of consumption elasticity. In this framework, the SDR is a decreasing function with respect to the share of DGCs in the total population. The integral of intertemporal utility proves an increasing function with respect to the share.

This article assesses the impact of an increase in the share of DGCs in the population, demonstrating no significant difference in the temperature decrease before 2100, under a certain threshold of DGCs around 40%. Above this threshold the trend of increasing temperatures is inverted within one century. A share of 50% of DGCs shows a temperature peak in 2120, with an increase of +3°C, below Nordhaus' optimal path.

These assessments reveal that changes in public opinion, such as the emerging movement in favour of reduced material consumption, or even degrowth, could lead to temperature effects in favour of the climate when reaching a certain threshold. In addition to preference changes, the inertia of both the natural climate system and capital investment argues for strong complementary economic policy measures to reduce GHGs emissions.

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1 Introduction

The COP21 Paris Agreement, signed in 2015 by the 195 countries participating seeks to limit the temperature increase in 2100 between +1.5 and +2°C compared to the average temperatures during the pre-industrial era. The ever-growing shift in public opinion since 2015, was exacerbated by the US government's decision to withdraw from the Paris Agreement. China, the US's biggest rival, has showed impressive consistency in ensuring that the goals set in 2015 were achieved. The past five years have showed an impressive rise in the amount of social media content linked to climate change, particularly by the under 30s.

The political world, especially in Europe, has been affected by this shift as green political parties continue to rise in the polls. This was highly visible with the results of the 2019 European elections, with the Greens seeing an increase in representation at the European Parliament by 40%, with the traditional left-right parties collapsing. Richer European countries polled the strongest progress of green parties . In Germany, the greens doubled their 2015 score reaching over 20% of votes and ending right behind Angela Merkel's party, which came first with 22,6%. This trend was also observed in France, with more than 13% of votes for the Green party, greatly overshooting the estimated scores. Despite a complicated political identity, the UK's greens also managed to improve their results by +4.2 points compared to 2015, reaching 12.1% in the polls, hence increasing their past results by over 50%. The statistical link in between wealth and the willingness to change consumer's behavior, to act against climate change, has already been implicitely discussed by Hausman in [8], where he underlined the link between high income (e.g. Western and Northern European countries) and smaller discount rates, with discount rates converging towards the prevailing interest rate on credit market as wealth increased.

In 2018, W. Nordhaus was awarded the Nobel Prize in economics, despite his DICE model results not really being aligned with the COP21 objectives. His baseline - business as usual - scenario predicted a temperature increase of almost +4°C. by 2100 with the increase even reaching +6°C. in the 23rd century. His optimal scenario - maximising the intertemporal utility function - shows that a +3.5°C. increase by 2100, superior to the COP21 Agreement. Climatologists and other scholars responded to this shockwave by underlining the deleterious consequences that such an increase would have on humans and biodiversity. Criticism rose against the DICE Model and its assumptions. One particular parameter is at the heart of the debate: the SDR. The SDR's value greatly affects the variation of temperature resulting in many economists publicly declaring that the SDR parameter of 1.5% was too high in Nordhaus' model, the most famous among them being Nicholas Stern.
Stern's (2007) [21] SDR of 0.1% yields to drastically different results for the optimal warming, with a lower temperature, fitting more accurately with the COP21 Agreement, below in between +2.0 and +2.5°C. by 2100. This result leads us to focus on the evaluation of the SDR parameter within the DICE model. The SDR debate is crucial in environmental economics, due to its forecasting potential on human behiavour.

The value and the manner in which the SDR parameter is set is at the heart of public policies. A deep division exists in how the discount rate is assessed, first brought to light by Arrow (1995) [1]. Welfare economics relies on the maximization of the social welfare function, which is an algebraic formula yielding a measure of the societal well being. The first approach - called the descriptive approach - implies that this function is driven by private sector and government choices, on the contrary, the prescriptive approach assumes that government and private sector choices do not reflect the true social welfare function and thus implies a reasoning from ethical principles ([7]). In all cases, this function must meet conditions of efficiency in consumption and production.

The descriptive approach is based on the compensation principle. According to this principle, a policy should be chosen if the winner could, in the future, compensate the looser. As Arrow [1] explains, investments in climate mitigation which yields fewer returns than others productive investments, would never be the optimal choice under this principle. The discount rate is therefore deducted from the market conditions and equals interest rate. This approach, used by Nordhaus as early as 1993 [14], has been thus criticized due of its inefficiency in solving the problem of climate change [1] [24].

By contrast, the prescriptive approach emphasizes on markets imperfections and sub-optimal-tax policies. With this approach, the discount rate is often renamed 'social discount rate' because of its ethical origins. In this article, we are dealing with climate change, which will be a source of externality - we do not consider perfect markets. Our focus on the prescriptive vision will help us to model economic policies to fight climate change. This approach is fully justified since Nordhaus' baseline scenario leads us to an air warming of 4°C. by 2100, which is unacceptable with regards to climate and biodiversity sciences recommendations [13].

The literature has hitherto couched growth rates in terms of centuries [7], resulting in uncertainty over time. In the DICE Model, growth is computed using the Extended Ramsey formula for every period in the future, omitting the need take this uncertainty into account. such as using .

This article introduces a new way of computing the SDR, and focuses on the impact of this new formula on global warming. We slightly modify the Ramsey formula by cutting the population in two distinct groups: "standard" and "deep green" consumers (DGCs). The DGCs are those willing to reduce their material consumption following a philosophical or thought movement known as "Degrowth", towards reducing global warming. From a theoretical point of view, a link can be made between the share of DGCs and the scores of the aforementioned environmental parties.

This article assesses the impact of an increase in the share of DGCs in the population, and shows that, below a threshold of DGCs in the 30%-40% range, no significant difference in temperature decrease before 2100 is found. However, above this threshold, the trend of increasing temperatures is inverted, within the time frame of one century. Thus, a share of 50% shows a temperature peak for temperature in 2120, with an increase of +3°C, below Nordhaus' optimal path.

As many theoretical models that study the endogenous discounting rate in the framework of climate change (Epstein and Hynes, 1983 [5] ; Obstfeld, 1990 [16]; Das, 2003 [3]), this article uses a flow variable (i.e. the consumption rate of growth) to endogenously determine the discount rate. Other recent theoretical models, however, introduce stock variables as the source of endogenous discounting: e.g. the wealth of a decision maker (Schumacher, 2009 [18], 2011 [19]; Six and Wirl, 2015 [20]) (in the opinion of Schumacher, 2009 and 2011, the wealthier a consumer is, the more he/she could afford to be patient and postpone consumption); or a time preference rate depending on both flow (consumption) and the state (environment) (Yanase, 2011 [25]); or the state only; (Ayong Le Kama and Schubert, 2007 [2] consider that the smaller the environmental quality is, the more pressing the environmental questions become and the more patient decision makers are); or the risk of a discontinuous drop in output due to climate change and emissions (Tsur and Zemel, 2009 [22]); etc.

These recent models often come up against problems of intertemporal incoherence or non-determination of their steady states. This is why we used a robust flow variable rather than the models mentioned above.

The implementation of DGCs in our model is implied simply with the use of the new SDR that we compute in this article (the rest of the model remains unchanged, allowing a sound understanding of the impact of these new DGC agents in this model). Several choices were made when doing this implementation such as: using an exogenous and constant share of DGCs: α, but an endogenous SDR. The choice was made to have a constant share of DGCs in order to modelize what would be the impact of having at least a certain share of today's population becoming DGCs. This voluntary simplification allows us to have a lower bound on the impact on the environment. The computation of an endogenous share of DGCs would have also made the model much more sophisticated, and probably less relevant in its conclusions, being subject to greater debate, on the DGCs share evolution rule especially. The choice of an endogenous SDR: was made as we show that strong inertia factors appear in the behaviour of people and the evolution of the global SDR, resulting in non-linear results in temperature evolution when the DGCs share changes.

The remainder of the article is organized as follows. In Section 2, the theoretical framework, and our new model assumptions are discussed. Section 3 then describes the data and code necessary to simulate the model. Section 4 and 5 present and discuss the main findings of our new global warming scenarios, with Section 6 concluding the paper.

2 Framework and New Assumptions

The prescriptive approach begins with the formula by [17],the Ramsey's rule, with d the social rate time of pure preference, g the economic growth, and n the absolute value of the elasticity of the marginal utility of consumption:

$$\rho = d + n * g \tag{1}$$

This equation comes from the intertemporal optimality condition of the utility. We will justify the values chosen for d and n in section 3.1.

This article will focus on the SDR and use the DICE model by Nordhaus [15]. The parameter ρ is defined as the "pure rate of social time preference", and represents how the value injected into social projects is perceived by contemporary citizens. Nordhaus uses it in the following way, when defining the utility which as to be maximized:

$$W = \sum_{i=1}^{Tmax} \frac{U(c(t), L(t))}{(1+\rho)^t} \tag{2}$$

With:

$$U(t) = \frac{L(t) * c(t)^{\gamma}}{1-\gamma} \tag{3}$$

Where $L(t)$ and $c(t)$ are respectively the population and consumption at time t; γ, the elasticity, representing aversion to generational inequality. Hence, with a low value of the SDR ($\lim \rho = 0$), the utility of future generations (we consider a 200-year horizon, $Tmax = 200$) is equally perceived by our contemporary selves. The consequence is that, if nothing is done for climate change, future utility is highly impacted, as today's consumption level cannot be sustained in a damaged environment. This will propel considerable efforts done by the generations of today to prevent climate change. However, with a value of ρ not being close to 0 (Nordhaus takes $\rho = 0.015$, i.e. 1.5%), the DICE Model predicts a warming of +3.5 C. by 2100 in the optimal scenario. And a higher value for ρ leads to an increased value of temperature growth.

This article introduces a new way of computing SDR and focuses on the impact on global warming. We modify the Ramsey formula given in Equation 1 by cutting the population in two distinct groups: Deep Green Consumers and standard consumers. This first part of the population is willing to reduce their material consumption in order to reduce the effects of global warming. The French branch of the sustainable degrowth current relies on Georgescu [6], and promotes degrowth as the only realistic solution to the sustainability of the economic system. For French scholar Latouche (2003) [11]: "It takes all the faith of orthodox economists to think that the science of the future will solve all the problems and that substitutability of unlimited nature by artifice is possible (...) unlike the reformist ecology of a Hermann Daly or a René Passet, the stationary state itself, and the Zero growth is neither possible, nor desirable (...)". More recently, Jackson [9] uses the Kaya identity [10] to show that, in his opinion, solving the climate problem is impossible regarding the past evolution of power efficiency, and that the only way to solve it proves is to restrict economic growth and promote the global revenue sharing, in order to meet the CO2 emission targets set by the IPCC.

Hence, this article aims to modelize the impact DGCs on the evolution of atmosphere temperature of a simili-degrowth movement. As ρ diminishes, the utility of generations to come is more seriously considered by today's generations. Thus, DGCs will have a lower discount rate than the rest of the population. Let's recall how the Ramsey rule given by Equation 1 is computed, in order to explain how we changed it for DGCs.

We suppose that we have a 2-period continuous economy with a single representative agent. Consumption at each period is denoted by c_0 and c_1, and we suppose that the utility function U can be written as:

$$U(c_0, c_1) = u(c_0) + e^{-dt} * u(c_1) \tag{4}$$

with u the instant utility at a certain period. For this instant utility, we choose to use the power utility function:

$$u(c) = \frac{u^{1-n}}{1-n} \tag{5}$$

The formula comes from the optimal equation:

$$\rho = ln(\frac{U'(c_0)}{U'(c_1)}) \tag{6}$$

By injecting equations 4 and 5, we get:

$$\rho = d - ln(\frac{c_1^{-n}}{c_0^{-n}}) \tag{7}$$

A classical assumption is that we can write:

$$c_1 = c_0 * e^g \tag{8}$$

with g the growth rate. As we will see later, this assumption will be challenged when considering the DGC.
Thus we get :

$$\rho = d + n * g \tag{9}$$

which is the expected result.

In the above definition of DGCs the natural reaction to a positive growth rate will be to reduce future consumption in order to drown the effects of global warming. The other part of the population, on the order hand, would increase its consumption. Following the DGCs behaviour, the Equation 8 is changed into:

$$c_1 = c_0 * e^{-g} \tag{10}$$

Consequently, the Equation 1 is transformed into:

$$\rho = d - n * g \tag{11}$$

Finally, we merge the two formulas into one by averaging them. We denote α the part of DGC into the total population. We thus have:

$$\rho_t = (1-\alpha)(d + ng_t) + \alpha(d - ng_t) \tag{12}$$

Which can be rewrote as:

$$\rho_t = d + ng_t(1 - 2\alpha) \tag{13}$$

The values of these exogenous parameters, g, d, and n, are discussed in the next section.

3 Data and Code

3.1 Estimation of Parameters

The parameters d, n, the social rate time of pure preference and the absolute value of elasticity, and α, the share of DCG, are difficult to estimate, as there is no real criterion to define them. Moritz A. Drupp, Mark Freeman, Ben Groom, and Frikk Nesje in [4] conducted an expert survey on the determinants of the long-term SDR. We are using the results from this total 185 quantitative articles survey, choosing to have a more robust value by collecting a maximum number of answers, to finally get the following values:

$$d = 1,1\%$$

$$n = 1.35$$

Moritz A. Drupp, Mark Freeman, Ben Groom, and Frikk Nesje surveyed over 200 experts to disentangle disagreement on the risk-free SDR into its component parts, including pure time preference, the wealth effect and return to capital. They showed that the majority of experts do not follow the simple Ramsey Rule, when recommending SDRs. Despite disagreement on discounting procedures and point values, they obtained a surprising degree of consensus among experts, with more than three-quarters finding the median risk-free SDR of 2 percent acceptable. Hence, we decided to use these values.

3.2 The Calculus of the Growth Rate

Nordhaus' 2013 model is implemented with an exogenous parameter for ρ. On the contrary, we implemented an endogenous calculation of ρ, with the model still converging in the long run.
A first issue was the instability of the results. Indeed the SDR is computed using a formula similar to $\rho_{t+1} = f(g_t)$. However, this formula induced some instabilities within the convergence process. As ρ_{t+1} values were computed only the last value of g_t and g_{t+1} was directly influenced by ρ_{t+1} a "ping-pong pattern" appeared, evolving back and forth in between two range of values, affecting the other parameters in other equations and ending in noisy curves. We then had to find a way to smoothen the values taken by g_t and hence, the values of ρ_t, as they are linearly linked. To flatten this curve, we chose to estimate the current value of g_t by performing a quadratic combination of the previous values of g:

$$g_t = \sqrt{\sum_{i=1}^{t} \frac{g_i^2}{t^2}} \tag{14}$$

3.3 A Maximum Share of DCGs in the Population

A second issue is the non convergence of the utility curve in some cases. As shown in Figure 1, the limit of utility is not equal to zero when $\alpha > 0.5$.

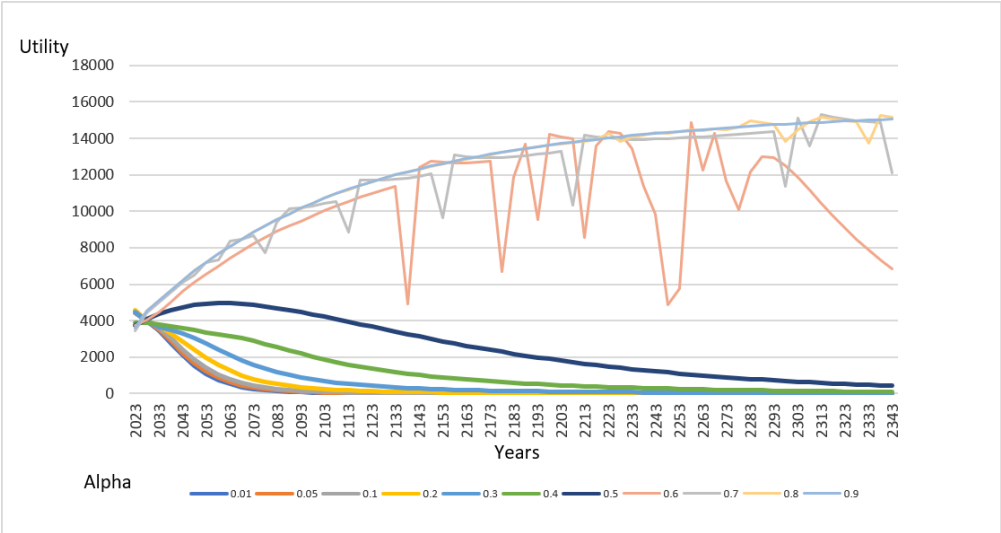

Figure 1: Evolution of utility with different values of α, the share of DGC in the population

It can be deduced that the area under the curve is not finite. Yet, an optimization problem - such as the DICE problem - can only be resolved on finite and convex sets. Therefore, we will limit α to $[0, 0.5]$. We think that the fact that ρ starts to decline with g when $\alpha > 0.5$ explains the non convergence of utility.

4 Results

We computed the DICE algorithm for several values of α within $[0, 0.5]$. We will discuss the values computed for the temperature, utility and the SDR.

4.1 General Evolution of the SDR

The evolution of ρ is depicted in Figure 2. The global trend is an early overshoot, the extent of which depends on the value of α and then a very slow convergence to d in the long term. This is in line with the definition of α: the more DGC in the population, the lower the SDR is.

For $\alpha = 0.5$, the SDR is constant. This is consistent with the Equation 13. The formula gives $\rho = d$ in this case which explains this flat curve on Figure 2.

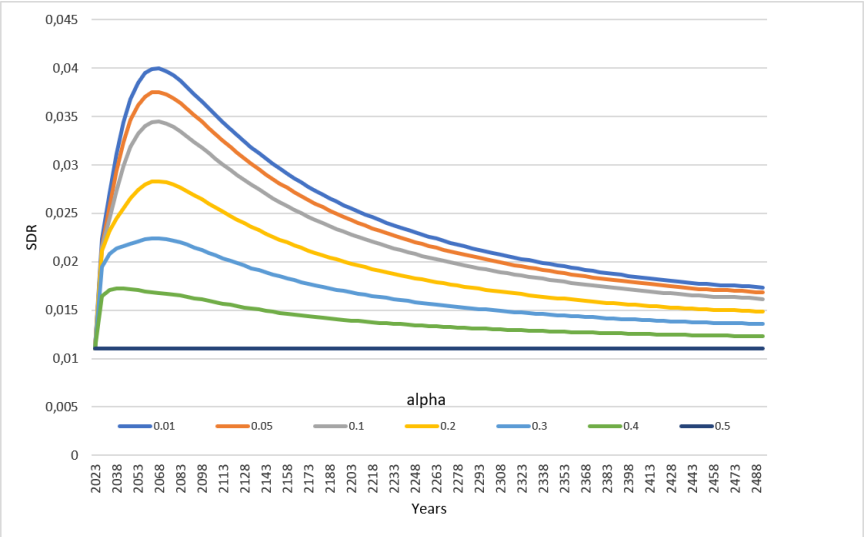

Figure 2: Evolution of the social discount rate with different values of α

The results concerning the impact of α on the SDR are as expected: the more important the share of DGCs, the lower the SDR will be. They appear to be perfectly ordered in our study. Yet, we observe that the period at which the maximum SDR is reached is further when the proportion of DGCs is low. This illustrates the following: as ρ is an increasing function with respect to g, the less DGCs we have, the later the growth rate will decline. This can be understood as a group effect: the lower the number of DGCs, the slower behaviors will change.

4.2 General Evolution of the Temperature Overshoot

The atmospheric temperatures for different values of α in between $[0, 0.5]$ are computed in Figure 3.

From a value of $\alpha = 0.3$, the temperature curves start to decline within the time horizon shown in Figure 3. We will denote this value $\alpha_{trigger}$, with $\alpha_{trigger} \in [0.2, 0.3]$.

In the regime $\alpha < \alpha_{trigger}$, the temperature doesn't change whatever the value of α. The system can either have 1% of DGCs or 20%, the temperature parameter does not seem to be affected. This is a surprising result as we could think that an increase in the number of DGCs would lead to a proportional decrease of the temperature increase.

Next, in the regime $\alpha_{trigger} < \alpha < 0.5$, the temperature overshoot now decreases with respect to α. This is in line with the early SDR overshoot observed in Figure 2 for each value of α. As a matter of fact, the influence of the SDR, by its definition, is put into effect in a long-time horizon. That is what explains how an early SDR increasing can influence the

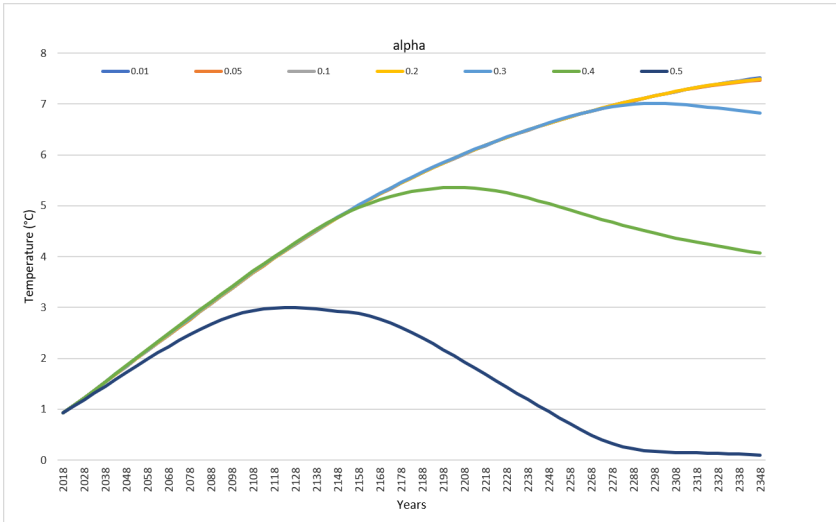

Figure 3: Evolution of atmospheric temperature overshoot with different values of α

temperature curve for hundreds of years as is the case here as the SDR tend to converge quite quickly.

Finally, when $\alpha = 0.5$, this curve is explained by the SDR becoming constant. The rise in temperature rises briefly before converging to 0 in the long run.

This model proves pessimistic and only predicts a null temperature overshoot when DGCs are predominant, which is far from being the case in today's population.

5 Interpretations

5.1 The Baseline Scenario

We first define what we are going to compare our results to: as explained above, we chose to make dynamic the previous static SDR in the Nordhaus DICE model. Hence, we can not simply use as reference the temperature curves of Nordhaus and the $3.5°C$. he found for the year 2100. We added DGCs into the model: our baseline is therefore the dynamic scenario where there are no DGCs ($\alpha = 0.01$).

5.2 The Evolution of Utility

In Figure 4, the area under the curves of utility grow non linearly with a increase in α. Indeed, the utility is being discounted by $\frac{1}{1+\rho}^t$. Therefore, the higher the value of α, the lower the value of ρ, and the greater the effect on discounting due to the power t.

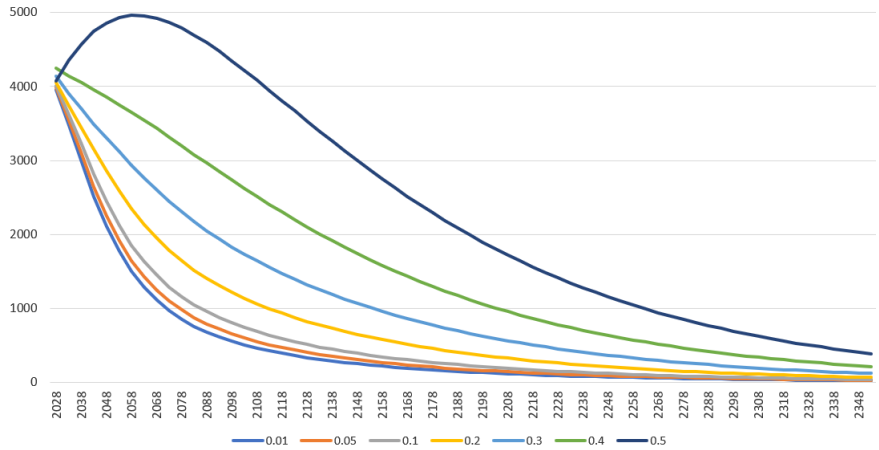

Figure 4: Evolution of utility with different values of α, the share of DCG in the population

5.3 The Evolution of Temperature

Given that α has an impact, both on the peak time for ρ and the value of its peak, we may now understand why the evolution of α is not linearly linked to the temperature evolution. This also explains why an $\alpha_{trigger}$ exists, further underlining the inertia that climate has. Moreover, the temperature evolution for $\alpha = 0.5$ does not take the same path as for the other values of α as mentionned before. This is due to ρ being constant for $\alpha = 0.5$, there is no peak for the SDR and therefore no "delayed effect" on temperature evolution. Indeed, as underlined by many climatologist, if we want to prevent the temperature from going above 2 or 3°C., the actions taken have to be quite radical. Here, this model shows a smooth evolution of mentalities that can slow the process.

Hence, a small number of DGC, such as $\alpha \in [0, \alpha_{trigger}]$ would not be effective to reduce the increase of atmosphere temperature in the long run. These results of course underline the impact of a change in our consumption on global warming, while also denoting that group inertia has a slowing effect on the fight against climate change. The example taken here is highly radical but we can see that any change to equation 8 has a real long-term impact.

5.4 Evolution on Main Macroeconomic Variables

Figure 5 shows that the next 15-20 years are crucial for climate change. The seemingly negligible time period where the variation of the GDP, ΔY, and that of the consumption, ΔC, are both negative is compared to the time period where this difference is positive. Under this comparison, consumption is lower in a 50% DGCs scenario than in a 1% DGCs scenario over a period of 20 years by almost half a base point. In the meantime,

GDP is also lower but only for a decade. On the other hand, investments are increased when the percentage of DGCs is important, both in the short and the long run.

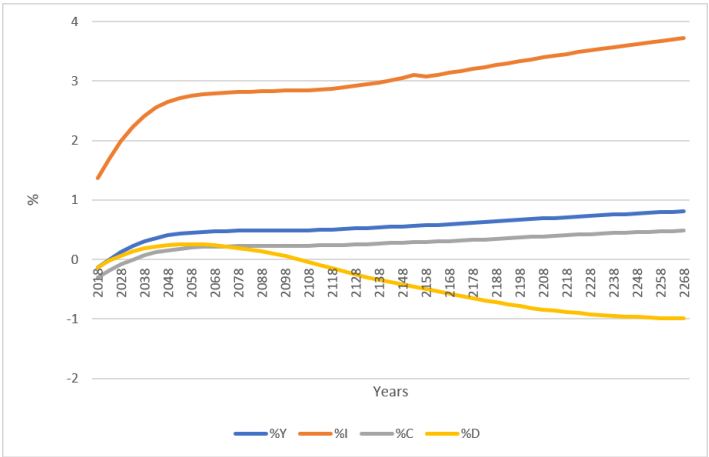

Figure 5: Comparison in % of macroeconomic indexes - $\Delta X = X_{0.5} - X_{0.01}$ where $X_{0.5}$ is the value of X for $\alpha = 0.5$. Y is the GDP, I is investment, C is consumption and D represents the damages on the environment (temperatures)

In the long run, GDP and consumption overcome the results of the 1% DGCs scenario, underlining the benefits that can be created when natural resources are well managed. However, it appears that in the short term, damages would be superior with a higher rate of DGCs, an effect which is logically inverted in the long term. Hence, it appears that having financial flows deflected from consumption or pure financial investment into specific green investment would highly impact the fight against climate change.

5.5 Policy Implications and Scenario Comparisons

At the level of public policy, Figure 5 justifies policies that push to change our behaviours towards more eco-friendly habits such as taxes, subsidies and so on. This also goes against the orthodox or mainstream hypotheses that the climate crisis problem will solve itself as prices are automatically pushed up by environmental damages. We show here that action and changes in our habits are needed in order to avoid disaster.

Let's compare our values with Nordhaus and Stern's results, by 2100. Nordhaus obtained $4°C$. for his baseline and $3.5°C$. for his optimal policy case. With Stern's discount rate, the predicted temperature overshoot is about $2.5°C$. by 2100. In our case, for $\alpha < 0.5$, we have, at least at the beginning, a similar trend to Nordhaus's optimal policy curve. For $\alpha = 0.5$, the trend looks closer to Stern's.

After 2100, the gap between our results and Stern or Nordhaus ones grows wider the further we get away. For $\alpha = 0.5$, the temperature overshoot converges to 0 faster than in Nordhaus' case. That difference

underlines the positive impact of a population majority changing its consumption habits. For $\alpha < 0.5$, there are several stalls, firstly for $\alpha = 0.4$ and then for $\alpha = 0.3$. The value of alpha has thus an influence on the time of the stall from our baseline, as defined above.

6 Conclusion

This article introduced a growing share of new consumers into Nordhaus' DICE model, by modifying the rate of preference for the present, via an endogenous SDR. The fact that part of the population diverts material consumption and tends to compensate for the deleterious effects of GDP growth and polluting emissions on the environment, by changing consumption patterns, would have significant effects on global GHG emissions. Besides, when rising temperatures falls with the share of DGCs, inter-temporal utility increases.

Changes in public opinion, such as the emerging movement of degrowth in the richest countries, will lead to significant effects in favour of climate however, were these societal movements to take on an enormous scale. Our calculations revealed significant effects at least half of DGCs in the total population. This is largely due to the inertia of the natural climate system modelized in DICE, and also the fact that this share of DGCs of 50% does not result in a dynamic overshoot in the discount rate (but a flat SDR) as observed for smaller shares. More DGCs therefore has an effect on the drop in temperature, provided that they are sizeable in the population. We have also shown that inertia remains strong even with this high share. All this can lead to calls for complementary solutions in order to boost the mitigation of GHG, as for example with strong climate and economic policy measures.

All of our conclusions are of course to be nuanced. As a matter of fact, the DICE Model is a simple one, assuming a number of hypotheses which are far from being verified such has a perfect market, quadratic evolution of temperature with respect to pollution, one single sector and one single country, etc. Moreover, the formula used to compute the growth rate, g_t, in this article, is subject to some debate (we chose the one with the most robust results): the square in the formula forces the values of g_t to be positive. In the present context, it would have been more accurate to include a dynamic share of DGCs, α. Indeed, ecological awareness is gaining ground in the public debate, and more citizens perceive themselves as being 'ecologists' [12].

To finally conclude, our new DCGs, more broadly the degrowth movement, acknowledge the possibility of green growth, or double dividend, win-win effects (with both more growth and more environmental quality in the long run). It however proves difficulties to settle questions relating to such long-term phenomena. The risk of radical vision leading to a deadlock at the global level, is exacerbated with antagonisms between countries/households that are already rich, and countries/households that are economic catching up or stagnate?

To overcome these existing issues and limitations, Van den Bergh [23] proposed the concept of a-growth - as opposed to both growth and de-

growth - by inviting economic, and therefore climate policies, to simply focus on internalising policies, regardless of the growth gains or losses they might produce in the long term. In the case of climate, the international community should therefore be more motivated to act, because of the long-term costs of climate change itself, as confirmed by the Intergovernmental Panel on Climate Change - IPCC 2013. These actions might be disassociated of the potential growth gains linked to investments and innovations. For Van den Bergh [23], well-being therefore remains the ultimate economic objective, regardless of the double dividend or green growth, of which it must be acknowledged, little is actually known empirically over the very long term.
Others have already tried to implement different way of endogenous discounting using variables such as stock variables or consumption [20].

Concerning the future paths that we could explore around the model, we think that it would be interesting to consider an endogenous share of DGCs. As said in the introduction, this would require a lot of work in order to make the evolution of DGCs credible. Several behavioral models should be considered in the DICE model to give an overview of the possibilities with some varying stress tests conditions, allowing to cover a range of scenarios.

We also wish to study, in future work, the impact of Nordhaus' DICE model or other existing microeconomics-fundations of the endogenous discount rate (for instance, based on the environment, as Schumacher, 2011 [19]; Six and Wirl, 2015 [20]) (despite the fear that well-known difficulties may arise).

7 Appendix

Date 2100	DGC : 1 to 40 %	DGC : 50%
Total carbon emissions (GtC)	1921,1	1339,6
Total CO2 emissions (GtCO2 per year)	81,1	9,2
Emission control rate of GHGs (%)	1	93
Increase in atmosphere temperature (°C)	3,5	2,9
GDP net of abatement and damages (trillions of 2010 USD per year)	341,5	509,3
Damages (trillions of 2010 USD per year)	11,7	11,8
Damages as fraction of gross output	0,033	0,022
Investment (trillions of 2010 USD per year)	34,2	131,2
Consumption (trillions of 2010 USD per year)	307,4	378,0
Carbon price (2010 USD per ton of CO2)	0,053	184,2

Date 2200	DGC : 1 to 30 %	DGC : 40%	DGC : 50%
Total carbon emissions (GtC)	4482,5	3616,9	982,1
Total CO2 emissions (GtCO2 per year)	98,3	8,8	-30,7
Emission control rate of GHGs (%)	1	91	120
Increase in atmosphere temperature (°C)	5,93	5,35	2,05
GDP net of abatement and damages (trillions of 2010 USD per year)	928,1	945,6	1555,9
Damages (trillions of 2010 USD per year)	96,1	78,8	17,8
Damages as fraction of gross output	0,094	0,077	0,011
Investment (trillions of 2010 USD per year)	92,8	94,6	405,0
Consumption (trillions of 2010 USD per year)	835,3	851,1	1150,9
Carbon price (2010 USD per ton of CO2)	0,0032	107,96	177,19

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