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Master thesis

Intertemporal Redistributive Policies in Environmental Economics

An Overlapping Generations approach to Intergenerational Equity and Intergenerational Redistributive Justice

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Master in Economics
May 2023

30 Credits

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Acknowledgments

This master thesis marks the end of my two years in the Master's in Economics programme at the University of Oslo. It has been a wonderful, and yet very humbling experience.

I want to thank, first and foremost, my supervisor Bård Harstad. I am so very grateful for his outstanding guidance and incredible patience. His invaluable input and insights are the reason I am completing this two-year journey.

I also want to thank my boyfriend, Kamil, whose tireless mental support, inspiring intelligence, and fascinating positive outlook on life have blessed me these past two years, and many more to come, with joy and unforgettable adventures.

I also want to express my gratitude to my wonderful parents. To my father for sparking my curiosity for Economics, and for always encouraging me to study the roots of economic inequality and social injustice.
To my mother for always supporting me and encouraging me, even when I was considering becoming a priest. I am so grateful for her sacrifices and irreplaceable unconditional love.

I would like to dedicate this work to the memory of my late philosophy professor, Angelo Bersini, whose unmatched support allowed me to pursue the path of higher education outside of Italy. His invaluable lessons and incredible dedication to the study of ethics will always be remembered.

Any inaccuracies or mistakes are exclusively my fault and I take sole responsibility.

Abstract

The Overlapping Generations model provides a comprehensive framework for the evaluation of policy designs with long time horizons. Indeed, the OLG approach gains its relevance in enabling economists to address the direct impacts of such policies on distinct consecutive generations. As there isn’t a need for the imposition of a social welfare function, that would substantially discount the utility of individuals as the time horizon progresses, the utility of each distinct generation can be weighted equally by the policymaker.

Since the OLG model represents a significantly fitting approach for policy evaluations with long time horizons, it is very suitable for the analysis of environmental policy designs aimed at reducing the levels of greenhouse gas emissions and of the Mean Global Temperature. In the OLG model, however, the environmental policy can also be aimed at establishing intergenerational equity through emission taxes and through the possibility of introducing intergenerational transfers.

This thesis studies the effects of how the policymaker’s willingness or ability to pursuit intergenerational equity affects the long-run levels of greenhouse gas emissions and mean global temperatures. This analysis will be conducted on the basis of the OLG model and numerical simulations formulated by economist Richard B. Howarth’s article *An Overlapping Generations Model of Climate-Economy Interactions* published in The Scandinavian Journal of Economics in 1998.

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1. Introduction

The aim of this thesis is to examine how the presence of a pursuit of intergenerational equity can determine the long-term outcomes of environmental policies aimed at reducing the level of greenhouse gas emissions and the mean global temperatures. Specifically, this examination will be carried through within the framework of an Overlapping Generations model which allows for the implementation of intergenerational transfers between consecutive generations.

This analysis will be based on the OLG model formulated by the economist Richard B. Howarth in his article *An Overlapping Generations Model of Climate-Economy Interactions* published in The Scandinavian Journal of Economics in 1998, which will be presented in the third chapter.
In his article, Howarth, explores the differences in the long-term environmental implications arising from policy choices that vary in their intergenerational redistributive nature, specifically on the basis of the presence of intergenerational transfers. Howarth's numerical simulations demonstrate how environmental policies require the presence of a level of intergenerational redistributive aims to produce robust long-term results. Howarth's analysis also stresses the importance of maintaining intergenerational equity as a fundamental objective even when institutional and societal obstacles do not allow for the real life implementation of a utilitarian First Best policy design.

Following the Illustration of Howarth's analysis, the fourth, and focal, chapter of this thesis will investigate whether the conclusions drawn on the basis of Howarth's article (1998) can be considered valid in the present time. To verify the current relevance of Howarth's conclusions, this chapter will present a series of projections, based on the formulations provided by Howarth, updated to current data and resulting from the alteration of certain assumptions of Howarth's model. The updated projections will be compared to Howarth's simulations and will be referred to in the concluding chapter to verify whether the interpretations drawn on Howarth's article still hold.

2. Literature Review

At the core of the field of study of Environmental Economics lies a concern for the well-being of the individuals that will be inheriting the strenuous economic and climatic conditions that humanity has generated since the advent of the Industrial Revolution. In attempting to relieve these innocent individuals from the burdens of the negative externalities produced by the populations of the past two centuries, economists and policymakers face numerous institutional, ideological or even ethical obstacles.

One of the primary challenges comes from the difficulty of finding mutual agreement on the extent to which economic efficiency in the present time should be sacrificed to ensure the health and safety of individuals that are not even born yet. While, given the subjective and moral nature of this matter, there isn't a straightforward objective solution to this debate, the OLG model can provide more clarity on the implications of adopting different trade-offs between economic and environmental objectives by enabling economists to address the direct impacts of environmental policies on distinct generations.

Hence, the OLG model provides a comprehensive framework for the study of the intergenerational effects produced by different policy designs and allows economists to perform detailed policy evaluations, even when considering very long time horizons, and draw conclusions on the implications of different policy designs also in the framework of intergenerational Distributive Justice.

On this basis, economists such as Tobias N. Rasmussen have adopted the OLG model as a framework for environmental policy evaluation. In his paper, *Modeling the economics of greenhouse gas abatement: An overlapping generations perspective*, published in the Review of Economic Dynamics in 2003, Rasmussen studies the distributional effects of different greenhouse abatements policies, such as carbon taxes and tradable emission permits, between generations. In particular, Rasmussen uses the OLG model to examine which generations are expected to carry the highest costs of these different policy instruments once the imposition of a social welfare function, that would greatly discount the utility of people living in the far future, is removed. As the OLG model allows for the study of intergenerational effects and interactions, it provides an extremely comprehensive framework for Rasmussen's analysis as he states that “abatement policies should be seen in the context of decisions involving intergenerational redistribution rather than intertemporal saving.” (Rasmussen, 2003, pp100).

Another article that analyses the long-term effects of environmental policies through an OLG model is *An Overlapping Generations Model of Growth and the Environment* published by economists Rowena Pecchenino and A. John in The Economic Journal in 1994. Pecchenino and John study the trade-off between the choice of economic growth and the maintenance of environmental quality by assuming individuals to make decisions regarding consumption, investment and pollution abatement with long-lasting effects in the span of their short life composed of two periods.

As illustrated by Rasmussen, since the OLG model focuses on the saving and consumption decisions of many short-lived individuals, it is often preferred, as a more realistic description of reality, to the Infinitely lived agent model. On this premise, economists Gunter Stephan, Pascal Previdoli, and Georg Müller -Fürstenberger compare the two models in their article *Overlapping Generations or Infinitely-Lived Agents Intergenerational Altruism and the Economics of Global Warming*. Stephan et al. study whether the absence of altruism in the decision-making process of the short lived agents would affect the presence of future climate change externalities and how these results would differ from the outcome of an altruistic infinitely-lived agent. They demonstrate that, even without the presence of altruism, the short-lived agents of the OLG model have incentives to reduce the future damages of climate change and implement greenhouse gas emission abatement. They conclude their paper by stating that, under the assumptions that carbon taxes are the only policy instrument to be employed in the greenhouse gas emission abatement process and that tax revenues are recycled, the long-run effects resulting in the OLG Model differ insignificantly from the effects resulting from the infinitely-lived agent model.

While the papers mentioned above are of great relevance in the literature regarding the use of the OLG model in theoretical assessments of environmental policy evaluations, the economist Richard B. Howarth can be considered a key contributor to this discourse thanks to his article *An Overlapping Generations Model of Climate-Economy Interactions.* Indeed, Howarth’s article stands out due to his use of an OLG model to study how varying the level of intergenerational redistribution in policy designs affects long-run levels of greenhouse gas emission and mean global temperature.

Indeed, the interesting feature of Howarth's analysis comes firstly from the fact that the different policy designs he presents vary in the policymaker's ability or willingness to pursue intergenerational equity. The variation in the underlining assumptions on the policymaker's willingness and ability to redistribute intergenerationally, determines the differences, for each policy design, in the magnitude of emission taxes implemented as well as the presence of intergenerational transfers. Moreover, following his numerical simulations, Howarth draws conclusions regarding the imperative of pursuing intergenerational equity even when extremely altruistic policy designs are not applicable to real economies.

The merit of analysing these outcomes within the framework of the OLG Model stems from the fact that the distinct generations are not grouped together, which allows for the introduction of the assumption that the lifecycle utility of each distinct generation has equal social weight. This feature gives the policymaker the option to refrain from using a social welfare function that would substantially discount the utility of people from a very far future compared to how the utility of people from a nearer future would be discounted.

Rather, the OLG model enables Howarth to observe the direct effect of emission taxes and intergenerational transfers on the consumption and emission levels of the distinct generations as well as to estimate the long-run effects these policy designs could have on emission levels and on the mean global temperature level.

3. Richard B. Howarth's Overlapping Generations approach: the remarkable effect of intergenerational redistribution on mitigating global warming and greenhouse gas emissions

In *An Overlapping Generations Model of Climate-Economy Interactions* (1998), Howarth presents his estimations of the outcomes from three possible scenarios of emission tax policy choices, which differ in their intergenerational redistributive nature, in an OLG model.

Howarth's estimations indicate that, in the long-run, emission tax policies characterised by the pursuit of intergenerational equity (and not strictly income redistribution in the present society) produce the most significant results in controlling the average increase in mean global temperature relative to the pre-industrial norm. Howarth also considers the possibility of an institutional system that would not allow for intergenerational transfers and, hence, for a policy design aimed exclusively at establishing intergenerational equity. On this assumption, Howarth formulates a numerical estimation for a Utilitarian Second Best option, in which the social planner still weighs equally the lifecycle utility of every generation while encountering institutional obstacles.

Thus, this paper gains its relevance in the discussion regarding intergenerational redistribution in climate change economics by identifying the highly intertemporal redistributive nature that policies aimed at reducing global warming should have, but also by stressing the applicability and necessity of pursuing intergenerational redistribution goals when the assumptions of a utilitarian First Best equilibrium cannot be reproduced in real-world applications.

3.1. The Model

In his model, Howarth assumes individuals to have perfect foresight of prices and economic conditions. These individuals live in a competitive OLG economy where the production of a homogenous consumption and investment good produces greenhouse gas emissions. In every period *t*, a new generation (n_t) of identical individuals is presumed to be born. Each period lasts thirty-five years. Hence, individuals are given a life span of seventy years which is divided into young age (up to the age of thirty-five) and old age (from the age of thirty-five to the age of seventy). At every stage of life, each individual supplies inelastically one unit of labour to the production sector. Moreover, individuals born in time t enjoy a level of consumption c_{yt} in period *t* (when under the age of thirty-five) and c_{ot+1} in period *t+1* (when between the ages of thirty-five and seventy-five).

At each period, the greenhouse gas emissions, resulting from the production of the consumption good, generate a negative externality on the welfare of the future generations by determining the increase in future temperature. Indeed, this negative externality is not only reflected in the dangerous environmental impacts that higher temperatures cause but also in the fact that higher temperatures are assumed to reduce the output of this economy.

The government can choose to impose a tax on greenhouse gas emissions in order to confront the issue of raising temperatures by redistributing welfare between generations.
The government's tax revenue is distributed to the individuals through the net income transfers π_{yt} at time *t* for young individuals and π_{ot+1} at time *t+1* for the now old individuals.

Based on these assumptions, Howarth assumes that, in the time period *t*, the individuals' preferences may be represented by the following utility function, logarithmic in consumption:

$$u_t = log(\, c_{yt} \,) + \frac{1}{1+\rho} log(\, c_{ot+1} \,). \qquad (1)$$

The parameter ρ, in the discount factor $((\frac{1}{1+\rho}))$, indicates the pure rate of time preference for consumption between young age and old age for each individual.

The model also allows for saving decisions. Indeed, individuals born at time *t* decide to invest capital k_{t+1} (with an interest rate r_t) in the production sector to fund their consumption in their old age. For their supply of labour, individuals earn a wage of w_t at the young age.
These assumptions produce the following budget constraint for an individual born at time *t*:

$$c_{yt} + k_{t+1} = w_t + \pi_{yt} \qquad (2)$$

$$c_{ot+1} = w_{t+1} + (1 + r_{t+1})\, k_{t+1} + \pi_{t+1} \qquad (3)$$

Resulting in the First Order Condition:

$$\frac{c_{ot+1}}{c_{yt}} = \frac{1+ r_{t+1}}{1+\rho} \qquad (4)$$

Meanwhile, the net production function in the economy determines the consumption possibilities of the individuals:

$$C_t + K_{t+1} = f(K_t, N_t, E_t, T_t) + K_t. \qquad (5)$$

Where $C_t = n_t c_{yt} + n_{t-1} c_{ot}$ (6) is the aggregate level of consumption from all young and old individuals in period *t* and $K_t = n_{t-1} k_t$ (7) is the aggregate capital stock in period *t*. Furthermore, in period *t*, the author specifies $N_t = n_{t-1} + n_t$ (8) to be the whole population. E_t is the residual emissions of greenhouse gases, and T_t is the increase in mean global temperature. As stated earlier, the mean global temperature is affected by the greenhouse gas emissions (as higher emissions increase future temperature). Thus, the future climate conditions are assumed to be determined by the time path.

$$T_t = T_t(E_0, \dots, E_{t-1}) \text{ with } \frac{\partial T_t}{\partial E_{t-i}} > 0 \ (i>0). \qquad (9)$$

The production function is assumed to have constant returns to scale and to be concave and increasing in capital, labour, and greenhouse gas emissions. Additionally, as stated previously, production decreases as the global mean temperature increases, meaning that: $\frac{\partial f_t}{\partial T_t} < 0$. Thus, higher emissions at time *t* imply a higher mean global temperature in the future, which implies a reduction in future output.

All competitive firms have the same access to the production technology and experience exogenous technological change. These firms are subject to the government's greenhouse gas emission taxes, v_t. To maximise their profits, firms choose capital inputs, labour inputs, and greenhouse gas emissions to equalise the marginal productivity of each factor to its price:

$$r_t = \frac{\partial f_t}{\partial K_t},\ w_t = \frac{\partial f_t}{\partial N_t},\ v_t = \frac{\partial f_t}{\partial E_t} \qquad (10)$$

Given the assumption of constant returns to scale, this allocation results in zero profits.

Howarth then proceeds to explain that any allocation, which equalises marginal productivity of the factors to their prices, produces a competitive equilibrium if the government allocates the transfers and the greenhouse gas taxes in accordance with the following balanced budget condition:

$$n_t \pi_{yt} + n_{t-1} \pi_{ot} = v_t E_t \qquad (11)$$

To conclude, Pareto Efficiency will be achieved when the government follows Pigou's tax rule by allocating emission taxes so that their marginal costs are equal to their discounted future benefits:

$$v_t = -\sum_{i=t}^{\bar{t}-t} \frac{\partial f_{t+1}}{\partial T_{t+1}} \frac{\partial T_{t+1}}{\partial E_t} \left(\prod_{j=1}^{i} \frac{1}{1+r_{t+j}}\right) \qquad (12)$$

Hence the emission tax, v_t, levied in time period *t*, reflects the aggregate sum of marginal damage that the increase in temperatures (resulted from the emission levels in time *t*) forces on the future economy ($-\frac{\partial f_{t+i}}{\partial T_{t+i}}$) as well as the damages that current emissions (in time *t*) impose on future temperatures ($\frac{\partial T_{t+i}}{\partial E_t}$) from period *t* to the end period $\bar{t}$.

Howarth produces the discount factor in the formula ($\prod_{j=1}^{i} \frac{1}{1+r_{t+j}}$) by equalising the social discount rate with the market rate of interest. This can be done because the market rate of interest is assumed to measure the marginal rate of time preference experienced by individuals.

An argument could be raised on whether the market rate of interest can be considered as the most appropriate measure of the marginal rate of time preference. Indeed, while the rate of time preference experienced by individuals stems rather from psychological characteristics, the market rate of interest can be subject to unpredictable changes due to economic shocks or changes in the monetary policy depending on the political standpoint of the politicians in power.

While a precise estimation of a subjective feature such as the marginal rate of time preference is almost impossible, economists such as Kenneth Arrow have argued for the use of the rate of return to risk-free investment as a more precise estimation of the marginal rate of time preference as it results from the psychological attitude in the financial decision making process on longer-term investments (Arrow et al., 2012). That said, Arrow et al also point out how even the rate of return to risk-free investment is subject to market imperfections and, furthermore, is more reflective of intragenerational preferences rather than intergenerational ones.

The end period, $\bar{t}$, in the formula should represent, in theory, the time of society's extinction, assuming that the lifetime of humanity is finite. A problem arises, hence, as the time of humanity's extinction remains uncertain. Nevertheless, if one where to assume that humanity's lifetime was not finite, this would also pose a challenge as Howarth suggests that as $\bar{t}$ tends to infinity the economy would exhaust its remaining capital (raising the market rate of interest and hence the social discount rate r_{t+j}) and the greenhouse gas emission tax, v_t, would fall to 0. This transition, however, would occur so far in the future that Howarth chooses to consider, as the long-run model solutions, the intermediate steady state occurring at roughly fifteen generations from the base year.

3.2. Implications of different intergenerational redistributive policies

In his paper, Howarth proceeds to display the long-term results of three different policy choices. These policy choices differ in the policymaker's ability and willingness of redistributing welfare across generations. To clarify, the three policy designs differ in how willing (or capable) the policymaker is to diminish the welfare of the present generations in order to improve the one experienced by the individuals that are not born yet.
The author produces his numerical simulations on the basis of the technical constraints exhibited by Nordhaus' DICE model (Nordhaus, 1994). Howarth does this by taking the year 2000 as the starting point for his numerical simulations.

To validate the significance of Howarth's result in the current academic discourse of intergenerational equity in climate change economics, the core of this paper, Chapter 4, will be dedicated to investigating whether the interpretations drawn by Howarth hold to this date.

3.2.1. No Transfer baseline

The first scenario is referred to as the *No transfer baseline*. In this approach, the policy maker has no intent to redistribute wealth from the present generations to the future ones. This means that consumption is flattened in time *t* (as the tax revenues are distributed equally to the living individuals) but not intergenerationally, as there are no net transfers of wealth from the present to the future generations.

Thus, emission taxes are still enforced and chosen to respect the Pigouvian tax rule (12) with the discount factor that equates the market rate of interest to the social discount rate.
The lump sum transfers allocated equally to all living individuals take, thus, the form:

$$\pi_{yt} = \pi_{ot} = v_t \frac{E_t}{N_t} \ . \qquad (13)$$

The emission tax policy resulting from this scenario delivers a level of greenhouse gas emissions abatement that starts from 16% in the base year 2000, reaches 24% after three periods (so in the year 2105), and stabilises to a rate of 25% in the long-run.

Howarth's results show that consumption increases in the long run (from \$4,058/yr in 2000 to \$15,268/yr in 1989 dollars), as a result of the increase in capital and labour productivity and higher capital stocks. Nevertheless, even though an increase in consumption is estimated in the *No transfer baseline* scenario, the upward trend that it exhibits is not as steep as the upward trend in consumption which will be exhibited in the following *Utilitarian Optimum* policy path.

Nevertheless, the main aspect to note is that these estimations exhibit also a substantial long-run increase in greenhouse gas emissions specifically from 8.6 billion tons of carbon equivalent/yr in 2000 to 24.2 billion tons of carbon equivalent/yr in the long-run. This effect can be attributed to the fact that even though emission taxes follow an upwards trend, they are never expected to exceed the relatively low level of \$76 per ton of carbon equivalent.

This process induces the Mean Global Temperature above the pre-industrial norm to rise from 1.7 Celsius in the base year to 4.6 Celsius in the third period and, finally, to 7.4 Celsius in the long run.

3.2.2. Utilitarian Optimum

The second scenario is referred to as the *Utilitarian Optimum*. In this case, policymaker aims to maximise the undiscounted aggregate of the lifecycle utilities of all present and future individuals.

Thus, the social planner's maximisation problem can be outlined as:

$$max \sum_{i=0}^{\bar{t}} n_t u_t \ . \quad (14)$$

This objective is carried through by not only imposing emission taxes for each period but also by enforcing intergenerational transfers, then granted specifically to the young individuals.

Clearly, a set of assumptions have to be imposed on the possibility to compare individual utilities and on the policymaker's presence of a high aversion to distributional inequality.

To identify the presence of an intergenerational transfer in this scenario, Howarth introduces the concept of a young person's net capital transfer, meaning the amount of capital received by a young person that is not derived strictly from his per capita share of greenhouse gas emission tax revenues in his time period.

Thus, a young person's net capital transfer takes the form of:

$$\pi_{yt} - v_t E_t / N_t \ . \quad (15)$$

The identification of the net capital transfer in the model denotes the existence of a lump sum transfer that does not stem from the government's greenhouse gas tax revenue. This formulation is in line with the Pigouvian tax rule (12) and is, hence, Pareto efficient.

Put more simply, young individuals born in period *t* are compensated for the externalities of the greenhouse gas emissions produced in period *t* (as are old individuals) but also for the negative effect that greenhouse gas emissions from the periods previous to their birth have caused on their welfare.

Howarth's numerical simulations demonstrate how including an intergenerational transfer in the policy design alters the intertemporal consumption allocation of the previous *No transfer baseline* scenario by smoothing consumption intergenerationally. Indeed, the results from the

Utilitarian Optimum framework compared to the ones of the *No transfer baseline* policy exhibit a reduction of per capita consumption in the base year 2000 of 22% (as consumption per capita falls from $4,058/yr to $3,161/yr) as well as an increase in the long-run per capita consumption of 18% (as per capita consumption rises from $15,268/yr to $18,053/yr). Howarth comes to the conclusion that, under the assumptions of the model, the long-run per capita consumption produced by the *Utilitarian optimum* policy design represents the highest level of consumption sustainable perpetually.

Another interesting result of Howarth's analysis of the *Utilitarian optimum* path is the increase in net capital transfer experienced by a young person as it rises from $2,098/yr in the short run to $13,614/yr in the steady state while the *No transfer baseline* path doesn't include any net capital transfer for the young individuals at any time. Intuitively, this increase makes perfect sense since, as time passes and greenhouse gas emissions rise and accumulate, young individuals will experience higher welfare losses and hence will receive higher compensations.

Hence, the Utilitarian Optimum path also exhibits a substantial increase in capital accumulation in the long-run (starting from $56 trillion in the base year 2000 to $2,221 trillion in the long-run) which directly affects the development of the market interest rate. Taking into account that the discount factor employed in the Pigouvian tax rule (9) is derived by equalising the social discount rate with the market rate of interest, the fitting discount rate applicable on the cost and benefits of the greenhouse gas emissions at each period falls from 4.2% yr in the base year 2000 to zero in the long-run (unlike the 2.8% yr in the long-run exhibited in the *No transfer baseline* path in which the rate of capital accumulation is far inferior).

The declining discount rate, paired with the fact that the increasing economic activity produces higher climate change damages (as these factors are proportional), raises the rates of greenhouse gas emissions abatement. In fact, with the assumptions of the *Utilitarian optimum* path emission abatement rates increase from the base year level of 48% up to the-long-run rate of 89%. This process is due to the long-run rise of emission taxes (from $131 per ton of carbon equivalent to $900) and the consequent long-run decline of greenhouse gas emissions to a level below the one of the base year 2000.

Indeed, while the level of greenhouse gases produced in the base year 2000 raises from a level 5.3 billion tons of carbon-equivalent/yr to a level of 7.1 billion tons of carbon-equivalent/yr in the third period (mainly due to intensified economic productivity), in the long-run emission levels decline to 5.2 billion tons/yr due to the increased cost of polluting imposed by the government on the production sector.

This prediction differs, of course, vastly from the *No Transfers* baseline estimates in which emission taxes reach a mere $76 per ton of carbon equivalent in the long-run and greenhouse gas emissions continuously grow up to the level of 24.2 billion tons/yr in the long-run.

The great reduction of long-run greenhouse gas emission concentrations in the atmosphere entails that temperatures in the long-run are estimated to exceed only by 3.4 C the pre-industrial level. A vastly different estimation from the 7.4 C of the *No transfer baseline* policy outcome.

3.2.3. Utilitarian Second Best Equilibrium

In the last framework proposed by Howarth, the policymaker has the same intergenerational utilitarian aim of the *Utilitarian optimum* social planner but is institutionally unable to enforce intergenerational transfers.

Hence, the policy maker reaches a *Utilitarian Second Best* equilibrium by maximising the undiscounted sum of each present and future individual's life cycle utility (14) but with the addition of a no transfers condition (13) enforced, previously, in the *No transfer Baseline* scenario.

Thus, the utility maximisation problem of the utilitarian social planner is still subject to the assumptions (1)-(10) but with the condition of allocating equally to old and young individuals at time period *t* the same lump sum transfer stemming strictly from the tax revenues from the emissions at time *t*.

Therefore, the social planner faces the following maximisation problem:

$$max \sum_{i=0}^{\bar{t}} n_t u_t$$

s.t.

$u_t = log(c_{yt}) + \frac{1}{1+\rho} log(c_{ot+1})$

$c_{yt} + k_{t+1} = w_t + \pi_{yt}$

$c_{ot+1} = w_{t+1} + (1 + r_{t+1})\, k_{t+1} + \pi_{t+1}$

$\frac{c_{ot+1}}{c_{yt}} = \frac{1+ r_{t+1}}{1+\rho}$

$C_t + K_{t+1} = f(K_t , N_t, E_t, T_t) + K_t.$

$T_t = T_t(E_0, \ldots, E_{t-1})$ with $\frac{\partial T_t}{\partial E_{t-i}} > 0$ ($i>0$)

$r_t = \frac{\partial f_t}{\partial K_t}$, $w_t = \frac{\partial f_t}{\partial N_t}$, $v_t = \frac{\partial f_t}{\partial E_t}$

$\pi_{yt} = \pi_{ot} = v_t \frac{E_t}{N_t}$

In this formulation, the policymaker can pursue intergenerational equity and redistribution solely through the implementation of greenhouse gas emissions taxes. Although this aspect poses an obstacle to the policymaker's ability to establish intergenerational equity, Howarth points out how the removal of the Pigouvian efficient tax rule constraint, allows the policymaker to implement much higher emission taxes in the *Utilitarian Second Best* path.

As a result, in spite of the impossibility to enforce intergenerational transfers, Howarth's predictions on the *Utilitarian Second Best* path still exhibit a reallocation of consumption from the present generations to the future generations as, in comparison to the *No transfer baseline* scenario, per capita consumption is decreased in the base year 2000 ($4,024/yr compared to $4,058/yr) and then exceeds the estimations of the No transfer baseline in the long-run ($15,811/yr compared to $15,268/yr).

This estimation is a result of a long-run rise in emission taxes which reach a level of $649 per ton of carbon equivalent compared to the *No transfer baseline* of $76 per ton of carbon. Consequently, emission abatement rates follow an upward trend that starts at 51% in the base year, reaches 68% in the third period, and stabilises at 76% in the long run. The resulting levels of greenhouse emission produced at each period, start off from 5.0 billion tons/yr in the base year 2000 and stabilise to 8.1 billion tons/y from the third period to the long run.
While higher than the level observed in the *Utilitarian Optimum* path, the long-run level is still substantially lower than the *No transfer baseline* scenario.

The emission abatement policies of this Second Best equilibrium generate a level of mean global temperature over the pre-industrial norm of 4.6 Celsius in the third period and ultimately, in the long run, a level of 4.3 Celsius.

Capital accumulation (and hence the market interest rate) is estimated to progress similarly to the *No transfer Baseline* path. However, unlike the *Utilitarian Optimum* scenario, the long-run increase in greenhouse gas emission abatement rates in the *Utilitarian Second Best* path has no connection to the increase in capital accumulation. Indeed, while the increasing abatement rates in the *Utilitarian Optimum* scenario were partly caused by the effect of capital accumulation on the social discount rate, the absence of the Pigouvian tax rule, and its relative social discount rate, in the *Utilitarian Second Best* scenario excludes this possibility.

The greenhouse gas emission abatement rates, however, are still higher than the ones exhibited by the *No Transfer baseline* path, and are much closer to the abatement rates resulting from the *Utilitarian Optimum* path. This is a result of the social planner's aim of maximising of the undiscounted sum of each present and future individual’s life cycle utility (14) through the allocation choices of greenhouse emission taxes in each period *t*.

3.3. Interpretation of the estimations

Howarth's analysis delivers a relevant contribution to the debate on the prioritisation of intergenerational equity over economic efficiency. Indeed, through his simulations, Howarth demonstrates that, even in the case where institutional and ideological obstacles prevent the policymaker from prioritising intergenerational equity through intergenerational transfers, second-best policies are still applicable to deliver a level of intergenerational redistribution of welfare. While less effective than the *Utilitarian Optimum* path, the presence of an underlining intergenerational redistributive nature in the *Utilitarian Second Best* scenario still produces very strong long-term results when compared to the effects of policies that prioritise present economic efficiency over a forward-looking perspective.

In fact, Howarth delivers a response to the economist Alan S. Manne, who points out the unrealistic character of the assumptions imposed under *Utilitarian optimum* policies (Manne, 1995), by stating that " It does not therefore follow that it is logically justified to base climate-change policies on standard efficiency criteria in a world where the distribution of welfare between generations may be suboptimal" (Howarth, 1998, page 589).

At the same time, Howarth's estimations on the effectiveness of Second Best policies can also act as a critique of economists and scholars, such as John Broome (Broome,1992) and William R. Cline (Cline, 1992), who regard pure utilitarianism as the exclusively preferred policy paths to pursue in environmental economics.

Having established the relevance of Howarth's work, a question remains open on whether his conclusions could still be drawn given the economic and population composition changes that the world has experienced since the publication of his article. The next section will, hence, attempt to address this particular question.

4. Applications of Howarth’s numerical approach with current data: Do the intuitions still hold?

This section aims to investigate whether Howarth’s interpretations of the effect of different environmental policy paths on future emission levels and mean global temperatures can still be drawn from projections based on current data.

Indeed, while Howarth produces his numerical simulations with the year 2000 as a base year, this section will study whether his conclusions would still hold by using the year 2021 as a base year with the addition of some slight alterations and simplifications to the formulas.

In line with Howarth’s assumption for his simulations, the current projections will consider the time period of fifteen generations after the base year as the long-run estimations (which is period t=15, year 2546).

As this thesis is of a theoretical nature, rather than of an empirical one, the focus of this chapter is on the interpretation that should be drawn from the difference in the projections of future greenhouse gas emissions and mean global temperatures rather than on the precision and magnitude of the estimations resulting from the application of Howarth’s formulas to current data.

4.1. Projecting the size of the young generation per period

The first thing to note, when studying Howarth's numerical simulations, is that he bases his estimations on the data presented by the *World Population Projections* published by the World Bank in 1990 (Bulatao et al, 1990) which finds that the proportion of the world population under the age of 35 is around 65%.

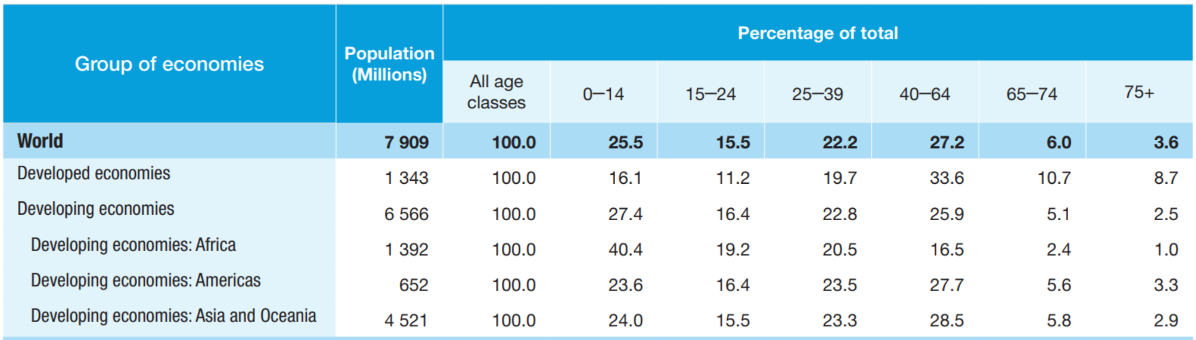
On this basis, Howarth constructs his model by supposing the young generation at each time period to be composed of individuals up to the age of 35 years, while he considers the old generation to be composed of individuals between the age of 36 and 70.

Today, data regarding the proportion of individuals under the age of 35 in the world is not as precise as when Howarth wrote his paper. However, the *UNCTAD Handbook of Statistics 2022* published by the United Nations Conference on Trade and Development gives an accurate approximation of the proportion of individuals under the age of 39 in the world in 2021. Furthermore, the world bank estimates that since 1998 (the year Howarth's paper was published) the world life expectancy has increased from 67 to 72 in 2021 (The World Bank, 2022).

Following these considerations, Howarth's model has been adapted to fit current (and precisely obtainable) data by considering young individuals to be between the ages of 5 and 39 and old individuals to be between the ages of 40 and 74. This shift in the age composition of the OLG is practicable as the time period *t* remains 35 years.

Following this alteration, the proportion of the global population belonging to the old generation in 2021 can be approximated to 33.2% (UNCTAD, 2022). By observing the data of the *UNCTAD Handbook of Statistics 2022* one can deduce that the proportion of individuals under the age of 40 in 2021 is 63.2%. Knowing that, in 2021, the proportion of children under the age of 5 was 8.5% (Oxford Martin School), the proportion of the global population belonging to the young generation in 2021 can be approximated to 54.7%.

Table 1: Age structure by group of economies 2021



Group of economies	Population (Millions)	Percentage of total						
		All age classes	0–14	15–24	25–39	40–64	65–74	75+
World	**7 909**	**100.0**	**25.5**	**15.5**	**22.2**	**27.2**	**6.0**	**3.6**
Developed economies	1 343	100.0	16.1	11.2	19.7	33.6	10.7	8.7
Developing economies	6 566	100.0	27.4	16.4	22.8	25.9	5.1	2.5
Developing economies: Africa	1 392	100.0	40.4	19.2	20.5	16.5	2.4	1.0
Developing economies: Americas	652	100.0	23.6	16.4	23.5	27.7	5.6	3.3
Developing economies: Asia and Oceania	4 521	100.0	24.0	15.5	23.3	28.5	5.8	2.9

Source: UNCTAD Handbook of Statistics, 2022, page 69

In *An Overlapping Generations Model of Climate-Economy Interactions* Howarth estimates the number of billions of young individuals alive in every time period to be:

$$N_{yt} = 5.27 - 1.42(0.57)^{t}. \qquad (16)$$

This formulation allows for a population growth rate of 1.1%yr which implies the number of overall individuals alive in the long run to be 10.54 billion.

Even before adapting this formulation to the previously mentioned alteration of the age composition of the two generations, one can already detect how this formula may not be as suitable for current estimations given that population growth was estimated to be 0.9% in 2022 by the *UNCTAD Handbook of Statistics 2022*.

Furthermore, Howarth's formulation (16) also exhibits a trend towards a fixed number as time progresses (since N_{yt} tends to 5.27 billion as t increases).

For these reasons, one could simplify the estimation of the number of young individuals alive in each period t, starting from 4.3 billion individuals in 2021, as:

$$N_{yt} = 4.3(1 + 0.37)^{t}\ . \qquad (17)$$

Assuming that each period t lasts 35 years and hence, based on the current estimates that the annual population growth rate is 0.9%, the growth rate for each period is 37% (see Appendix 1).

Nevertheless, when estimating the number of young individuals for each time period it's also important to keep in mind that the current global population is experiencing a substantial ageing process. Indeed, the World Health Organization estimates that "By 2050, the world's population of people aged 60 years and older will double" (World Health Organization, 2022). As the proportion of young individuals in the population is estimated to decline with the change in population age composition, it seems appropriate to consider the population growth rate as declining for the young generation.

Nevertheless, even with the premise of an ageing process of the population, it can be tricky to formulate the precise nature of the reduction of the growth rate as one cannot know for certain how the age composition of the population will change. However, in order to account for the assumption of the ageing process of the population, an additional alteration can be made to the formula (16) by inserting an additional numerical term which declines with time:

$$\widehat{N_{yt}} = 4.3[1 + (0.37)(0.999)]^{t}. \qquad (18)$$

The introduction of a more precise estimation of the age composition of the population in each period is relevant with regards to discussing the descriptive accuracy of Howarth's formulations, but, most importantly, it will also determine the projected path of Gross Global Product in section **4.2..**

4.2. Projecting Gross Global Product per Period

In order to determine the greenhouse gas emission and temperature changes at each period, Howarth first calculates the World Gross Output in trillions of dollars per period (Y_t) by using a Cobb-Douglas production function of inputs of capital and labour:

$$Y_t = A_t K_t^{0.25} N_t^{0.75} \ . \qquad (19)$$

He considers A_t as an index for total factor productivity and determines the input-output elasticities of each factor on the premise that wage income accounts for three-quarters of gross output in the global economy.

However, current indexes of factor productivity and of the input-output elasticities of labour and capital are extremely difficult to determine precisely at a global level.
Another obstacle in adapting Howarth's formula (19) to current data lies in the fact that World Gross Output is not a commonly used measure of economic activity as Gross Global Product is. Because of the much more comprehensive nature of Gross Global Product compared to World Gross Output in measuring economic activity, data of the latter regarding the years from 2021 onwards is not publicly available. For this reason, this paper will instead employ the level of Gross Global Product currently available.

Given this choice of parameter, one might expect the numerical results regarding the effective levels of greenhouse gas emission projected for each type of policy design to be marginally smaller than the ones that would have occurred if the measure of World Gross Output was to be employed. This feature will be acknowledged in section **4.5** when comparing the projections of this paper with the estimations made by Howarth**..**

Hence, the projections for the Gross Global Product at each period will be estimated on the basis of the most recent estimations reported by *Statista* (O'Neill, 2023) of Gross Global Product to be $97.076 trillion in 2021, $101.560 trillion in 2022, $106.181 trillion in 2023 (O'Neill, 2023), and thereafter by employing the yearly global growth rate of 3.3% estimated by the International Monetary Fund after the year 2023 (IMF, 2022).

The application of the yearly global growth rate of 3.3% on the Gross Global Product from the year 2023 is, by no means, an assertion on the fixed nature of the growth rate of the Gross Global Product. Rather this fixed rate is chosen as a necessary simplification given the impossibility to predict the exact fluctuations in the growth rate of the Gross Global Product over a long time horizon.

Nevertheless, although no claim can be made regarding the precise magnitude of the Gross Global Product's growth rate in the next five-hundred years, the effect of the changing age composition of the global population on the growth rate should be held into account. Indeed, as implied by formula (18), the proportion of the global generation per period is expected to decline. The ageing process experienced by the global population would, hence, affect the Gross Global Product.

In fact, although there is no way to precisely estimate how the population ageing process will affect Gross Global Product, it's safe to assume that its growth rate could be affected by factors such as the decline of the labour force (and the consequent possible decrease in productivity and global output) or the prevalence of consumption patterns typical of the older population (such as costly healthcare services and fewer new technologies).

On this basis, a projection will be also drawn with the application of a slightly declining Gross Global Product growth rate, in line with formula (18). Still, given the presence of factors such as technological progress, the pace at with the Gross Global Product growth rate will be projected to decline will be much lower than the pace at which the proportion of young individuals is expected to decline in formula (18).

This projection will be determined, as follows, for all periods following the base period (hence for all $t \neq 0$):

$$\widehat{\mathrm{Y}}_{\mathrm{t}} = 106.181[1 + (0.033)(0.999999)]^{\tau(\mathrm{t})}. \quad (20)$$

The parameter $\widehat{\mathrm{Y}}_{\mathrm{t}}$ represents the projected Gross Global Product with a declining growth rate expressed in trillion of American dollars, while $\tau(t)$ is a function of the time period, *t*, which identifies the number of years passed since 2023 as follows:

$$\tau(t) = 35t - 2023. \quad (21)$$

This specification is necessary as the International Monetary Fund estimates the growth rate of 3.3% to arise from the year 2023.

4.3. Projecting greenhouse gas emission per period

The estimation of the world gross output per period is a necessary step in Howarth's analysis because he considers the level of potential greenhouse gas emissions in each period to be linearly proportional to the world gross output.

Indeed, Howarth determines the level of potential greenhouse gas emissions in each period t with the following formula:

$$E_{0t} = (0.181 + 0.189(0.622)^t)Y_t \,. \qquad (22)$$

Howarth specifies how the term "potential emissions" indicates "the level of greenhouse emissions that would arise in the absence of pollution abatement" (Howarth, 1998, page 582).

In his analysis, Howarth determines the level of potential emissions by considering the measure of World Gross Output per period as 1989 U.S. dollars. Given that Howarth's formula for Potential greenhouse gas emissions per period (22) was designed on this assumption, the current data utilised in this paper's projections will be adapted, based on the estimates provided by the U.S. Bureau of Labor (Bureau of Labor Statistics, 2023), to inflation in order not to compromise the reliability of the formula in this framework.

Thus, once established the level of potential emissions per period (22), the resulting effective level of greenhouse gas emissions projected for each period will depend on the emission abatement level resulting from the type of policy path that Howarth presented. Once a representative projection of the resulting greenhouse gas emission levels for each policy path will have been generated, the main objective will consist of examining whether the interpretations of these projections match the ones drawn by Howarth in his numerical simulations.

4.4. Projecting Mean Global temperature above pre-industrial level per period

The final point of this section is to confirm whether Howarth's conclusion on the effect of intergenerationally redistributive policies, compared to the *No transfer baseline* approach, on the level of mean global temperature still holds.

Put simply, the first objective is to corroborate whether the only really effective policy measures to mitigate the negative externalities of pollution (in particular global warming) are the policy paths of highly intergenerational redistributive aims.

The second objective of this analysis is to stress that when the *Utilitarian Optimum* policy design is not applicable in the real world, due to institutional obstacles and the strictness of its assumptions, the policymaker does not need to abandon intergenerational redistributive aims but, rather, he can still achieve great improvements in mitigating global warming, compared to the *No transfer Baseline* approach, by implementing the *Utilitarian Second Best* policy design.

Thus, this paper seeks to confirm the conclusion drawn from Howarth's estimations that institutional obstacles and standard economic efficiency criteria do not justify the abandonment of intergenerational redistribution aims as the only alternative.

For the estimations of the mean temperature change above pre-industrial levels in each period *t* starting from the year 2021, Howarth presents the following formula:

$$T_t = \frac{(5.29 log(\frac{Q_t}{590}) + F_t)}{1.41} \,. \qquad (23)$$

The first term of this formulation, Q_t, represents "the effective stock of carbon dioxide and chlorofluorocarbons in the atmosphere, measured in billion tons of carbon-equivalent" (Howarth, 1998, page 583) in period *t*.

To estimate the values of this parameter at each period, Howarth utilises the level of stock of carbon dioxide present in the previous period as well as the level of effective greenhouse gas emissions of the previous period with the following formulation:

$$Q_{t+1} - 590 = 0.64E_t + ((1 - 0.00833)^{35}(Q_t - 590)). \qquad (24)$$

From this equation, it is quite simple to identify the formulation for Q_t:

$$Q_{t+1} = 0.64E_t + ((1 - 0.00833)^{35}(Q_t - 590)) + 590 \qquad (25)$$
$$Q_t = 0.64E_{t-1} + ((1 - 0.00833)^{35}(Q_{t-1} - 590)) + 590\ . \qquad (26)$$

Knowing that the level of effective stock of carbon dioxide and chlorofluorocarbons in the atmosphere in the base year 2021 was approximately 36.3 billion of tonnes (IEA, 2022) and that 37.12 billion metric tons of carbon dioxide were produced in 2021 (Tiseo, 2023), the estimation of the stock of carbon dioxide and chlorofluorocarbons in the following periods is rather straightforward.

One noteworthy difference between the characteristics of the stock of carbon dioxide and chlorofluorocarbons present in the atmosphere when Howarth published his paper, is that, currently, the proportion of chlorofluorocarbons present in the atmosphere in comparison to carbon dioxide is rather minuscule. Hence chlorofluorocarbons are not considered to be significantly contributing to global warming as they were in 1998 (Bréon et al., 2013). This change is due to the effect of the Montreal Protocol of 1987 which was implemented to eliminate all production of chlorofluorocarbon gases by 2010 in order to protect the ozone layer (Ashworth, 2023).

The second term of the mean temperature formula (23), F_t, represents the Radiative Forcing, meaning the amount of radiation that came to Earth and didn't leave the atmosphere(MIT Climate Portal, 2020), measured in *watts/*m^2.

The Radiative Forcing parameter in Howarth's estimations depends exclusively on the number of periods *t* that have passed since the base year 2000:

$$F_t = 1.42 - 0.764(0.523)^t. \qquad (27)$$

Because this equation was formulated specifically on the assumption of having the year 2000 as a base year, the projections will keep the year 2000 as a base year for this formula instead of updating it to 2021.

As the only variable of the function is the period *t* (and not any other economic factor that has changed since the year of publication) the interpretation of the results is not affected.

4.5. Does Howarth's interpretation hold to the present day?

The following section will illustrate the resulting projections for greenhouse gas emission levels per period and Mean Global temperature above the pre-industrial level per period, and compare them to the numerical results estimated by Howarth in his simulations.

It's important to note that the scope of these projections is not one of observing the precise magnitude of each parameter as an accurate estimate for the future, but rather of verifying whether these parameters change in accordance to Howarth's numerical simulations when varying the policymaker's regard for intergenerational equity.

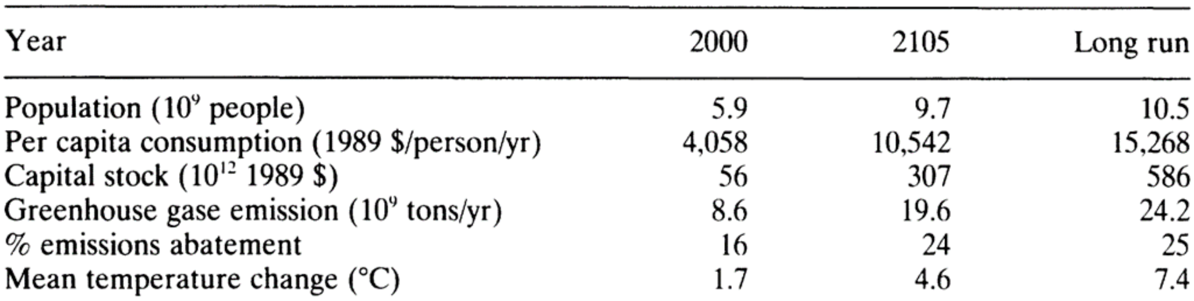
With this objective in mind, the aim of this section will be to compare the impacts of the implementation of the different greenhouse gas emissions abatement rates of the three policy designs presented by Howarth, and to verify whether the interpretations drawn on Howarth's numerical simulations still hold.

4.5.1. The path of Greenhouse Gas emissions

When comparing Howarth's estimations to the current projection of the greenhouse gas emission production path (based on the emission abatement policies resulting from the three different policy paths presented by Howarth) the first noticeable trait is that updating the data of the base year generates numerical results that are higher than the ones obtained by Howarth. This would not be a noteworthy aspect if the analysis of Howarth's article was limited to short time horizons. However, as Howarth's estimations extend to the long run (or to 525 years to be precise), it's important to stress the increase in the magnitude of the numerical results for long time horizons that stem from updating the projections to the base year as 2021.

This can be seen, for instance, when confronting the resulting greenhouse gas emission production paths for the *No transfer Baseline* policy design:

Table 2: Howarth's estimations for the *No transfer baseline* path



Year	2000	2105	Long run
Population (10^9 people)	5.9	9.7	10.5
Per capita consumption (1989 $/person/yr)	4,058	10,542	15,268
Capital stock (10^{12} 1989 $)	56	307	586
Greenhouse gase emission (10^9 tons/yr)	8.6	19.6	24.2
% emissions abatement	16	24	25
Mean temperature change (°C)	1.7	4.6	7.4

source: Howarth, R.B. (1998) "An Overlapping Generations model of climate-economy interactions" Scandinavian Journal of Economics, 100(3), pp. 586

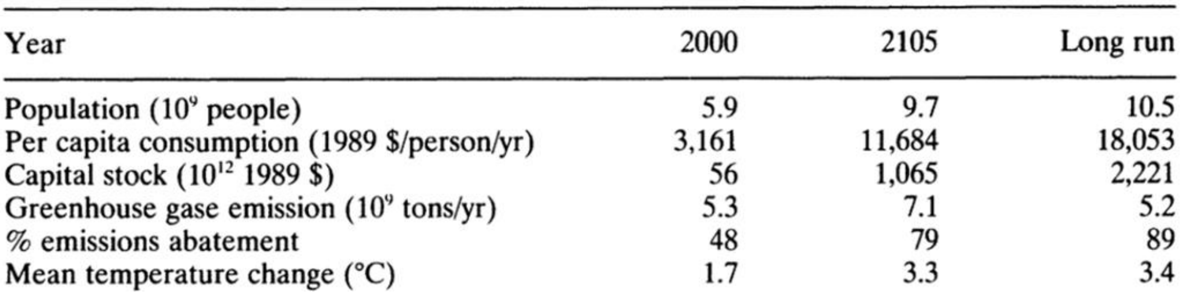
Table 3:*No transfer baseline* path current projections with fixed Gross Global Product growth rate and focus on greenhouse gas emissions

Periods t (35 years)	0.00	3.00	8.00	12.00	15.00
Year	2021.00	2126.00	2301.00	2441.00	2546.00
Population (10^9 people)	7.89	20.28	97.89	344.84	886.70
Young Individuals-fixed growth rate (10^9 people)	4.30	11.06	53.36	187.98	483.37
Young Individuals-declining growth rate (10^9 people)	4.30	11.05	53.25	187.37	481.41
Greenhouse gase emission (10^9 tons/yr)	12.20	147.63	21,999.24	1,358,657.05	30,209,948.55
Mean temperature change (°C)	-9.82	-0.37	10.53	25.67	37.29
%emission abatement	16.00	24.00	24.99	25.00	25.00
Gross world output (trillion of american dollars)	97.08	2,229.88	393,364.60	24,660,775.97	549,433,748.36
Gross world output (trillion of 1989 american dollars)	44.94	902.61	159,226.33	9,982,201.63	222,400,076.33
Potential emissions (10^9 tons/yr)	14.52	194.25	29,327.04	1,811,536.74	40,279,924.77
Radiative forcing	0.90	1.35	1.42	1.42	1.42

Even with the implementation of the same greenhouse gas emission abatement rate of 25% in the long run, updating the projections for current levels of stock of carbon dioxide in the atmosphere and current projected Gross Global Product in *Table 3* produces much higher levels of greenhouse gas emission than Howarth's estimations portrayed in *Table 2*.
Indeed, while Howarth estimates the greenhouse gas emission level to reach 24.2 billion tons/yr in the long run, this paper's projections expect a level of 30,209,948.55 billion tons/yr in period 15 (year 2546).

The same effect can be seen when confronting Howarth's estimations to current projections for greenhouse emission abatement levels of the *Utilitarian Optimum* policy path, namely 48% in the base year, 79% in period *t*=3, and tending to 89% in the long run:

Table 4[1]: Howarth's estimations for the *Utilitarian Optimum* path



Year	2000	2105	Long run
Population (10^9 people)	5.9	9.7	10.5
Per capita consumption (1989 $/person/yr)	3,161	11,684	18,053
Capital stock (10^{12} 1989 $)	56	1,065	2,221
Greenhouse gase emission (10^9 tons/yr)	5.3	7.1	5.2
% emissions abatement	48	79	89
Mean temperature change (°C)	1.7	3.3	3.4

source: Howarth, R.B. (1998) "An overlapping generations model of climate-economy interactions" Scandinavian Journal of Economics, 100(3), pp. 587

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[1] It should be noted that, when illustrating the tables for his numerical simulations, Howarth writes a typographical error in the table presenting the effects of the *Utilitarian Optimum* policy. Indeed, while Howarth's table presents a rate of emission abatement of 289%, he specifies below the table that "The rate of emissions abatement relative to unconstrained levels grows from 48% to 89%" (Howarth, pp587, 1998).This error has been corrected in the presentation of Howarth's tables.

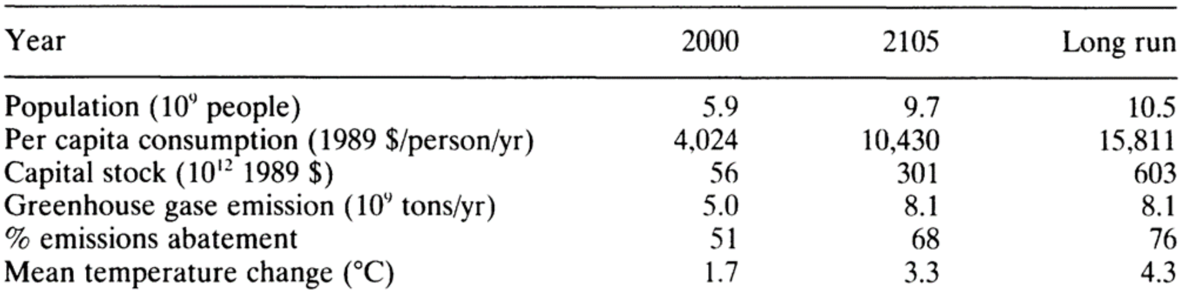
Table 5: *Utilitarian Optimum* path current projections with fixed Gross Global Product growth rate and focus on greenhouse gas emissions

Periods t (35 years)	0.00	3.00	8.00	12.00	15.00
Year	2021.00	2126.00	2301.00	2441.00	2546.00
Population (10^9 people)	7.89	20.28	97.89	344.84	886.70
Young Individuals-fixed growth rate (10^9 people)	4.30	11.06	53.36	187.98	483.37
Young Individuals-declining growth rate (10^9 people)	4.30	11.05	53.25	187.37	481.41
Greenhouse gase emission (10^9 tons/yr)	7.55	40.79	4,061.45	212,872.62	4,430,791.72
Mean temperature change (°C)	-9.82	-0.66	5.55	18.89	30.24
%emission abatement	48.00	79.00	86.15	88.25	89.00
Gross world output (trillion of american dollars)	97.08	2,229.88	393,364.60	24,660,775.97	549,433,748.36
Gross world output (trillion of 1989 american dollars)	44.94	902.61	159,226.33	9,982,201.63	222,400,076.33
Potential emissions (10^9 tons/yr)	14.52	194.25	29,327.04	1,811,536.74	40,279,924.77
Radiative forcing	0.90	1.35	1.42	1.42	1.42

In the *Utilitarian Optimum* scenario, Howarth estimates the greenhouse gas emission level to reach 5.2 billion tons/yr in the long run while the updated projections present a level of 4,430,791.72 billion tons/yr in period 15 (year 2546).

The same observation can be made when confronting Howarth's estimations to current projections for greenhouse emission abatement levels of the *Utilitarian Second Best* policy, namely 51% in period *t*=1, 68% in period *t*=3, and tending to 76% in the long run:

Table 6*:*Howarth's estimations for the *Utilitarian Second* Best path



Year	2000	2105	Long run
Population (10^9 people)	5.9	9.7	10.5
Per capita consumption (1989 $/person/yr)	4,024	10,430	15,811
Capital stock (10^{12} 1989 $)	56	301	603
Greenhouse gase emission (10^9 tons/yr)	5.0	8.1	8.1
% emissions abatement	51	68	76
Mean temperature change (°C)	1.7	3.3	4.3

source: Howarth, R.B. (1998) "An Overlapping Generations model of climate-economy interactions" Scandinavian Journal of Economics, 100(3), pp. 588

Table 7:*Utilitarian Second Best* path current projections with fixed Gross Global Product growth rate and focus on greenhouse gas emissions

Periods t (35 years)	0.00	3.00	8.00	12.00	15.00
Year	2021.00	2126.00	2301.00	2441.00	2546.00
Population (10^9 people)	7.89	21.18	109.92	410.34	886.70
Young Individuals-fixed growth rate (10^9 people)	4.30	11.06	53.36	187.98	483.37
Young Individuals-declining growth rate (10^9 people)	4.30	11.05	53.25	187.37	481.41
Greenhouse gase emission (10^9 tons/yr)	8.15	65.42	7,253.76	436,338.30	9,669,200.05
Mean temperature change (°C)	-9.82	-0.61	6.99	21.44	33.02
%emission abatement	51.00	68.00	75.41	75.93	76.00
Gross world output (trillion of american dollars)	97.08	2,229.88	393,364.60	24,660,775.97	549,433,748.36
Gross world output (trillion of 1989 american dollars)	44.94	902.61	159,226.33	9,982,201.63	222,400,076.33
Potential emissions (10^9 tons/yr)	16.63	204.42	29,494.18	1,813,105.13	40,288,333.55
Radiative forcing	0.90	1.35	1.42	1.42	1.42

In the *Utilitarian Second Best* scenario, Howarth estimates the greenhouse gas emission level to reach 8.1 billion tons/yr in the long run while the updated projections present a level of 9,669,200.05 billion tons/yr in period 15 (year 2546).

These differences are not quite inconceivable when considering the process of intensification of economic activity, particularly in developing countries, of the last twenty-five years.

Another contributor to the higher magnitude of the numerical results is the much higher level of Gross Global Product to be factored in the calculations when updating the base year to 2021. That said, one should not exclude the presence of some economic factors, not present in Howarth's formulation, that might have inflated the results.

For instance, a possible interpretation as to why the production of greenhouse gas emissions is projected to be much higher when updated to current data could be an overestimation in the formulas of the role that Gross World Output (and hence Gross Global Product) plays in the production of potential greenhouse gas emissions (E_{0t}) in the formula (22). As the level of effective greenhouse gas emissions is dependent on the level of potential greenhouse gas emissions in Howarth's formulation, this would certainly have an impact.

This is not to say that greenhouse gas emissions should not be expected to increase with a higher gross world output, but rather to stress the development of production technologies that the production sector has experienced in the last twenty-five years.

For instance, a possible way of perfecting the formulas could be to research in what proportion gross world output (and thus Gross Global Product) actually affects the production of greenhouse gas emissions when factoring in the development of energy production through renewable energies developed in the last quarter of a century. When considering the decline in the cost of renewable energy sources and the increase in their efficiency, the proportion of gross world output affecting the production of greenhouse gas emissions should, perhaps, also be considered declining in long time horizons. This consideration can also made on the basis of the steps that international organizations have taken towards the implementation of renewable energies in the production sector.

That said, the aim of this section is not to provide exact estimations of the predicted emission levels and temperature levels in the far future but rather to employ the numerical results of the updated projections as representative instruments to address the reliability of Howarth's conclusion on the effectiveness and applicability of intergenerational redistributive aims in environmental policy designs.

With this aim in mind, it seems appropriate to determine whether the trends exhibited by Howarth's numerical simulations differ from the ones produced by this paper's projections and, if so, whether the conclusions drawn from Howarth's article are still applicable.

Figure 1 illustrates the trend exhibited by this paper's projections on the levels of greenhouse gas emissions in billions of tons/yr while *Figure 2* illustrates Howarth's estimated trend for Greenhouse gas emission levels.

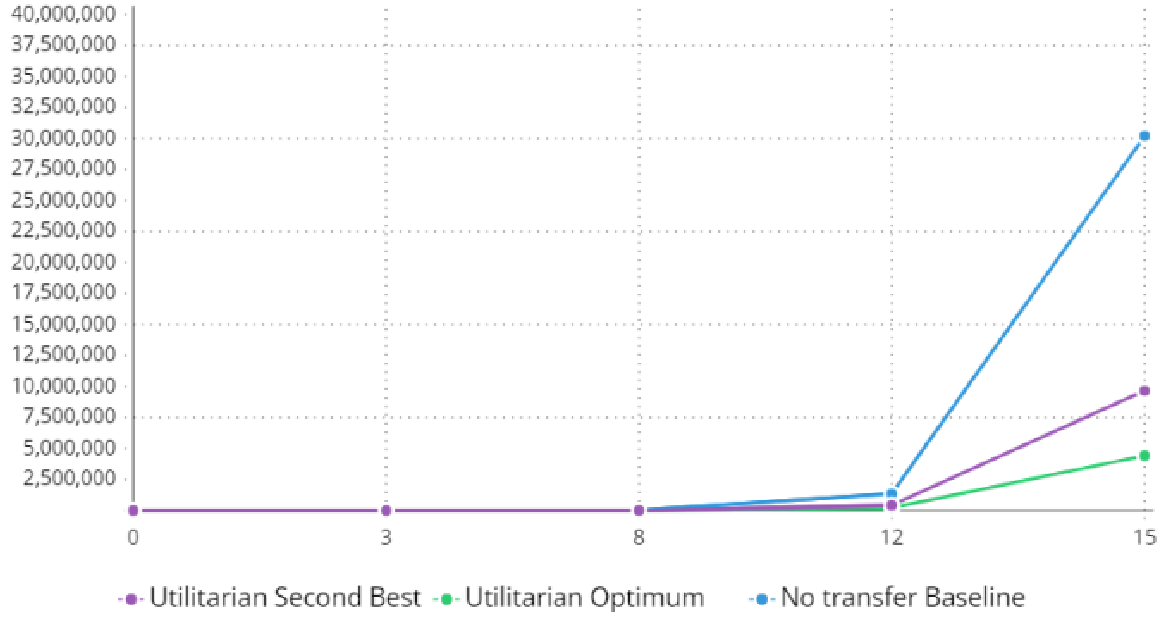


Figure 1: Projected trend for Greenhouse gas emission levels with fixed Gross Global Product growth rate (billions of tons/yr)

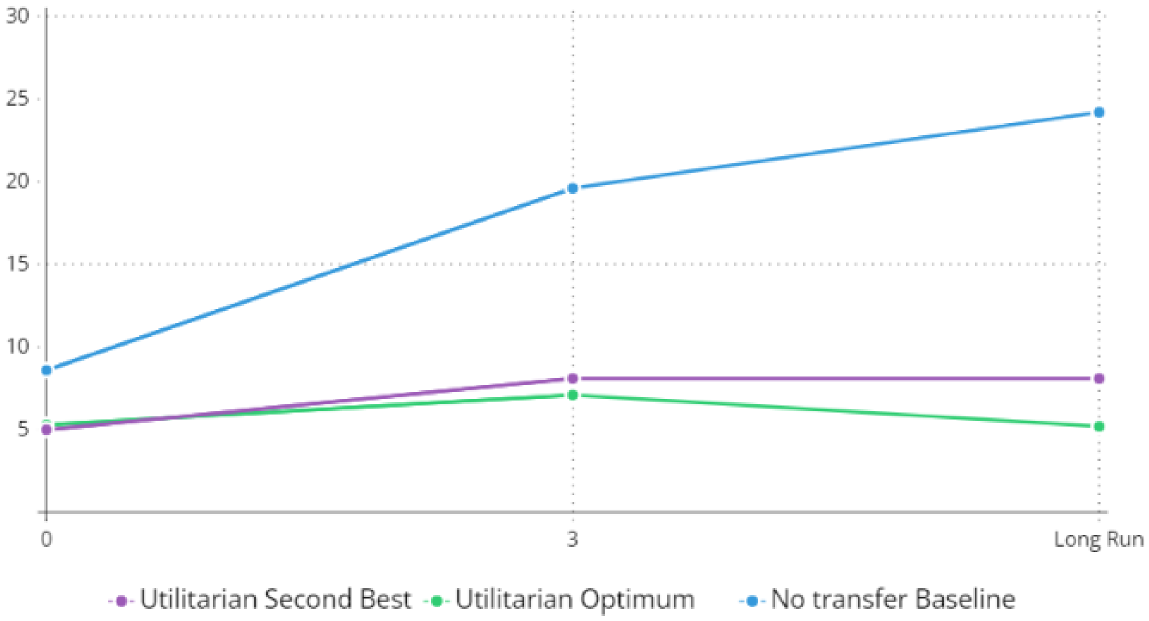


Figure 2: Howarth's estimated trend for Greenhouse gas emission levels (billions of tons/yr)

When confronting *Figure 1* and *Figure 2* the first feature that should be highlighted is the fact that, as expected, both figures exhibit the steepest upwards trend, and the highest resulting levels of greenhouse gas emission, for the *No transfer Baseline* path.

Furthermore, in both figures the difference between the emission levels exhibited by *No Transfer Baseline* path and the *Utilitarian Second Best* path exceeded greatly the difference between the emission levels exhibited by the *Utilitarian Second Best* path and the *Utilitarian Optimum* policy design. While these similarities will be of great importance in assessing the reliability of Howarth's intuitions in the current economic environment, it's important to emphasise the differences that these two figures present and the possible reasons behind them.

Firstly, unlike this paper's projections, Howarth estimates that the greenhouse gas emission production trend will change in period t=3 (which would be the year 2105 in his simulations) for all three policy designs. Indeed, in the *No Transfer Baseline* policy the rate at which the greenhouse gas emission production increases is expected to decline (while an upward trend still persists) in the third period. In the *Utilitarian Optimum* policy the trend is estimated to adopt a downward slope in the third period, and in the *Utilitarian Second Best* policy the trend is estimated to flatten in the third period.

The change in trend exhibited in Howarth's estimations is largely due to the expected increase in the cost of producing greenhouse gas emissions stemming from the emission taxes levied by the government. This applies in particular to the *Utilitarian Optimum* policy design in which Howarth expects emission taxes to increase to the point of inverting the trend of expansion of the production sector. Indeed, as explained in section **3.2.2.**, the intergenerational transfers implemented in the *Utilitarian Optimum* policy in the form of transfers to the young generations produce great levels of capital accumulation which prompts the market rate of interest to decline. As Howarth employs the market rate of interest as the social discount rate, capital accumulation results in a lower social discount rate in his formulation of the Pigouvian tax rule employed in the *Utilitarian Optimum* policy design. The emission taxes resulting from the declining social discount rate and the higher climate change damages (stemming from increased economic activity) are expected, in Howarth's analysis, to make the greenhouse gas emission level of the third period unprofitable in the long run for the *Utilitarian Optimum* framework.

This paper's updated projections, on the other hand, exhibit an increasing trend for the production path of greenhouse gas emissions in all the three policy paths even when applying the exact same greenhouse emission abatement rates for each policy design. In particular, the updated projections expect all of the three upwards trends to become steeper from period t=12 onwards. The differences between the trends exhibited in *Figure 1* and *Figure 2* are the result of the choice of altering the measure of intensification of economic activity, in particular the alteration of how the Y_t term is calculated.

Howarth employs world gross output per period in estimating the level of greenhouse gas emissions per period and, as previously illustrated, expects it to decline from period $t=3$ in the *Utilitarian Optimum* path. This paper, on the other hand, employs the measure of Gross Global Product and estimates its magnitude per period on the basis of the growth rate estimated by the IMF, namely 3.3% from 2023.

These alterations produce two main consequences. Firstly, the choice of the Gross Global Product as the measure of economic activity Y_t produces the estimated level of potential greenhouse gas emissions in the base year 2021 to be somewhat lower than the actual level registered. Indeed, the Gross Global Product is a more accurate measure of economic activity when compared to the Global Gross Output but it also presents a slightly lower number. As the effective level of greenhouse gas emissions estimated for each period is a result of the potential level of greenhouse gas emissions of that period combined with the emission abatement rates of each policy design, the effective level of greenhouse gas emissions in the base year 2021 projected on the basis of Howarth's formulation are also lower than the actual registered level even with the *No Transfer Baseline* emission abatement policy.
Indeed, while the actual level of greenhouse gas emissions produced in 2021 is estimated to be 37.12 billion metric tons of carbon dioxide (Tiseo, 2023), the projected level is 12.20 billion metric tons of carbon dioxide with the *No transfer Baseline* emission abatement levels, 7.55 billion metric tons of carbon dioxide with the *Utilitarian Optimum* emission abatement levels, and 8.15 billion metric tons of carbon dioxide with the *Utilitarian Second Best* emission abatement levels.

Secondly, estimating Gross Global Product per period on the basis of the 3.3% growth rate estimated by the IMF, implies that the value Y_t is always increasing and in a particular substantial matter in long time horizons (in this case from period t=12). This feature differs greatly to Howarth's assumption that the Y_t value should experience a flatter upwards trend or even diminish from period t=3. The different resulting trend in the parameter Y_t can explain, at least partially, the difference in trends between *Figure 1* and *Figure 2*.

Howarth's use of formula (19) also bases the estimations for the parameter Y_t on the premise that, in the global economy, the elasticity of output with respect to labour equals 0.75 implying that labour accounts for three quarters of gross output, and that the elasticity of output with respect to capital equals 0.25 implying that capital accounts for one quarter of gross output. When taking into consideration the technological advancement of the past twenty-five years, and thus possibly the increase in the productivity of capital, formula (19) isn't necessarily a realistic description of the input composition of the current global economy.

For instance, economists Dale Jorgenson and Khuong Vu estimated, in their article *Information and Technology in the World Economy* published in the Scandinavian Journal of Economics in 2005, that since 1995 the contribution of capital input in the global output growth rate has grown (at the time of their publication) to 47% while the contribution of labour input reached 26% (Jorgenson and Vu, 2005). This estimation does not necessarily imply that the proportion of capital input accounting for global gross output exceeds that proportion of labour input accounting for global gross output, but it can imply that capital has had a higher increase in its impact on global gross output in relation to labour. Studies such as the one conducted by Jorgenson and Vu can question the descriptive accuracy of Howarth's formula (19) with regards to the current economy. Hence, the Gross Global Product, employed in the estimations of the parameter Y_t for the updated projections, may reflect a very different composition in the contribution of inputs for the global economy's productivity when compared to Howarth's formulation. This feature could further explain the difference in the trends and in the magnitude of the levels of greenhouse gas emissions.

As stated in section **4.2.**, the assumption of a constant growth rate is a simplification that undercuts the precision of the estimations of the actual Gross Global Product in long time horizons. If it was possible to accurately estimate the Gross Global Product growth rate for each single period, one would expect the Y_t value to fluctuate rather than to follow an upward trend. That said, a perfect estimate of the Global Product growth rate per period would not necessarily deliver lower levels of greenhouse gas emissions based on Howarth's formulation. While unexpected economic downturns, such as the 2008 financial crisis or the 2020 Coronavirus pandemic, might reduce the value of Y_t, unexpected boosts in the economy might also increase the value of Y_t and produce even higher levels of greenhouse gas emissions in projections based on Howarth's formula for the potential emission levels (22). Indeed, even when recognising that a growth rate of 3.3% for Gross Global Product is a rather high rate, it wouldn’t be unreasonable to expect possible boosts in global production especially when considering the rate at which some developing countries, such as India or Vietnam (Cheston, 2022), are expanding their economy and investing in technological progress.

The analysis of the effects of the fixed growth rate imposed on the Gross Global Product can be extended by retrieving the considerations presented in section **4.2.** regarding how the ageing process, experienced by the global population, could affect the growth rate of the Gross Global Product.

Indeed, when considering an expected decline in the labour force and a modification of the individuals’ consumption patterns, formula (20) was presented as a representative estimation of the Gross Global Product per period characterised by a very slightly declining growth rate.

The implementation of formula (20), for the estimation of the Gross Global Product per period (as opposed to estimating the Gross Global Product with a fixed growth rate), produces lower levels of greenhouse gas emissions in long time horizons. This can be observed in *Table 8* for the *No transfer baseline* policy, *Table 9* for the *Utilitarian Optimum* policy, and *Table 10* for the *Utilitarian Second Best* equilibrium.

Table 8: *No transfer baseline* path current projections with declining Gross Global Product growth rate and focus on greenhouse gas emissions

Periods t (35 years)	0.00	3.00	8.00	12.00	15.00
Year	2021.00	2126.00	2301.00	2441.00	2546.00
Population (10^9 people)	7.89	20.28	97.89	344.84	886.70
Young Individuals-fixed growth rate (10^9 people)	4.30	11.06	53.36	187.98	483.37
Young Individuals-declining growth rate (10^9 people)	4.30	11.05	53.25	187.37	481.41
Greenhouse gase emission (10^9 tons/yr)	12.20	147.63	21,999.07	1,358,640.50	30,209,488.36
Mean temperature change (°C)	-9.82	-0.37	10.53	25.67	37.29
%emission abatement	16.00	24.00	24.99	25.00	25.00
Gross world output (trillion of american dollars)	97.08	2,229.87	393,361.42	24,660,475.74	549,425,378.90
Gross world output (trillion of 1989 american dollars)	44.94	902.61	159,225.04	9,982,080.10	222,396,688.53
Potential emissions (10^9 tons/yr)	14.52	194.25	29,326.80	1,811,514.69	40,279,311.19
Radiative forcing	0.90	1.35	1.42	1.42	1.42

In the *No transfer baseline* policy path long-run emission levels fall from 30,209,948.55 billion tons/yr to 30,209,488.36 billion tons/yr when implementing a declining Gross Global Product growth rate.

Table 9: *Utilitarian Optimum* path current projections with declining Gross Global Product growth rate and focus on greenhouse gas emissions

Periods t (35 years)	0.00	3.00	8.00	12.00	15.00
Year	2021.00	2126.00	2301.00	2441.00	2546.00
Population (10^9 people)	7.89	20.28	97.89	344.84	886.70
Young Individuals-fixed growth rate (10^9 people)	4.30	11.06	53.36	187.98	483.37
Young Individuals-declining growth rate (10^9 people)	4.30	11.05	53.25	187.37	481.41
Greenhouse gase emission (10^9 tons/yr)	7.55	40.79	4,061.42	212,870.03	4,430,724.23
Mean temperature change (°C)	-9.82	-0.66	5.55	18.89	30.24
%emission abatement	48.00	79.00	86.15	88.25	89.00
Gross world output (trillion of american dollars)	97.08	2,229.87	393,361.42	24,660,475.74	549,425,378.90
Gross world output (trillion of 1989 american dollars)	44.94	902.61	159,225.04	9,982,080.10	222,396,688.53
Potential emissions (10^9 tons/yr)	14.52	194.25	29,326.80	1,811,514.69	40,279,311.19
Radiative forcing	0.90	1.35	1.42	1.42	1.42

In the *Utilitarian Optimum* policy path long-run emission levels fall from 4,430,791.72 billion tons/yr to 4,430,724.23 billion tons/yr when implementing a declining Gross Global Product growth rate.

Table 10: *Utilitarian Second Best* path current projections with declining Gross Global Product growth rate and focus on greenhouse gas emissions

Periods t (35 years)	0.00	3.00	8.00	12.00	15.00
Year	2021.00	2126.00	2301.00	2441.00	2546.00
Population (10^9 people)	7.89	21.18	109.92	410.34	886.70
Young Individuals-fixed growth rate (10^9 people)	4.30	11.06	53.36	187.98	483.37
Young Individuals-declining growth rate (10^9 people)	4.30	11.05	53.25	187.37	481.41
Greenhouse gase emission (10^9 tons/yr)	8.15	65.42	7,253.70	436,332.99	9,669,052.76
Mean temperature change (°C)	-9.82	-0.61	6.99	21.44	33.02
%emission abatement	51.00	68.00	75.41	75.93	76.00
Gross world output (trillion of american dollars)	97.08	2,229.87	393,361.42	24,660,475.74	549,425,378.90
Gross world output (trillion of 1989 american dollars)	44.94	902.61	159,225.04	9,982,080.10	222,396,688.53
Potential emissions (10^9 tons/yr)	16.63	204.42	29,493.94	1,813,083.06	40,287,719.85
Radiative forcing	0.90	1.35	1.42	1.42	1.42

In the *Utilitarian Optimum* policy path long-run emission levels fall from 9,669,200.05 billion tons/yr to 9,669,052.76 billion tons/yr when implementing a declining Gross Global Product growth rate.

The resulting differences in the magnitude of the greenhouse gas emission levels in the long run can result unnoticeable when observing the trends exhibited by the greenhouse gas emission production in the three policy designs following the implementation of a declining Gross Global Product growth rate (*Figure 3*) in comparison to the ones resulting from a fixed Gross Global Product growth rate (*Figure 1*).

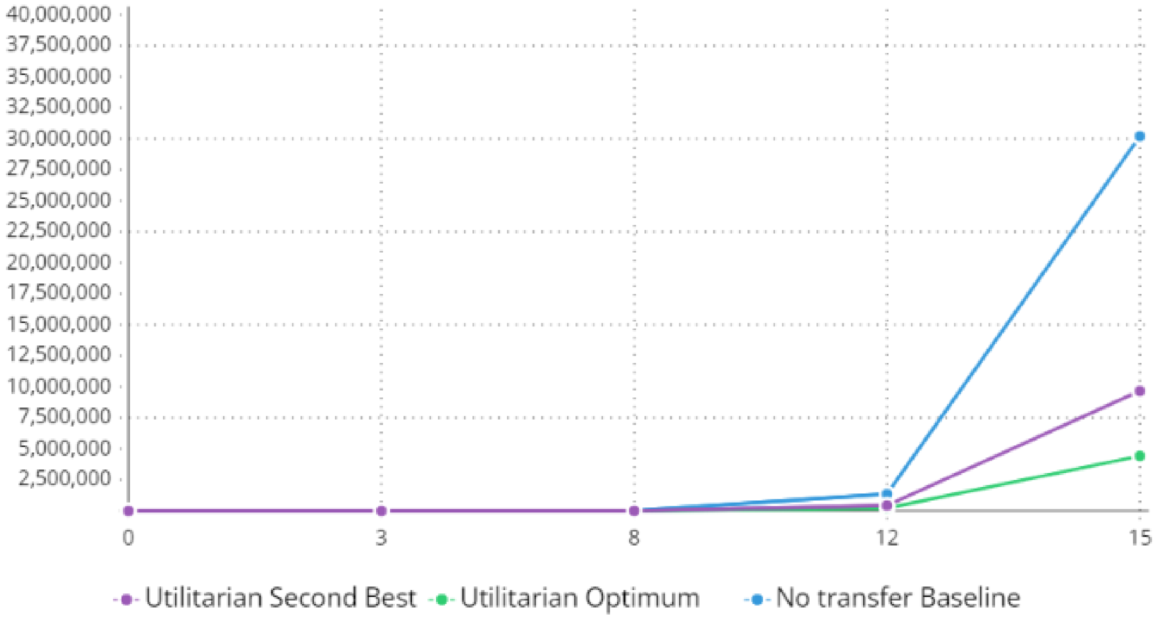


Figure 3: Projected trend for Greenhouse gas emission levels with declining Gross Global Product growth rate (billions of tons/yr)

However, if these differences are considered in absolute terms, the implementation of a very slightly declining Gross Global Product growth rate produce an impressive decrease in the level of long-run greenhouse emissions of 460.19 billion tons/yr in the *No transfer baseline* path, 67.49 billion tons/yr in the *Utilitarian Optimum* path, and 147.29billion tons/yr in the *Utilitarian Second Best equilibrium.*

A similar test could be also implemented with regards to a predictable decline in the proportion of gross world output affecting the production of greenhouse gas emission when considering the technological advancement of renewable energies and, in some countries. This application, however, would be difficult to estimate, even in a very simplified formulation, as it is dependent on truly unpredictable factors such as future agreements implemented by the international community and single governments on the implementation of renewable energies.

Indeed, as previously described in this section, Howarth's formulation for the potential levels of greenhouse gas emissions per period (22), and consequently effective levels of emissions, lacks of a component that describes in what proportion the intensification of economic activity should affect the level of pollution when considering the presence of energy sources in the production sector that do not emit a large level of greenhouse gases. This feature was stressed as a possible cause behind the difference in the magnitude of the long time horizon numerical results of the greenhouse gas emission levels per period projections. This could also be a possible reason behind the difference in the trends exhibited by the greenhouse gas emissions paths in *Figure 1* and in *Figure 2*.

Determining the exact proportion in which intensified economic activity actually affects greenhouse gas emission levels, and even assuming that this proportion is declining in the long run, in formula (22) would slow down the upwards trends illustrated in *Figure 1*.

Another possible alteration that could be made to Howarth's model to draw a more accurate description of the economy, would be to find a different measure than just the market rate of interest for the social discount rate employed in the Pigouvian tax rule for the *Utilitarian Optimum* policy path. Indeed, while the rate at which future benefits and costs should be discounted has definitely an economic nature to it, specifically when addressing the lower marginal utility that society would experience in the future if high economic growth is expected, psychological traits and ethical principles also play a role in decision making processes on investments with long time horizons. As previously presented, the downward trend from period *t=3* experienced by the greenhouse gas emissions production path in Howarth's simulation for the *Utilitarian Optimum* framework is greatly affected by the reduction in the market rate of interest resulted from the increase of capital accumulation that the intergenerational transfers cause.

If the discount factor employed in the Pigouvian tax rule (12) presented by Howarth did not assume that the social discount rate was solely dependent on the market rate of interest, capital accumulation would not play such a relevant role in the process of the social discount rate's decrease (and hence in the decrease of the Gross World Output and in the decrease of greenhouse gas emission levels) in Howarth's *Utilitarian Optimum* numerical simulation. A consideration could be raised on whether it is appropriate to expect the policymaker to reduce the social discount rate based purely on economic factors such as capital accumulation or a possible change in the monetary policy implemented at the time.

Having examined the differences exhibited by Howarth's numerical simulations in comparison to this paper's projections, it remains to address whether the conclusions drawn on the basis of Howarth's results are still applicable.

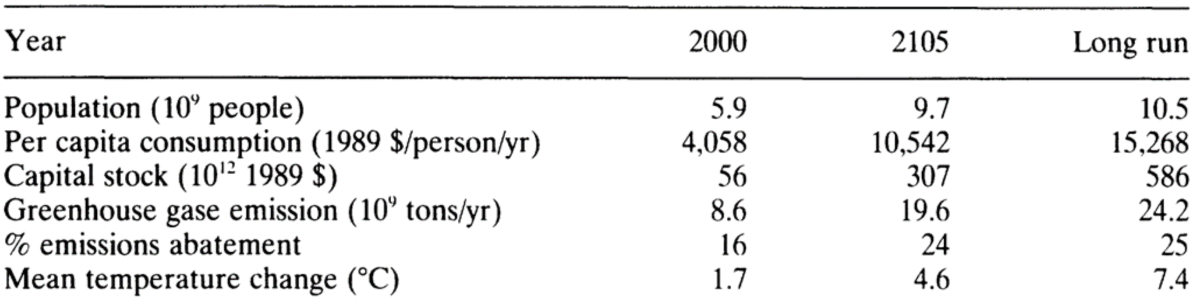
Howarth's analysis demonstrated how, with the institutional impossibility of implementing the *Utilitarian Optimum* path, pursuing intergenerational equity through the second-best compromise still delivered extremely effective results when compared to a *No transfer baseline* policy design. Although not as optimistically, this conclusion can still be drawn when factoring the vastly different economic activity and composition resulting from more than twenty years of technological development and societal change.
Even with the process of updating data to the base year of 2021 and of performing slight alterations to some of Howarth's formulas to more accurately fit the availability of current available data, the implementation of Howarth's model still demonstrates how choosing to pursue intergenerational equity through the *Utilitarian Second Best* approach delivers extremely great improvements over abandoning intergenerational redistributive aims when the *Utilitarian Optimum* path is not institutionally and realistically applicable.

Indeed, when studying Howarth's estimations one can conclude that implementing the *Utilitarian Second Best* policy path over *the No transfer baseline* policy design produces long-run benefits and consequential social welfare gains which greatly exceed the welfare loss experienced by society in compromising to choose this second-best policy over the *Utilitarian Optimum* path. From this interpretation, Howarth draws the conclusion that institutional obstacles or economic efficiency concerns raised against the implementation of policy designs such as the *Utilitarian Optimum* are certainly not valid grounds to reject the aim of intergenerational equity in climate change. The same conclusion can be drawn when observing the trends this paper's projections demonstrate.

4.5.2. The path of the Mean Global temperature above the pre-industrial level

Similarly, to what was presented for the levels of greenhouse gas emissions, the updated projections of the Mean Global temperature above the pre-industrial level per period exhibit higher numerical results in long time horizons when compared to Howarth's estimations.
This difference is, once again, exhibited in all of the three policy designs.
This can be observed when confronting Howarth's estimations for the *No transfers baseline* approach in *Table 11* to this paper's updated projections based on the emission abatement rates of the *No transfer baseline* policy in *Table 12*:

Table 11: Howarth's estimations for the *No transfer baseline* path



Year	2000	2105	Long run
Population (10^9 people)	5.9	9.7	10.5
Per capita consumption (1989 $/person/yr)	4,058	10,542	15,268
Capital stock (10^{12} 1989 $)	56	307	586
Greenhouse gase emission (10^9 tons/yr)	8.6	19.6	24.2
% emissions abatement	16	24	25
Mean temperature change (°C)	1.7	4.6	7.4

source: Howarth, R.B. (1998) "An Overlapping Generations model of climate-economy interactions" Scandinavian Journal of Economics, 100(3), pp. 586

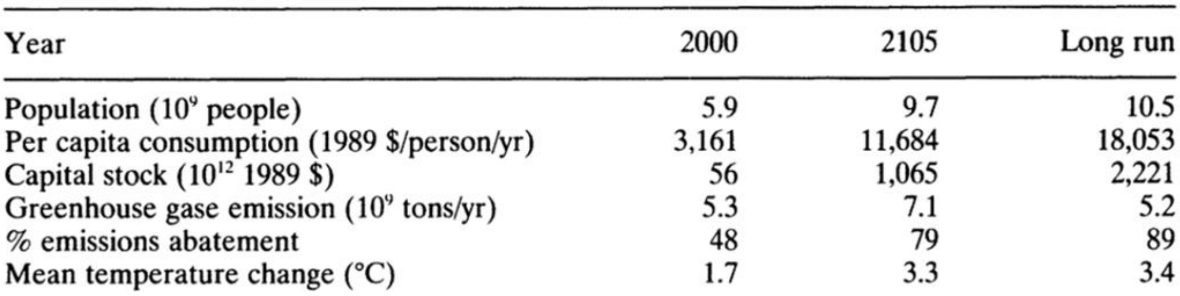
Table 12: *No transfer baseline* path current projections with focus on Mean Global temperature above the pre-industrial level

Periods t (35 years)	0.00	3.00	8.00	12.00	15.00
Year	2021.00	2126.00	2301.00	2441.00	2546.00
Population (10^9 people)	7.89	20.28	97.89	344.84	886.70
Young Individuals-fixed growth rate (10^9 people)	4.30	11.06	53.36	187.98	483.37
Young Individuals-declining growth rate (10^9 people)	4.30	11.05	53.25	187.37	481.41
Greenhouse gase emission (10^9 tons/yr)	12.20	147.63	21,999.24	1,358,657.05	30,209,948.55
Mean temperature change (°C)	-9.82	-0.37	10.53	25.67	37.29
%emission abatement	16.00	24.00	24.99	25.00	25.00
Gross world output (trillion of american dollars)	97.08	2,229.88	393,364.60	24,660,775.97	549,433,748.36
Gross world output (trillion of 1989 american dollars)	44.94	902.61	159,226.33	9,982,201.63	222,400,076.33
Potential emissions (10^9 tons/yr)	14.52	194.25	29,327.04	1,811,536.74	40,279,924.77
Radiative forcing	0.90	1.35	1.42	1.42	1.42

Indeed, even with the application of the same emission abatement rates, while this paper projects the mean global temperature above the pre-industrial level to reach 37.29 Celsius in period *t*=15, Howarth doesn't expect it to exceed 7.4 Celsius in the long run.

This can be also observed when confronting Howarth's estimations (*Table 13*) to the updated projections (*Table 14*) in the *Utilitarian Optimum* policy design:

Table 13: Howarth's estimations for the *Utilitarian Optimum* path



Year	2000	2105	Long run
Population (10^9 people)	5.9	9.7	10.5
Per capita consumption (1989 $/person/yr)	3,161	11,684	18,053
Capital stock (10^{12} 1989 $)	56	1,065	2,221
Greenhouse gase emission (10^9 tons/yr)	5.3	7.1	5.2
% emissions abatement	48	79	89
Mean temperature change (°C)	1.7	3.3	3.4

source: Howarth, R.B. (1998) "An Overlapping Generations model of climate-economy interactions" Scandinavian Journal of Economics, 100(3), pp. 587

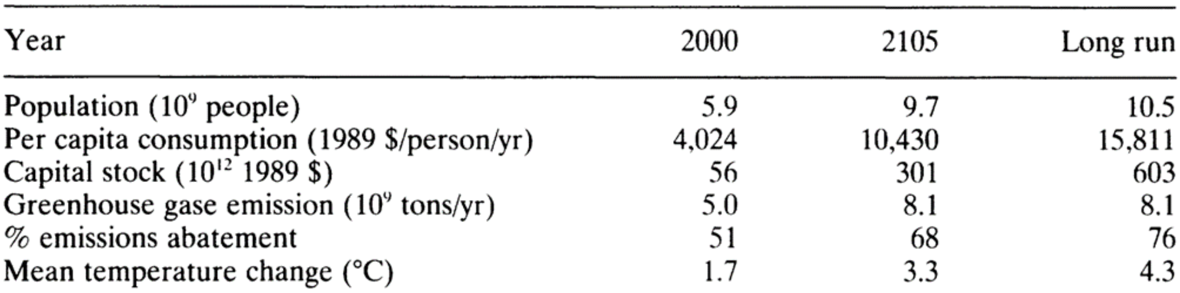
Table 14: *Utilitarian Optimum* path current projections with focus on Mean Global temperature above the pre-industrial level

Periods t (35 years)	0.00	3.00	8.00	12.00	15.00
Year	2021.00	2126.00	2301.00	2441.00	2546.00
Population (10^9 people)	7.89	20.28	97.89	344.84	886.70
Young Individuals-fixed growth rate (10^9 people)	4.30	11.06	53.36	187.98	483.37
Young Individuals-declining growth rate (10^9 people)	4.30	11.05	53.25	187.37	481.41
Greenhouse gase emission (10^9 tons/yr)	7.55	40.79	4,061.45	212,872.62	4,430,791.72
Mean temperature change (°C)	-9.82	-0.66	5.55	18.89	30.24
%emission abatement	48.00	79.00	86.15	88.25	89.00
Gross world output (trillion of american dollars)	97.08	2,229.88	393,364.60	24,660,775.97	549,433,748.36
Gross world output (trillion of 1989 american dollars)	44.94	902.61	159,226.33	9,982,201.63	222,400,076.33
Potential emissions (10^9 tons/yr)	14.52	194.25	29,327.04	1,811,536.74	40,279,924.77
Radiative forcing	0.90	1.35	1.42	1.42	1.42

The updated projections present the mean global temperature above the pre-industrial level to reach 30.24 Celsius in period *t*=15 while Howarth doesn't expect it to exceed 3.4 Celsius in the long run.

Lastly, the same observation can be made when confronting the mean global temperature above the pre-industrial level resulting from the *Utilitarian Second Best* emission abatement rates in Howarth's estimations and in the updated projections (*Table 15* and *Table 16*):

Table 15: Howarth’s estimations for the *Utilitarian Second Best* path



Year	2000	2105	Long run
Population (10^9 people)	5.9	9.7	10.5
Per capita consumption (1989 $/person/yr)	4,024	10,430	15,811
Capital stock (10^{12} 1989 $)	56	301	603
Greenhouse gase emission (10^9 tons/yr)	5.0	8.1	8.1
% emissions abatement	51	68	76
Mean temperature change (°C)	1.7	3.3	4.3

source: Howarth, R.B. (1998) “An Overlapping Generations model of climate-economy interactions” Scandinavian Journal of Economics, 100(3), pp. 588

Table 16: *Utilitarian Second Best* path current projections with focus on Mean Global temperature above the pre-industrial level

Periods t (35 years)	0.00	3.00	8.00	12.00	15.00
Year	2021.00	2126.00	2301.00	2441.00	2546.00
Population (10^9 people)	7.89	21.18	109.92	410.34	886.70
Young Individuals-fixed growth rate (10^9 people)	4.30	11.06	53.36	187.98	483.37
Young Individuals-declining growth rate (10^9 people)	4.30	11.05	53.25	187.37	481.41
Greenhouse gase emission (10^9 tons/yr)	8.15	65.42	7,253.76	436,338.30	9,669,200.05
Mean temperature change (°C)	-9.82	-0.61	6.99	21.44	33.02
%emission abatement	51.00	68.00	75.41	75.93	76.00
Gross world output (trillion of american dollars)	97.08	2,229.88	393,364.60	24,660,775.97	549,433,748.36
Gross world output (trillion of 1989 american dollars)	44.94	902.61	159,226.33	9,982,201.63	222,400,076.33
Potential emissions (10^9 tons/yr)	16.63	204.42	29,494.18	1,813,105.13	40,288,333.55
Radiative forcing	0.90	1.35	1.42	1.42	1.42

The updated projections present the mean global temperature above the pre-industrial level to reach 33.02 Celsius in period t=15 while Howarth doesn’t expect it to exceed 4.3 Celsius in the long run.

Having observed a similar effect when projecting the greenhouse gas emission levels with the current data and the slight alterations performed in the previous sections, these differences are not unexpected. Once again the higher numerical results of the updated projections can be attributed, at least partially, to the role of the Gross World Output (and hence Gross Global Product) plays in the production of potential greenhouse gas emissions (E_{0t}) in the formula (22).

As was previously stated, the level of effective greenhouse gas emissions is dependent on the level of potential greenhouse gas emissions. Hence, higher levels of estimated effective greenhouse gas emissions in period t will produce a higher stock of carbon dioxide in the period *t+1* (as is illustrated in formula(24)). Knowing from formula (23) that the Mean Global temperature above the pre-industrial level per period, T_t, is positively related to the stock of carbon dioxide in the atmosphere, Q_t, at the same period, the considerations made for the magnified numerical results of the levels of greenhouse gas emissions per period hold for the projected levels of the Mean Global temperature above the pre-industrial level as well.

A second feature that shadows the projections of the greenhouse gas emission levels is the Mean Global temperature above the pre-industrial level resulting, from the application of formula (23), in the base year 2021. Indeed, just as in the greenhouse gas emission projections, the estimated numerical result is quite lower than the actual registered level of 2021. While the World Meteorological Organization estimated the Mean Global temperature to be 1.11 (± 0.13) Celsius above the pre-industrial (1850-1900) levels in 2021, applying Howarth's formula for the estimation of the Mean Global temperature above the pre-industrial level, T_t, (23) produces a very low value of -9.82 Celsius. This phenomenon could be explained, as for the level of greenhouse gas emissions, by the employment of the Gross Global Product as the measure of economic activity Y_t rather than the World Gross Output.

An ulterior explanation could also lie in the fact that the radiative Radiative Forcing parameter, F_t, might be actually higher in 2021 than the level resulting from the application of formula (27), as the presence of the time period t as the only variable in the formula doesn't allow for the incorporation of any possible recent economic or climatic changes. However, when compared to the impact of the stock of carbon dioxide, changes in the Radiative Forcing have rather marginal effects on the level of the Mean Global temperature above the pre-industrial level.

Having, thus, observed and examined a similar effect in the projections for the levels of greenhouse gas emission in the base year 2021, the difference between the projected and actual values of the Mean Global temperature above the pre-industrial level can be considered predictable.

Hence, the focus will be turned, once more, to observing the trends that Howarth's projections exhibit in comparison to this paper's projections and whether it can be concluded, as in section **3.3.**, that the interpretations drawn by Howarth on the effectiveness and applicability of intergenerational equity-oriented policies are still valid. This analysis is carried through with the same intention of using the projections' numerical results as purely representative parameters to compare the effects of implementing theoretical policies with different approaches towards intergenerational equity.

Figure 4 presents the trend exhibited by the updated projections on the Mean Global temperature above the pre-industrial level per period based on the emission abatement rates of the three policy paths, while *Figure 5* presents the trends exhibited by the three policy designs in Howarth's estimations.

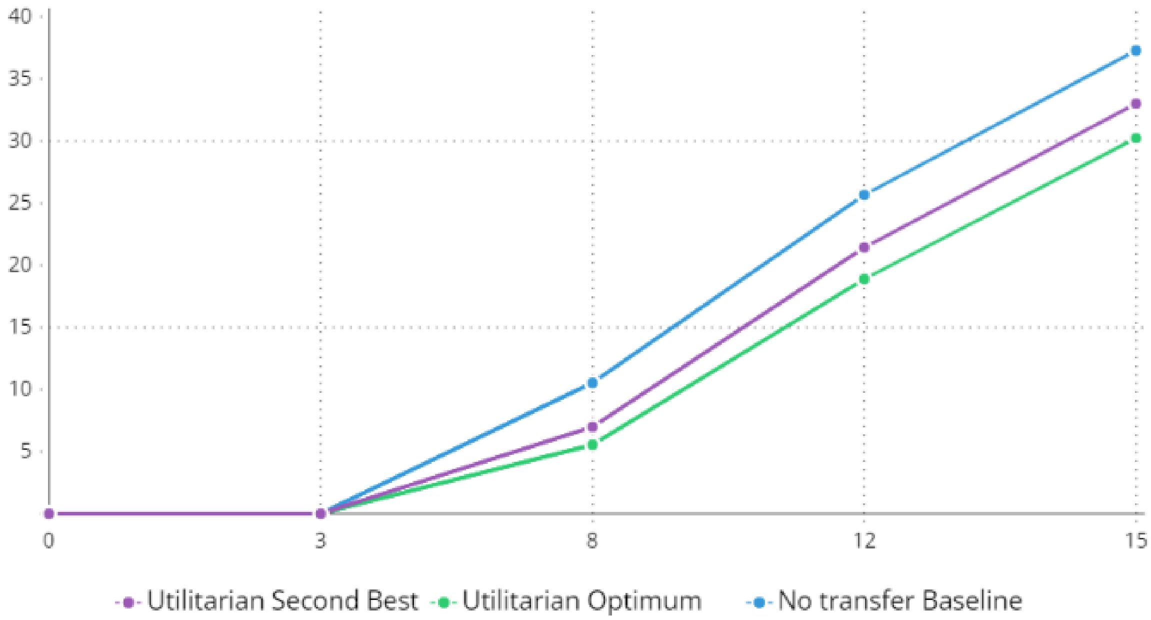


Figure 4: Projected trend for the Mean Global temperature above the pre-industrial level

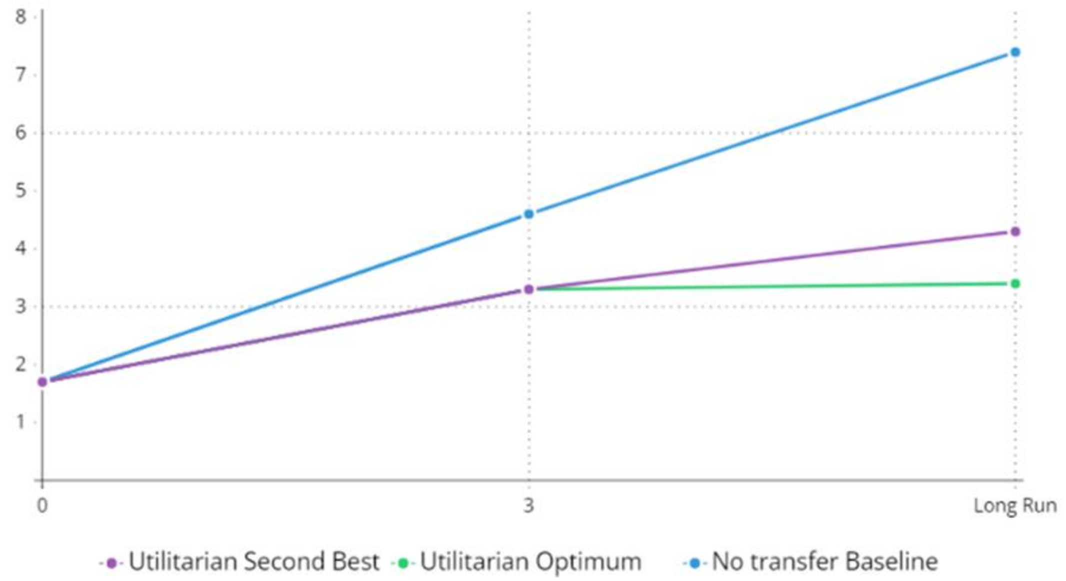


Figure 5: Howarth's estimated trend for the Mean Global temperature above the pre-industrial level

The main noticeable difference in the two figures' trends is, unexpectedly, somehow shadowing the trends exhibited in the greenhouse gas emission paths. Indeed, starting from the third period Howarth's estimations exhibit a flatter upward trend in the level of the Mean Global temperature above the pre-industrial level for all three policy designs. In the *Utilitarian Optimum* path, the increase in the Mean Global temperature above the pre-industrial level from the third period to the long run is so slight that it's barely observable on the graph (from 3.3 Celsius to 3.4 Celsius).

The difference between this shift in the slope of Howarth's trends, compared to the steep increasing trends of this paper's projections, is a consequence, at least in part, of the previously examined effect of assuming a constant growth rate of 3.3% to estimate the Gross Global Product at each period (and hence an always increasing value of Y_t) in contrast to Howarth's assumption that the World Gross Output is to eventually decline, specifically after the third period. This is a consequence of Y_t's indirect effect on the stock of carbon dioxide in the atmosphere in the following period Q_{t+1} and hence on the Mean Global temperature above the pre-industrial level of the following period, T_{t+1}.

In a similar way, part of the difference between the slope of Howarth's trends compared to the steep increasing trends of this paper's projections can be attributed to the previous discourse regarding how the parameter Y_t employed by Howarth results from the assumption that labour accounts for three quarters of gross output while capital accounts for one quarter of gross output. As the updated projections employ, instead, the Gross Global Product as a measure of Y_t, they may be reflecting a very different composition in the contribution of inputs for the global economy's productivity when compared to Howarth's formulation.

In contrast to what was observed for the updated projections regarding the greenhouse gas emission levels per period, on the other hand, the implementation of a slightly decreasing growth rate for the Gross Global Product (as in formula (20)) does not produce significant changes in the projected Mean Global temperature above the pre-industrial level per period.

Furthermore, the discussion of the effect of capital accumulation on the production sector in the *Utilitarian Optimum* scenario, illustrated in section **4.5.1**., is also still relevant in explaining, at least partly, the flatter upward trend that the Utilitarian Optimum path exhibits from period t=3.

Having understood the differences in the two figures' trends, it's important to recognise the key commonalities that the two figures share. The first similarity is of no surprise and lies in the fact that the *No transfer baseline* policy path exhibits the steepest upwards trend among all the policy designs. The second, and most important, commonality can be observed in the fact that the *Utilitarian Second Best* policy design, once more represents a substantial improvement over the *No transfer baseline* results to the point where its projected levels of Mean Global temperature are far closer to the ones resulting from the Utilitarian *Optimum* path than to the *No transfer baseline* levels.

5. Conclusion

Overall, the projections presented in this thesis estimate that the difference between the *Utilitarian Second Best equilibrium* and the *No transfer Baseline* levels of greenhouse gas emission and the Mean Global temperature above the pre-industrial level significantly exceeds the difference between the *Utilitarian Optimum* and the *Utilitarian Second Best* levels.

Hence, one could argue that the welfare gain obtained from choosing a second-best policy design, that still pursues intergenerational equity, over the *No transfer baseline* approach would be much higher than the welfare loss experienced in the compromise of implementing the *Utilitarian Second Best* policy over the *Utilitarian Optimum* policy, when the First Best equilibrium assumptions are not applicable in the real world.
This is the same conclusion that can be drawn from Howarth's numerical simulations.

The first conclusion to be drawn from Howarth's analysis is the absolute necessity of including a high willingness to intergenerationally redistribute and an aversion towards intergenerational inequity in the social planner's decision-making process.

Secondly, once it has been established that the social planner aims at maximising the undiscounted sum of each present and future individual's life cycle utility, Howarth illustrates how, even in the presence of institutional and ideological obstacles to the social planner's objective, intergenerational redistribution aims ought not to be discarded on the principle of economic inefficiency and unrealistic assumptions.

Regardless of the higher magnitudes exhibited by the projected levels of greenhouse gas emissions and by the Mean Global temperatures above the pre-industrial level, these two extrapolations continue to be valid to this day, after twenty-five years of development in the economic and societal framework.

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Appendix

1. The Population growth rate over a 35 years period

   Considering that the annual population growth rate is 0.9% and the population in 2021 to be 7.9 billion, one can estimate the magnitude of the global population in 35 years to be:

   $P_{t=35} = 7.9 \cdot (1 + 0.009)^{35} = 10.809$ billion

   To calculate the growth rate over the 35 years period one can simply find the percentage change between the initial population and the population at the end of the period:

$$R_{35} = \frac{(P_{t=35} - P_{t=0})}{P_{t=35}} \cdot 100 = \frac{10.809 - 7.9}{7.9} \cdot 100 = 36.822\% \approx 37\%$$