The role of *warm-glow* in the prevention of Climate Change

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(Working paper)

Abstract

Climate change is creating high economic costs for the present and future generations, and people are taking actions to tackle the problem. In 2015, the Paris Agreement reflected that awareness and the necessity of making compatible the economic growth and the sustainability of the planet. This escalating public concern supports a link between the two theories of *warm-glow giving* and economic growth with directed technical change. This link provides a way to analyse the response of clean energy innovation to the premium that people are voluntarily paying for more sustainable energy. We present a model that considers: (i) an economy where final consumption is produced using two different energy sources, clean (renewable) and dirty (non-renewable); (ii) individuals receive a *warm-glow* from adopting clean energy consumption; and (iii) dirty energy consumption generates environmental degradation. We concluded that under complementarity between both energy sources, environmental disaster can not be avoided, but *warm-glow* contributes to delay it over time. Under the substitutability case, the design of environmental policies based on the more active role of the public could avoid an environmental disaster and reduce the economic distortion of the exclusive use of carbon tax and innovation subsidies.

1 Introduction

It is a fact that energy is responsible for the performance of virtually every economic activity. Energy is not going to lose its importance in the years to come, as the global society will demand more, not only to encourage growth in developing regions but also to sustain and improve the already developed regions. By 2040, in twenty years, global GDP is set to double and energy demand to increase by about 30% [BP, 2018].

This economic growth has been driven by fossil fuels. When these fuels are burnt they release excessive amounts of carbon dioxide (CO2) and other greenhouse gases (GHGs) which have been affirmed as the cause of climate change. Climate change materialises through extreme temperatures, variation in the precipitation patterns, storm location and frequency, snow-packs, river runoff, water availability, and ice sheets [Nordhaus, 2008]. These environmental problems are creating high economic costs for present and future generations, because they reduce productivity and limit options for economic growth, specifically in regions which are still in early stages of development.

The actions required to tackle the environmental degradation are challenging to the extent that they will achieve benefits in the very distant future but they involves redistribution of current resources and sacrifices in current social welfare. In other words, society must decide how balance the welfare of the present generation and future ones, taking into account the right of future generations to enjoy an environment similar to the one everyone is enjoying now, society's ethical obligation to preserve the planet, and the fact that future generations will be richer and have more resources to deal with the possibility of a worse climate.

Another difficult issue in combating climate change is its inherent characteristic of being a public good. Therefore, traditional economic theory has established that people do not recognise the impact of some of their actions on other people, and governments have to intervene to correct market failures. However, as

[Falkner, 2016] explains, in the last decade, around the world, local community groups have spring up to advance voluntary carbon emissions reductions; multinational corporations have increasingly invested in low-carbon business opportunities and adopted corporate social responsibility approaches with an explicit focus on climate change; institutional investors have begun to demand greater transparency on climate risks in business operations; and subnational authorities (cities and municipal governing bodies) have taken it upon themselves to create climate mitigation pledges and policies.

This awareness of the necessity of making compatible the economic growth and the sustainability of the planet, has been changing domestic policies and stimulating the global coordination interest for finding definitive environmental solutions in each country. In 2015, as a result of those different forces, Paris Agreement emerged as a more decisive accord to abate climate change, and, apart of the critiques about that the initial pledges might not be enough to limit the temperature increase below 1.5°, its potential relies on the idea of making public those pledges, they will be compared and reviewed internationally, then global ambition can be increased through a process of "naming and shaming".

One of the theoretical explanation about why the Paris agreement might work is found in the behavioural forces behind the changes in the public concern about environmental degradation previously stated. According to [Andreoni, 1990] one of these forces might be what he has called "impure altruism", some individuals are donating to privately provide public goods to receive a "warm-glow" for many factors other than altruism. Moreover, individuals knows that their individuals actions are negligible in the solution of the problem, but they are still persisting, because they want to satisfy social and psychological objectives by taking actions considered virtuous [Feddersen and Sandroni, 2009].

The recent literature of the economics of climate change, which has been following the goals established for the different international climate change accords, analyses the impacts of economic activity on the environment. It usually proposes strategies to internalise the real cost of environmental degradation, by levying taxes that discourage the production of carbon energy, and by providing subsidies for sustainable energy innovation. The largest part of this literature has been based on the Integrated Assessment Models (IAMs), a framework that brings together knowledge from economic and physical science to find the optimal policy and how far the current and alternative policies are from it. A second approach, linked with economic growth theory and less detailed climate variables, analyses policy options to promote innovation in less energy intensive technologies and cleaner energy sources.

In this sense, the aim of this paper is to model how public concern about climate degradation may contribute to transitioning towards more sustainable energy with less governmental distortions (taxes and subsidies). In order to do that, an economic growth model with directed technical change and environmental constraint developed by [Acemoglu et al., 2012], will be extended. This extension reflects the "warm-glow" received by the individual when unilaterally decides to consume clean over dirty energy. Hence, this study is the first one to search for an alternative and voluntary channel to correct environmental externalities by giving individuals a more active role in combating climate change and not wait passively for governmental intervention.

This paper is organised as follows: section 2, reviews the literature of the economics of climate change and empirical evidence of the willingness to pay for sustainable energy; section 3, describes the general framework of the model and the decentralised solution; section 4, detailed the implementation of the optimal solution; and section 5 presents the main conclusion.

2 Related literature

The literature of economics of climate change concentrates on estimating: impacts of economic activity on the environment, reduction in social welfare because of climate change, and cost of abatement polices.

[Nordhaus, 1991] was the first attempt to explain and measure the economic impacts of climate change over welfare in an integrated model and to advise about optimal policies. However, the most recognised IAM was developed by [Nordhaus, 1993] and called Dynamic Integrated Climate and Economy Model (DICE). DICE extended the Ramsey Model to include detailed climate constraints and permits estimation of the social cost of carbon, conventionally termed carbon tax.

ENTICE [Popp, 2004] and MIND [Edenhofer et al., 2005] were the first IAMs to consider the endogenous technical change. ENTICE was based on empirical evidence in the US, where changes in the relative prices among energy sources were related to innovation in the energy industry. MIND segregated the energy sector and concluded, first, that endogenous rather than exogenous technological change substantially reduced abatement costs, and, second, that optimal mitigation was required to increase energy efficiency in the short and medium term, and in the long term (after 2050), to decrease fossil fuel consumption by transitioning to renewable.

[Acemoglu et al., 2012] introduced directed technical change and environmental constraints into a growth model, which simplifies mathematically the treatment of the environment. The term “directed” refers to a way to endogenise the direction and bias of new technical change, and, in this model these changes are driven by public policies. This paper concludes that in the long run, with zero intervention, advancement in dirty innovation causes dirty input production and drives the economy to an environmental disaster. However, if an optimal policy (carbon tax (Pigovian tax) and clean R&D subsidy) is implemented, advancement in the clean sector takes place and an environmental disaster will be avoided.

[Acemoglu et al., 2014] extended their previous work to evaluate how global coordination is necessary to avoid an environmental disaster in the economy of two countries, the North and the South, which produce the same final good using clean and dirty inputs. The model assumes that the North practices innovation in both sectors and is more technically advanced, and the South evolves through imitation of the technology in the North. The paper concludes that under free trade, a global central planner must impose differentiated carbon taxes and clean R&D subsidies in both countries to avoid an environmental disaster.

[Hémous, 2016] built on [Acemoglu et al., 2014] in the following two ways; by differentiating between highly polluting and non-polluting tradable sectors, and by including the possibility of innovation in the South. He demonstrates that a more complex policy (carbon tax, clean R&D subsidy and trade tax) must be imposed in the North to prevent an environmental disaster. [Manson and Rémi Morin, 2018] returned to the seminal approach and proposed a neoclassical growth model where utility is a function of three variables: consumption, level of pollution, and capacity of renewable resources to produce energy. This approach introduces the concept of sustainability (societal well-being must never decline) and links it to the need to eliminate the consumption of non-renewable polluting resources.

During the last twenty years interest in defining how much different societies are willing to pay for environmental conservation has increased. For example, [Perfecto et al., 2005] established a theoretical approach for the success of environmental certification that depends on consumers willing to pay premium prices for a product that conserves biodiversity. From an empirical point of view, there are two works that link to my hypothesis, the fist one is [Arnot et al., 2006] which concludes that in the US, ethical attributes may be the primary influence on coffee purchasing behaviour for most consumers of fair trade coffee. The second, [Carlson, 2009] concludes that if fair trade coffee costs more than the non-fair trade coffee, most of this extra cost will be covered by the consumers, and could mean that moral consumers would be a solution to negative externalities and there would be no need for Pigovian taxes.

There is literature which addresses contingent evaluation studies in different countries and regions to find specific evidence about the willingness to pay for sustainable energy. [Murakami et al., 2015] found that awareness of global environmental problems combined with knowledge of what is required to reduce GHGs emissions move people to pay for sustainable electricity in the US and Japan. In addition, [Ivanova, 2013] discovered that consumers in Australia expressed willingness to pay for renewable energy, and [Soon and Ahmad, 2015] meta-analysis showed that most EU consumers are willing to pay for green energy. [Lee et al., 2017] demonstrated that people in South Korea are willing to pay higher prices for their monthly electricity bills, especially when they have young children and an awareness of global environmental problems. Finally, there is evidence of willingness to pay for sustainable energy in developing countries such as China, Crete and Slovenia ([Xie and Zhao, 2018],[Zografakis et al., 2010] and [Zorić and Hrovatin, 2012] correspondingly).

3 The Model

The proposed approach is an extension of growth model with directed technical change and environmental constraint developed by [Acemoglu et al., 2012] in an infinite-horizon discrete time. The main extension is modification in the utility function which reflects the *warm-glow* individuals receive when they choose to improve the environment by consuming the clean energy option.

As was established by [Acemoglu et al., 2012] and [Acemoglu, 2008] the key factors of a growth model with directed technical change are the *market size* and the *price* effects. The market size effect drives innovation towards the sector with higher allocation of labour meanwhile the price effect will do towards the sector which has higher prices. In that sense, if the theory proposes in this study is true, prices will be the channel across which the *warm-glow* will operates to stimulate clean energy innovation with low (or without) governmental intervention. However, whichever the effect dominates their magnitudes depend on two factors: (i) elasticity of substitution between two sectors; and (ii) the relative levels of development of the technologies of the two sectors.

The main implication of the analysis is that, if we assume the world as single economy, the foundations of the Paris Agreement will be reflecting in the warm-glow parameter ϕ to the extent that average individual is giving more value to clean over dirty energy consumption in her utility. This new approach might alter the inevitable result of environmental disaster obtained in [Acemoglu et al., 2012] and [Acemoglu et al., 2014] under decentralised equilibrium and it also shows that governmental intervention via carbon taxes and clean R&D research subsidies to avoid that disaster could be lower or suppressed.

3.1 Household Problem

Let us assume there is a unit mass of homogeneous workers, each of them endowed with one unit of labour, a unit mass of homogeneous scientists, each of them endowed with one unit of research services, and a unit mass of homogeneous potential entrepreneurs. There is also a unit mass of identical households grouping each a worker, a scientist and an entrepreneur.

Preferences of the representative household are represented by

$$u_t = \sum_{t=0}^{\infty} \beta^t \frac{(C_t E_t)^{1-\theta}}{1-\theta} \tag{1}$$

Where C_t is consumption as defined below and E_t is the quality of the environment; $\beta = \frac{1}{1+\rho}$ is the subjective discount factor and $\theta > 1$ is the inverse of the inter-temporal elasticity of substitution.

Finally let us consider that final consumption C_t is a CES utility function representing household preferences on both clean c_{ct} and dirty c_{dt} final consumption according to:

$$C_t = \left((1+\phi)c_{ct}^{\frac{\epsilon-1}{\epsilon}} + c_{dt}^{\frac{\epsilon-1}{\epsilon}}\right)^{\frac{\epsilon}{\epsilon-1}} \tag{2}$$

The elasticity of substitution between clean and dirty consumption is $\epsilon > 0$. *Warm-glow* is modelled here through the parameter ϕ, $\phi \geq 0$. We interpret the case $\phi = 0$ as the situation where people only care about the direct utility of consuming the clean good, ϕ, measuring any addition to utility related to the fact that they are feel a *warm-glow* by helping to reduce pollution.

At any period t, the representative household choses c_{ct} and c_{dt} to maximise consumption (2) subject to the budget constraint:

$$p_{ct}c_{ct} + p_{dt}c_{dt} = w_t + \pi_{ct} + \pi_{dt}$$

The price of both energy sources p_{ct} and p_{ct}, wages w_t, and profits earned by scientists and entrepreneurs, π_{ct} and π_{dt}, are all taken as given. The labor supply is assumed to be infinitely inelastic, as well as the supply of scientists and entrepreneurs. Scientists may direct their effort to the clean or the dirty sectors. Their sectorial choice is studied in Section 3.4. Combining the first order conditions for both c_{ct} and c_{dt} it can be easily shown that:

$$\frac{p_{ct}}{p_{dt}} = (1+\phi)\left(\frac{c_{dt}}{c_{ct}}\right)^{\frac{1}{\epsilon}} \tag{3}$$

Households are willing to pay more for clean goods, the larger the *warm-glow* parameter ϕ is. As it will become clear later, households face no inter-temporal trade-off, then there is no Euler equation associated to the representative household problem.

3.2 Environment

$$E_{t+1} = \text{max}\{ \text{ min } \{\bar{E}, -\xi c_{dt} + (1+\delta)E_t\}, 0\} \tag{4}$$

where $\xi > 0$, measures the environmental degradation caused by producing the dirty consumption good; δ is a natural environmental regeneration rate. When E_t crosses zero, emissions are sufficiently large to cause an environmental disaster with the economy reaching a "point of no return".

Notice that sustainability requires that $c_{dt} < \frac{(1+\delta)\bar{E}}{\xi}$, a necessary but not sufficient condition. Sustainable growth then requires dirty production to be bounded.

3.3 Production

There are two types of producers: Final and intermediate goods producers. A unit mass of identical firms produce the clean consumption good and another unit mass of identical firms produce the dirty consumption good. Both operate under perfect competition and use sector specific intermediate goods as the sole production input. Intermediate producers operate under monopolistic competition and use labour as the sole production factor.

3.3.1 Clean and dirty energy sources

Firms in the clean and dirty sectors use a continuum of intermediate inputs x_{jit}, for j $\in \{c, d\}$ and i $\in$ (0, 1), to produce the clean and dirty consumption goods, respectively. The production function is CES, for j $\in c, d$, is

$$c_{jt} = \left(\int_0^1 (A_{jit}x_{jit})^\alpha \, di \right)^{\frac{1}{\alpha}} \tag{5}$$

With parameter $\alpha \in$ (0, 1); in each sector (clean or dirty) the elasticity of substitution among intermediate good is $\frac{1}{1-\alpha}$.

The representative firm producing good j, $j \in \{c, d\}$, solves the following problem

$$\underset{\{x_{jit}\}}{Max} \quad p_{jt}c_{jt} - \int_0^1 p_{jit}x_{jit} \text{ di}$$

subject to technology (5), taking prices as given, where p_{jit} represents the price of intermediate input *i* in the production of good *j*, $j \in \{c, d\}$. The optimal (inverse) demand function of intermediate input *i* in sector *j* is:

$$\frac{p_{jit}}{p_{jt}} = \left(\frac{c_{jt}}{x_{jit}}\right)^{1-\alpha} A_{jit}^{\alpha} \tag{6}$$

Conditional on prices, clean and dirty firms optimally buy more of better quality intermediate inputs.

3.3.2 Intermediate Inputs

There is a unit mass of monopolistically competitive intermediate firms, each producing a specific differentiated intermediate input *i* , *i* ∈ (0, 1), in each sector *j*, $j \in \{c, d\}$. Intermediate firm *i* requires an entrepreneur to be operative, and produces one unit of output per unit of labour.

Subject to the demand function (6), the firm producing intermediate input *i* for sector *j* solves the following problem

$$\pi_{jit} = \underset{\{p_{jit}, x_{jit}\}}{Max} \quad p_{jit}x_{jit} - x_{jit} \tag{7}$$

Monopolistically competitive profits π_{jit} are appropriated by the entrepreneur. Labour is adopted as numeraire, then wages are normalised to one. As a consequence, firms optimally charge a constant markup $\frac{1}{\alpha}$ to a constant marginal cost:

$$p_{jit} = \frac{1}{\alpha} \tag{8}$$

The same for all intermediate firms and time invariant. After substituting the optimal price rule (8) into the demand function (6), production is shown to be demand driven:

$$x_{jit} = (\alpha p_{jt})^{\frac{1}{1-\alpha}} c_{jt} A_{jit}^{\frac{\alpha}{1-\alpha}} \tag{9}$$

being larger for firms producing higher quality A_{jit}.

After substituting (9) into (7), for $j \in \{c, d\}$, profits become

$$\pi_{jit} = \nu p_{jt}^{\frac{1}{1-\alpha}} c_{jt} A_{jit}^{\frac{\alpha}{1-\alpha}} \quad \text{with} \quad \nu = (1-\alpha)\alpha^{\frac{\alpha}{1-\alpha}}$$

After substituting (9) into (5), for $j \in \{c, d\}$, the price of clean and dirty goods, $j \in \{c, d\}$, becomes:

$$p_{jt} = \frac{1}{\alpha A_{jt}^{\frac{1-\alpha}{\alpha}}} \qquad \text{with} \qquad A_{jt} = \left(\int_0^1 A_{jit}^{\frac{\alpha}{1-\alpha}} di\right) \tag{10}$$

Where A_{jt} represents the average quality in sector *j*, $j \in \{c, d\}$. Notice then that the ratio of prices (clean vs dirty) is equal to the inverse of the ratio of average productivities with exponent $\frac{1-\alpha}{\alpha}$.

$$\frac{p_{ct}}{p_{dt}} = \left(\frac{A_{dt}}{A_{ct}}\right)^{\frac{1-\alpha}{\alpha}} \tag{11}$$

Total profits $\pi_{ct} + \pi_{dt}$ are redistributed to households as the return to entrepreneurial activities, for $j \in \{c, d\}$,

$$\pi_{jt} = \int_0^1 \pi_{jit} di = \nu p_{jt}^{\frac{1}{1-\alpha}} c_{jt} A_{jt} \tag{12}$$

3.3.3 Labour Market Clearing

The labour market clearing condition reads:

$$\int_0^1 x_{cit} di + \int_0^1 x_{dit} di = 1 \tag{13}$$

Since one unit of labour is required to produce one unit of intermediate goods. It reads:

$$\frac{c_{ct}}{A_{ct}^{\frac{1-\alpha}{\alpha}}} + \frac{c_{dt}}{A_{dt}^{\frac{1-\alpha}{\alpha}}} = 1 \tag{14}$$

which results from substituting (10) into (9) and then into (13).

Combining (3) and (11) with (13), clean and dirty consumption become

$$c_{ct} = \frac{(1+g)^{\epsilon}}{\left((1+\phi)^{\epsilon} A_{ct}^{\frac{\alpha-1}{\alpha}} + A_{dt}^{\frac{\alpha-1}{\alpha}} a_t^{\frac{\epsilon(1-\alpha)}{\alpha}}\right)} \quad \text{and} \quad c_{dt} = \frac{a_t^{\frac{\epsilon(1-\alpha)}{\alpha}}}{\left((1+\phi)^{\epsilon} A_{ct}^{\frac{\alpha-1}{\alpha}} + A_{dt}^{\frac{\alpha-1}{\alpha}} a_t^{\frac{\epsilon(1-\alpha)}{\alpha}}\right)} \tag{15}$$

Let us define $a_t = \frac{A_{dt}}{A_{ct}}$ and $r_t = \frac{c_{dt}}{c_{ct}}$, then, the relative clean consumption can be expressed as:

$$r_t = (1+\phi)^{-\epsilon} a_t^{\frac{(1-\alpha)\epsilon}{\alpha}} \tag{16}$$

The larger the *warm-glow* parameter is, the most labor is allocated to the production of the clean good. Moreover, the elasticity of the relative demand of dirty to clean goods with respect to the relative productivity of dirty to clean technologies is equal to the elasticity of substitution of these two technologies as clearly emerges from equation (3).

3.4 Innovation

Innovation drives growth by improving the quality A_{jit}, $j \in \{c, d\}$ and $i \in (0, 1)$, of differentiating intermediate inputs in both sectors (see equation (18)). As in [Acemoglu et al., 2012] and [Acemoglu et al., 2014], at the beginning of period t, scientists decide in which sector they will *direct* their research, with s_{ct} optimally doing research in the clean sector and s_{dt} in the dirty sector; s_{ct} + s_{dt} = 1. Then, scientists are randomly allocated to one of the intermediate inputs in the sector; they do research in this sector and if successful, monopoly rights are assigned to them. They operate this variety as entrepreneurs. Monopoly rights of the remaining intermediate inputs, for both $j \in \{c, d\}$, are randomly assigned to potential entrepreneurs.

Each scientist has a probability $\eta_j \in$ (0, 1), $j \in \{c, d\}$, of being successful on improving the quality of the particular intermediate input she was assigned to. When a scientist is successful, the quality of the intermediate input increases at the rate $\gamma > 0$. Consequently, the quality of intermediate input *i* in sector *j*, $j \in \{c, d\}$, follows the process:

$$A_{jt} = \begin{cases} (1+\gamma)A_{jt-1} & \text{with probability} \quad \eta_j \\ A_{jt-1} & \text{with probability} \quad 1-\eta_j \end{cases} \tag{17}$$

which means that the average qualities follow:

$$A_{jt} = (1 + \gamma\eta_j s_{jt})A_{jt-1} \tag{18}$$

A scientist, in order to decide the sector in which she will direct her research, compares expected returns on both sectors. So, given that π^s_{jt} are profits conditional on being successful and η_j the probability of being successful, then the unconditional expected profits of a scientist are:

$$\eta_j \pi^s_{jt} = \Pi_{jt} = \eta_j \left(\frac{1-\alpha}{\alpha}\right) p_{jt}^{\frac{1}{1-\alpha}} c_{jt} A_{jt} \tag{19}$$

The ratio of expected profits in the clean vs dirty sector reads, after using equations (3) and (11),

$$\frac{\Pi_{ct}}{\Pi_{dt}} = \frac{\eta_c}{\eta_d}\left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1}{1-\alpha}} \frac{c_{ct}}{c_{dt}}\left(\frac{A_{ct}}{A_{dt}}\right) \tag{20}$$

$$\frac{\Pi_{ct}}{\Pi_{dt}} = (1+\phi)^{\epsilon} \underbrace{\frac{\eta_c}{\eta_d}\left(\frac{(1+\gamma\eta_c s_{ct})}{(1+\gamma\eta_d(1-s_{ct}))}\right)^{\frac{(1-\alpha)\epsilon-1}{\alpha}}}_{=\frac{1}{\Gamma(s_{ct})}} \left(\frac{A_{ct-1}}{A_{dt-1}}\right)^{\frac{-\varphi}{\alpha}} \quad \text{where} \quad \varphi = (1-\alpha)(1-\epsilon) \tag{21}$$

Corner solutions: There are two possible corner solutions associated with the allocation of scientists. The economy will assign all scientists to the clean sector if

$$\left(\frac{A_{ct-1}}{A_{dt-1}}\right)^{\frac{-\varphi}{\alpha}} > (1+\phi)^{-\epsilon} \quad \Gamma(s_{ct}=1)$$

and all scientists to the dirty sector if

$$\left(\frac{A_{ct-1}}{A_{dt-1}}\right)^{\frac{-\varphi}{\alpha}} < (1+\phi)^{-\epsilon} \quad \Gamma(s_{ct}=0)$$

Notice that if clean and dirty consumption are gross substitutes and at the initial time any of these two inequalities hold, it will hold forever. In this case, the economy will never reach the interior solution. However, if they are complements and one of these two inequalities hold initially, the economy will likely converge on a finite time to the interior solution. We discuss this issue below when analysing the behaviour of the interior solution.

Interior solution: From equation (19) and using the definition of r_t and a_t, a scientist will be indifferent between performing research in any of the two sectors if and only if

$$r_t = \hat{\eta}\frac{a_t^{\frac{1}{\alpha}}}{a_{t-1}} \tag{22}$$

By combining (11), (16) and (20), the dynamics of innovation can be studied by solving the following difference equation on a_t, for $t \geq 1$ and $a_0 > 0$:

$$a_t = \frac{\left(\hat{\eta}(1+\phi)^{\epsilon}\right)^{\frac{\alpha}{(1-\alpha)\epsilon-1}}}{a_{t-1}^{\frac{\alpha}{(1-\alpha)\epsilon-1}}} \tag{23}$$

For a past relative productivity a_{t-1}, equation (23) shows the equilibrium current productivity that makes scientists indifferent between working for the dirty or clean technologies. The concavity of this relation critically depends on the elasticity of substitution between dirty and clean consumption in people's preferences (3). When dirty and clean consumption goods are substitute, and initially the dirty technology is more efficient that a the stationary equilibrium, technical change is directed more towards the clean technology reducing its relative price, which induce substitution in consumption. The corresponding increase in clean consumption supports then a reallocation of production labor towards the clean sector.

The dynamics of a_t in (23) has a unique stationary interior solution:

$$a^* = \left((1+\phi)^\epsilon \hat{\eta}\right)^{\frac{-\alpha}{\varphi}}$$

The stationary interior solution a^* is stable if dirty and clean goods are complements, but unstable if they are gross substitutes. In the later case, depending on initial conditions the economy converges to one of the corner stationary equilibria. *Warm-glow* will no solve the un-sustainability problem, but by reducing a_t it will make the economy to survive for longer time before reaching the "point of no return".

The interior solution monotonically converges to a^* if clean and dirty consumption are gross complements, i.e., if $\epsilon \in$ (0, 1). Consequently, complementarity makes the equilibrium non sustainable, since in a growing economy both clean and dirty consumption will grow. If the economy was initially in a corner solution, it will converge to the interior solution, then to the interior steady-state.

In the case of substitutability, since $\epsilon > 1$, for any interior initial condition $a_0 < a^*$ the equilibrium monotonically decreases until reaching the corner solution with $s_{ct} = 1$. At this stage A_{dt} becomes constant and a_t converges to $a_t = 0$; equilibrium being sustainable. Unsustainability occurs if initially the relative productivity of the dirty sector is too high, with $a_0 > a^*$. In this case, a_t converges to infinity. *Warm-glow* may solve the problem by increasing a_t and making that the initial conditions enter the sustainable zone -i.e., $a_0 < a^*$.

Since at the balanced growth path (BGP) the quality of both goods increases at the same rate, the allocation of scientists to the clean and dirty sectors must be constant and equal to:

$$s_c^* = \frac{\eta_d}{\eta_d + \eta_c} \quad \text{and} \quad s_d^* = \frac{\eta_c}{\eta_d + \eta_c}$$

Differences in R&D technologies needs to be compensated by a larger use of scientists in the less productive sector. Complementarity in consumption rationalise such a long term equilibrium.

Notice that

$$a_t = \frac{1 + \gamma\eta_d s_d}{1 + \gamma\eta_c s_c} a_{t-1}$$

Which make a_t to be bounded in the interval $\left((1+\gamma\eta_c)^{-1}a_{t-1}, (1+\gamma\eta_d)a_{t-1}\right)$.

4 Central planner allocations

In this section is assumed that a central planner implements a solution, which will call optimal policy, to correct all imperfections found in the market, then they will maximise the household's utility (1) subject to constraints (2), (4), (5), (13), (18) and market clearing for scientists. After obtaining the first-order conditions, we represent the shadow price of total consumption by λ_{1t}, the shadow price of dirty and clean consumption by λ_{2t} and λ_{3t} respectively, and the shadow price of machine *i* in sector *j* by λ_{7t}.

If we divide each shadow price by λ_{1t}, it turns out that the all shadow prices will be defined in terms of total consumption and equal to the definition of prices established in the decentralised equilibrium. To start with, let us call the ratios for dirty and clean consumption such as $\hat{p}_{ct}$ and $\hat{p}_{dt}$, then in the case of clean sector we have:

$$(1+\phi)\left[\frac{C_t}{c_{ct}}\right]^{\frac{1}{\epsilon}} = \frac{\lambda_{2t}}{\lambda_{1t}} = \hat{p}_{ct} \tag{24}$$

However, in the case of dirty energy consumption, when we compare the result found here with the decentralised equilibrium where the marginal utility of the dirty energy consumption is exactly equal to its price, it is not difficult to see that now we have a wedge between these two terms. Following [Acemoglu et al., 2012] and [Acemoglu et al., 2014] this wedge is referred to as the carbon tax (τ_t) that the central planner establishes to internalise the externality that dirty energy consumption is causing to the environment[1]:

$$\left[\frac{C_t}{c_{dt}}\right]^{\frac{1}{\epsilon}} - \frac{\lambda_{6t+1}\xi}{\lambda_{1t}} = \frac{\lambda_{3t}}{\lambda_{1t}} = \hat{p}_{dt} \qquad \Longrightarrow \qquad \frac{1}{\hat{p}_{dt}}\left[\frac{C_t}{c_{dt}}\right]^{\frac{1}{\epsilon}} - \underbrace{\frac{\lambda_{6t+1}\xi}{\lambda_{1t}\hat{p}_{dt}}}_{\tau_t} = 1$$

$$\left[\frac{C_t}{c_{dt}}\right]^{\frac{1}{\epsilon}} = (1+\tau_t)\hat{p}_{dt} \tag{25}$$

Taking the ratio between (24) and (25)

$$\frac{\hat{p}_{ct}}{\hat{p}_{dt}} = (1+\phi)(1+\tau_t)\left[\frac{c_{dt}}{c_{ct}}\right]^{\frac{1}{\epsilon}} \tag{26}$$

It is known that a central planner eliminates any positive profits in the economy, so production of machines will take place under perfect competition. If one unit of labour is required to produce one unit of machine *i* and in this economy wages are the numeraire, then this cost is equal to one. After dividing the shadow prices of machine *i* in sector $j \in$ {c,d} by λ_{1t} again, the isoelastic inverse demand for machine *i* in each sector is:

$$x_{cit} = \hat{p}_{ct}^{\frac{1}{1-\alpha}} c_{ct} A_{cit}^{\frac{\alpha}{1-\alpha}} \tag{27}$$

$$x_{dit} = \hat{p}_{dt}^{\frac{1}{1-\alpha}} c_{dt} A_{dit}^{\frac{\alpha}{1-\alpha}} \tag{28}$$

As before, equations (27) and (28) can be used into equation (13) to find:

$$\frac{\hat{p}_{ct}}{\hat{p}_{dt}} = \left(\frac{A_{dt}}{A_{ct}}\right)^{\frac{1-\alpha}{\alpha}} \quad \text{where} \quad A_{jt} = \left(\int_0^1 A_{jit}^{\frac{\alpha}{1-\alpha}} di\right) \quad j \in \{c, d\} \tag{29}$$

Opposite to the laissez-faire equilibrium, the local central planner is going to allocate more scientists to innovate in clean energy sector, because it recognises the present and future social welfare gains from cleaner consumption and innovation. Then, the shadow price of innovation in each sector can be divide by λ_{1t} and after doing some iterations, they become[2]:

$$\frac{\frac{1-\alpha}{\alpha}\sum_{v=0}^{\infty}\beta^{t+v}C_{t+v}^{-\theta}E_{t+v}^{1-\theta}\left[\hat{p}_{ct+v}^{\frac{1}{1-\alpha}}c_{ct+v}A_{ct+v}\right]}{A_{ct}} = \lambda_{4t} \tag{30}$$

$$\frac{\frac{1-\alpha}{\alpha}\sum_{v=0}^{\infty}\beta^{t+v}C_{t+v}^{-\theta}E_{t+v}^{1-\theta}\left[\hat{p}_{dt+v}^{\frac{1}{1-\alpha}}c_{dt+v}A_{dt+v}\right]}{A_{dt}} = \lambda_{5t} \tag{31}$$

Following the same strategy with the shadow price of scientist allocation in each sector, it also gives:

$$\lambda_{4t}\gamma\eta_c A_{ct-1} = \lambda_{8t} \quad \text{and} \quad \lambda_{5t}\gamma\eta_d A_{dt-1} = \lambda_{8t} \tag{32}$$

[1] λ_{6t} is the shadow price of the quality of the environment

[2] Here λ_{4t} is the shadow price of clean innovation and λ_{5t} is the shadow price of dirty one

After combining (30) and (31) with their corresponding expressions in (32), we can take the ratio between both results to obtain:

$$\frac{\eta_c(1+\gamma\eta_d(1-s_{ct}))}{\eta_d(1+\gamma\eta_c s_{ct})}\underbrace{\frac{\sum_{v=1}^{\infty}\beta^{t+v}C_{t+v}^{-\theta}E_{t+v}^{1-\theta}\left[\hat{p}_{ct+v}^{\frac{1}{1-\alpha}}c_{ct+v}A_{ct+v}\right]}{\sum_{v=1}^{\infty}\beta^{t+v}C_{t+v}^{-\theta}E_{t+v}^{1-\theta}\left[\hat{p}_{dt+v}^{\frac{1}{1-\alpha}}c_{dt+v}A_{dt+v}\right]}}_{Q_t} \tag{33}$$

Where we are using the fact that $s_{dt} = 1 - s_{ct}$.

The central planner corrects the myopia of the monopolists in their innovation decisions by determining the allocations of scientists as a function of the discounted value of the entire flow of additional revenues generated by their innovation in both sectors (knowledge externality in the innovation possibilities frontier). However, the central planner does recognise that innovation in the dirty sector generates environmental degradation, then she must allocate scientists to the sector with the higher social gain from innovation. The social optimum implies that scientists will be allocated to the clean sector whenever (33) will be greater than 1.

When (33) is compared with the relative profits obtained under the decentralised equilibrium (23), now there is an extra term (Q_t). This expression reflects the adjustments that must be done to implement the optimal policy, adjustments that incorporate carbon tax and clean R&D subsidies.

5 Implementation of the optimal policy

As it was established in the decentralised equilibrium, the *warm-glow* is insufficient to avoid an environmental disaster. If the dirty energy technology started with an advantage over clean energy no matter if both inputs are gross complements or substitutes, *warm-glow* could delay the disaster over time but not avoid it.

According to the analysis of optimal policy, if both inputs are sufficiently substitutable, a carbon tax on dirty energy consumption and subsidy to the clean energy R&D will drive all innovation to that sector (clean energy sector) and an environmental disaster will be avoided. Furthermore, the intervention might be temporary, because profits from innovation in clean energy are going to be higher than profits from innovation in the dirty energy sector.

Considering τ_t as the carbon tax on the price of dirty energy, the budget constraint to be faced by households will be:

$$p_{ct}c_{ct} + (1+\tau_t)p_{dt}c_{dt} = w_t + \pi_{ct} + \pi_{dt} \tag{34}$$

Given this new budget constraint, relative price of clean energy consumption is now given by:

$$\frac{p_{ct}}{p_{dt}} = (1+\phi)(1+\tau_t)\left(\frac{c_{dt}}{c_{ct}}\right)^{\frac{1}{\epsilon}} \tag{35}$$

The problems from the production side do not change, which implies that:

$$p_{jt} = \frac{1}{\alpha A_{jt}^{\frac{1-\alpha}{\alpha}}} \quad \text{and} \quad A_{jt} = \left(\int_0^1 A_{jit}^{\frac{\alpha}{1-\alpha}}di\right) \tag{36}$$

However, the definition of clean and dirty consumption have changed:

$$c_{ct} = \left[\frac{(1+\phi)^{\epsilon}(1+\tau_t)^{\epsilon}}{A_{ct}^{\frac{\alpha-1}{\alpha}}(1+\phi)^{\epsilon}(1+\tau_t)^{\epsilon} + a_t^{\frac{(1-\alpha)\epsilon}{\alpha}}A_{dt}^{\frac{\alpha-1}{\alpha}}}\right] \qquad c_{dt} = \left[\frac{a_t^{\frac{(1-\alpha)\epsilon}{\alpha}}}{A_{ct}^{\frac{\alpha-1}{\alpha}}(1+\phi)^{\epsilon}(1+\tau_t)^{\epsilon} + a_t^{\frac{(1-\alpha)\epsilon}{\alpha}}A_{dt}^{\frac{\alpha-1}{\alpha}}}\right] \tag{37}$$

Under this new setup, the unconditional expected profits of a scientist in clean sector changes and becomes:

$$\eta_c \pi_{ct}^s = \Pi_{ct} = (1+q_t)\eta_c \left(\frac{1-\alpha}{\alpha}\right) p_{ct}^{\frac{1}{1-\alpha}} c_{ct} A_{ct} \tag{38}$$

Where $(1+q_t)$ is the subsidy that will be necessary to drive innovation towards clean energy sector. In dirty sector, the unconditional expected profits of a scientist does not change:

The ratio of expected profits in the clean vs dirty sector reads:

$$\frac{\Pi_{ct}}{\Pi_{dt}} = (1+q_t)\frac{\eta_c}{\eta_d}\left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1}{1-\alpha}} \frac{c_{ct}}{c_{dt}}\left(\frac{A_{ct}}{A_{dt}}\right)$$

$$\frac{\Pi_{ct}}{\Pi_{dt}} = (1+q_t)(1+\phi)^{\epsilon}(1+\tau_t)^{\epsilon} \underbrace{\frac{\eta_c}{\eta_d}\left(\frac{(1+\gamma\eta_c s_{ct})}{(1+\gamma\eta_d(1-s_{ct}))}\right)^{\frac{(1-\alpha)\epsilon-1}{\alpha}}}_{=\frac{1}{\Gamma(s_{ct})}} \left(\frac{A_{ct-1}}{A_{dt-1}}\right)^{\frac{-\varphi}{\alpha}} \tag{39}$$

As before, if both inputs are complements, an interior solution will be reached and (39) will be equal to 1. However, no matter if there is substitutability or complementarity between both energy sources, if the economy started with a dirty technology advance over a clean one, optimal innovation always involves $s_{ct} = 1$. The subsidy q_t has to be chosen to make this expression greater than one; in other words, the subsidy has to be:

$$(1+\tau_t)^{-\epsilon}(1+\phi)^{-\epsilon} \quad \Gamma(s_{ct}=0)\left(\frac{A_{dt-1}}{A_{ct-1}}\right)^{\frac{-\varphi}{\alpha}} - 1 \equiv \hat{q}_t \leq q_t \tag{40}$$

The difference is that the optimal point under complementarity, the clean R&D subsidy, must be removed once equation (39) becomes equal to 1 and the economy will be reaching its BGP. Nevertheless, under the substitutability case, the clean R&D subsidy could be removed when clean technology is sufficiently advanced and does not need external support.

6 Numerical simulation

In this part two quantitative exercises of the model discussed are explained. The first exercise aims to show the size of environmental *warm-glow* parameter ϕ required in order to transition towards a more sustainable energy and avoid an environmental disaster in a defined period of time. The second exercise aims to determine the size of governmental intervention required, so the model is simulated assuming that at the beginning the carbon tax and clean R&D subsidy are zero and the model will define the future paths for these two instruments that are going to avoid an environmental disaster.

6.1 Parameter values

In both exercises, each period corresponds to five years, which means that the model is calibrated over 400 years. This horizon is common in models where environmental degradation is studied due to the long time that the environment takes to react to a certain level of accumulated emissions. The utility function used in both exercises is identical to one described in the model section. The share of machines is set $\alpha = 1/3$ and the probability of successful innovation per year is $\eta_j = 0.002 \in$ {c,d}.

As [Acemoglu et al., 2012] and [Acemoglu et al., 2014], the initial levels of technology for both sectors are set to match the implied values of world renewable and fossil energy consumption at a certain year (2018).

Specifically, consumption of dirty energy was fixed as 11.272 millions of tonnes of oil equivalent (Mtoe) and clean energy as 2.004 (Mtoe) [BP, 2018]. As it was mentioned in the description of the model one of its key parameters is the elasticity of substitution between two kinds of energy, ϵ. So, the model was simulated considering three levels of ϵ: (i) assuming that they are gross complements, $\epsilon = 0.8$; (ii) gross substitutes $\epsilon = 5$; and (iii) there is a high level of substitutability between them, $\epsilon = 10$.

With regard to *warm-glow* parameter, ϕ, it was calibrated following the results obtained by [Ma et al., 2015] where they are using a meta-regression analysis to determine the people's willingness to pay for a premium in their electricity bills when energy is coming from renewable sources. The paper worked on 29 different studies carried out in an equal number of countries to determine that the premium on average was 14% over the value of kilowatt/hour paid for the households and has a maximum 160% the current value paid. Therefore, the *warm-glow* parameter was calibrated by using the three premiums over the average price of kilowatt/hour paid in the USA in 2019 of 10.9 kilowatt/hour[3]:14%, 70% and 160%, as three different scenarios for this parameter.

The parameters related to the environmental degradation are set following [Acemoglu et al., 2012] who defined a general function $\Phi(\Delta)$ as the costs from the degradation of environmental quality where Δ denotes the temperature increase relative to the pre-industrial level ($\Phi(\Delta) < 0$). In order to specify $\Phi(\Delta)$ as:

$$\Phi(\Delta) = \frac{(\Delta_{disaster} - \Delta(S))^{\lambda} - \lambda \Delta_{disaster}^{\lambda-1}(\Delta_{disaster} - \Delta(S))}{(1-\lambda)\Delta_{disaster}^{\lambda}} \tag{41}$$

Where $\lambda = 0.1443$ to match this function with Nordhaus's damage function over the range of temperature increases up to 3°,C. It is set $S = C_{CO2,disaster} - max(C_{CO2}, 278)$ and the following relationship between temperature increase and CO2-concentration (S) in the atmosphere measured in parts per million (ppm):

$$\Delta = 3 * log_2(S/278) \tag{42}$$

Where 278 ppm is the pre-industrial level of CO2-concentration and $C_{CO2-disaster}$ denotes the concentration level associated with the disaster temperature increase, which [Acemoglu et al., 2012] sets to disaster = 6°C. The constant regeneration rate of atmosphere, δ, is assumed equal to 0.005 per year and the rate at which dirty production reduces the quality of the environment regeneration rate, ξ, equals to 0.0015.

Regarding the values of discount rate, this study does not take part in the discussion about what is the fairness value to be assumed (Nordhaus's research, Sterm's research, etc) and the results are evaluated using two different cases used in [Acemoglu et al., 2012]: $\rho = 0,001$ and $\rho = 0.015$.

7 Results

7.1 Decentralised equilibrium

Figure 1 shows the increase in the temperature that will be reached with different levels of *warm-glow* and substitutability. As it can be concluded from the three graphs, there is a way in which a decentralised economy can detour its progression towards an environmental disaster for a significant time only when *warm-glow* is over 0.14 and $\epsilon = 5$, which means people must be enough aware of the damage that their consumption habits may have when they are not linked to the sustainability of the planet and both inputs must be gross substitutes.

Figure 2 illustrates the allocation of scientists in clean energy research. As before, when the model has gross substitutability between both sources and high values of *warm-glow* parameter, most of the scientists will be allocated to the clean energy sector during the first periods. When they are complements, all scientists are allocated to the clean sector until clean technology catches up with the dirty one.

[3]in 2006 us dollars to match with the same units used in the study

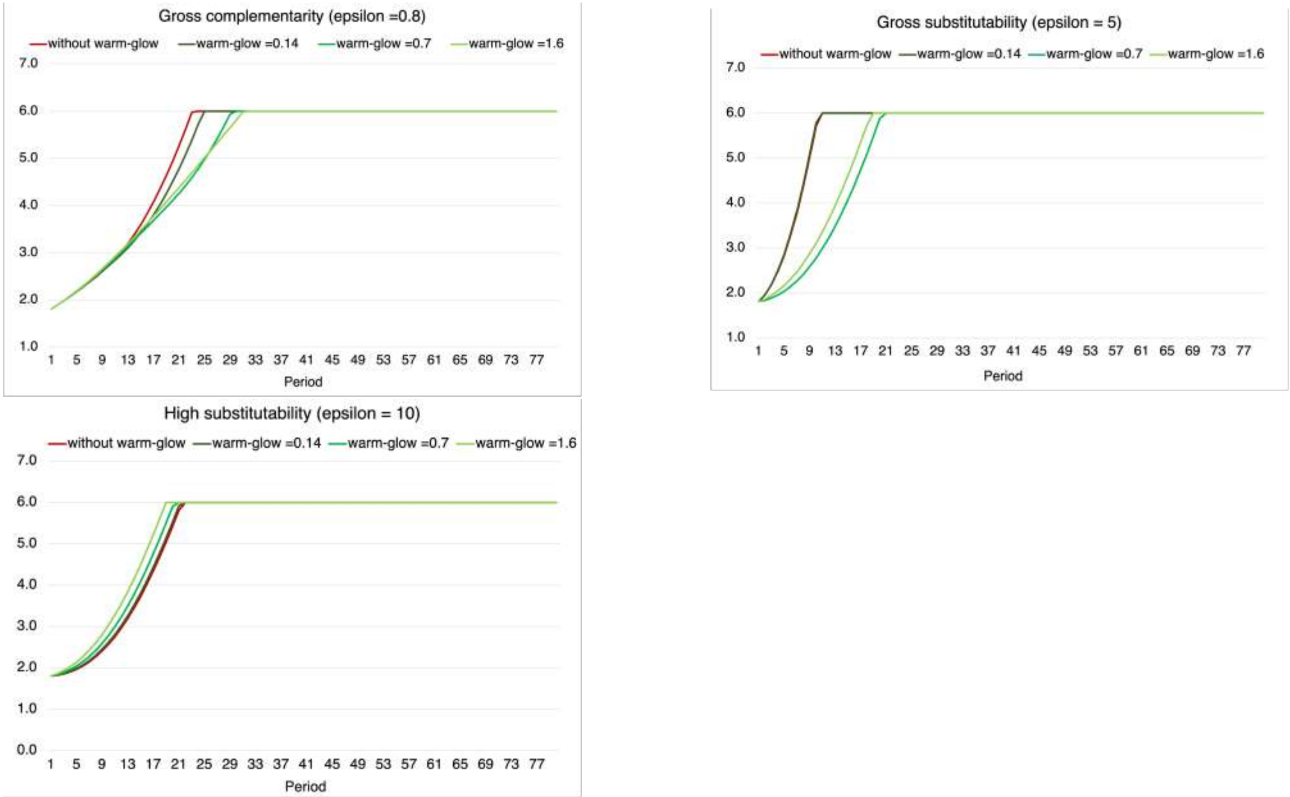


Figure 1: Decentralised equilibrium: Temperature increase

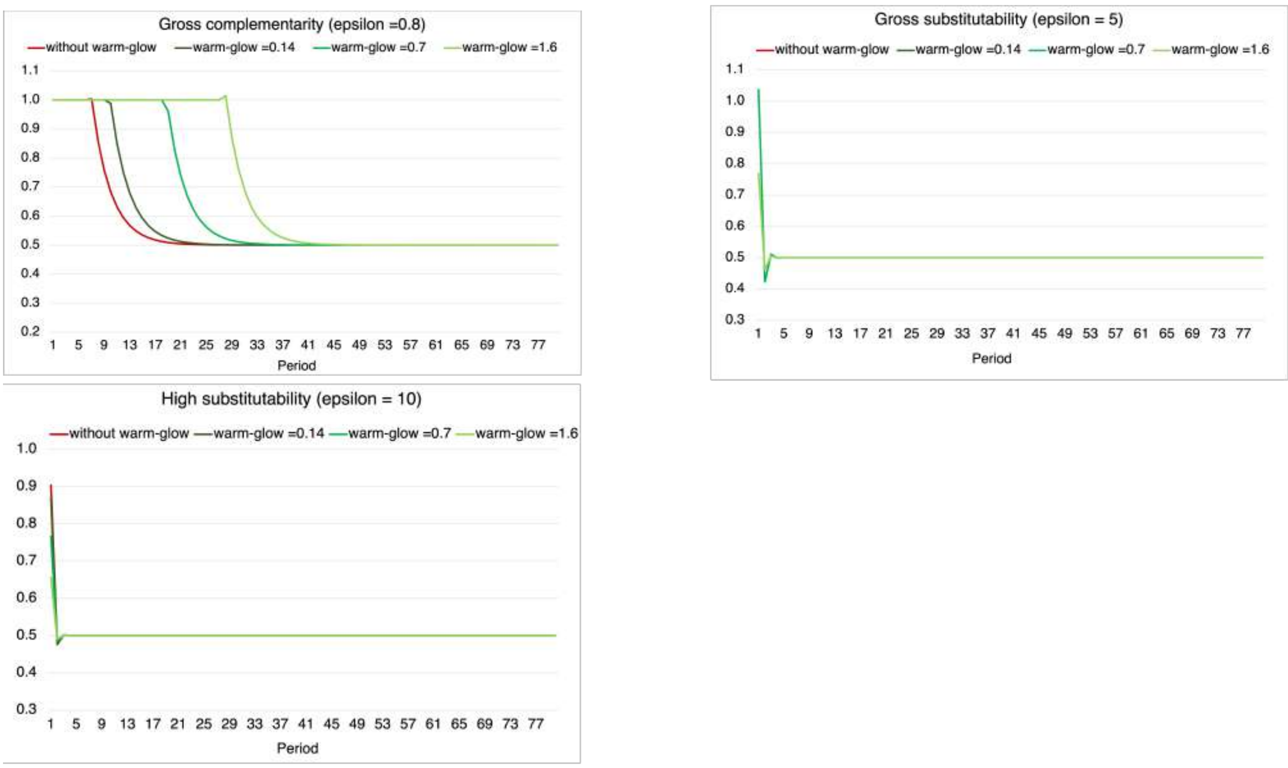


Figure 2: Decentralised equilibrium: Scientists allocation in clean sector

Figures 3, 4 and 5 show the evolution of clean and dirty technologies. When the level of substitutability is in the lowest limit, the higher the *warm-glow*, the greater the growth rate of clean technology is. However, under both scenarios of substitutability, clean technology eventually catches up with the dirty one, but it takes more time to do it. Evidently, in these two cases, *warm-glow* is playing an important role.

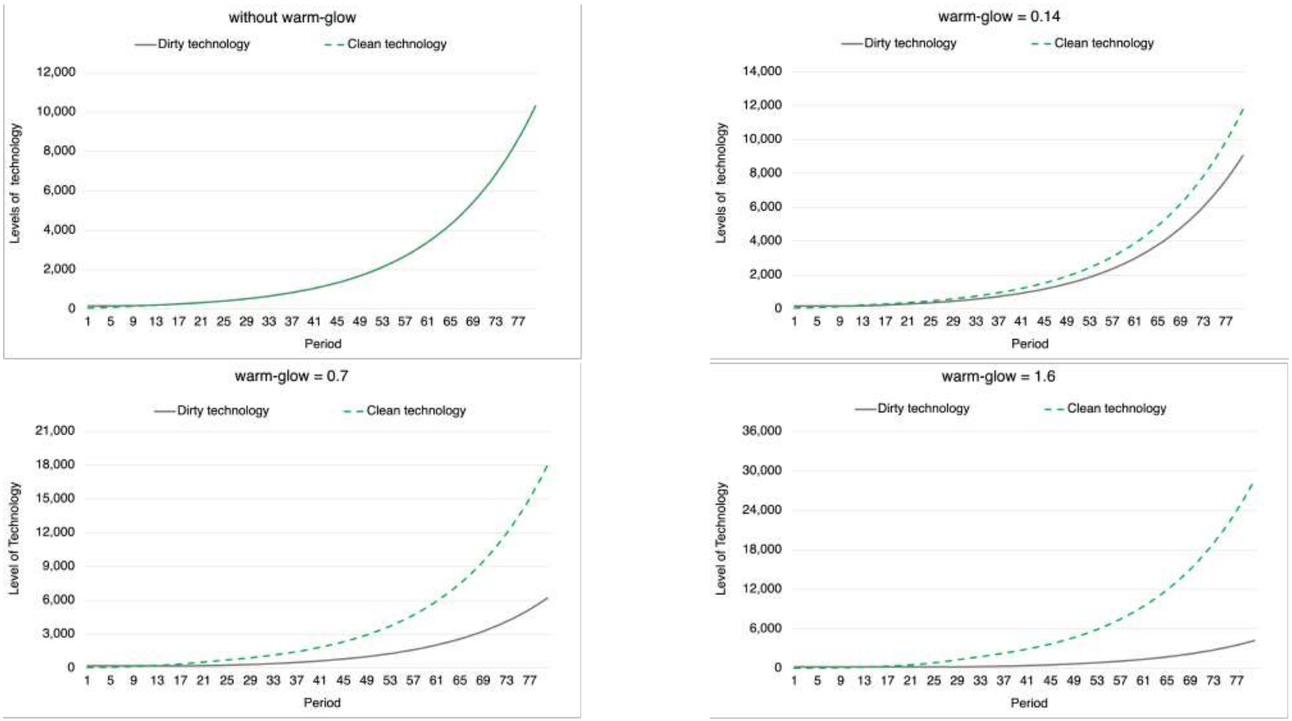


Figure 3: Decentralised equilibrium: Gross complementarity (epsilon = 0.8)

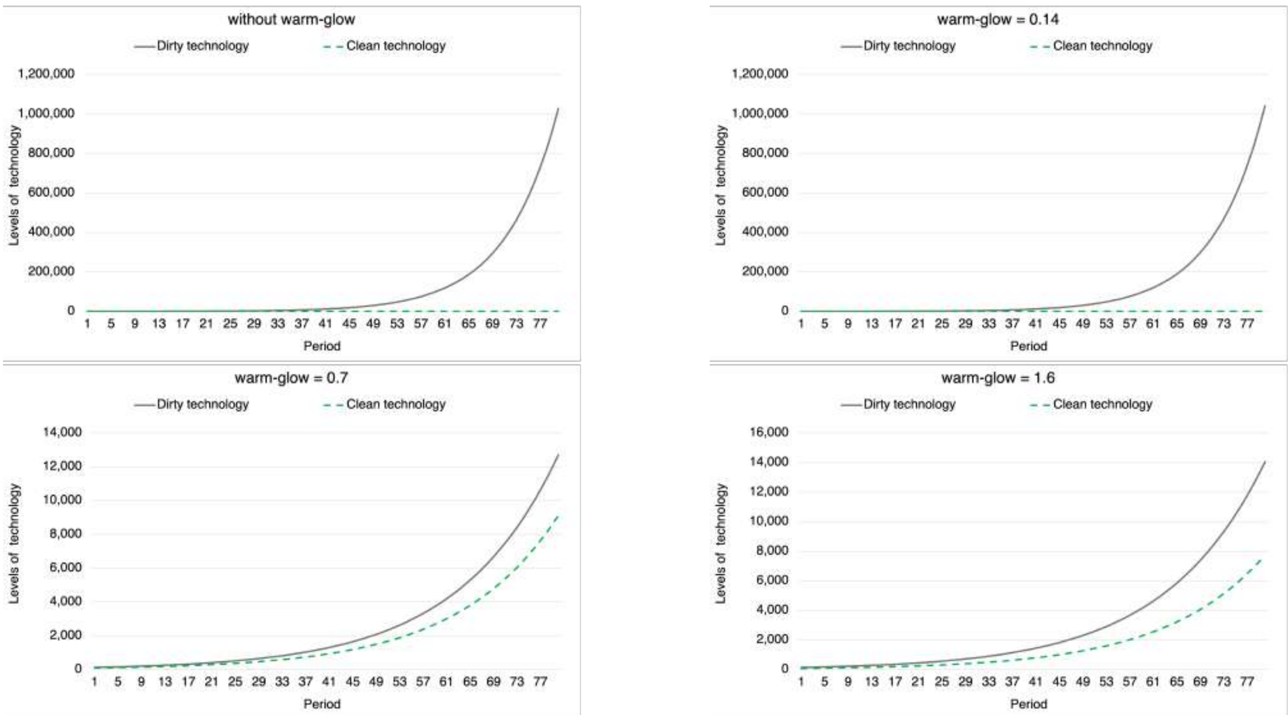


Figure 4: Decentralised equilibrium: Gross substitutability (epsilon = 5)

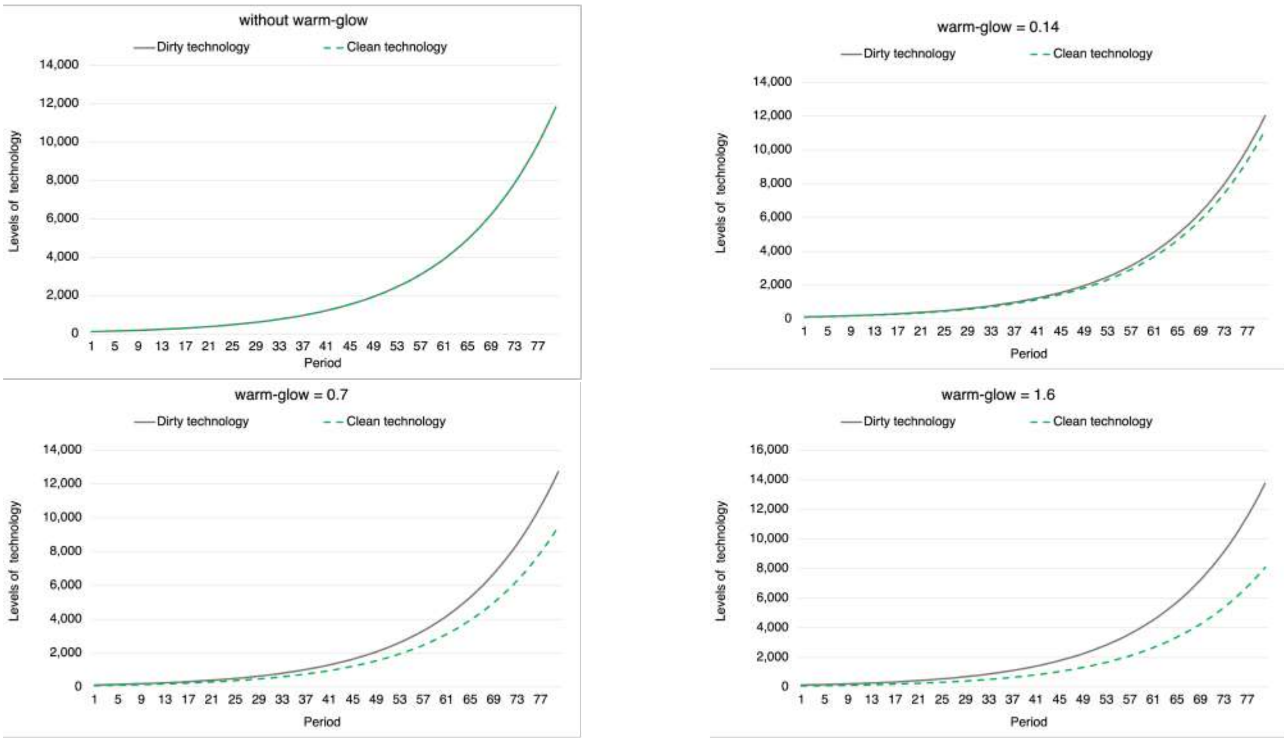


Figure 5: Decentralised equilibrium: High substitutability (epsilon = 10)

Finally, if it is assumed that $\epsilon < 1$, which means that both energy sources are complements, as it was explained above, the model will have an interior solution where scientists will be allocated to both sectors and the model reaches a steady-state. If this is the case, the environmental *warm glow* parameter will not avoid an environmental disaster in a coherent time horizon, but as it can be observed in figure 6, what the environmental *warm glow* will actually do is to reduce the steady-state ratio between two sectors, a^*, and postpone the environmental disaster.

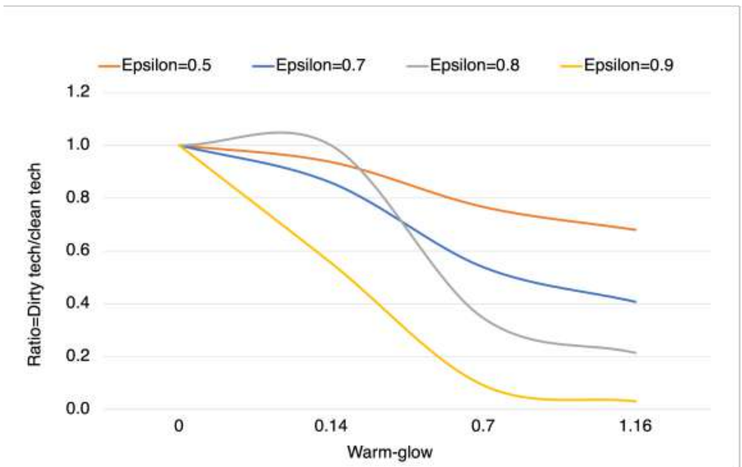


Figure 6: Decentralised equilibrium: Relative dirty technology in the BGP

All results are robust at different levels of discount rate.

7.2 Optimal policy

Regarding the optimal policy simulation, figure 7 illustrates the increase in the temperature under optimal policy. As it was expected under all levels of substitutability, an environmental disaster is avoided, but under complementarity, by definition, it is not possible to avoid the disaster, the economy always consumes both energy sources.

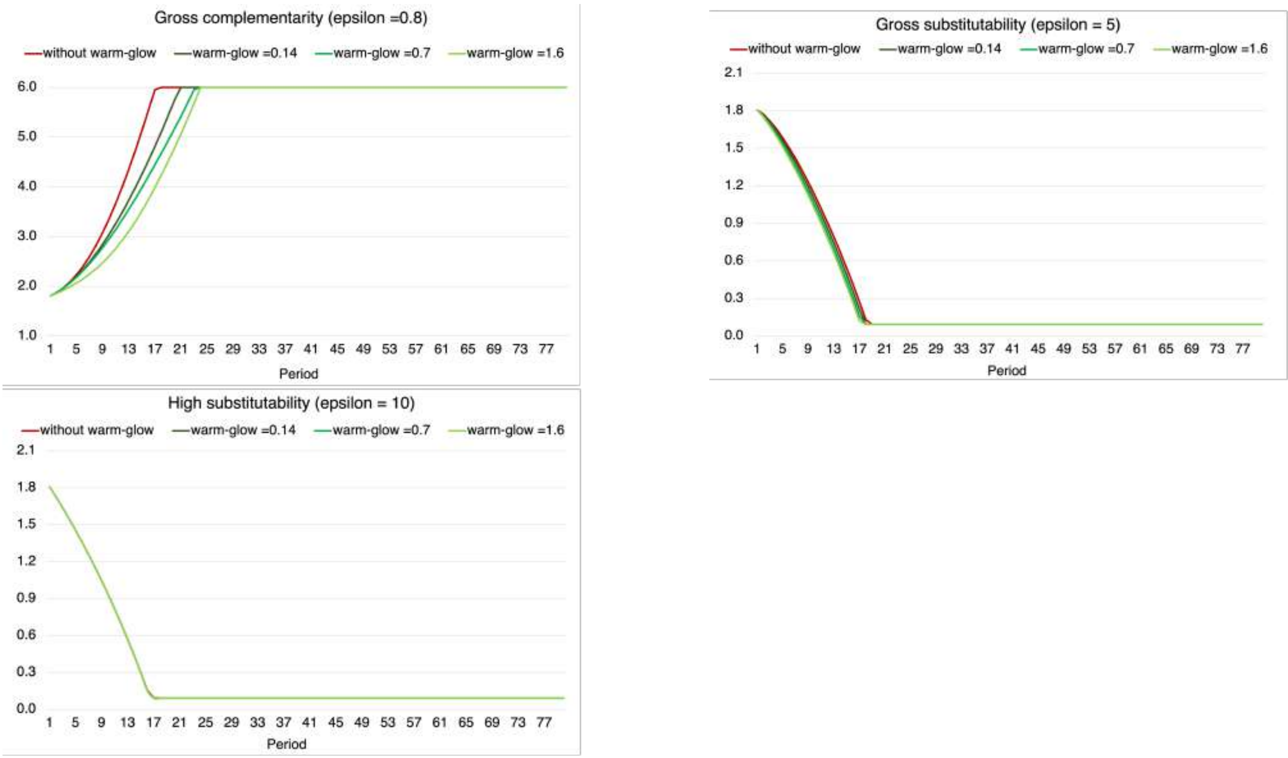


Figure 7: Optimal policy: Temperature increase vs pre-industrial era

Figure 8 shows the allocation of scientists to the clean sector. When energy sources are complements, the growth in the *warm-glow* parameter increases the proportion of scientists directed to the clean sector during the first 30 periods, after which the allocation of scientists in the clean sector remains higher for both extreme values of the *warm-glow* parameter. In the substitutability scenarios, different dynamics are observed in both scenarios: when $epsilon = 5$ the higher levels of the "warm-glow" parameter allocates more scientists into the clean energy sector, while the opposite relationship occurs when $epsilon = 10$. As we observed in the decentralised equilibrium, any level of the *warm-glow* greater than 0.7 reverses its positive effect in the allocation of scientists in that clean sector.

Figures 9, 10 and 11 show the evolution of the clean and dirty technologies under different levels of *warm-glow* and the elasticity of substitution between both inputs, $epsilon$. As it is expected, clean energy grows more quickly than the dirty one under the complementarity case. The economy must reach its BGP, and to do that, it needs to close the gap between both sectors. In the substitutability scenarios, it takes much more time for clean technology to catch up with the dirty technology, but eventually, it achieves this before period 80. It is also noteworthy to say that the level of technology reached is higher than the complementarity scenario under these scenarios.

Regarding the policy instruments, the left panel in figure 12 shows the level of the carbon tax required under each value of the elasticity of substitution (ϵ) and *warm-glow* parameter. Similar to the findings highlighted in [Acemoglu et al., 2012], the carbon tax does not go to zero during the period analysed. Considering the gross complementary and gross substitutability cases, the carbon tax was getting lower

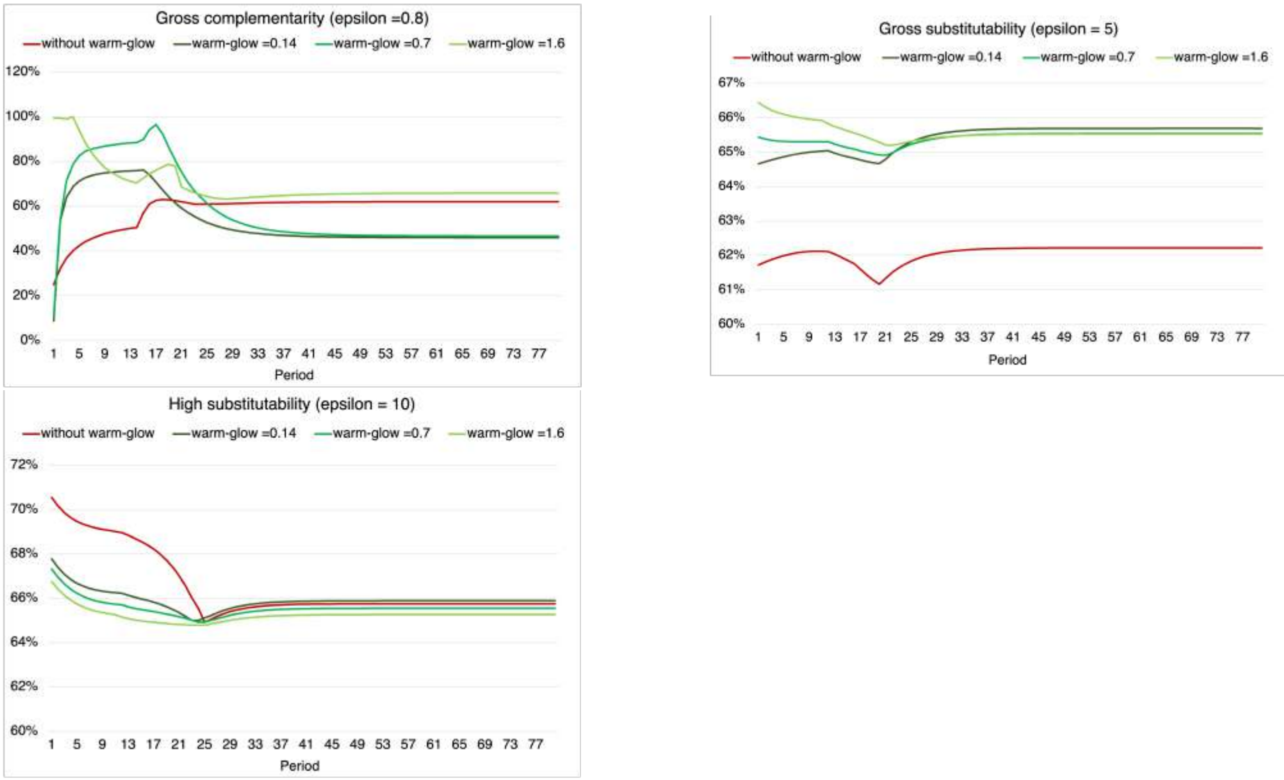


Figure 8: Optimal policy: Scientist allocation in clean sector

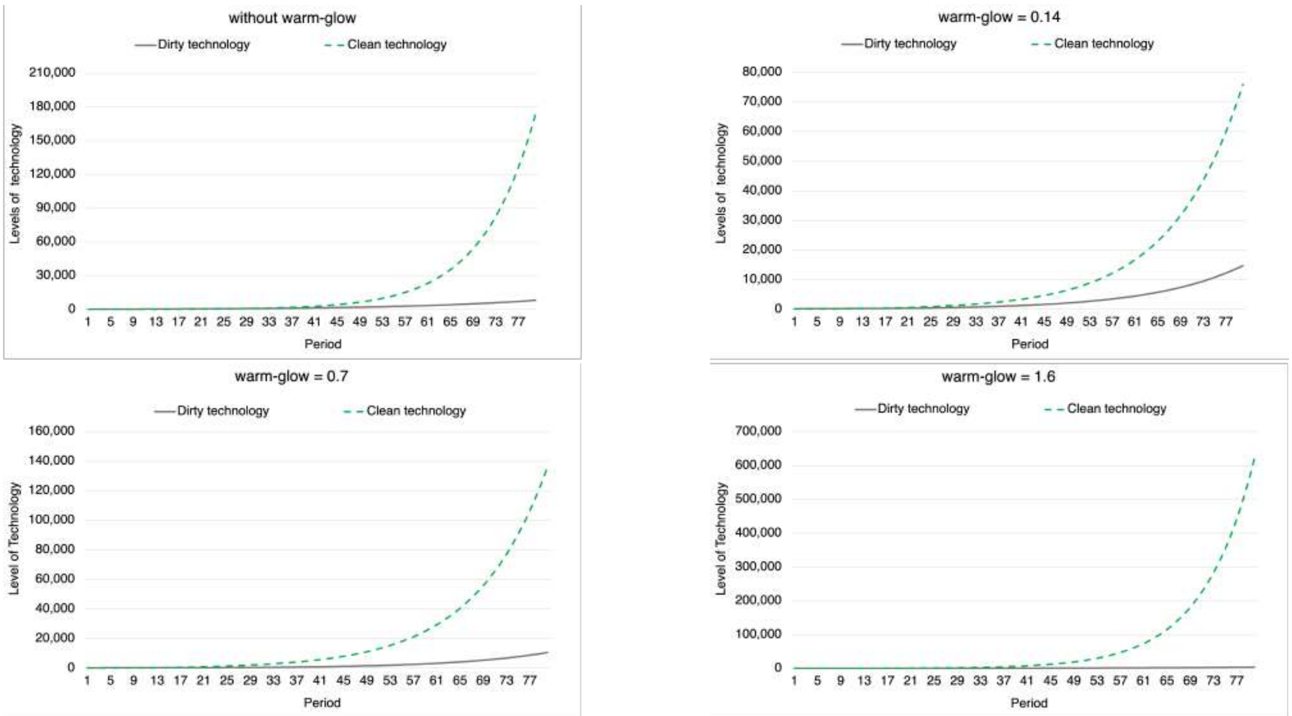


Figure 9: Optimal policy: Gross complementarity (epsilon = 0.8)

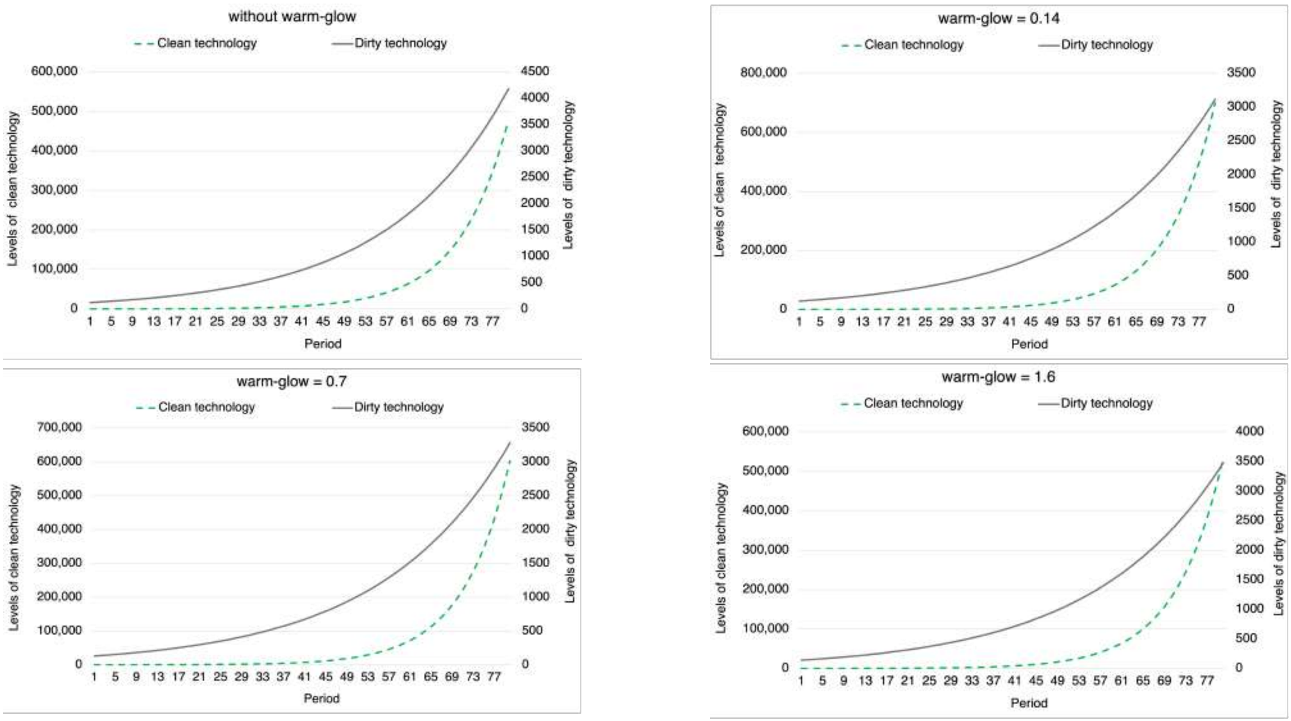


Figure 10: Optimal policy: Gross substitutability (epsilon = 5)

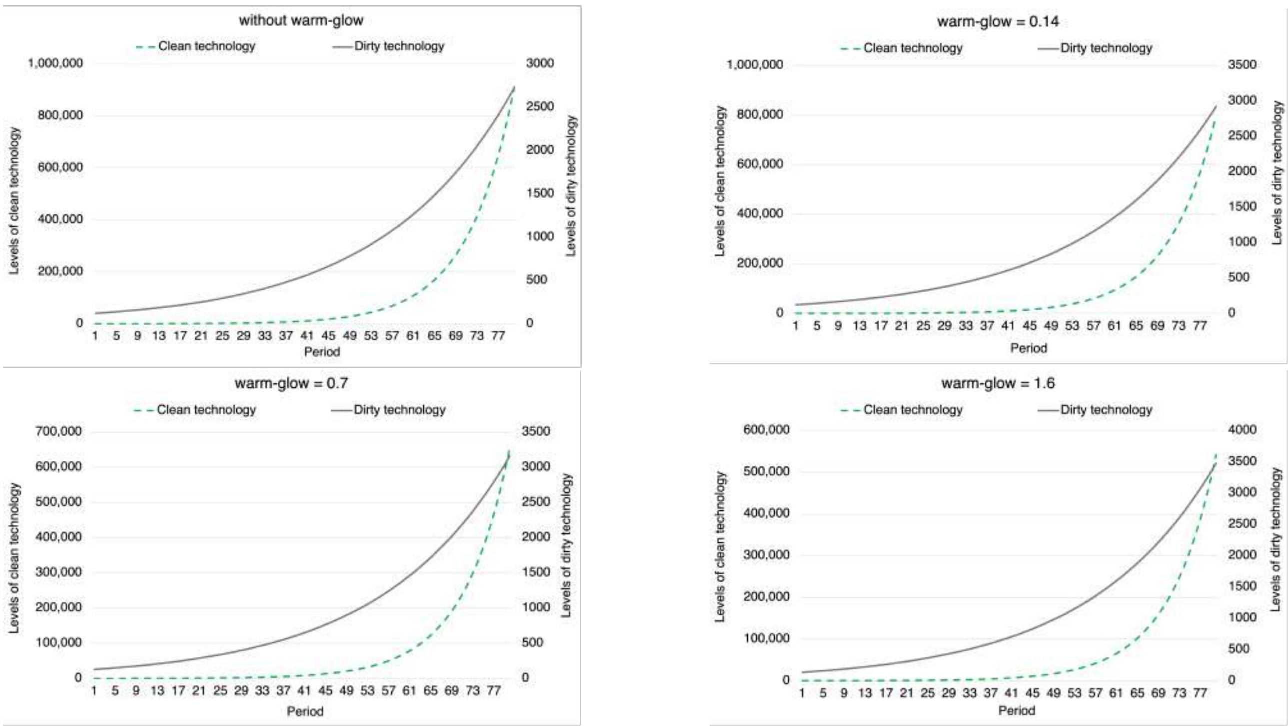
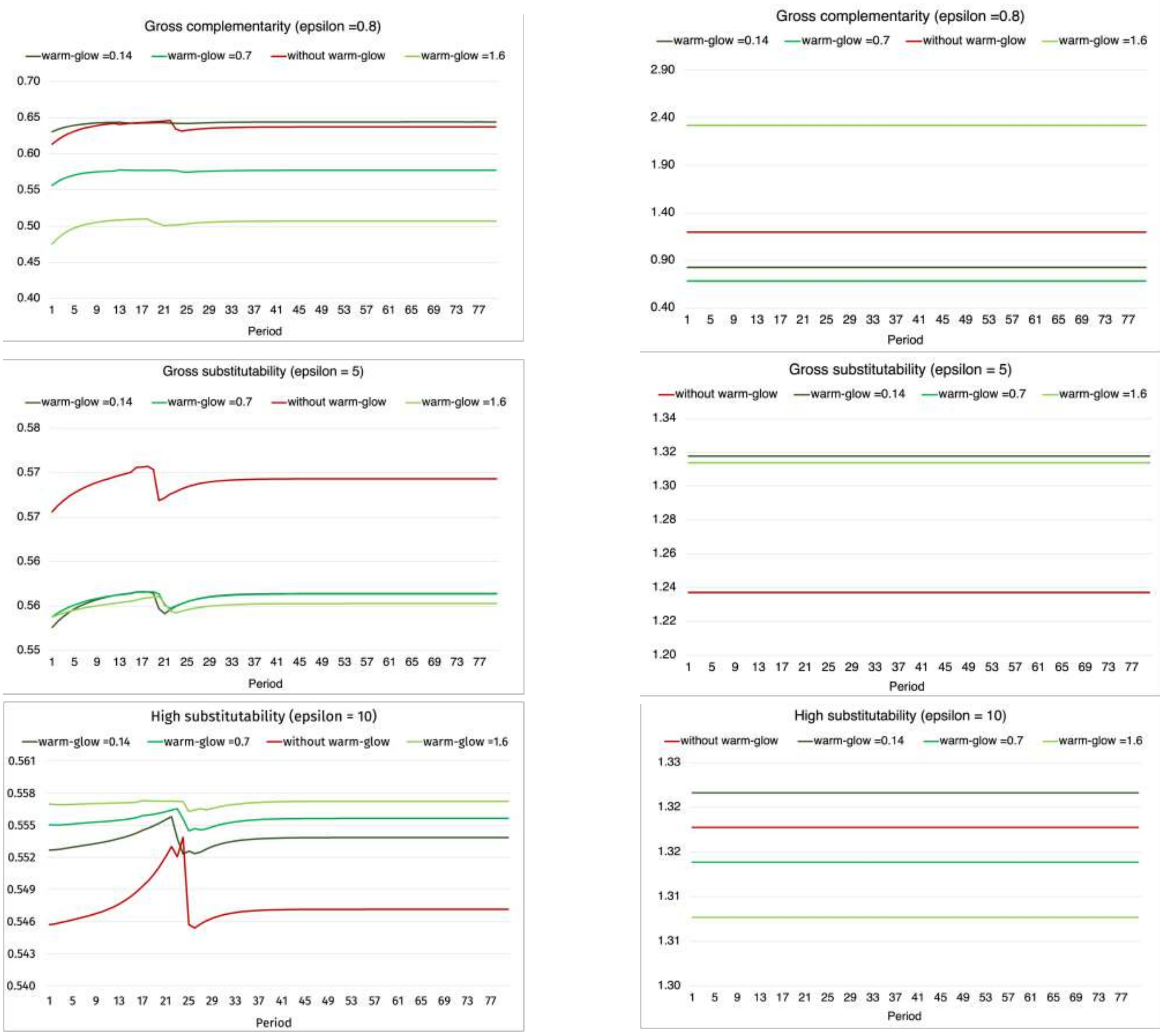


Figure 11: Optimal policy: High substitutability (epsilon = 10)

when the *warm-glow* parameter was getting higher. The situation changes if the level of substitutability is high ($\epsilon = 10$); in this case, it would not be necessary to have a "warm-glow" parameter greater than 0.7 because when it exceeds that level, the tax increases.



Carbon tax

Clean R&D subsidy

Figure 12: Optimal policy: Carbon tax and clean R&D subsidy

The right panel in figure 12 illustrates the behaviour of the subsidy. The value of this instrument remains stable overall periods and across all scenarios. However, the subsidy follows a similar dynamic to the carbon tax when substitutability is considerably high; higher values of the *warm-glow* parameter drives higher values of the subsidy

8 Conclusions

Climate change is one of the most challenging and universal problems that the global society has been facing in the last four decades. Being in particular, the results of the spectacular use of fossil fuels to leverage the economic growth experimented by a group of countries that today have the wealthiest economies.

The problem is and will be getting worse if it considers that the majority of global economies are still in low and middle levels of development, and they will keep increasing the global energy demand to make their way toward the developed status.

From a certain point of view, it is possible to say that problem lies more in the quality of energy that the world is consuming rather than the quantity. If energy comes from sustainable sources, society can consume as much energy as it wishes. Therefore, there is not a more suitable way to pursue that status than investing in innovation which makes global society less dependent on non-renewable sources without sacrificing economic growth and well-being.

[Nordhaus, 1991] and [Nordhaus, 1993] started the study of the link between economic growth and climate change formally, and the topic has been getting more and more attention over the years that today there are a vast majority of studies that look for a better way to conciliate economic growth and sustainability of the planet. In particular, in this study, we work on an extension of the growth model developed by [Acemoglu et al., 2012].

We develop and simulate a theoretical framework that brings together two different economic theories: economic growth and *warm-glow* giving, to determine if an individual receives a *warm-glow* for their unilateral decision of consuming more renewable energy than non-renewable one, it will make the avoidance of an environmental disaster possible with or without low governmental intervention.

The laissez-faire solution of the model shows that it can not tackle an environmental disaster, regardless of substitutability between sources. As we demonstrated above, under the complementarity scenario by definition, the economy will always consume both inputs, so environmental degradation keeps occurring because dirty energy must always be present. However, the presence of *warm-glow* delays the disaster over time. The numerical simulation also confirms that the higher *warm-glow* parameter, the further the time horizon in which the disaster occurs. When both sources are substitutes, the disaster still takes place, but interestingly only under specific ranges of values for the *warm-glow* parameter (0.14, 0.7), it is possible to delay the disaster considerably. It seems like *warm-glow* has a limited power to solve the problem.

The implementation of the optimal policy enables the economy to avoid the environmental disaster only when both energy sources are substitutes and under all levels of *warm-glow*. Supporting our theory, higher levels of *warm-glow* reduce the values of intervention (carbon tax and clean R&D subsidy) than otherwise take place if that intervention would not be present. However, as in the decentralised equilibrium, the power of *warm-glow* is bounded because, under high levels of substitutability, its positive effects are reverses.

All in all, the intervention must be established if the environmental disaster is wanted to be avoided; nevertheless, the presence of *warm-glow* contributes to delay or limits the problem quicker. Regarding its power, it was showed that the long term effect of the *warm-glow* parameter strictly depends on the elasticity of substitution ϵ. When clean and dirty consumption are complements, an increase in *warm-glow* will reduce the steady-state value of the ratio between dirty and clean technology, making the economy converge to a solution with a lower weight of the dirty sector. Unfortunately, it does not solve the problem of non-sustainability. When clean and dirty consumption are gross substitutes, indeed, the increase in *warm-glow* until a certain level ($\phi \leq 0.7$) increases the size of the interval in which growth is sustainable, reducing the need for policy intervention.

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