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Taking environmental limits as binding constraints:

Feasible and optimal economic growth for a society

Paul Froger (40970)

Abstract. Science informs us about environmental limits that should not be exceeded, nevertheless few models in conventional economics are looking at what happens when environmental constraints are truly binding. By using the tool of conventional economics and by solving a maximization problem, this master's thesis looks at the optimal level of production for a society when considering the need to limit climate change as a binding environmental constraint. One of the main result is that when society have to stay within a limited "environmental budget", the environmental intensity (here the carbon intensity) represents the environmental price which is associated with production at period t. Then, if it is possible to forecast that this carbon intensity will decrease and be far lower in the future, it can be rational for a society to downscale its economy in the first place to keep environmental budget for the future when the production will be environmentally more efficient. In this sense this paper supports the idea that the possibility of degrowth should be considered also by conventional economics.

Keywords: Binding environmental constraint, carbon intensity, carbon budget, optimal growth.

JEL: 044, Q01, Q56

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1 Introduction

In March 2017, the World Meteorological Organization (WMO) stated that 2016 was the warmest on record and announced that extreme weather condition will continue in 2017. One month before, Gilbert (2017) published a study in *Nature* to show the link between global warming and the fact that "oxygen levels have declined by 2 percent in the global ocean over the past five decades, probably causing habitat loss for many fish and invertebrate species." David Carlson, Director of the World Climate Research Programme, said in a statement, "We are now in truly uncharted territory".

Hence, the whole scientific community is raising alarm on the degradation of the environment on Earth. Concerning climate change the scientific community have clearly established that exceeding the limit of 2°C warmer than pre-industrial temperature would seriously put into danger the capacity of humanity (and most of Earth's biodiversity) to survive. Others says that the 2°C limit corresponds already to dramatic changes in our environment which leads to more extreme weather, food insecurity, migration etc. The Paris Agreement, adopted during the COP21 in December 2015 and ratified by the requisite number of countries by October 2016, implies that our society should target a maximum global warming of 1.5°C.

In short, science informs us about environmental limits that we should not exceed. Nevertheless, most of the economics literature has not looked at environmental constraints as binding. Indeed, economics has studied the link between growth and environment mainly with the concept of Environmental Kuznets Curve (EKC) which predicts that a high level of GDP is associated at some point with a diminishing of environmental impact (an inverted U shape curve). Others economists are constructing new indicators such as the measurement of genuine savings to be able to measure more precisely the sustainability of a society, but as is the case EKC there is no explicit consideration of absolute limits. The failure or unwillingness to include such constraints might issue from the traditional concern of economics with equilibrium outcomes and a widely shared trust in prices reflecting relative scarcities being able to prevent the full exhaustion of resources.

Therefore, even if the links between economic production and environmental externalities are being studied, few models in conventional economics look at what happens when environmental constraint are truly binding. For instance, in the case of EKC, although it says something about the possibility that pollution can be reduced even with a growing GDP, it does not say anything concerning the aggregation of different types of pollution and whether or not the decline of pollution is important and rapid enough to stay within environmental limits.

That is the reason why some economists and other intellectuals such as Tim Jackson, Herman

Daly and Peter Victor, by considering what science says on environmental limits, are questioning the feasibility and necessity of growth. Indeed, these economists are developing what can be called the degrowth theory which suggests that it is not possible anymore, considering our current level of overuse of natural resources and pollution, to continue to grow and avoid environmental catastrophes at the same time. A considerable part of this critique has focused on the productivist nature of our current economic system and not least on the consequences of GDP as the key indicator of economic success of nations. As such they have, unlike the analysis of more mainstream environmental economics, integrated the idea that there are binding constraints if growth is not to end in environmental catastrophe.

I want to contribute to this debate on the link between growth and environment by looking at the optimal level of production for a society when considering a binding environmental constraint. By using the tool of conventional environmental economics and by solving a maximization problem for the utility function of households the aim of this master's thesis is to study how traditional trade-offs are affected by a binding environmental constraint.

This master's thesis starts from the realization of the existence of environmental limits that humanity cannot exceed without putting into danger its capacity to survive on earth. Therefore, I will begin by presenting what science says about these different limits and will focus myself on the particular case of climate change. A literature review will then expose what have been the economic work until now concerning the link between growth, environment and sustainability and the argumentation of "degrowth theorists" concerning our capacity to continue to grow economically without exceeding environmental limits. In a third part we will propose a way to model environmental thresholds in the economy. Starting with a general model where pollution affects the utility function of households we will discuss how this negative effect on utility modify the trade-off of households.

We will then focus on the specific case when the environmental threshold is constraining and apply this model to study the optimal level of production of France and the USA when being constrained by the level of CO_2 emissions that they can add to the atmosphere. We will solve this optimization problem in two different situations: considering that CO_2 intensity is declining at a constant rate over year and considering the possibility to invest in CO_2 abatement. By doing so, the contribution of this thesis is to provide, using standard approaches of conventional environmental economics, an extension that is commensurate with the notion of absolute limits as now generally agreed upon amongst environmental scientists. As such it is suggestive of the extent to which heterodox approaches such as ecological economics, and in particular degrowth theory, can productively inform mainstream research on climate change.

2 Background

In this part we will present briefly what the scientific literature says about environmental limits on earth by focusing on the conclusion of a study published in *Science* in January 2015. This will allow me to discuss with a greater degree of precision the case of climate change and thereby provide inputs on the environmental constraint that will be the focus of this study.

Along with 17 co-authors, Will Steffen, Executive Director of the Australian National University's Climate Change Institute in January 2015 published a paper assessing the existence of nine "planetary boundaries". As one of the co-authors, Johan Rockström, the Executive Director of the Stockholm Resilience Centre, puts it in an interview for Ideas.Ted (Carey, 2015):

> humanity has already raced past four of the nine boundaries keeping our planet hospitable to modern life. The climate is changing too quickly, species are going extinct too fast, we are adding too many nutrients like nitrogen to our ecosystems, and we keep on cutting down forests and other natural lands.

Table 1: Four environmental limits for which humanity is beyond the boundary

	Boundary	**Where are we today**
Climate change	Atmospheric concentrations of carbon no more than 350ppm	Carbon dioxyde level are at 400 ppm and climbing
Lost of biodiversity (as species become extinct)	Maintain 90% of bidoviersity	Biodiversity has dropped to 84% in parts of the world such as Africa.
The addition to phosphorus,nitrogen (and others element) to the world's crops and ecosystem	Worldwide use per year of about 11 teragrams (Tg) of phosphorus and 62 Tg of Nitrogen	Up to about 22 Tg per year of phosphorus and 150 Tg of Nitrogen
Deforestation and other land use change	Maintain 75% of the planet's original forests	Down to 62%

Source: author's adoption from Ideas.Ted (5 March 2015).

NB: the five others limits are: emissions of aerosols; stratospheric ozone depletion; ocean acidification; freshwater use; and dumping of organic pollutants, radioactive materials and other man-made substances into the environment.

These ideas were first communicated in Rockström et al. (2009) and that paper was especially important in pointing out that crossing these boundaries can "shove the Earth into completely different states", Will Steffen is quoted as saying in Carey (2015), since it can lead to phenomenon of acceleration and irreversibility. For instance, if the temperature of the planet raise too much, the ice of the Poles can melt, less of the sun's heat will be reflected back and therefore global warming will accelerate. That is the reason why some threshold should not be exceeded if humanity does not want to lose control over climate change and endanger its capacity to live on the planet.

In the particular case of climate change we often quote the target of keeping climate change under 2°C comparing to pre-industrial temperature. Nevertheless, it has to be noted that 2°C already corresponds to severe impacts for people and ecosystems. This is what is explained by the Structured Expert Dialogue (SED) in their 2013–2015 review (Secretariat, UNFCCC, 2015). Indeed a world 2°C warmer than in pre-industrial times already is already threatening some species that cannot move sufficiently fast to migrate to their preferred temperature zone. It would also cause arctic summer sea ice to be significantly reduced and increase ocean acidification threatening marine life, leading to extreme weather which put at high risk human health and food security and so on.

Therefore, the Intergovernmental Panel on Climate Change (IPCC) classifies a 2°C target as a "an upper limit, a line that needs to be stringently defended, while less warming would be preferable". Indeed, we are already experiencing negative impact of climate change and "the risks of abrupt or irreversible changes increase as the magnitude of the warming increases" (IPCC, 2014, p.1). The negotiation of the COP21 have been based on this scientific input and the Paris Agreement have therefore endorsed a limit of 1.5°C defining what society considers dangerous (especially for some islands that are highly threatened by sea rising).

Even if this target of 1.5°C seems more and more difficult to reach we understand clearly that science indicates that our world has indeed some environmental constraint that we cannot exceed without experiencing dramatic destabilization of our capacity to live in a secure way on earth. In this study I will focus on the case of climate change by considering the limit (in term of CO_2 equivalent emissions) associated with a probability superior to 66% to limit global warming to less than 2°C.

3 Literature review

In this literature review I will have a look at the different attempt of economists to introduce environmental considerations into growth theory. Environmental concerns are not new and in order to answer the question of the feasibility of "sustainable growth" numerous economists are studying the link between growth of production and different types of pollution.

Firstly, based on the review of the state of the art made by Xepapadeas (2005), "Economic growth and the environment" published in the *Handbook of Environmental Economics*, we will see how environmental considerations are being added to conventional models. I will present the concept of the Environmental Kuznets Curve (EKC) which dominates economics research concerning the link between economic growth and environment. Secondly I will introduce the approach of genuine savings which develops a new way to measure wealth for countries in order to evaluate their sustainability and to do so in a framework that is directly relevant to how we measure economic growth. Finally, I will complete this brief literature review by looking at the contribution of degrowth theorists, the rationale for extending the discussion in include this heterodox school of thought being their explicit inclusion of the notion of absolute limits to resource use, limits that need to be honoured if developed countries are not exceed the environmental limits as established by environmental scientists.

3.1 Introducing environmental consideration into economic models

More than four decades ago, Brock (1973, p.441) wrote that "Received growth theory is biased. It neglects to take into account the pollution costs of economic growth". From then, over the past few decades, numerous research works have explored the links between economic growth and the environment centred on several questions such as:

- is environmental protection compatible with economic growth?
- is it possible to have sustained growth in the long run without accumulation of pollution?

Firstly, economics has introduced environmental components in the supply and demand side of the existing model. Concerning the supply sides economists have included the use of natural resources and the flow of pollutions that is the result of production into the production function (see for example Bovenberg and Smulders (1995), Smulders and Gradus (1996), Mohtadi (1996), Rubio and Aznar (2000)). As described by Xepapadeas (2005) one way of doing this is to write the flow of emissions Z at time t as a function of production Y.

$$Z(t) = vY(t) \tag{1}$$

As Xepapadeas notes this can be rewritten as $Z = \phi Y$, where ϕ is the unit emission coefficient or, in other words, emissions per unit of output

As it is explained by Xepapadeas, you can from then split the stock of capital into productive capital, which is the capital Kp that generates pollution, and abatement capital Ka, which reduce pollution. In this case, the production function can be written as

$$Y = F(K_p, AL, K_a). \tag{2}$$

Then

$$Z = \phi(K_a)Y. \tag{3}$$

The evolution of environmental quality, or equivalently the evolution of the stock of environmental goods E, can be described by a formulation which is equivalent to modelling environmental quality as a renewable resource, or

$$E = R(E)Z \tag{4}$$

where R(E) is an environmental regeneration function and Z represents reduction in environmental quality.

We see that the logic, which is always the same (and will be the same in this study), is to link the amount of environmental degradation to the amount of production and a unit emission coefficient which account for the "environmental efficiency" of the production. This is what is done in the work of several economists such as Krautkraemer (1985), Bovenberg and Smulders (1996), Heal (1998) and Krutilla and Reuveny (2002).

On the demand side Xepapadeas explains how the environmental dimension is introduced into the utility function by including both consumption and and environmental quality among the factors determining the satisfaction derived by individuals. In this case pollution is represented as disutility for individuals.

Thus we have for the ith individual:

$$U(c_i, Z)\ or\ U(c_i, P) \tag{5}$$

WIth P or Z representing reduction in environmental quality (pollution).

3.2 The relation between growth and environment: Environmental Kuznet Curve

The Environmental Kuznets Curve (EKC) has been and still is the main concept to analyse the link between production and pollution. Xepapadeas (2005, p.1253) thus suggests that "The EKC has dominated the discussion regarding the empirical relationship between growth and environmental pollution" and Brock and Taylor (2010, p.128) similarly note that "The EKC has captured the attention of policymakers, theorists and empirical researchers alike since its discovery in the early 1990s. The theory literature has from the start focused on developing models that replicate the inverted U shaped relationship".

The EKC states that there is an inverted U relationship between level of pollution and GDP per capita. This idea of a break between growth and pollution emerged in 1990s [World Bank 1992; Panayotou 1992). As explained by Brock and Taylor (2010, p.128), "prominent explanations [for EKC] are threshold effects in abatement that delay the onset of policy, income driven policy changes that get stronger with income growth, structural change towards a service based economy, and increasing returns to abatement that drive down costs of pollution control".

For example, Grossman and Krueger (1995) find an inverted U-shape relationships for two measures of air pollution (sulphur dioxide and smoke) and several measures of water pollution (oxygen loss and concentrations of several heavy metals). Their evidence is confirmed in related work by Selden and Song (1994) and the World Bank Development Report (1992) that finds similar patterns. Grossman and Krueger (1995) calculate that the turning point of the inverted U curve is GDP per capita of USD 8000 (1985 dollars) for most of the pollutants examined.

Nevertheless, these findings have been questioned. Thus, Harbaugh, Levinson and Wilson (2002) suggest that the pollution–income relationship is less robust than previously thought and it is important to notice that this break seems to be associated more with local pollutants than with global pollutants (e.g., CO_2).

Then most of the models that have been developed have searched to replicate this EKC curve by introducing environmental consideration into already existing model. This is for instance the case of Brock and Taylor (2010, p.128) who developed the Green Solow model, "a variant of the Solow model where technological progress in abatement and diminishing returns to capital play leading roles". As they had already explained in their previous paper, "The Kindergarten rule of sustainable growth", there is "a direct role for technological progress in abatement which ensures that all economies capable of continuing growth will, at some point, experience falling pollution levels and rising environmental quality" (Brock and Taylor 2003, p.4). Therefore, reproducing the result of the EKC the authors go on to "provide conditions under which long run economic growth with rising environmental quality is both feasible and optimal".

Similarly, by presenting the Ramsey–Cass–Koopmans (1965) model with environmental pollution, where households maximize their utility (with pollution affecting negatively their "felicity"), Xepapadeas (2005, p.1235) concludes that "although disutility from pollution enters the household utility function, the steady-state outcome is not affected by this disutility. Only the approach path to the steady state is affected".

Therefore, we understand that quite numerous models have been developed trying to introduce environmental considerations. Most of them are based on the theory behind the EKC. By introducing pollution into the utility function of households, and by introducing natural resources use and pollution into the production function, they often reach the same conclusion as does Stokey (1998) in "Are there limits to growth", namely that:

> if increased productive capacity allows both consumption growth and improved environmental quality, then growth may continue without bound ([. . .] whether or not such a point is reached depends on the effects of pollution abatement on long-run rates of return.

In conclusion, none of these models suggest a necessity of curbing growth per se. Even if it is conditional to the effectiveness of abatement, thanks to the mechanisms behind the EKC, they conclude that it is possible to get both growth and what they call "improved environmental quality" which means a decrease of pollution.

3.3 The measurement of genuine savings : modifying our way to measure wealth

Another approach that is being developed, especially by the World Bank (1997, 2006, 2011), to study the link between growth and environment is the measurement of genuine saving. This notion was first presented briefly and informally in Hamilton (1994, 1996) and in Pearce and Atkinson (1993). It takes into account the critique that GDP is not an appropriate way to measure wealth and therefore proposes an alternative. In order to measure whether or not a country is sustainable a considerable amount of research effort has been expanded to create new indicators taking into accounts natural resources and environmental degradation. The approaches based on saving rules — i.e. genuine savings — is a central component of this. As it is explained in Atkinson and Hamilton (2007), genuine savings or adjusted net savings can be defined as,

$$G = \sum_{i=1}^{N} p_i K_i \tag{6}$$

with K_i the stocks of assets in the economy, and p_i their shadow prices. We understand that genuine saving is then measured as the change in real wealth. As it is explained by the authors, "to measure sustainability, in a comprehensive way, it is important that genuine saving span as wide a range of assets as possible, including assets with negative shadow prices such as pollution stocks". Atkinson and Hamilton (2007, p45), Therefore, we understand that genuine savings is a method which attribute a monetary value to environmental resources and (the effect of) pollution. An adjustment is also made for education expenditure, which is taken to be an important contributor to increases in human capital. Indeed, the genuine savings approach assumes the possibility of substitution between "natural" and "man-made" capital (see Pearce and Atkinson 1992 for the discussion of the reality of this substitution).

As it is stated by Heal and Kriström (2005, p.1209), genuine savings are defined by the World Bank as

> net savings plus the value of investment in human capital minus value of resource depletion minus the value of environmental degradation. As conceptualized in Hamilton and Clemens (1999), genuine savings can rigorously be defined as the change of wealth over time along the optimal path [. . .] If genuine savings are negative in some period t, this indicates that the economy is living off its assets, rather than creating new wealth.

It has been shown that negative levels of genuine savings imply unsustainability and must be associated with future declines in utility (Hamilton and Clemens, 1999; Pezzey, 2004)

Obviously the measurement of genuine savings come with the difficult challenge to monetise exhaustible resources and environmental degradation. Therefore, much research has been developed to measure environmental assets (see Atkinson and Hamilton 2007 for an example of the valuation of oil stock). In turn, the measurement of wealth has been applied to calculate the genuine savings for a large number of countries, as reported for instance in The Little Green Data Book, issued annually by the World Bank. Hamilton and Clemens (1999) for instance have reported that the genuine savings rate in sub-Saharan Africa was marginally positive in the 1970s, after which the rates have been negative.

3.4 The contribution of "degrowth economists"

The degrowth theory starts from the assessment of the existence of environmental limits. This theory is based on two main arguments that combined together lead these economists to conclude that countries that are already developed should voluntary downscale their economy to leave ≪ ecological space ≫ to developing countries.

Firstly, some economists raise some critics against GDP as an indicator and against growth as the main objective of economic policies for developed countries. Secondly, based on the warnings of sciences on environmental crisis, other economists argue that ≪ sustainable growth ≫ is not feasible at a global level.

3.4.1 The critics of GDP as an indicator and as the first economic target for developed countries.

Several economists such as Cobb, Halstead and Rowe (1995) and Stiglitz, Sen and Fitoussi (2010) have pointed out major flaws of Gross Domestic Product. The main arguments that has been developed on this topic are the followings. As stated by Cobb, Halstead and Rowe (1995, p.4),

• GDP "left out two large realms: the functions of family and community on the one hand, and the natural habitat on the other. Both are crucial to economic well-being. But because the services they perform are outside the price system, they have been invisible in our national accounting";

• GDP would consider as economic gain some disaster and breakdown of social structure (criminality, addiction, reconstruction after war, environmental disasters . . .); and

• GDP does not say much about the distribution of income.

We can also remind ourselves here that Kuznets (1934), who helped the US government to develop this indicator, concluded the report about GDP by saying, "The welfare of a nation" can "scarcely be inferred from a measurement of national income as defined above". In this vein, the economists mentioned immediately above support the idea that we should consider a wider set of indicators and stop to focus so much (in macroeconomic analysis, policies but also in macroeconomic university courses) on GDP and growth. Other economists have pointed out that growth GDP is not anymore the main condition for well-being of people in already developed countries. There is on this question an ongoing debate following the numerous papers of Easterlin (1974, 1995, 2005) who finds little significant evidence of a link between aggregate income and average happiness. Some economists such as Kubiszewski et al. (2013, p.57) which have studied the correlation between Genuine Progress Indicators (an indicator designed to take fuller account of the well-being of a nation) and GDP to conclude that:

> Globally, GPI/capita does not increase beyond a GDP/capita of around \$7000/capita. If we distributed income more equitably around the planet, the current world GDP (\$67 trillion/yr) could support 9.6 billion people at \$7000/capita. While GPI is not the perfect economic welfare indicator, it is a far better approximation than GDP.

Therefore, it is argued that growth of GDP is neither a sufficient neither a necessary condition for well-being in developed countries. For instance, Wilkinson and Pickett (2009) show in their paper that inequalities are closely linked to health and social problems, in turn suggesting that modern economies should focus more on reducing inequalities than on increasing GDP.

3.4.2 The impossibility of sustainable growth

Another important concern that have been raised by economists concerning growth as the main objective of public policies for the 21st century is the impossibility of having growth of world GDP without experiencing environmental catastrophes. Some economist work such as the report of the Club or Rome *The Limits to Growth* (Meadows et al. 1972) and its new version (2004) as well as the research of scientist on the environmental limits of earth (Steffen et al., 2015) raised the question of the sustainability of growth. Therefore, the central question in economics have been to know whether or not it was possible to achieve "sustainable growth" or "absolute decoupling" (absolute reduction of environmental impact and growth of GDP)

In one of the most serious report on this topic, "Decoupling natural resource use and environmental impacts from economic growth", Fischer-Kowalski and Swilling (2011, p.72) UNEP conclude that:

• relative decoupling (when the growth rate of resources used is lower than the growth rate of GDP, though resource use continues to grow) is feasible thanks to technological progress leading to more efficiency, "dematerialization" of economy, recycling... etc.);

• "Absolute reductions of resource use are rare, as they require resource productivity to grow faster than GDP".

The same is true concerning the CO_2 emissions at a global level where we can observe a relative decoupling but not an absolute one. Moreover, the question is not only whether or not it is possible to have growth and decrease our environmental impact at the same time but also if this decrease of environmental impact will be sufficiently important and fast to not exceed environmental limits. This question is especially important when we take into account that rich countries are largely over a sustainable level of consumption as shown by these tables. (In 2015 the overshoot day was the 8th of August.)

Table 2: World overshoot day: the day from which humanity have consume what earth can provide in one year.

Year	Overshoot day
2005	October 20
2007	October 26
2008	September 23
2009	September 25
2010	August 21
2015	August 8

Source: author's adoption from Global Footprint Network

Is it possible to continue to have GDP growth and diminish our environmental impact at a sufficiently rapid rate in order to avoid environmental catastrophes? Tim Jackson (2011) answer this question by presenting what he calls the arithmetic of growth developed by Paul Ehrlich and John Holdren (1995). The Ehrlich equation reveals that the impact (I) of human activity is the product of three factors: the size of the population (P), its level of affluence (A) expressed as income per person, and a technology factor (T), which measures the impact associated with each dollar we spend. ($I = PAT$).

Applying this method to the climate change issue and knowing that "The IPCC's Fourth Assessment report suggests that achieving a 450 ppm stabilisation target means [. . .] reducing annual emissions at an average rate of 4.9% per year between now and 2050" (IPCC, 2007). Jackson (2011,p.54) calculate that:

> To achieve an average year-on-year reduction in emissions of 4.9% with 0.7% population growth and 1.4% income growth T has to improve by approximately $4.9 + 0.7 + 1.4 = 7\%$ each year.

This is ten times what have been done between 1990 and now (approximately 0.7% of improvement of T). This is the case with a global income growth of ≪ only ≫ 1.4%, Tim Jackson also do the arithmetic for others scenarios and get the following results Therefore, Jackson (p. 57) concludes that:

Table 3: How many earth do we need if world population live like...

How many Earths do we need If the world's population lived like...	
Australia	5,4
USA	4,8
Germany	3,1
France	3,0
UK	2,9
China	2,0
India	0,7
World	**1,6**

Source: author's adoption from Global Footprint Network

> The truth is that there is as yet no credible, socially- just, ecologically-sustainable scenario of continually growing incomes for a world of nine billion people. In this context, simplistic assumptions that capitalism's propensity for efficiency will allow us to stabilise the climate or protect against resource scarcity are nothing short of delusional. Those who promote decoupling as an escape route from the dilemma of growth need to take a closer look at the historical evidence – and at the basic arithmetic of growth.

Tim Jackson compare these figures with the carbon intensity of the world in 2007 which was 768 gCO_2/$ or the one of the UK at this same time which was 347 gCO_2/$

Some economists such as Victor (2011) have modelled the effect of economic degrowth on CO_2 emissions and other economic variable (employment, consumption etc). In his work Victor (2011) simulate future growth and CO_2 emissions for Canada with a dynamic macro-economic model. As it is explained by Kallis et al. (2012), the "Victor model shows that 'selective growth', i.e. a structural shift of the economy to lower-intensity commodities, will not work. The production of such commodities entails intermediate expenditures on high intensity commodities". In his model he shows that with a zero growth scenario Canada's CO_2 emissions will be in 2035 only 22% less than in 2005. He then simulates a degrowth scenario which is associated with CO_2 emissions 78% lower than in 2005. This degrowth scenario goes with a sharp decline of hours worked to maintain full employment.

Table 4: Carbon intensity now and required to meet 450ppm target

Scenarios	Carbon intensity required to meet 450ppm target (gCO2/$)
9 billion people : trend income growth	36
11 billion people: trend income growth	30
9 billion people: income at equitable 2007 EU level	14
9 billion people: income at equitable 2007 EU level + 2% growth	6

Source: author's adoption from Tim Jackson (2011)

Therefore, degrowth economists argue that already developed countries have the possibility and should research ≪ prosperity without growth ≫ in order to leave ecological space for developing countries which still need GDP growth to increase well-being of their population.

3.5 Conclusion

We see in this literature review that environmental economics does not consider environmental constraint as binding. Most of the models that have been built to study the link between growth and environment are replicating the Environmental Kuznets Curve and then often support the idea of sustainable growth. Even if degrowth theory assess the existence of environmental constraint to critic the feasibility and necessity of GDP growth in already developed country we see that few models have been developed to study how an environmental binding constraint can affect the optimal level of production across time.

Therefore, to expand the argument of conventional economy it can be interesting to study what happen if we consider environmental constraints as binding. By taking the case of climate change and using the tools of conventional economy (utility function and production function) this master thesis aims to study whether or not economic growth is still feasible and optimal once we consider that society cannot exceed a certain amount of CO_2 emissions

4 Modeling environmental limits

In this section we will present the model that we use for our optimization problem. Firstly, we describe how this model function and justify why it is a coherent to represent the link between the production of a society, the utility that this society get from this production and the environmental degradation that it creates. We discuss briefly how the introduction of environmental degradation in this model affects the choices of households. We then discuss the specific case of environmental limit being a binding constraint. This model is largely inspired by existing model in macroeconomy, the main addition is the modelling of environmental threshold.

4.1 Presentation of the model

4.1.1 Utility function of Households

In this model, households value both the production (from which they can consume and invest) and their leisure time. Both production and leisure have a decreasing marginal utility that is represented by the logarithm function. Households also value the current state of their planet (P). Indeed, people are negatively affected by environment degradations by direct effect (such a fog of pollutions for instance) or by indirect effect such as the more extreme weather conditions linked to climate change which can lead to disorder in agriculture, loss of biodiversity, migration due to climate change etc.

Another way through which environmental degradation is affecting the well-being of people is through the repeated alerts of scientists concerning catastrophes that could occur in a close future if our society does not change drastically. Indeed, scientific research inform us that climate change could all have dramatic effects on our well-being by causing more frequent extreme weather conditions (floods, drought, storm) and by undermining our capacity for feeding humanity as it is discussed in Wheeler Von Braun (2013). We could add to this an inherent value for the ≪ beauty ≫ of nature that people also value.

That justifies the valuation of the "state of Planet" by households. We consider here that the way people consider environment is by comparing the actual state of the Planet to the limits that should not be exceeded. By getting closer to these environmental limits their utility decrease because some effects are already affected them and the feeling of the likelihood of an environmental catastrophe make them worried. Therefore, households get more utility by keeping the difference between and as big as possible.

If the limit is exceeded the disutility is multiplied because of the multiplication of dramatic effects on households. Here is the most important feature of this model, since it takes into account the fact that there is a limit that should not be exceeded. Indeed, some environmental threats such as climate change do not have linear effects. Environmental scientists inform us that there are for ecosystems some threshold and that if we overtake the it put humanity into danger. In the case of climate change for instance, we know that the ecological system will at some point become uncontrollable and will enter in a vicious cycle where global warning effect reinforce the emissions of greenhouse gas (with for instance the melting of the permafrost).

Hence we can write the utility function of households at a period t as follow

$$U(Y_t, H_t, P_t) = \log Y_t + \log(1 - H_t) + \beta(\overline{P} - P_t) \tag{7}$$

With $\overline{P}$ being the environmental threshold (limit of accumulation of CO2 emissions for instance), P_t being the additional pollution/environmental degradation (eq: CO2 emission) which reduce environmental quality at time t and beta having two possible value

$$\beta_{low} \ if \ (\overline{P} - P_t) > 0 \tag{8}$$

$$\beta_{high} \ if \ (\overline{P} - P_t) < 0 \tag{9}$$

4.1.2 Production of the firms and environmental degradation

It is important to precise here that in this model we consider that firms are owned by the households. Indeed, since we are searching for a question which is concerning what is an optimal situation for a society the relation between the firms and the households (through salary or rent of capital) does not affect the result. We consider that households decide how much time they want to work at a period t, given the capital stock of this period and the total factor productivity. Therefore, by deciding hours of work they decide to produce a certain amount of goods that they can use for consumption or investment (capital accumulation).

For simplicity we express here the production as a function of the number of hours worked and the productivity of work. This labour productivity noted A_t is a function of productive capital K_{Pt}, human capital K_{Ht} and technology T_t.

$$Y_t = A_t H_t \tag{10}$$

with

$$A_t = F(K_{Pt}, K_{Ht}, T_t) \tag{11}$$

$$A_{t+1} = A_t(1 + g_A) \tag{12}$$

Their production leads to an amount of environmental degradation D_t which is a function of the amount of production Y_t and an environmental intensity factor E_t which is the amount of environmental degradation per unit of production (the amount of equivalent CO_2 equivalent emissions per dollar of production). From this amount of pollution, we deduce the amount of what earth can “recycle” or “absorb” on each period $\overline{R}$

$$D_t = E_t \times Y_t - \overline{R} \tag{13}$$

In this first version of the model the environmental intensity factor (E_t) is decreasing at a rate g. Therefore we have:

$$E_{t+1} = E_t(1 - g_E) \tag{14}$$

We can estimate this g by looking at the one of the previous year and either do the mean of it or take the best improvement as a reference.

Then this deterioration of environment at period t determine the state of the planet of this period.

$$P_{t+1} = P_t + D_{t+1} \tag{15}$$

4.1.3 Summary of the optimization problem

Therefore in this first model the households face the following maximization problem:

$$max \sum_{t=0}^{\infty} (1 + \rho)^{-t} [\log Y_t + \alpha \log{(1 - H_t)} + \beta(\overline{P} - P_t)] \tag{16}$$

subject to

$$Y_t = A_t H_t \tag{17}$$

$$A_{t+1} = A_t(1 + g_A)\ A_0\ given \tag{18}$$

$$D_t = E_t \times Y_t - \overline{R} \tag{19}$$

$$E_{t+1} = E_t(1 - g_E)\ E_0\ given \tag{20}$$

$$P_{t+1} = P_t + D_{t+1}\ P_{-1}\ preexisting\ pollution\ is\ given \tag{21}$$

$$\tag{22}$$

We have to note that if this model says something about the utility of a society as a whole, it does not take into accounts the divergence of interest inside a specific society. In this sense we can say that this is not a model of individual behavior but more a social welfare model which says something about what would be optimal for a society where all individuals care collectively for environment. By taking into account that firms are owned by households, the model lost some complexity which could be useful to understand better which type of economic policies should be introduced. Indeed, this model just aims to give a sense of rationality of what could be optimal for a society. Therefore, we have to keep in mind that this model is not an attempt to predict what is going to happen in a society and cannot help us to understand precisely what should be a good economic policy to implement the optimal level of production.

Moreover we see that this is here a proposition for modelling an environmental threshold in general. We will firstly discuss how this environmental threshold can influence the trade-off of households before going to the particular case when this limit is a binding constraint.

4.2 How this model inform us on the trade off of households when considering environmental limits?

Firstly, we will briefly discuss, what are the trade-off between production, environmental degradation and leisure time in this model. We will then study what are some implications of the environmental limit being a binding constraint.

Let's first consider that households do not value leisure time to concentrate on state of the planet and consumption. In this case to maximize their utility households set their consumption at the point where the marginal benefit of it equal it is marginal environmental cost. The benefit of a marginal unit of production is:

The benefit of a marginal unit of production is:

$$MU(Y_t) = \frac{1}{Y_t} \tag{23}$$

The environmental cost of a marginal unit of production on one period is

$$\beta E_t \tag{24}$$

But this additional environmental degradation will stay over time therefore we get:

$$\beta E_t \times (1 + \frac{1}{(1+\rho)} + \frac{1}{(1+\rho)^2} + ...) \tag{25}$$

$$\beta E_0 (1-g)^t \times \frac{1}{1 + \frac{1}{(1+\rho)}} \tag{26}$$

We now understand that when you add to this situation the fact that households value leisure time it only adds an additional "cost" to production. Indeed, we can consider that society faces the following trade-off: households choose how to work to set a level of production knowing that this production will get them a positive utility by allowing themselves to consume some goods and services. On the other side, this production has a negative opportunity cost since to produce less could add to the amount of leisure time that this society can enjoy. (NB the question of the sharing of work is a crucial question in degrowth theory, but is outside the scope of the present thesis to address.) Finally, as we have seen above there is also an environmental cost to this production which is persistent and then produce a negative utility over all following period.

We can get a sense of it by simply expressing the amount of hours of work in term of Y_t and A_t. Then we get

$$H_t = \frac{Y_t}{A_t} \tag{27}$$

Then we can redefine the optimization problem

$$max \;\; \log Y_t + \alpha \log{(1 - \frac{Y_t}{A_t})} + \beta(\overline{P} - (P_{t-1} + E_t Y_t) \tag{28}$$

$$\tag{29}$$

and take the first order condition in respect of Y_t for one period.

$$\frac{1}{Y_T} - \frac{\alpha}{(A_t - Y_t)} - \beta E_t \times \frac{1}{1 + \frac{1}{(1+\rho)}} = 0 \tag{30}$$

With this equation we understand that when $\overline{P}$ =P$_t$ a marginal unit of environmental degradation will be associated to a sharp increase in β and therefore a sharp decrease in the optimal level of production.

We see that the model presented above is a way to represent economically the effect of an environmental limit or threshold where the disutility is demultiplied once the limit have been reached.

We can now consider the particular case of the environmental being a binding constraint which correspond to a case where $\beta_h igh$ is close to infinity (for instance when the overtaking of the limit means the impossibility to live on earth for humanity).

In this case you need to set Y_t such that $D_t = 0$ when you reach $\overline{P} = P_t$.

Then we can define the period T as the period when

$$D_t = 0 \iff Y_t E_t = \overline{R} \tag{31}$$

In this case of exogenous growth we can specify that:

$$Y_T = \frac{\overline{R}}{E_0(1 - g_E)^t} \tag{32}$$

This period will happen at some point as soon as $E_t Y_t$ is decreasing (if $g_E > g_Y$)

Basically we can express this as an optimization problem uunder an integral constraint.

$$max \sum_{t=0}^{\infty} (1+\rho)^{-t} [\log Y_t + \alpha \log 1 - H_t - \beta_{low} P_t)] \tag{33}$$

subject to

$$\int_{t=0}^{T} E_t Y_t - \int_{t=0}^{T} \overline{R} \leq \overline{P} - P_0 \tag{34}$$

Therefore we can from here, in the case of exogenous growth model, see whether or not a stable level of production is possible given your rate of improvement.

Indeed in this case we have

$$Y_t = Y_0 \tag{35}$$

We can then simply determine precisely the period T

$$Y_0 = \frac{\overline{R}}{E_0(1-g_E)^T} \tag{36}$$

$$\tag{37}$$

$$(1-g_E)^T = \frac{\overline{R}}{E_0 Y_0} \tag{38}$$

$$\tag{39}$$

$$T = \frac{ln(\frac{\overline{R}}{E_0 Y_0})}{ln(1-g_E)} \tag{40}$$

Looking at this result and looking whether or not

$$\int_{t=0}^{T} E_t Y_t - \int_{t=0}^{T} \overline{R} \leq \overline{P} - P_0 \tag{41}$$

is a simple way to answer to the question whether or not, given your current rate of improvement in environmental efficiency, it is possible to have a stable level of production.

It is important to note that we will not solve this model in this master thesis mathematically by giving all the value of H_t (the variable of choice for households) over time as a relation of the other variables. We will use a solver (Excel) to solve this model with real values and taking the case of climate change for two countries: France and the US.

5 Solving the optimization problem for France and the USA

In this section, we apply the optimization problem that have been presented in the previous part. Firstly, based on scientific discussion, we discuss the estimation of the key components of our model: environmental limits concerning CO_2 emissions, the level of sustainable CO_2 emissions, how to account for CO_2 emissions. . . . Then we solve the maximization problem for France and the USA and discuss the results. Finally, based on a report of McKinsey (2007), we study how the possibility to invest for abatement modify the optimization problem for the USA.

5.1 Estimation of the key components of the model

5.1.1 Evaluating the environmental limit

We understand that being able to evaluate the limit $\overline{P}$ and determining the "budget of pollution" that we can emit before reaching this limit is crucial to answer to the question of the possibility to grow without exceeding this limit. Therefore, in this part I present the scientific evaluation of the budget of carbon emission that we can emit in the atmosphere to stay under the limit of 2°C.

On this question there is an ongoing scientific debate. To make it clearer, please note that the difference of estimation of this budget come from three main sources. The first one is that we do not know the true sensitivity of global temperature to the greenhouse gases that cause warming. Secondly each carbon budget is associated with a percentage of chance to stay within the limit of 2°C. Therefore, the result depends whether we consider that we should target a 66% percent chance to stay below 2°C or a 50% chance. Finally, there is still debate about the reaction of earth ecosystem to global warming. For instance, Ying Sun of the University of Texas at Austin and colleagues (2014) consider that we underestimated the amount of carbon dioxide that plants absorb by about a sixth. On the other hand, Hansen (2013) argues that "cumulative emissions of 1000 billion tons, sometimes associated with 2°C global warming, would spur 'slow' feedbacks and eventual warming of 3–4C with disastrous consequences". These "slow feedbacks include greenhouse-gas releases from ecosystems as forests die and permafrost melts". Therefore, we understand that there are some differences in assessing how much carbon we can still emit in the atmosphere. To make sure that there is no confusion it is important to remind here that there is a difference between CO_2 emission and carbon emission: 3.67g of CO_2 is equivalent to 1g of carbon. One of the most serious estimation of this carbon budget has been made in the assessment of the science of climate change of the International Panel on Climate Change. In this report the IPCC (2013) tries for the first time to calculate the carbon budget and conclude that:

> a two-thirds chance of keeping warming below two degrees required the world to limit its total carbon emissions since 1860 to no more than a trillion tons of carbon. Of this grand all-time total, 515 billion tons had already been emitted by 2011.

So, according to the IPCC, we had in 2011 approximately 485 billion tons left from 2011. Nevertheless, other scientific quote others numbers. As it is stated in an article of Yale environment

360 (2014):

> A big study in Nature Climate Change in September by Michael Raupach of the Australian National University in Canberra and others, quotes 381 billion tons. The International Institute for Applied Systems Analysis, a think tank based in Laxenberg, Austria, and the Global Carbon Project says we have 327 billion tons to go. While the International Geosphere-Biosphere Programme, an international research consortium based in Sweden, say 250 billion tons.

In a paper published in *Nature* Meinshausen, M (2009) et al conclude that:

> Limiting cumulative CO_2 emissions over 2000–50 to 1,000Gt CO_2 yields a 25% probability of warming exceeding 2C—and a limit of 1,440 Gt CO_2 yields a 50% probability—given a representative estimate of the distribution of climate system properties.

In this thesis we will take as a reference the limit indicated in a report of the United Nationals Environment Programme.In this report, based on scientific evidence, UNEP (2014) considers that starting from 2014 it is possible to emit "less than 1,000 Gt of CO_2 before locking the planet in to dangerous temperature rises of more than 2°C above pre-industrial levels" (approximately 30 years of emissions). Since this was applicable starting from 2014 we have to substract the 40Gt of emissions of the year 2015. Therefore, we can put

Therefore we can put $P_0 = 0$ and $\overline{P} = 960\ Gt\ \mathrm{CO_2}$ equivalent.

How to share this budget between countries is a highly political and sensitive issue. For instance, some could argue that because already developed countries have historical emissions per capita which are higher and given that others countries still need to develop themselves they should have the possibility to emit a biggest share (compared to their population). On the other side, it is possible to consider that we should rather look at the percentage of reduction, but still accept that countries with higher emissions per capita today continue to emit a bigger share than others in the future. Therefore, it is important to be aware that these are political questions that does not represent a consensus admitted by everyone and that they could have been different.

Nevertheless, for simplicity, we will share the environmental budget in proportion of the country's population putting it equal to:

$$\overline{P}_{country} = \frac{Pop_{country}}{Pop_{world}} \times \overline{P}_{world} \tag{42}$$

5.1.2 Evaluating the sustainable level of emissions

Another important question to evaluate the possibility to grow economically is to evaluate R, the capacity of earth to absorb pollution. Once again there is here a scientific debate which is still continuing.

Concerning CO_2 emissions there is two major carbon sinks, forests and the ocean. As Pieter Tans, co-author of a study from the National Oceanic and Atmospheric Administration published in Nature (Ballantyne et al. (2012), said:

> Globally, these carbon dioxide 'sinks' have roughly kept pace with emissions from human activities, continuing to draw about half of the emitted CO_2 back out of the atmosphere. However, we do not expect this to continue indefinitely

Indeed a series of recent studies (Le Quéré, C et al, 2007; Nabuurs, G et al, 2013) put into evidence that natural sinks of carbon dioxide might no longer be keeping up with the increase rate of emissions which would lead to an acceleration of climate change.

Nevertheless, in their evaluation of the carbon budget IPCC and other scientists take into account these effect of carbon sinks. The only question which is interesting here is to know until when we are considering that carbon emissions accumulate into the atmosphere and what level of emissions can be consider as "neutral" for the climate. In their study Ballantyne et al. (2012) explain that the average rate of capture of carbon have gone from 2.4 billion to 5 billions tons of carbon per year. Therefore, we will consider here that at a low level of emissions the Earth can absorb 2.4 billion tons of carbon (=8.8 billions tons of equivalent CO_2). It means that we consider that once a country reaches a level of emissions which is equal to:

$$\overline{R}_{country} = \frac{Pop_{country}}{Pop_{world}} \times \overline{R}_{world} \tag{43}$$

it will have no additional effect on climate change.

5.1.3 How to count CO_2 emissions

Even if this question can seem obvious, given that there are good and developed statistics for CO_2 emissions per country, it is important to point out why it is also an important economic and politic question. Indeed, there is a major difference, especially in developed countries such as France, Sweden, UK etc., between emissions linked to the production of this country and emissions associated with their consumption. These economies have a developed service sector (banking, consulting) which is less polluting than the manufacturing or agriculture sector. Indeed, they are importing most of their goods such as electronics (phones, computer, washing machine), clothes and so forth. As it is stated in the study of Davis Caldeira (2010, p.5687),

> In some wealthy countries, including Switzerland, Sweden, Austria, the United Kingdom, and France, 30% of consumption-based emissions were imported, with net imports to many Europeans of 4 tons CO_2 per person in 2004.

In 2012 in France it is 211 millions of tons CO_2 equivalent that are not accounted in the national account of CO_2 emissions. It represents approximately 50% of the estimated CO_2 emissions of France.

Therefore, even if for a question of simplicity we will consider here the World Bank data which represent the emissions associated with the production on the territory, it is important to keep in mind this situation to not misinterpret the result. Even if the conclusion is that some countries can continue to grow with staying into their carbon budget it is only mean that they can increase their production of goods and services given the state of their economy and emissions intensity. It does not mean that the inhabitants of these countries does not have to decrease or change their consumption.

Finally, we have to emphasise that we here consider the CO_2 equivalent emissions which means that we are taking into account other greenhouse gas such as methane for instance. Most of these gases stay less time than CO_2 in the atmosphere but have a stronger warming effect. We can aggregate all these emissions by looking at their warming effect during their life time and expressing it in term of CO_2 equivalent.

5.1.4 Evaluating β

To be able to see the result of the maximization of this model we have to evaluate how much disutility households get from emitting one ton of CO_2 equivalent (if P_t is expressed in tons). This is obviously, as always when evaluating utilities of people, a theoretical exercise. Really few research has been done on this topic. We can nevertheless have a look on the paper of Achtnicht (2012) which evaluates the willingness to pay of car buyers in Germany to reduce their CO_2 emissions; they evaluate the willingness to pay for a car which emit less carbon everything else equal. The conclusion is that, "For the reference group, the median WTPs case could be accordingly translated into 256.29 and 89.44 per tCO_2". They also note (p. 20) that

> Nonetheless, all values are extremely high compared to the price that would have to be paid for a CO_2 certificate on the market for emission certificates in Europe (which could be used to offset

one's own emissions).

Another paper by Brouwer, Brander and Van Beukering (2008, p. 1) "the subjective perceived risk of climate change and society's willingness to pay (WTP) to avoid these risks" for air travel passengers. Their results are that:

> In the whole sample, passengers are willing to pay on average 60 eurocents per 100 km they fly. This corresponds with an average WTP of about 25 euros per tonne tCO_2-eq

This is much closer to the price that people can pay to compensate their emissions. Indeed, some private groups offer to people to pay to compensate their emissions by investing into projects that will reduce CO_2 emissions somewhere in the world. In its report concerning carbon compensation in France, the platform "info-compensation carbone" informs us that in total in 2014 there have been 1,238,978 ton CO_2 equivalent compensated for a total of EUR 6,718,864 . Prices are varying between EUR 0.80 and 30 per ton and the average price is EUR 5.4/ton equivalent CO_2.

Therefore, in this master thesis we will take EUR 5.40 (approximately USD 6) as a reference for the willingness to pay for reducing emissions by one ton of carbon. Then we will set β so that the average utility bring by USD 6 of production in society is equal to the disutility of one ton of carbon. By applying this reasoning to France in 2015 we get the following result:

$$\beta = log(Y) \times \frac{6}{Y} \tag{44}$$

$$\beta = 2.69E - 11 \tag{45}$$

It has to be noted that this method is just to have an estimation of beta which is not totally unrealistic. More research is needed however to evaluate the disutility that people associate with the emissions of one ton of carbon compare to the utility they get from the production link to this pollution.

5.2 Application for France and USA

We apply this model for the United States and France. These two countries are both developed countries with a relatively stable population. Nevertheless, their carbon intensity is quite different since the one of the US is approximately twice the one of France.

The US is one of the leading emitters in the world with 6.343 E+9 tons of CO_2 equivalent in 2012 (Worldbank data). Taking into account that these emissions are decreasing by about 2.2% since 2008, we estimated their current emissions to 5922 E+6 tons of CO_2 equivalent for 2015. At this year their GDP is equal to 1.659 E+13 (constant 2010 US$) (Worldbank data) which represent an estimated carbon intensity of 3.568 E-4 in 2015. This carbon intensity is decreasing since 10 years by approximately 3.3%. Concerning their labour market there was in 2015 157,129.9 thousands people (Worldbank data) working an average of 1790 hours annually (OECD). Then we can evaluate the productivity of labour at USD 59/hours. Over the past 10 years, this productivity has increased on average by 3.03% a years. Finally, with a population of 325 millions people (Worldbank data), the United States represent 4.4% of the world population. We can therefore attribute them 4.25E+10 tons of CO_2 equivalent as their carbon budget before reaching their sustainable level of emissions, which is 389 E+6 tons of CO_2 equivalent.

With a similar way of reasoning we get that France emitted approximately 483 E+6 CO_2 in 2015 (Worldbank data) for a GDP of 2.77E+12 (constant 2010 US$) (Worldbank data). This represent a carbon intensity of 1.74 E-4. The average rate of decrease of CO_2 equivalent emissions intensity over the previous 10 years is 2.2%. With 29,477.43 thousand people in work (Worldbank data) and an average of 1482 hours worked annually (OECD) we can estimate the total hours worked in France at 43,685 E+6 hours. The productivity of labour in 2015 is then USD 55.37 per hour worked and over the past 10 years this has increasing by approximately 1% per year. Finally, with a population of 66 millions people (Worldbank data), the French population represents 0.9% of the world population. Therefore, France has a carbon budget of 8.409 E+9 tons of CO_2 equivalent before reaching its sustainable level of emissions, at 79.642 E+6 tons CO_2 equivalent.

5.2.1 Is it possible to keep a stable GDP with this rate of progression for carbon intensity?

First of all we consider whether or not, at this rate of progression of carbon intensity, it is possible to keep a stable GDP without exceeding their carbon budget. We see that neither of the two countries is on the right path if we acknowledge a global limit of 960 GtCO_2 before reaching a sustainable level. Indeed, at this rate of progression for carbon intensity, the US will reach a sustainable level of emissions in 2095 if keeping their GDP stable. By that time, they will have emitted 1.66 E+11 tons of CO_2 equivalent, which is 1.2E+11 more than their limit. We therefore see that even if we consider a higher limit or if we attribute a bigger part of the global limit to the US it will still be true to say that the US is not decreasing its carbon intensity fast enough to be sustainable without diminishing its production. We can calculate that to stay within the environmental limit with a stable GDP, the US would need to decrease by 13% (4 times more than today) every year until 2034, the year by which the US will then reach its sustainable level of emissions.

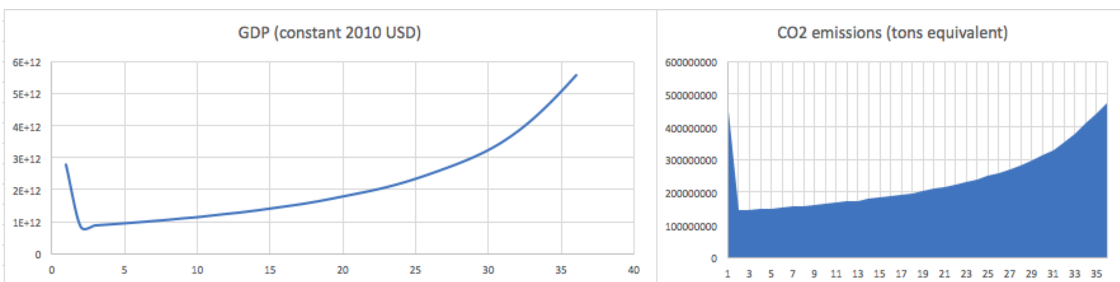
Concerning France, at this rate of reduction in the carbon intensity it is only in 2102 that it will reach a sustainable level of emissions. By that year, France will have emitted 1.98 E+10 CO_2 equivalent, which is 1.14E+10 CO_2 equivalent more than the limit. Nevertheless, we observed a clear difference with the US since it is only by having an annual decrease of 3% that France can have a stable GDP without exceeding its environmental limits.

5.2.2 Solving for the optimal level of production

Then we solve the maximization problem by putting $\overline{P}$ as a binding constraint and considering the number of hours worked as the variable of choices for households. The level hours worked with the productivity determine the level of production. This level of production is link to the carbon intensity to give the amount of CO_2 emissions.

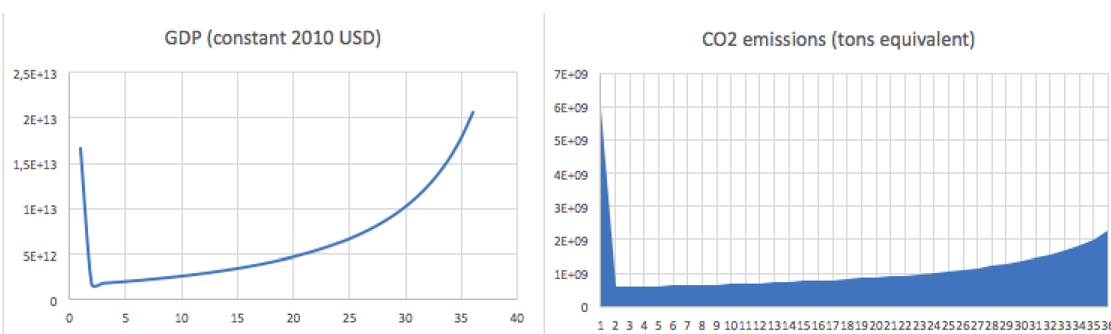
We see that in both cases the optimal level of production is represented by an extremely sharp decrease the first year following by an increasing rate of growth of GDP the following years.

Figure 1: Optimization for France with 2,2% annual decrease of carbon intensity (and without limit for rate of growth or degrowth)



Source: author's calculation.

Figure 2: Optimization for the USA with 3,3% decrease of carbon intensity (and without limit for rate of growth or degrowth)

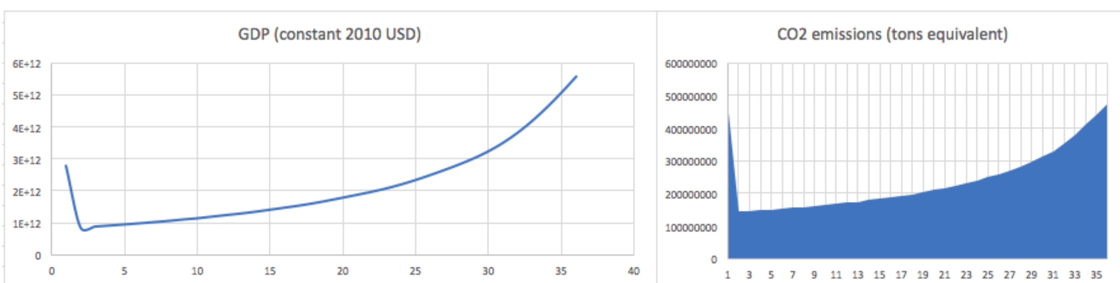


Source: author's calculation.

We see that these results do not make a lot of sense if we consider a real society. First of all, this is so because the utility that people get from their consumption can be considered as relative to their consumption in the previous years. Therefore, it will not make sense that a society choose to experience in one year such an enormous decrease of their consumption (69% in France). Nevertheless, we understand that if the solver gives this solution it is because experiencing such a decrease leave some ecological space to have an even bigger growth in the future (approximately 6 to 10% of growth of GDP between 2040 and 2050 for France). Of course, such levels of GDP growth are also unrealistic.

What is maybe more surprising and interesting is that we find similar type of result for France even when considering an annual decrease of 5% of carbon intensity. It means that even with a rate of progress which make it possible for france to grow with staying under the environmental limit, it is more optimal to first experience a sharp decrease of consumption to be able to grow even more afterwards. (Once again this situation is associated with extremely high rate of growth, between 6 and 11% after the first year).

Figure 3: Optimization for France with 5% annual decrease of carbon intensity (and without limit for rate of growth or degrowth)

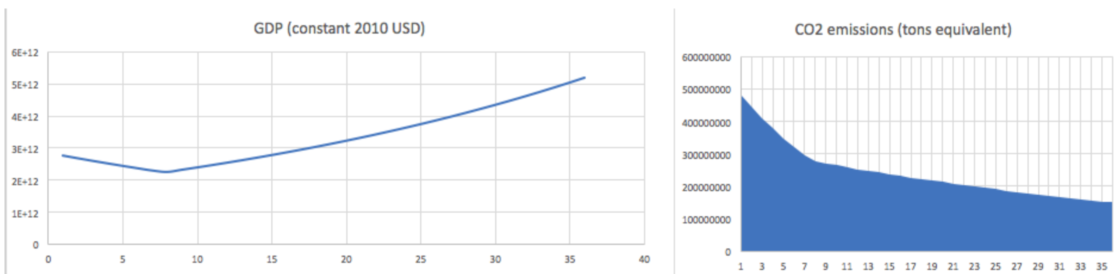


Source: author's calculation.

Moreover even if we consider an environmental limit which is two times higher or if we increae the discount rate to 5% we always find back an important decrease of production follow by increasing growth rates.

We can control for unrealistic rate of growth or degrowth by not allowing any growth of GDP greater than 3% and any decrease of GDP greater than 3%. This give the following results type of results for France (Fig. 5).

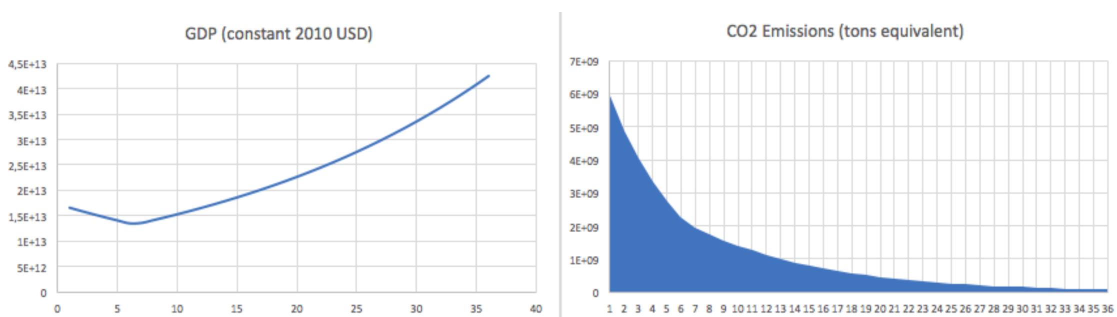
Figure 4: Optimization for France with 5% decrease of carbon intensity
(with a limit of 3% for rate of growth and degrowth)



Source: author's calculation.

Similarly, for the US, even if we consider that they can achieve an annual decrease of carbon intensity of 14% (and then have the capacity to continue to grow without exceeding the environmental limits) the optimal path of production still begins by a decrease. Figure 6 shows the results when allowing no increase or decrease of GDP by more than 4%.

Figure 5: Optimization for the USA with 14% decrease of carbon intensity
(with a limit of 4% for rate of growt and degrowth)



Source: author's calculation.

Therefore, the main results of this maximization problem is that even when it is not necessary to downscale the economy (as in the case in France) it can be rational to do so as soon as there is a binding environmental constraint. Indeed, introducing the environmental binding constraint in the optimization problem make that the carbon intensity of each year represent the "environmental price" of consumption. Therefore, because this price is declining quite rapidly (for instance by 5% per year) it is rational for a society to choose to consume less for waiting the period when the environmental price will be lower.

Even if as in the case of France having a carbon intensity decreasing by 5% it is more optimal to decrease its production first to have the possibility to experience in the future an even bigger rate of growth. We therefore understand clearly that this trade-off is also dependent on the fact that a society has the capacity to grow at a relatively high rate in the future.

To summarize, we can say that as soon as a society recognizes an environmental constraint as binding, also if it is possible to have sustainable growth, it has to compare the environmental price of today to the one of the future. Indeed, it can be optimal to reduce in the present the production of the society to "keep environmental budget" for a time when the environmental price will be far lower. Then this decrease in production is associated with the hope to be able to produce even more in the future. This result is an important finding, one which support the idea that our societies should consider and discuss about the possibility to collectively choose to limit our production and to research how it is possible to do so without experiencing an increase in social problems (poverty, unemployment etc.).

5.3 Including the possibility to invest for CO_2 abatement in the USA

In this second part, we re-consider the question with the possibility to invest into emissions abatement. Indeed, households can choose to invest a part of their production to modify their emission intensity and diminish the impact of their production on environment. This possibility modifies the choice and the trade-off that households face by giving them the opportunity to gain environmental space in the future by sacrificing part of their consumption today. First of all, we need to explain why these investment need to be considered separately from the typical capital investment that we find in all conventional models. Indeed, in his call for a "new macroeconomy" Jackson (2011, p.111) suggests that,

> we might want to separate investment dedicated to reducing the demand for resources from conventional business investments aimed at the recapitalisation of productive capacity.

The main difference of these investment compared to investment in productive capital is that they are often "substitution investment". It means that they are not done to accumulate new capital, but are done for the purpose of replacing existing capital which is not yet fully depreciated (such as all the infrastructure of the coal and oil industry). For this difference to be significant we need to be sure that they are indeed in substitution of polluting infrastructure, which means for instance that investment in renewable energy lead to a reduction of the use of fossil fuel energy and not just to a rise of global energy consumption. In this case, though, these investments will not help to accumulate new productive capital and does not represent an opportunity to produce more in the future. These investments are made to replace polluting infrastructure with cleaner one and then reducing the emission intensity of production.

Therefore, we have to look at abatement opportunities and the abatement cost curve for each society. This is exactly what McKinsey (2007) has done in several report for specific countries (Poland, Germany, USA) but also at a global level. McKinsey (2007) identifies several opportunities for CO_2 abatement by looking at energy efficiency of vehicles, buildings, and industrial equipment. It's indeed possible to reduce energy consumption by investing for more fuel-efficient car engines, better insulation of buildings, efficiency controls on manufacturing equipment...

Shifting energy supply from fossil fuels to low-carbon alternatives. This concern for instance electricity production from wind, nuclear, or hydro power, equipping fossil fuel plants with carbon capture and storage (CCS), replacing conventional transportation fuel with biofuels...

The possibility of "Halting ongoing tropical deforestation, reforesting marginal areas of land, and sequestering more CO_2 in soils through changing agricultural practices"

From this, and by looking at the cost of the different investment that are needed, McKinsey (2007) constructs an abatement cost curve which present for each possible investment (e.g. active forest management, distributed solar PV and other interventions) it's potential of abatement in Gigatons/year and the abatement cost which is associated with it (in USD per ton CO_2e). From this it is possible to calculate the average cost for reducing by one ton/year CO_2 emissions.

Therefore, we will use this work from McKinsey (2007) to model the opportunity of investment for CO_2 abatement to see how it modifies the trade-off that households face and how it changes the result that we presented above

We now have:

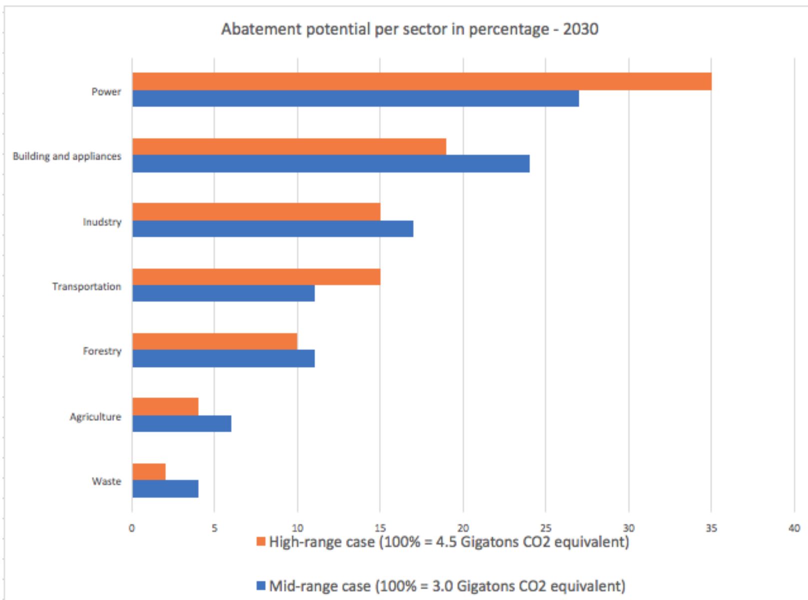
$$P_t = D_t - A_t \tag{46}$$

$$A_{t+1} = A_t - \frac{I_{A_t}}{\overline{C}} \tag{47}$$

With A_t being the level of abatement realized at period t and $\overline{C}$ the average cost of abatement.

This abatement cannot exceed the total potential of abatement that is presented, for every sector, in the report of McKinsey (2007) (see table 5). We will consider here the high range case with a possibility of 4.5Gt of abatement in comparison with the business as usual scenario and an average cost of abatement of 40$/ton.

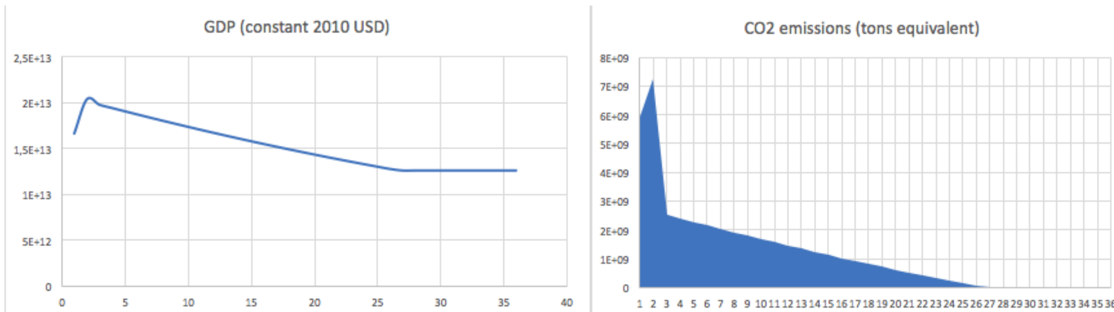
Table 5: US abatement potential by sector - 2030



Source: author's adoption from McKinsey

Solving this new optimization problem for the case of the USA give the results presented in Figure 7.

Figure 6: Optimization for the USA with the possibility to invest in CO_2 abatement



Source: author's calculation

We see that in this case first there is an increase of production which is associated with massive investment in abatement and then a steady decrease of production. These result are in line with the mechanism of environmental price presented above. Indeed, here, with the possibility to invest for abatement, all the progress in environmental price can be made at once. Afterwards there is no future decrease in environmental price and therefore, because of the preference for the present and because the abatement potential is limited, the results show a degrowth of GDP.

6 My contribution

In this master's thesis I have studied how taking into account an environmental constraint as binding affects the optimal level of production and growth in a society. By introducing the concept of environmental limits into a "conventional" economic model, this master's thesis makes clear that "sustainable growth" requires more than only having growth and diminishing level of pollution. Indeed, economics have to look whether or not this decrease of pollution is important and rapid enough to be able to continue to grow economically without exceeding environmental limits.

Firstly, I have shown that neither France nor the US have a rate of decrease of carbon intensity which is sufficient to achieve a stable level of production without exceeding their respective carbon budgets. This shows, especially in the case of the USA, that achieving sustainable growth is an extremely difficult challenge. It cannot be achieved without rapid and important investment in abatement technology for an environmentally cleaner production.

Secondly, the main finding of this master's thesis is that including in the analysis environmental constraint as binding is a way to attribute an environmental price to production. The part of your environmental budget that you consume now is something that you will not be able to consume later. Therefore, if the environmental price of production (here the carbon intensity) is decreasing fast enough, even if degrowth is not "necessary" (you can continue to grow and stay within environmental limits) it can still be economically optimal. Indeed, because the environmental price of today is way costlier than the one of the future, it is optimal to "sacrifice" production/consumption now to be able to produce/consume even more in the future, once progress will have been made in term of environmental intensity. Therefore, this master's thesis supports the idea that we should consider more seriously the position of degrowth economists and have more research directed at judging whether or not degrowth is environmentally necessary or optimal.

Finally, this paper supports the idea that, concerning investment in CO_2 abatement, the sooner the better. Therefore, this master's thesis could contribute to the public debate and confirm the idea that delaying action, when facing a binding environmental constraint, is costly.

These results are illustrated by using tools of conventional economics and show the sense of rationality behind the idea of degrowth. Therefore, the approach employed here can help expand our understanding and argumentation of traditional economics when it comes to introducing environmental limits into current models. It aims to foster the economic debate not only into academic circles but also for decision makers who want to preserve a good social and economic situation and avoid environmental catastrophes at the same time.

7 Future research

In order to make the model closer to the reality, in this section I will discuss what the possible improvement for future research are. I will set out by discussing how it would be possible to represent the possibility of investing for adaptation, then I will look at the case when considering population growth. Finally, we will discuss on other way to represent disutility associated with pollution.

First of all, a more complex model could introduce the possibility for a society to invest for adaptation. Indeed, some investments can be made in order that the disutility that the society get from pollution is attenuated. Therefore, we could imagine a model where beta would be a function of previous investment for adaptation. Of course, this comes with an important challenge, namely concerning the way how to measure the effect of investment on our capacity to adapt for climate change or other environmental problems.

Secondly a more complex model should include the effect of population growth. It would be interested to discuss such a model by also looking at the consumption and emissions per capita. Taking into account change in population raise questions about the attribution of global carbon budget between countries. Indeed, some could argue that a society is responsible for "controlling" its population and that therefore the "emissions budget" should be fixed at some point and time and not be dependent of the evolution of the population. On the contrary, others could consider that every human should have the same "right" to emit and therefore the limit should be determined also given the projection of population growth.

Moreover, this model considers that the disutility from pollution is linear until a threshold is reached. Future research could discuss other ways to better represent the effect of pollution on a society. Without leaving out the notion of thresholds some could argue that an exponential function represents in a better way how people are affected by pollution before reaching the limit.

Finally, it is legitimate to ask ourselves whether this type of model could be applied to other environmental limits such as nitrogen for instance. Indeed, because some environmental issues are linked to specific sectors (e.g. agriculture) it is more hazardous to analyse them with a direct link between global production (GDP) and environmental degradation. On the other side it has to be recalled that climate change is not the only limit that we should not exceed and that we should look at the possibility to study environmental issues in an aggregate way in order to really say something about the sustainability of a society. We can also point out that the access of data can be a problem, in term of applicability to different environmental issues, since all environmental problem are not documented as much as climate change. Therefore, more research on coherent ways to aggregate different environmental degradation would be needed.

8 Conclusion

My paper shows that considering an environmental constraint as binding affects the optimal level of production and growth for a society. Indeed, since the society have to stay within a limited "environmental budget", the environmental intensity (here the carbon intensity) represent the environmental price which is associated with production at a period T. This paper shows that if it is possible to forecast that this carbon intensity will decrease and be far lower in the future, then it can be rational to downscale its economy in the first place to keep environmental place for the future when the production will be environmentally more efficient. Therefore, this paper supports the idea that "degrowth theory" should be actively considered and made subject to debate, indeed that the possibility of degrowth should be considered by conventional economics. Moreover, since science indicates that some environmental limits (biodiversity, climate change etc) are indeed binding and cannot be exceeded without threatening the capacity of humanity to survive on Earth, this paper is an invitation to deepen macroeconomics research and modelling taking such constraints into account.

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