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Non-CO2 Greenhouse Gas Mitigation Modeling with Marginal Abatement Cost Curves: Technical Change, Emission Scenarios and Policy Costs

By **Samuel Carrara**, Fondazione Eni Enrico Mattei (FEEM) and Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Italy

Giacomo Marangoni, Fondazione Eni Enrico Mattei (FEEM) and Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Italy

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Summary
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Keywords: Non-CO2 Greenhouse Gases, Marginal Abatement Cost Curve, Technical Change

JEL Classification: Q54, Q55

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement n° 282846 (LIMITS).

Address for correspondence:

Samuel Carrara
Fondazione Eni Enrico Mattei
Corso Magenta 63
20123 Milan
Italy
Phone: + 39 02 52036932
Fax: + 39 02 52036946
E-mail: samuel.carrara@feem.it

Non-CO_2 greenhouse gas mitigation modeling with marginal abatement cost curves: technical change, emission scenarios and policy costs

Samuel Carrara and Giacomo Marangoni

Climate Change and Sustainable Development Division of the Fondazione Eni Enrico Mattei (FEEM), Milan, Italy

Climate Impacts and Policy Division of the Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Milan, Italy

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Abstract

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Corresponding author: Samuel Carrara, Corso Magenta 63, 20123 Milan, Italy. Tel: + 39-02-52036932, Fax: + 39-02-52036946, E-mail: samuel.carrara@feem.it

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1 Introduction

According to the IPCC Fourth Assessment Report [1], there is unequivocal scientific evidence that world climate is undergoing a process of global warming. Human activities reasonably play a major role in this sense, as – the Report states – "most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations". It has been calculated that, without any structural interventions in terms of emission abatement, global temperature is likely to increase by 2.3 ÷ 4.5°C with respect to the pre-industrial levels, which could imply dramatic consequences both from an environmental and a socio-economic point of view: a 2°C-increase has in fact been identified as the threshold beyond which irreversible changes in natural ecosystems may occur.

The reduction of greenhouse gas (GHG) emissions is thus a vital target for the coming decades. Carbon dioxide (CO_2) is by far the most important factor contributing to the phenomenon, nevertheless human activities produce several other GHGs, which must be accounted for in order to give an exhaustive analysis of the problem. Basing on this assumption, the Kyoto Protocol [2] widened the perspective beyond mere carbon dioxide, formulating international agreements in terms of a "basket of greenhouse gases", with a complete substitutability among them through the Global Warming Potential (GWP), which accounts for the "greenhouse power" of a GHG compared to carbon dioxide, and the consequent introduction of the concept of CO_2eq. In particular, apart from carbon dioxide, this basket includes methane (CH_4), nitrous oxide (N_2O) and the so-called fluorinated gases, i.e. hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6). These gases will be referred at as other greenhouse gases (OGHG) henceforth.

Following a thorough literature review, Lucas et al. [3] inferred that a multi-gas mitigation approach could entail many advantages, such as i) higher flexibility in finding abatement solutions, ii) lower costs with respect to CO_2-only strategies, thanks to the relative cheapness of some OGHGs abatement, and iii) more rapid environmental benefit if efforts are concentrated on the abatement of short-lived gases. However, up to the middle of the past decade, most studies were still concentrated on carbon dioxide only (see for instance [4] and [5]), mainly due to the lack of exhaustive information concerning the real abatement potential for the various OGHGs and the relating costs.

In 2006 the Energy Modeling Forum (EMF) promoted a model comparison study (EMF-21 [6]) in order to fully assess the potential of OGHG abatement and thus the opportunity of a multi-gas mitigation strategy, in comparison with a single-gas approach: results showed that a 30 ÷ 60% cost reduction is attainable in the former case [6] [7]. The OGHG abatement potentials and costs were provided in the form of marginal abatement cost (MAC) curves, which indicate the abatement cost of an additional ton of gas given the absolute amount or the relative share of avoided emissions. The use of MAC curves has become a standard approach in most models for evaluating OGHG mitigation, not only in those involved in EMF-21 (e.g. [8] ÷ [12]), but also in others (e.g. [13]). Exceptions are fairly rare (e.g. [14], where abatement possibilities are directly modeled, in a bottom-up scheme, as substitution elasticities in the production function).

The MAC-based approach is used also in WITCH, the Integrated Assessment Model (IAM) developed by the CCSD (Climate Change and Sustainable Development) research group at FEEM and adopted for this work. WITCH (World Induced Technical Change Hybrid) is a climate-energy-economy model written in the GAMS language aiming at studying the socio-economic impacts of climate change. It is defined hybrid because it combines an aggregated, top-down inter-temporal optimal growth Ramsey-type model with a disaggregated, bottom-up description of the energy sector. Two key features distinguish this model. Firstly, technical change in the energy sector is endogenously modeled through innovation and diffusion processes, boosted by Learning-by-Doing and Learning-by-Researching (R&D), which yield advancements in carbon mitigation technologies; international technology spillovers are also considered. Secondly, the model presents a game-theoretic set up which can work according to two different schemes: in the first one, the thirteen macro-regions in which world countries are grouped cooperate in order to find a solution which is globally optimal, while in the second one, which has been adopted in this work, the regions interact according to an open-loop Nash game to define the solution which is strategically optimal for each of them (Nash equilibrium). The thirteen economic regions are USA (United States), WEURO (Western EU and EFTA countries), EEURO (Eastern EU countries), KOSAU (South Korea, South Africa and Australia), CAJAZ (Canada, Japan and New Zealand), TE (Transition Economies, namely Russia and Former Soviet Union states and non-EU Eastern European countries), MENA (Middle East and North Africa), SSA (Sub-Saharan Africa), SASIA (South Asian countries), EASIA (South-East Asian countries), CHINA (People's Democratic Republic of China and Taiwan), LACA (Latin America and Central America) and INDIA (India). For further information about the model, see [15] and [16].

Marginal abatement cost curves for the OGHGs in WITCH were derived from [17], an EPA report which was released in the EMF-21 context as well, being manipulated ruling out negative values for conservative reasons[1] and normalizing the provided absolute values on baseline emissions, in order to obtain percentage data. The curves are built defining eleven cost categories, from 10 to 200 $/tCeq, associating to each of them, for every region and every gas, the relative share of emissions which is abatable at that cost. This stair-step formulation, implemented in the previous version of the code, has one important defect, though: the research of the optimum abatement share can be performed only discretely, being automatically identified in one of the curve steps.

Furthermore, another important limitation affects the MAC formulation provided in EMF-21 study: the set of cost-abatement data is provided for 2010 only[2] and thus no information is available concerning the evolution of mitigation opportunities after that year. Considering also that in many regions the highest allowable abatement is very low and that the latter is unlikely to remain constant over time, an exogenous technical improvement was implemented. In particular, for the highest category only (200 $/tCeq), a technical progress factor (TP) multiplying the relevant abatement share over time was introduced, fixing an upper bound to the amount of gas which could be potentially abated and setting it equal to 90%. Initially TP was fixed so that it reached 2 in 2050 and the upper bound of 3 in 2075; afterwards it was revised, introducing a growth of 1/7 per 5-year period, starting from 1 in 2010 (and 2005) up to the limit of 4, which was reached in 2115[3]. Nevertheless, such a scheme to model the technical change can lead to some criticisms, not as much referred to the concept of a multiplying exogenous technical progress factor itself, but on its relevance for the highest cost category only: as will be discussed further on, in fact, TP is normally relevant for the whole marginal abatement cost curve. A discussion on the amount of TP was necessary as well. In this work, different TP values have been considered in order to perform a complete sensitivity analysis and choose more consciously the proper value for that factor.

Finally, it must be also considered that up to the present work, WITCH featured baseline OGHG emissions, exogenously fixed, still referring to 2006 data (also in this case provided by EPA [18]), and thus an updating of the emission projections was considered mandatory.

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[1] Those values refer to interventions which might yield a positive cost-benefit ratio.

[2] Actually absolute abatement data are available for 2010 and 2020, but relative ones are the same for both years.

[3] WITCH simulations cover the period 2005 ÷ 2100, nevertheless, in order to avoid end-of-the-world effects, the optimization process is performed up to 2150.

Summing up, the objectives of the work are:

1. update baseline OGHG emissions, in order to produce and discuss more reliable results;
2. show the importance of considering or neglecting the impact of OGHGs on determining environmental and economic scenario evolution;
3. interpolate the discrete marginal abatement cost curves provided by EPA, in order to obtain continuous functions which could make the optimization of the abatement share more rational and precise, and describe the new mathematical formulation of the problem in WITCH;
4. carry out a sensitivity analysis varying the technical progress factor, in order to evaluate the effects of different advancement scenarios in OGHG abatement.

Calculations have been carried out following two different policy scenarios:

- Carbon Tax;
- Stabilization 535.

Within each of these, five scenarios concerning the technical progress factor have been identified:

- CO_2 only;
- TP off;
- TP low;
- TP medium;
- TP high.

The meaning of these categories is immediate, and will be fully described further on. All results are compared to those obtained in the Business-as-Usual (BaU) scenario.

The paper is structured as follows. Section 2 is dedicated to the updating of OGHG baseline emissions and to the quantitative evaluation of the importance of taking into account those gases in assessing energy, economic and environmental impacts of climate change. In Section 3 marginal abatement cost curves are presented, in particular dealing with their interpolation and the effects of technical change on their shape. Section 4 describes more in depth the aforementioned policy and TP scenarios, while in Section 5 the results of the code calculations are presented and discussed. Conclusions in Section 6 close the paper.

2 OGHG baseline emissions and impact

As mentioned in the Introduction, the Kyoto Protocol OGHG basket features methane (CH_4), nitrous oxide (N_2O) and the so-called fluorinated gases, i.e. hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6). In addition, nitrogen fluoride (NF_3) is also considered in the 2011 EPA report which has been taken as a reference for the evaluation of baseline emissions [19]. Fluorinated gases are grouped into two categories in WITCH: short-lived and long-lived fluorinated gases (SLFs and LLFs), depending on whether their lifetime in the atmosphere is higher or lower than 100 years. In particular, PFCs, SF_6 and NF_3 belong to the latter category, while all HFCs belong to the former, with the main exception of HFC-23.

OGHGs are produced by a large number of sources; Table 1 summarizes the main ones, grouping them into four sectors: energy, industrial processes, agriculture and waste.

The EPA report provides detailed annual baseline emissions from 1990 to 2030 (2035 for SLFs), thus coupling a historical data survey with a mid-term forecast[4], for each table item and for each country, which then have been aggregated into the four OGHG categories and the thirteen WITCH regions. Data are already reported in megaton of equivalent CO_2 ($MtCO_2eq$), thus no conversion through the GWP is needed. However, for the sake of completeness, 100-year GWPs[5] for the four OGHG categories are listed below:

- CH_4: 21
- N_2O: 310
- SLFs: 1430
- LLFs: 22800

Beyond 2030/2035, we have assumed growth rates taken from IIASA-MESSAGE-B2 scenario [20], which is based on similar assumptions as WITCH and, in particular, has a similar regional decomposition.

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[4] The base year for WITCH simulations is 2005.

[5] Due to the different lifetime of the various OGHGs, GWP is not a univocal value, but depends on the considered time period: as WITCH simulations extend up to 2100, the 100-year value is properly adopted.

Sector/Source	Gas
Energy	
Natural Gas and Oil Systems	CH_4
Coal Mining Activities	CH_4
Stationary and Mobile Combustion	CH_4, N_2O
Biomass Combustion	CH_4, N_2O
Other Energy Sources	
Waste Combustion	CH_4, N_2O
Fugitives from Solid Fuels	N_2O
Fugitives from Natural Gas and Oil Systems	N_2O
Industrial Processes	
Adipic Acid and Nitric Acid Production	N_2O
Use of Substitutes for Ozone Depleting Substances	HFCs (SLF)
HCFC-22 Production	HFCs (LLF)
Electric Power Systems	SF_6
Primary Aluminum Production	PFCs
Magnesium Manufacturing	SF_6
Semiconductor Manufacturing	HFCs (LLF), PFCs, SF_6, NF_3
Flat Panel Display Manufacturing	PFCs, SF_6, NF_3
Photovoltaic Manufacturing	PFCs, NF_3
Other Industrial Processes	
Chemical Production	CH_4
Iron and Steel Production	CH_4
Metal Production	CH_4, N_2O
Mineral Products	CH_4
Petrochemical Production	CH_4
Silicon Carbide Production	CH_4
Solvent and Other Product Use	N_2O
Agriculture	
Agricultural Soils	N_2O
Enteric Fermentation	CH_4
Rice Cultivation	CH_4
Manure Management	CH_4, N_2O
Other Agriculture Sources	
Agricultural Soils	CH_4
Field Burning of Agricultural Residues	CH_4, N_2O
Prescribed Burning of Savannas	CH_4, N_2O
Open Burning from Forest Clearing	CH_4
Waste	
Landfilling of Solid Waste	CH_4
Wastewater	CH_4
Human Sewage - Domestic Wastewater	N_2O
Other Waste Sources	
Miscellaneous Waste Handling Processes	CH_4, N_2O

Table 1 – OGHG sources [19].

The following charts report the resulting OGHG baseline emissions. In particular, Figure 1 shows the detailed emissions sorted by gas, while Figure 2 shows the cumulative ones.

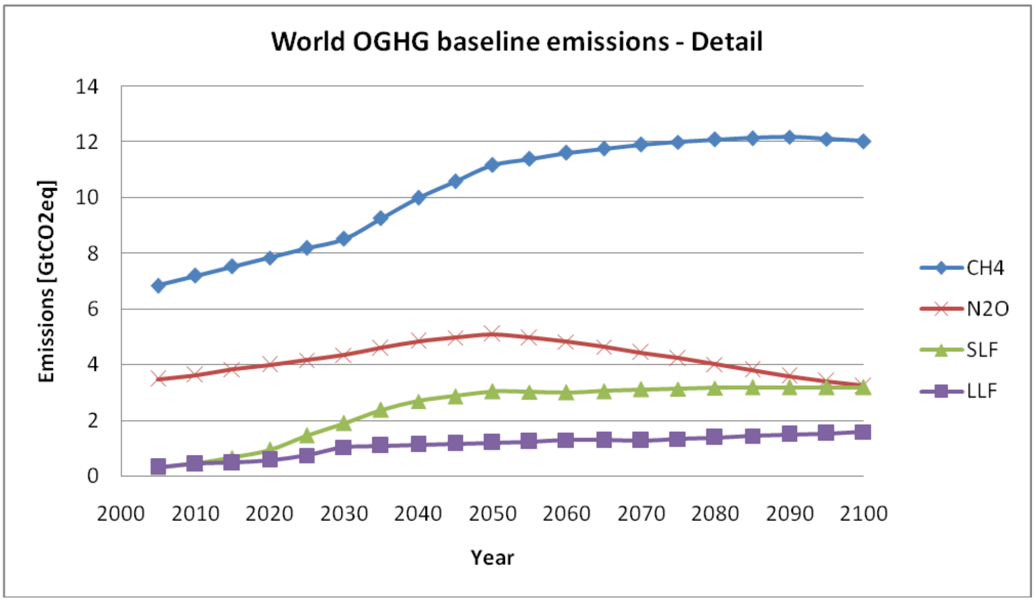

Figure 1 – OGHG baseline emissions: detail.

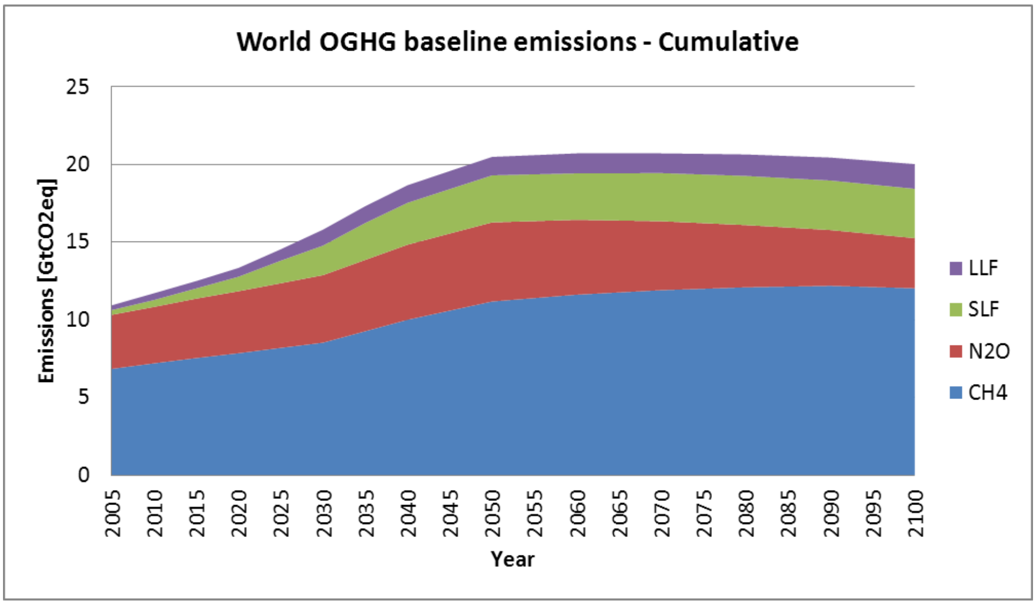

Figure 2 – OGHG baseline emissions: cumulative.

As one can see in Figure 1, emissions are expected to grow over the century – considerably in the first half, almost imperceptibly in the second one – for all OGHGs except for nitrous oxide, which firstly increases up to the middle of the century by some 50% and then decreases slightly below the 2005 value in 2100. Methane emissions, which represent by far the most significant contribution (constantly 55 ÷ 60%), almost double over the century, while fluorinated gases show a heavier increase, which is tenfold and fivefold for SLFs and LLFs, respectively. SLF emissions almost reach N_2O ones at the end of the century (16% share).

The resulting cumulative behavior is visible in Figure 2: OGHG emissions roughly double (from 10.9 $GtCO_2eq$ to 20 $GtCO_2eq$) in the first half of the century, and then remain essentially constant from 2050 to 2100.

In order to evaluate the OGHG greenhouse effect, it is interesting to compare these results with CO_2 emissions. It must be specified that, differently from OGHG baseline emissions which are exogenously imposed, in WITCH carbon dioxide ones are endogenously calculated by the code as a result of the optimization process. In order to obtain baseline emissions, it is then sufficient to run the code without imposing any kind of policy or technology constraint, i.e. under a Business-as-Usual scenario. Figure 3 shows the unconstrained growth over the century of CO_2, whose annual emissions rise from 33.6 Gt to 92 Gt, and the global GHG annual emissions, which grow from 44.5 $GtCO_2eq$ to 112 $GtCO_2eq$ as a result of the OGHG addition. Basing on these numbers, OGHG share is equal to 25% in 2005 and then decreases down to 18% in 2100.

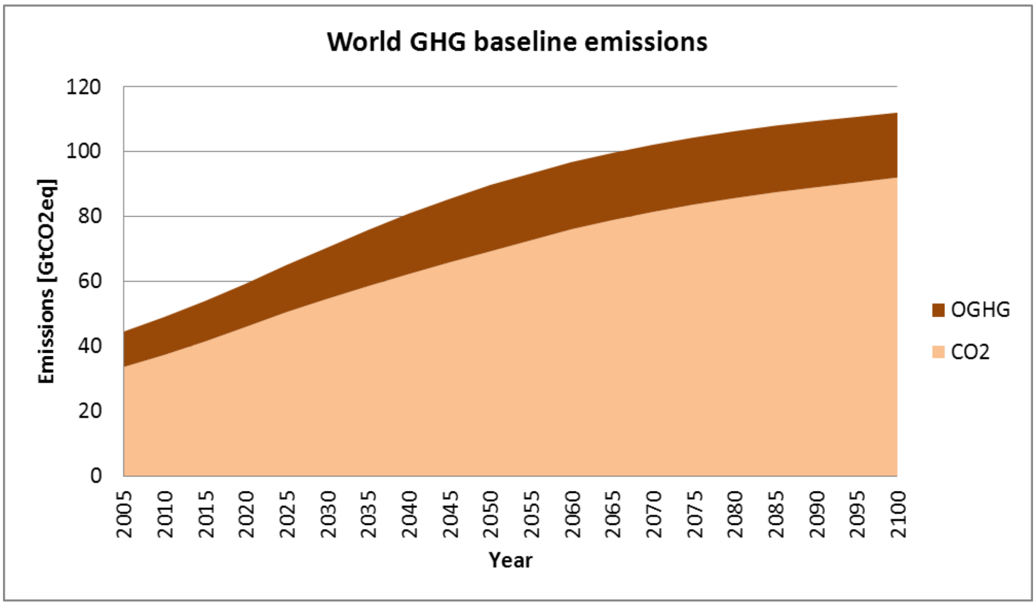

Figure 3 – GHG baseline emissions.

However, it is known that the real greenhouse effect of a gas is not measured through the annual emissions, but through the radiative forcing (RF), which accounts for the impact in terms of heating action on the atmosphere as a function of the concentration[6]. The pie charts of Figure 4 and Figure 5 show 2005 and 2100 (baseline) RF shares, comparing CO_2 and OGHGs disaggregated into the four categories. If OGHG emission share is 25% and 18% in 2005 and 2100, in terms of radiative forcing the percentage rises up to 27% and 23%. Not surprisingly, long-lived fluorinated gases show a stronger impact than short-lived ones, if compared to their emissions.

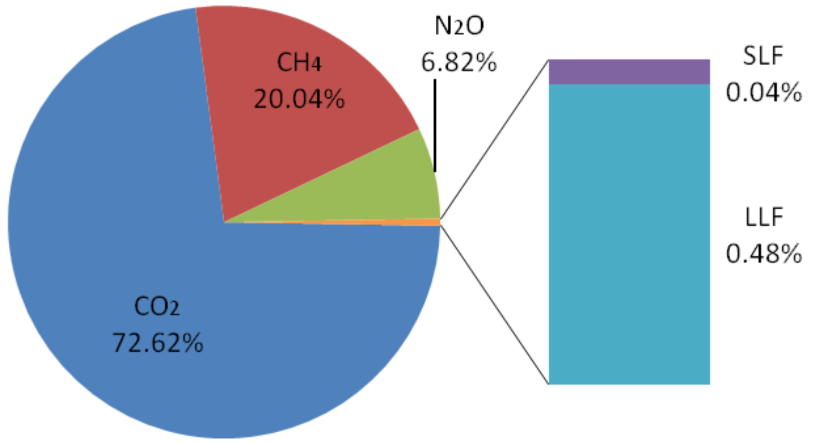

Figure 4 – GHG radiative forcing share in 2005.

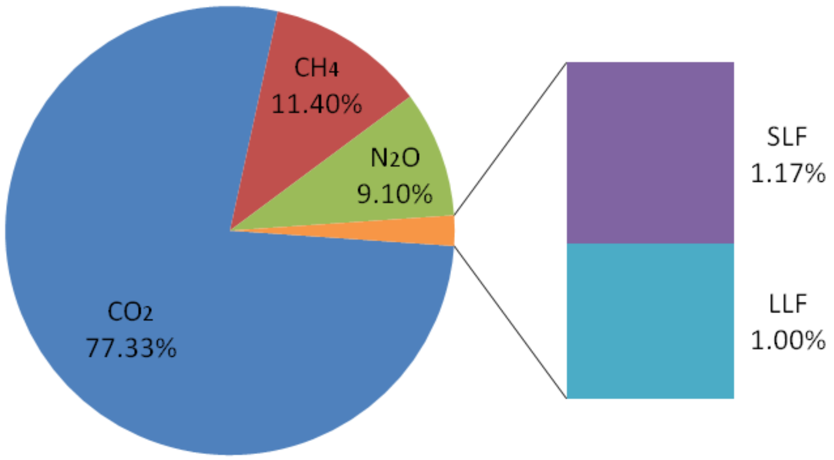

Figure 5 – GHG radiative forcing share in 2100 (baseline).

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[6] The equations which translate emissions into concentrations, and the latter into radiative forcing, are taken from the IPCC 2007 report [1] as far as CO_2 is concerned, while they are taken from the MERGE code for non-CO_2 gases [21].

Observing these data, one can easily understand why considering OGHGs is crucial in evaluating global impacts of gas emissions. Limiting the analysis to mere carbon dioxide emissions would entail an underestimation of the phenomenon by roughly one quarter, thus oversimplifying the problem and miscalculating optimal solution strategies.

3 Marginal abatement cost curves and technical change

3.1 MAC updating in WITCH

Marginal abatement cost curves represent a consolidated approach for the evaluation of non-CO_2 greenhouse gas emission abatement potential and are used by most integrated assessment models (IAMs) [8] ÷ [12]. A MAC curve indicates the abatement cost of an additional ton of gas given the absolute amount or the relative share of avoided emissions: the subtended area gives the specific abatement cost.

The MAC curves used in WITCH are taken from the 2006 EPA report [17]. The report not being very recent, data have been undergoing a process of updating and some preliminary values of the new report have recently been released [22], but since they refer just to few sources or sectors, old data have been maintained for the present work. However, the main problem which affects the old formulation in WITCH is that MAC curves have a step shape, being built defining eleven cost categories, from 10 to 200 $/tCeq, and associating to each of them, for every region and every gas, the relative share of emissions which is abatable at that cost. This implies that the research for the optimum abatement level is carried out discretely, the chosen abatement share being naturally identified in one of the curve steps, which may not correspond to the real optimum one. Table 2 at the next page summarizes the maximum abatement shares reachable in 2010, showing that fluorinated gases are characterized by the highest average levels, followed by methane and nitrous oxide, while Figure 6 reports an example of a MAC curve shaped as described above[7].

[7] As specified, cost data are provided in $/tCeq, nevertheless tons of equivalent carbon dioxide have been taken as a reference for gas emissions in this work, therefore all results and graphs will be reported referring to this unit henceforth. Since 1 tC = 44/12 tCO_2, cost values are simply shifted downwards by this factor. It must be also said that cost data are expressed in $(2000), while WITCH adopts $(2005), therefore, a downscale of the MACs by a factor of 0.788 has been carried out before running the simulations.

Region	CH_4	N_2O	SLF	LLF
USA	72.30%	12.45%	30.89%	43.58%
WEURO	17.64%	15.57%	31.95%	25.70%
EEURO	25.91%	3.81%	29.37%	43.34%
KOSAU	20.26%	2.92%	33.16%	44.77%
CAJAZ	25.29%	20.07%	35.16%	40.02%
TE	25.91%	3.81%	29.37%	43.34%
MENA	18.03%	1.75%	31.39%	58.24%
SSA	20.26%	2.92%	33.16%	44.77%
SASIA	11.31%	14.30%	27.62%	30.91%
CHINA	39.62%	38.55%	33.33%	82.02%
EASIA	20.26%	2.92%	33.16%	44.77%
LACA	20.26%	2.92%	33.16%	44.77%
INDIA	11.31%	14.30%	27.62%	30.91%
Average	**25.26%**	**10.49%**	**31.49%**	**44.40%**

Table 2 – OGHG maximum abatement potentials (2010).

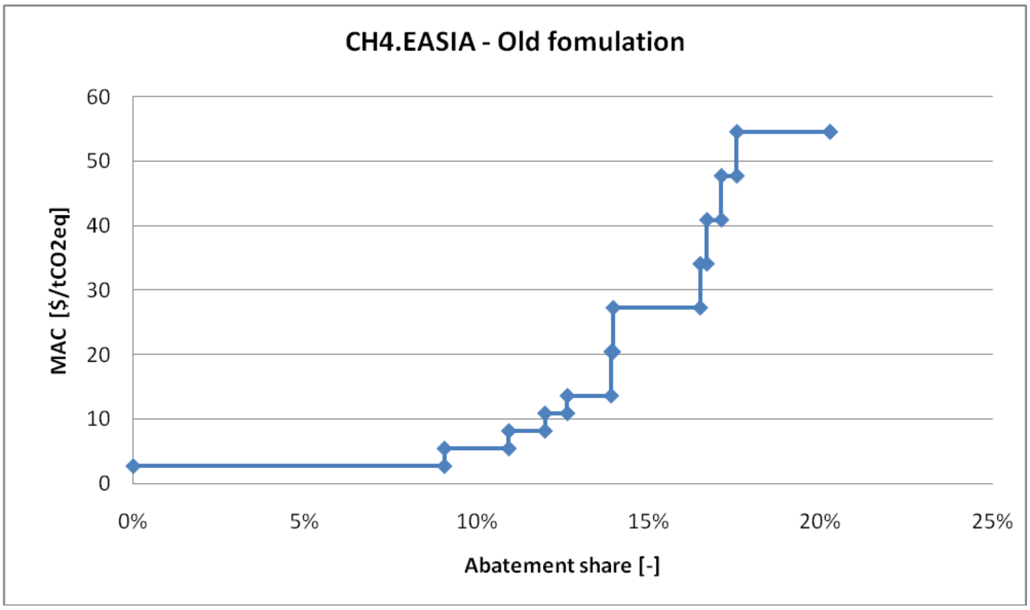

Figure 6 – Example of a step MAC curve in the previous version of WITCH.

For the new version of the code, MAC curves have then been modified, deriving interpolating continuous curves from the previous ones. More in detail, firstly the midpoints corresponding to each step of the previous curves were identified; subsequently they were interpolated; the resulting curves were then normalized to 1 dividing the values by the maximum available abatement share (which will allow for their evolution over time according to the technical progress, as will be described further on); exponential trendlines were calculated adopting the least square method and finally they were slightly manipulated in order to obtain the continuous curves in the following form:

$$MAC\_norm = a + b \cdot \exp(c \cdot ABAT) \quad (1)$$

where MAC_norm is the normalized marginal abatement cost, ABAT is the relative abatement share, i.e. the ratio between the actual abatement share and the maximum available one (so it can vary between 0 and 1), while a, b and c are the coefficients calculated in the interpolation process. Figure 7 shows an example of a new MAC_norm curve derived as described.

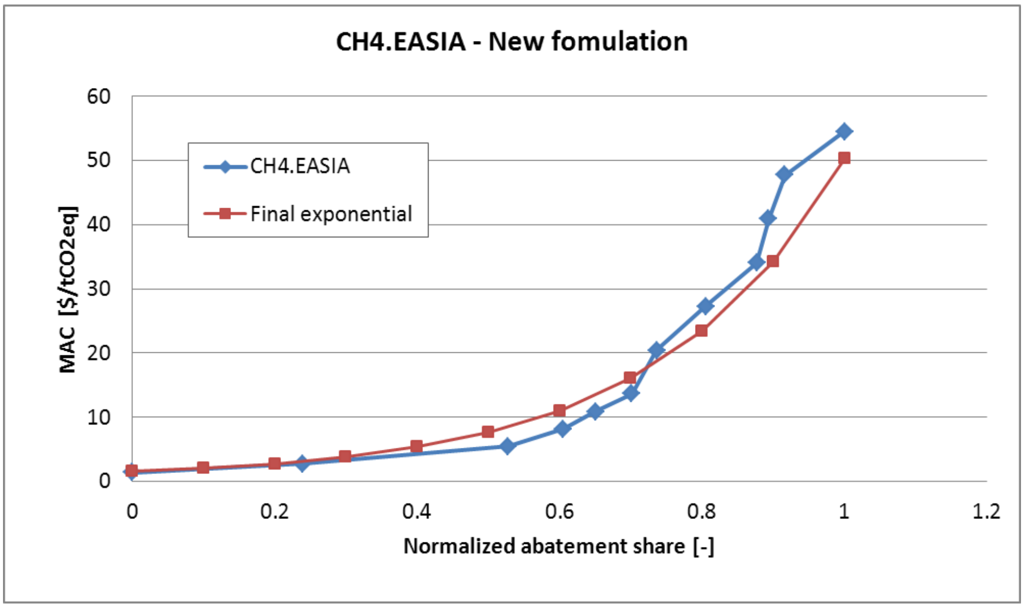

Figure 7 – Example of a step MAC curve in the updated version of WITCH.

3.2 Mathematical formulation

As stated above, given a marginal abatement cost curve, the abatement cost is equal to the subtended area. In our formulation normalized MACs assume the form indicated in (1), thus the normalized abatement cost (AC_norm) will be:

$$AC\_norm(ABAT) = \int_0^{ABAT} MAC\_norm = \int_0^{ABAT} (a + b \cdot \exp(cx))dx = \left[ax + \frac{b}{c}(\exp(cx)) \right]_0^{ABAT} =$$

$$= a \cdot ABAT + \frac{b}{c}\left(\exp(c \cdot ABAT) - 1\right) \qquad (2)$$

where ABAT is now the chosen relative abatement normalized on the available maximum. Being this specific cost referred to the normalized curve, it will be expressed in \$/tCO_2eq_max_ab, i.e. in dollars per maximum potentially abatable ton of equivalent CO_2. The abatement cost will then be given by the multiplication of this quantity by the maximum abatement share, abat_max (expressed in tCO_2eq_max_ab/tCO_2eq_em, i.e. the abatable tons of equivalent CO_2 over the emitted ones) and by the baseline emissions, emi_BL (obviously expressed in tCO_2eq_em):

$$ab\_cost_{oghg,t,n} = emi\_bl_{oghg,t,n} \cdot abat\_max_{oghg,t,n} \cdot AC\_norm_{oghg,n}(ABAT_{oghg,t,n}) \qquad (3)$$

This formula provides the abatement cost for every gas (oghg), time period (t) and region (n). In the WITCH Ramsey-type aggregated economic model, this cost, summed over the set of all OGHG gases, constitutes a negative contribution in the calculation of the final good production function, i.e. the GDP, for each time and region considered. Therefore the evaluation of the optimized abatement level (identified through the variable ABAT) is the result of a trade-off between the necessity of abating emissions according to the imposed policy, if any, and the need for keeping as high as possible the GDP. In case no constraint on emissions is imposed, like in baseline calculations of Section 2, no abatement is then performed.

3.3 Technical change

Technical change regarding non-CO_2 greenhouse gas mitigation is an awkward problem. First of all, when both baseline emissions and the marginal abatement cost curves are exogenously fixed, as it usually happens, technical change, i.e. MAC evolution over time, will normally obey an exogenous path as well. Nevertheless it is very difficult to forecast the real evolution of the reachable abatement levels, even because OGHGs are emitted by a great number of different sources, hence there is no uniformity among the various IAMs concerning the scheme followed for MAC evolution and its extent.

Some models do not allow for any kind of evolution over time at all (e.g. [9] [12] [13]). The reference EPA report itself does not provide any information in this sense. However often technical change is taken into consideration (e.g. [10]). Baker et al. [23] provide a thorough overview of all the possible evolution schemes which may be applied to marginal abatement cost curves (referring not only to OGHGs, however) and the most frequently adopted solutions are those which provide lowering MACs over time according to various paths, such as downscale, pivoting, rightwards dilatation, etc. (e.g. [24] and [25]).

When OGHGs are taken into account, a typical solution is to rightwards dilate the MAC curve, i.e. one hypothesizes to obtain an increasing level of abatement at the same cost class (e.g. [3] [8] [21]), scaling the curve by a proper factor. This is the solution that has been adopted in the new version of WITCH (see the example in Figure 8).

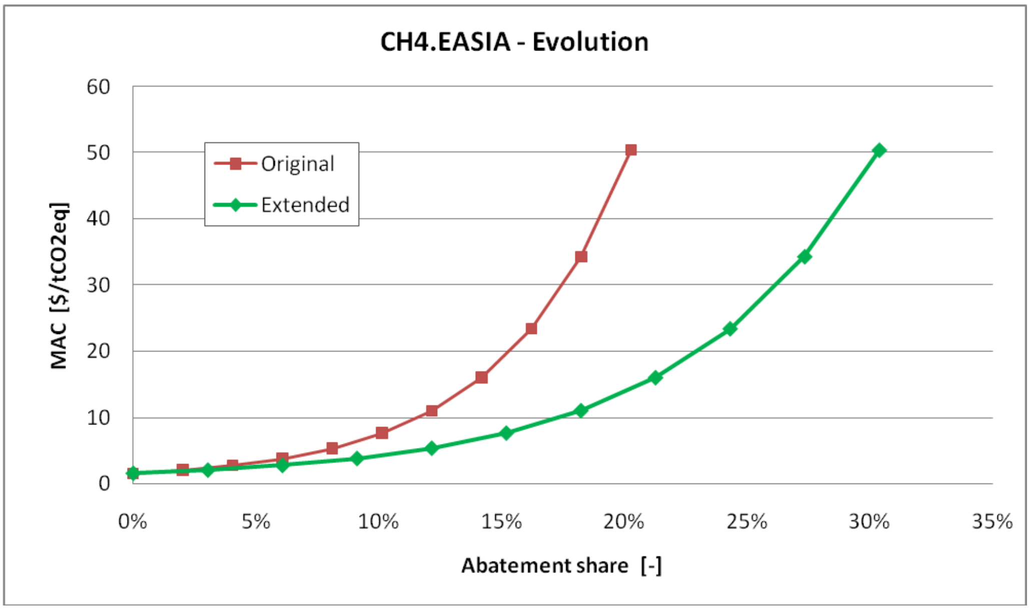

Figure 8 – Example of MAC evolution over time.

Thanks to the normalized formulation described in the previous section, the evolution takes place by simply multiplying the maximum abatement share by a technical progress factor (TP), which increases over time starting from 1, while the normalized curve does not change.
The core of the problem is then fixing a value for TP. For instance, in FAIR [8] a +2% every five years is imposed, which results in about 1.5 as a TP in 2100, while in MERGE [21] TP is 2 in 2100, with a linear growth every ten years equal to +1/8 up to 2050 and +1/10 up to 2100.
In the Introduction it has already been said that the previous version of WITCH featured a technical progress factor increasing by 1/7 every five years from 1 in 2005/2010 to 4 in 2115, fixing an upper limit equal to 90% to the maximum abatement share (indeed this progress was applied to the last cost class only, thus no complete MAC evolution took place).
As one can see, there is a certain arbitrariness concerning TP choices and indeed the main objective of this work is to perform a sensitivity analysis aiming at evaluating the economic, energy and environmental consequences related to choosing different technical progress factors, under different policy scenarios.

4 Simulation scenarios

4.1 Technical progress scenarios

In order to perform a complete sensitivity analysis, five technical change scenarios have been considered:

- CO_2 only: no OGHG abatement is allowed, i.e. all mitigation requirements are met through carbon dioxide abatement only (in a sense, TP is always 0);
- TP off: no technical change takes place, i.e. marginal abatement curves do not vary over time (TP is always equal to 1);
- TP low: TP grows by 1/20 every five years starting from 1 in 2005/2010 up to 2.05 in 2115, remaining constant up to 2150 (this scenario is similar to the MERGE one [21]);
- TP medium: TP grows by 1/10 every five years starting from 1 in 2005/2010 up to 3.1 in 2115, remaining constant up to 2150;
- TP high: TP grows by 1/7 every five years starting from 1 in 2005/2010 up to 4 in 2115, remaining constant up to 2150 (this scenario is similar to the old WITCH one [16]);

In any evolution scenario, the 90% upper bound as a maximum abatement share is maintained.

Table 3 summarizes the values assumed by TP over time in the various scenarios.

Technical progress factor (TP)					
Year	**CO_2 only**	**TP off**	**TP low**	**TP medium**	**TP high**
2005	0	1	1	1	1
2010	0	1	1	1	1
…	…	…	…	…	…
2050	0	1	1.4	1.8	2.14
…	…	…	…	…	…
2100	0	1	1.9	2.8	3.57
…	…	…	…	…	…
2115	0	1	2.05	3.1	4
…	…	…	…	…	…
2150	0	1	2.05	3.1	4
Maximum abatement share: 90%					

Table 3 – Technical progress factor scenarios.

They grey part in the table related to the years between 2105 and 2150 reminds that those time periods are eventually discarded in our simulations. Nevertheless an evolution up to 2115 has been allowed all the same, in coherence with the previous version of WITCH.

For illustrative purposes, Figure 9 and Figure 10 provide a visual representation of the maximum abatement share evolution according to the technical progress factor, starting from the values shown in Table 2, referring for instance to methane and to the TP low and TP high scenarios[8].

[8] One may note that some lines seem not to be present. Actually, as one can infer from Table 2 where some maximum values are equal to each other, some MAC data are identical in some regions, essentially for reasons related to the aggregation of regional data (EPA values are in fact provided according to a regional aggregation not completely in line with the WITCH one).

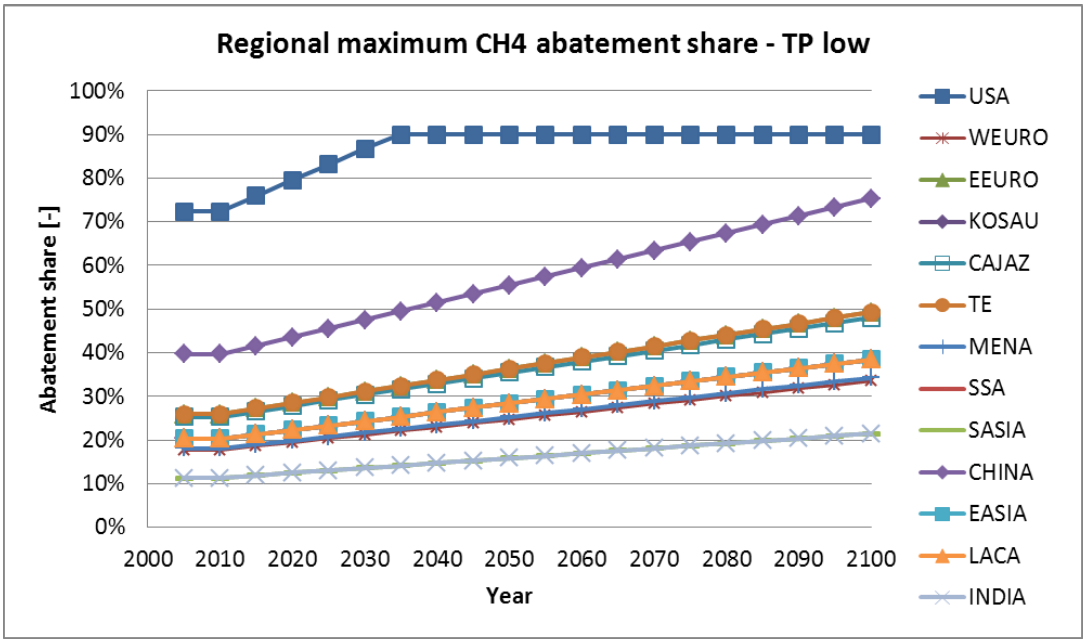

Figure 9 – Regional maximum CH_4 abatement share evolution over time (TP low case).

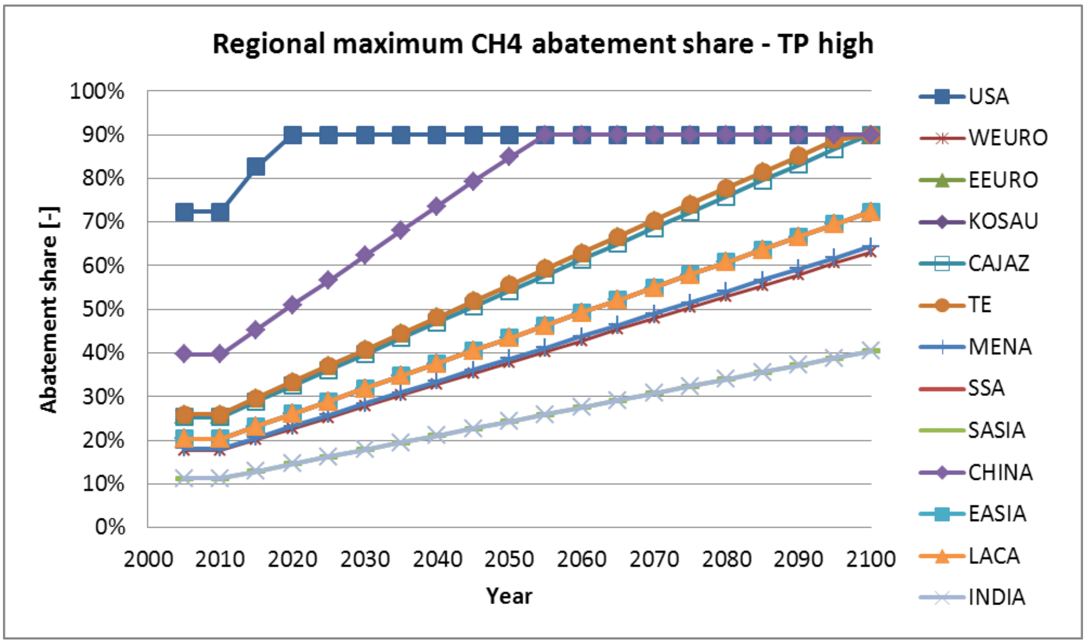

Figure 10 – Regional maximum CH_4 abatement share evolution over time (TP high case).

Finally, for each of the two policy scenarios (described in the next section), the results obtained in the defined five scenarios will be compared to the Business-as-Usual case, with respect to which, for instance, cumulative emissions and policy costs will be calculated.

4.2 Policy scenarios

Two policy scenarios have been taken into account in this work:

- Carbon Tax (CTAX) where no emission cap is applied and no carbon market takes place, but a pre-determined carbon tax (whose progress over time is shown in Figure 11) is imposed to emissions;
- Stabilization 535 (Stab535), where an emission cap is fixed so that a GHG concentration of 535 ppmCO_2eq is reached in 2100. In this case the carbon cost is not imposed exogenously like in the previous one, but derives endogenously from the evolution of the economic, energy and environmental scenario. Where but not when flexibility is allowed, i.e. trade of the carbon permits across regions (where) is performable, while banking and borrowing (when) is not.

As one can see, the scenarios follow two different frameworks with respect to carbon emission modeling: in the former (CTAX) carbon price is exogenously fixed, and thus the strategic economic decisions are made just following this external constraint, while in the latter (Stab535) the constraint is imposed on emissions and thus the carbon price is an actual variable of the problem, which derives from the optimization process, and it is natural to allow for a carbon permit market as an additional means for reaching the mitigation targets.

In both cases the policy starts in 2015, so that 2005 and 2010 MAC data are actually provided for reference only.

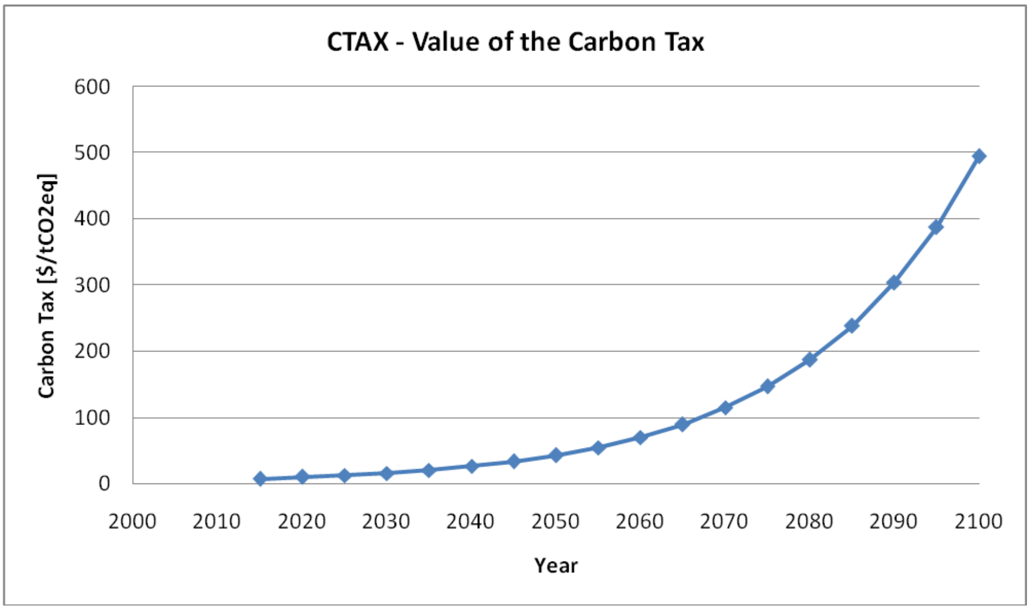

Figure 11 – CTAX: value of the carbon tax.

5 Results and discussion

5.1 Carbon Tax

Figure 12 and Figure 13 respectively show, for the considered scenarios, global OGHG detailed emissions and the cumulative ones over the century, the latter being expressed in relative terms with respect to the BaU case (whose emissions are fixed to 100).

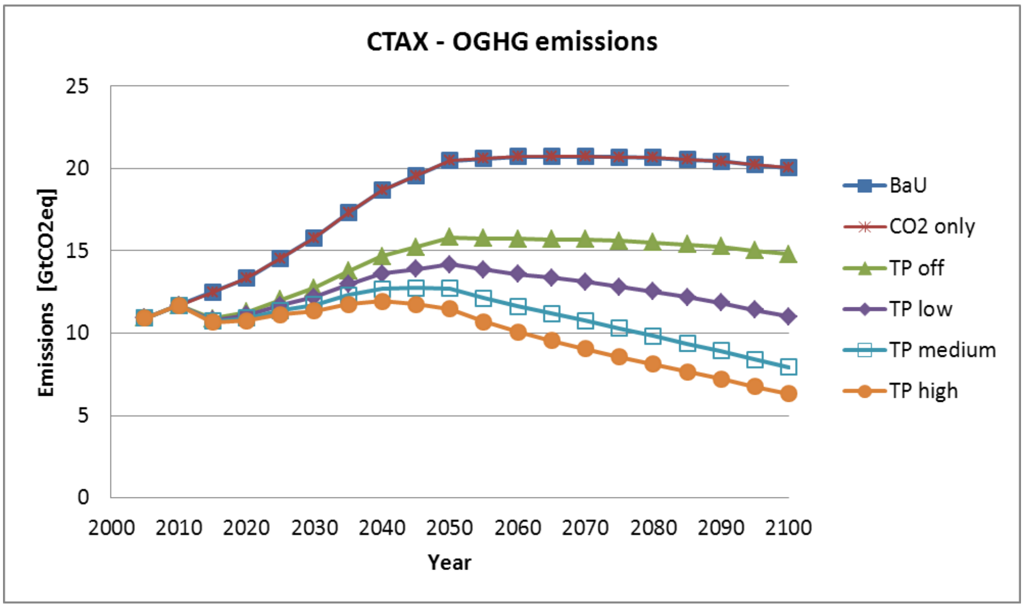

Figure 12 – CTAX: OGHG emissions.

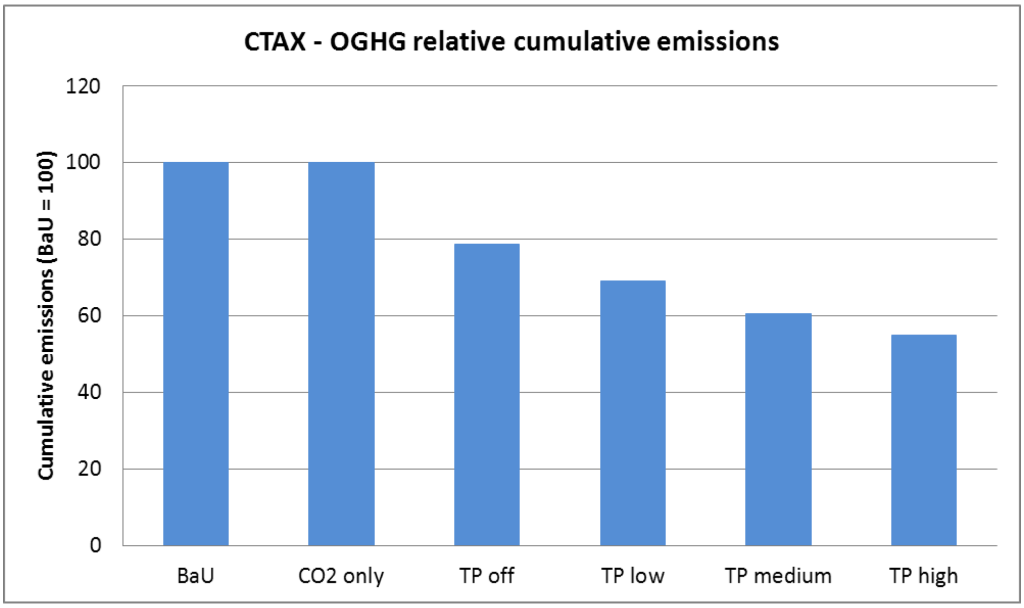

Figure 13 – CTAX: OGHG relative cumulative emissions.

It is evident how the different scenarios impact on the non-CO_2 gas emissions. As already shown in Section 2, baseline emissions start from about 11 $GtCO_2eq$ in 2005 and reach 20 $GtCO_2eq$ in 2100; results in the CO_2 only case obviously replicate them, because in this scenario no OGHG mitigation is performed. In the other cases, instead, mitigation takes place and emissions are heavily abated, gradually decreasing to 15 $GtCO_2eq$ in 2100 in the TP off case and to 6 $GtCO_2eq$ in the TP high one. In the latter case, cumulative emissions are almost halved with respect to the Business-as-Usual scenario.

At first glance, these results seem qualitatively predictable – higher TP scenarios result in lower global emissions – but on the other hand one may argue that even if in the various scenarios the maximum abatement level differently evolves following the TP evolution, this would not necessarily mean that the optimum abatement share should grow accordingly. In fact, for instance, the system could find it convenient to cut 20% of emissions, and in that case it would not change anything if the maximum allowable abatement were equal to 30% or 50%. Nevertheless what emerges from calculations is that for all scenarios, gases and regions, the normalized relative abatement ABAT gradually grows and reaches 1 by the middle of the century, i.e. the social planner, apart from the initial transient, tends to abate as much as possible, that is the maximum abatement share, whose growth with increasing TPs results in lower and lower emissions. Indeed, as the normalized MAC does not change over time, and thus is not dependent on TP, the optimum ABAT, for a certain gas and region, is exactly equal in all scenarios. Figure 14 shows an example of ABAT evolution over time, always taking methane and the EASIA region as a reference.

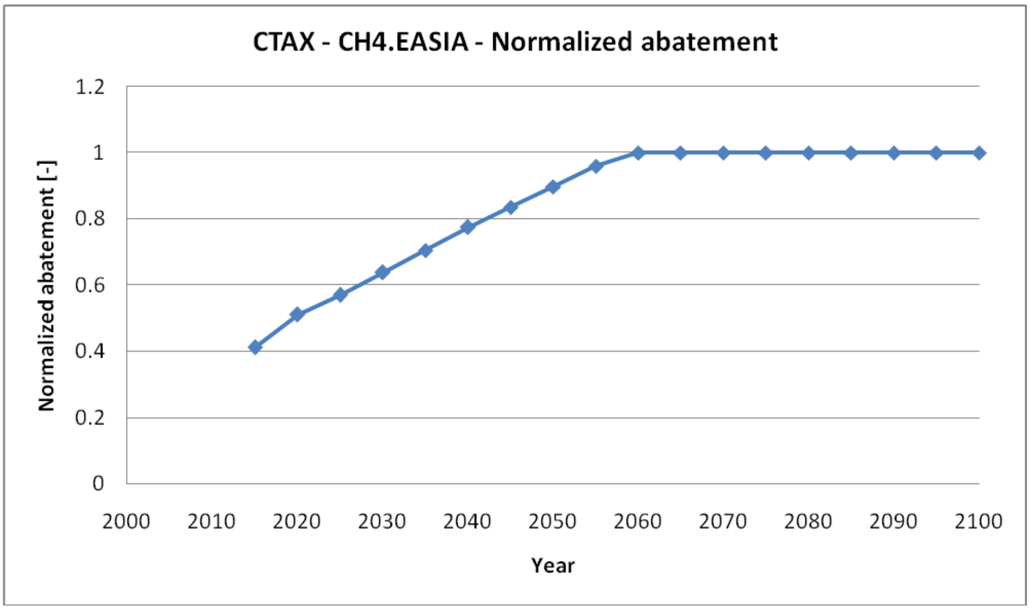

Figure 14 – CTAX: evolution of ABAT for methane in the EASIA region for all TP scenarios.

The importance of such a result deserves a mathematical proof.

First of all, it is necessary to remind that, since no emission cap is imposed, carbon dioxide and OGHG abatement is performed independently. In fact the OGHG sector is modeled just through the given baseline emissions and the MACs, and it does not influence nor is influenced by the strategic choices relevant for carbon dioxide. Thus in all TP scenarios, the optimization related to carbon dioxide emissions is exactly the same and produces the same results: all the differences are up to the OGHG part. As a consequence, the global optimization just depends on the minimization, through the identification of the optimal abatement share, of OGHG-related costs, which are the abatement cost (ab_cost) and the one related to the carbon tax (ctax_cost). Therefore, one can write[9]:

$$\text{OGHG\_cost} = \text{ab\_cost} + \text{ctax\_cost} \qquad (4)$$

The abatement cost has already been described in equation (3). The carbon tax cost is instead:

$$\text{ctax\_cost} = \text{ctax} \cdot \text{emi} = \text{ctax}\,(\text{emi\_bl} - \text{emi\_ab}) = \text{ctax} \cdot \text{emi\_bl}\left(1 - \frac{\text{emi\_ab}}{\text{emi\_bl}}\right) =$$
$$= \text{ctax} \cdot \text{emi\_bl}\,(1 - \text{abat\_abs}) = \text{ctax} \cdot \text{emi\_bl}\,(1 - \text{ABAT} \cdot \text{abat\_max}) \qquad (5)$$

Many straightforward passages are shown. First of all, the carbon tax is applied to the actual emissions only (emi, thus ctax · emi), which are the difference between the baseline (emi_bl) and the abated ones (emi_ab). Highlighting the actual absolute abatement share (abat_abs), and expressing it as the multiplication of the normalized abatement ABAT by the maximum available share abat_max, one obtains the final expression.

The sum of the two contributions will be then:

$$\text{OGHG\_cost} = \text{emi\_bl}\,(\text{abat\_max} \cdot \text{AC\_norm} + \text{ctax}\,(1 - \text{ABAT} \cdot \text{abat\_max})) \qquad (6)$$

In order to obtain the optimum abatement, i.e. the one that minimizes costs, it is sufficient to derive this expression in ABAT and equalize it to zero. It is important to note that AC_norm depends on ABAT, but for the moment it is not necessary to write explicitly the expression, as the derivative will simply be the original MAC_norm.

[9] The functional dependency is for simplicity neglected.

Hence one has:

$$\frac{d(OGHG\_cost)}{d(ABAT)} = emi\_bl\ (abat\_max \cdot MAC\_norm - ctax \cdot abat\_max) =$$

$$= emi\_bl \cdot abat\_max\ (MAC\_norm - ctax) = 0 \quad \Rightarrow \quad MAC\_norm = ctax \qquad (7)$$

Therefore the minimization of the OGHG costs takes place for the abatement share so that the normalized marginal abatement cost equalizes the value of the carbon tax. If one develops MAC_norm in order to highlight the optimum ABAT, obtains:

$$ABAT\_opt = \frac{1}{c} \cdot \ln\left(\frac{ctax - a}{b}\right) \qquad (8)$$

Plotting this theoretical optimal ABAT for the EASIA region and methane, and comparing it with the one calculated in the optimization run shown in Figure 14, one obtains what is shown in Figure 15: at first the actual ABAT perfectly follows the theoretical optimal curve, then, when the latter overcomes 1, which is infeasible, it continues maintaining this upper bound value up to the end of the century.

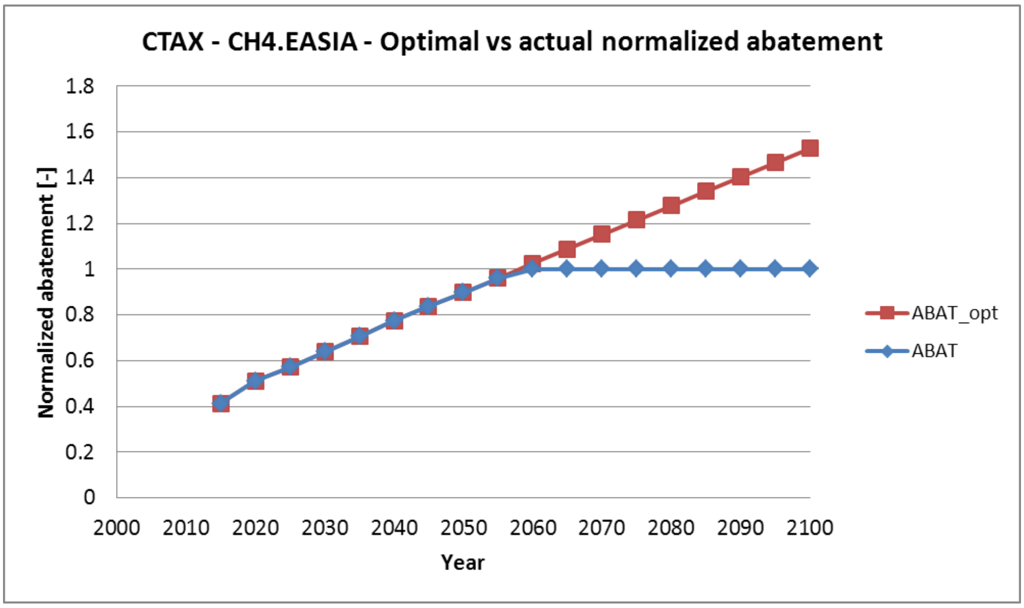

Figure 15 – CTAX: theoretically optimal and calculated normalized abatement share.

The consequence is exactly what has been discussed in the previous pages: with the described formulation of the problem in which MACs evolve over time, but remain the same in normalized terms with respect to the maximum available abatement, the optimum actual abatement share varies according to the latter, so that the optimum ABAT remains constant. As shown in Figure 16, in fact, MAC rightwards dilatation makes the intersection take place at a higher abatement share. OGHG abatement is therefore directly proportional to the technical progress factor, and thus increases over time, thus explaining the emission behavior of Figure 12.

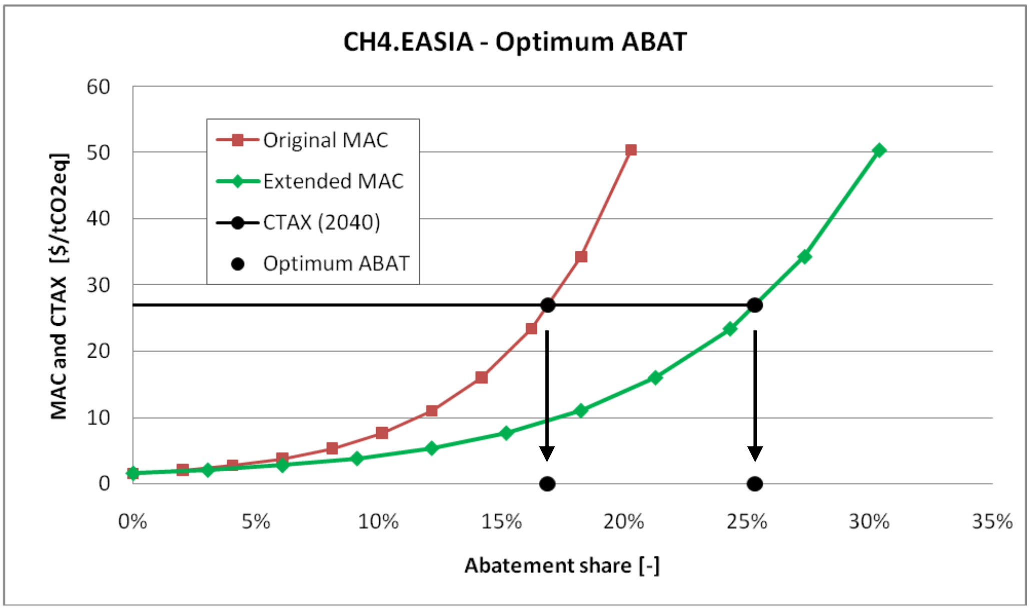

Figure 16 – CTAX: optimum ABAT evaluation at different TPs.

As already specified, carbon dioxide abatement is completely independent of the technical progress factor. This is evident in Figure 17, which shows CO_2 emissions in the different scenarios: results are identical, short of computational differences. It is interesting to note that the application of the carbon tax, fixed as shown in Figure 11, determines a two-third reduction of CO_2 emissions with respect to baseline (from 92 Gt to 29 Gt). The behavior of total GHG emissions, shown in Figure 18, will be then given by the simple sum of the results of Figure 12 and Figure 17: 2100 GHG global emissions range from 36 $GtCO_2eq$ in the TP high scenario to 49 $GtCO_2eq$ in the CO_2 only one, where OGHG emissions are the baseline ones.

Figure 19 and Figure 20 instead show carbon dioxide and total GHG concentrations which derive as a direct consequence of the two previous graphs. Again, the behavior of CO_2

concentration does not depend on the scenario and, starting from 380 ppm in 2005, achieves 578 ppm in 2100, against 761 ppm in BaU: the application of the carbon tax results in a substantial halving of the projected concentration increase. On the other hand, global greenhouse gas concentration starts from 375 ppmCO_2eq in 2005 and grows up to 675 ppmCO_2eq in 2100 in the best case (TP high) and up to 765 ppmCO_2eq in the worst one (CO_2 only): a 90-ppm difference. These values must be compared with the BaU result, which overcomes the one-thousand barrier, achieving 1007 ppmCO_2eq.

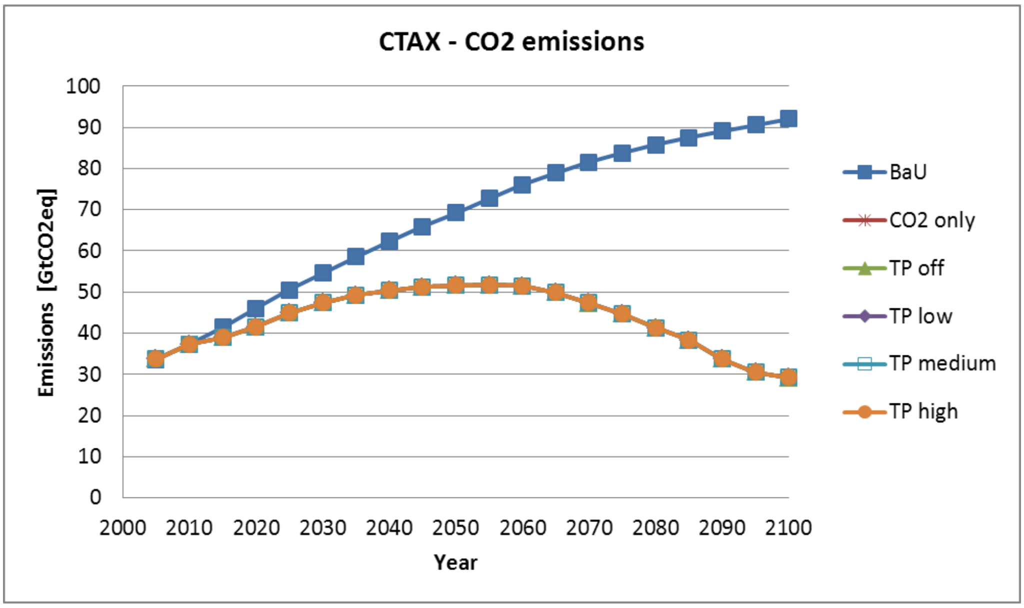

Figure 17 – CTAX: CO_2 emissions.

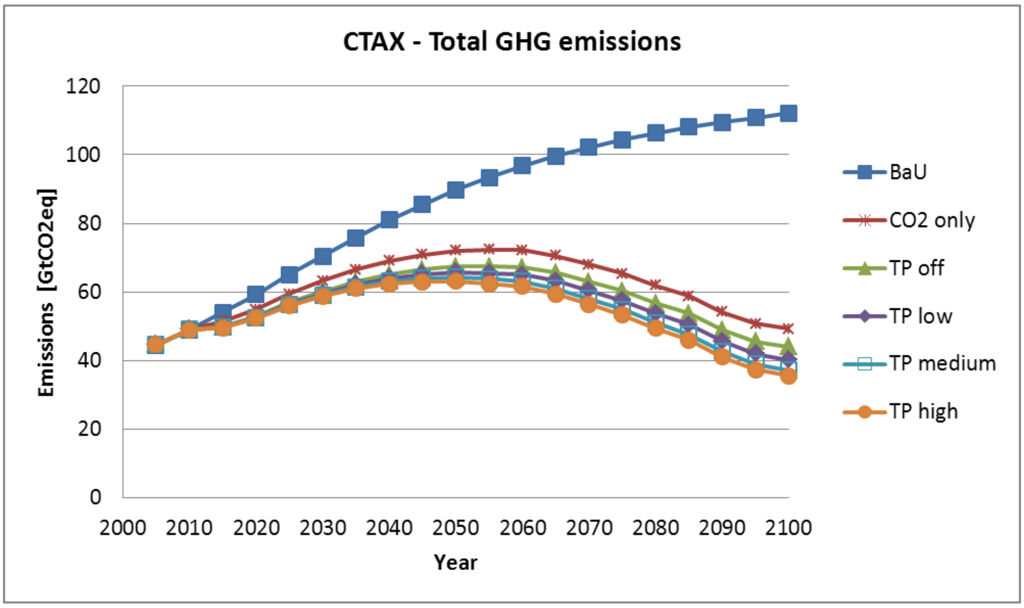

Figure 18 – CTAX: total GHG emissions.

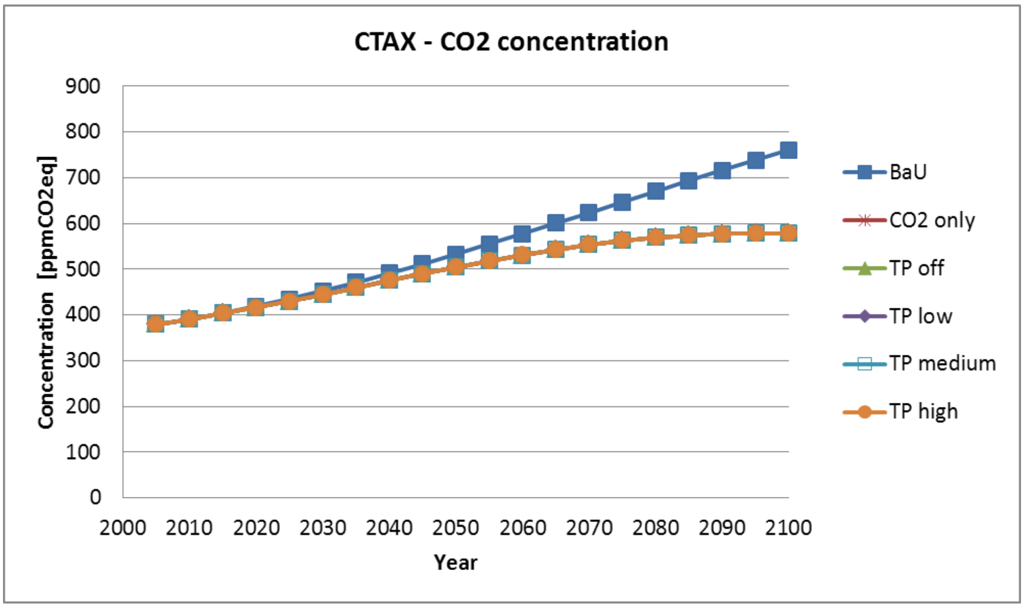

Figure 19 – CTAX: CO_2 concentration.

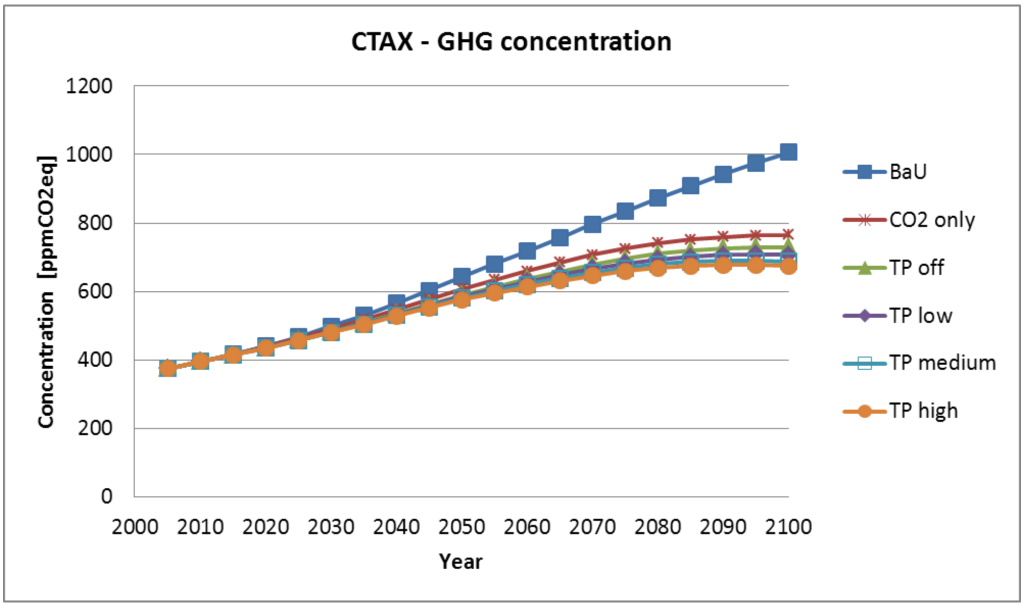

Figure 20 – CTAX: total GHG concentration.

The immediate remark which may arise observing these results is that 2005 OGHG concentration is lower than CO_2 one (375 ppmCO_2eq against 380 ppm), despite the additional contribution of non-CO_2 gases, which is not negligible, and could not be negative anyway. Actually one has to remember that global GHG concentration is affected also by another factor, i.e. aerosols, fine solid particles or liquid droplets dispersed in the atmosphere, such as black carbon or sulfur dioxide, which have a cooling effect on it (e.g. by promoting cloud formation, with a consequent increase of re-irradiation of solar rays towards the outer space), and thus are accounted for in the code through an equivalent reduction of global greenhouse gas concentration. Figure 21 shows the quantitative impact of aerosols, as exogenously fixed in WITCH: in 2005, when they almost perfectly counter OGHG effects, their contribution is quantified in about 52 ppmCO_2eq, then this value constantly diminishes over the century, becoming essentially negligible in 2100, as it is hypothesized that this kind of emissions will be gradually phased out in the next decades.

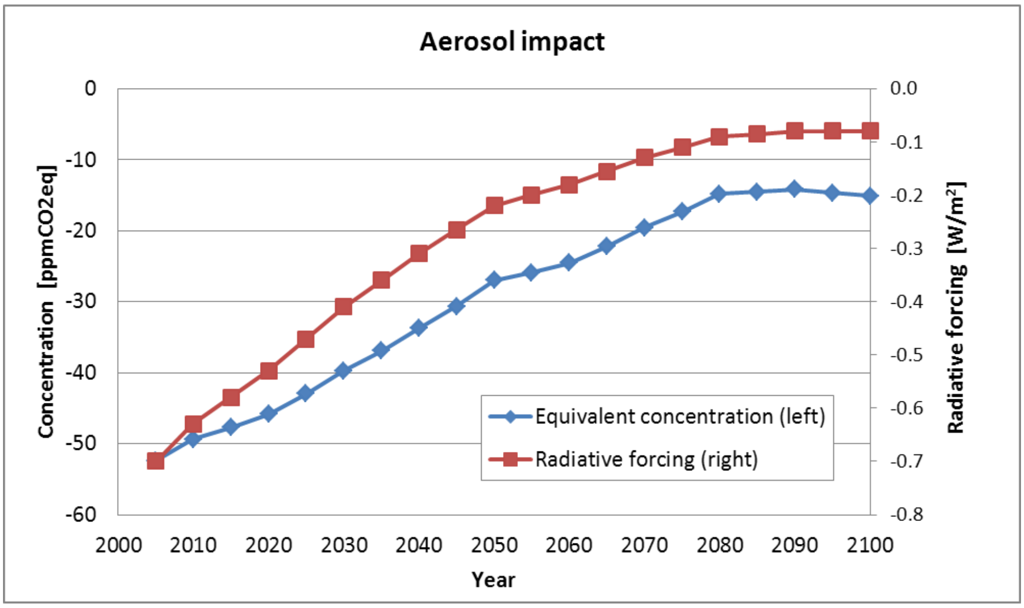

Figure 21 – Aerosol impact on GHG equivalent concentration.

Figure 21 reports aerosol effects also in terms of equivalent negative radiative forcing, showing its diminution from 0.7 W/m^2 in 2005 to 0.08 W/m^2 in 2100.

Still referring to radiative forcing, Figure 22 presents the RF contributions for all greenhouse gases in 2100, according to the different scenarios, comparing results with the 2005 value (equal to 2.3 W/m^2, which results in an equivalent real RF of 1.6 W/m^2 taking into account aerosols). As already discussed, CO_2 contribution in 2100 does not vary across scenarios, and is always equal to 3.92 W/m^2 (-27% with respect to the BaU value, which is 5.39 W/m^2), while OGHG contribution varies from 1.57 W/m^2 in the CO_2 only case to 0.90 W/m^2 in the TP high one (which overall means 5.49 W/m^2 and 4.82 W/m^2, against 6.97 W/m^2 for BaU). It is interesting to analyze how the weights vary within OGHGs: the graph, in fact, clearly shows how methane RF declines way more than nitrous dioxide one, which is in line with the lower abatement potentials shown in Table 2 for the latter gas.

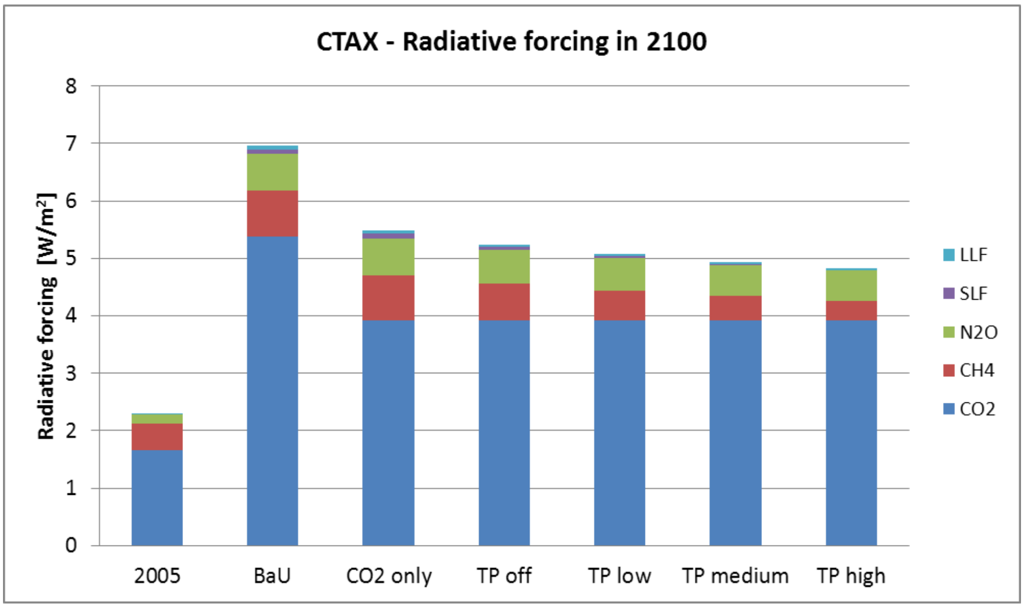

Figure 22 – CTAX: radiative forcing in 2100.

The reported RF values finally lead to a temperature increase with respect to the pre-industrial age which is comprised between 3.15°C for the TP high scenario and 3.53°C for the CO_2 only one (respectively -1.04°C and -0.66°C than the Business-as-Usual peak, 4.19°C), as shown in Figure 23. These estimates are far higher than the 2°C increase which has been identified as a desirable target to avoid potentially heavy climate impacts on ecosystems. This means that, should this kind of policy be implemented, a much higher carbon tax should be applied to obtain remarkable results.

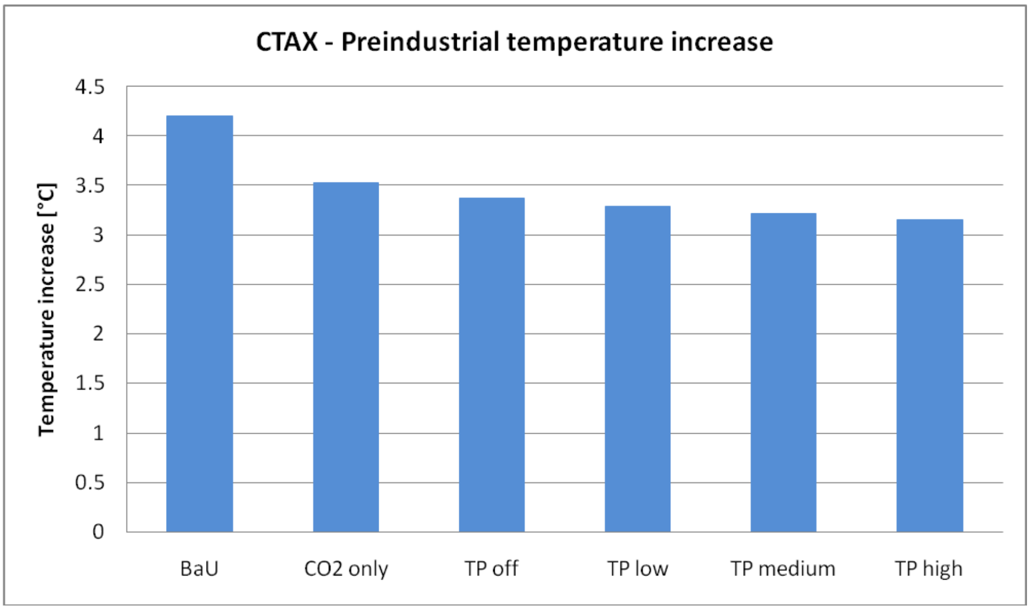

Figure 23 – CTAX: temperature increase with respect to the preindustrial age.

Indeed, one may note that these temperature values have been obtained with a final GHG concentration ranging from 675 ppmCO_2eq to 765 ppmCO_2eq: in the Stabilization 535 policy case constraints will be much stronger, and thus climate impacts will be less severe. Moreover, as OGHG abatement has already been intense in this policy scenario, it is easy to forecast that the burden requested to meet these caps will be placed on carbon dioxide emissions, with a consequent impact on costs.

Concerning costs themselves, the ones related to the abatement of the non-CO_2 gases is shown in Figure 24. Not surprisingly, the TP high case is characterized by the highest costs, which gradually decrease moving towards the TP off case. All four curves show an analogous behavior, i.e. a rapid growth up to about 2060, followed by a much less strong increase in the remaining part of the century.

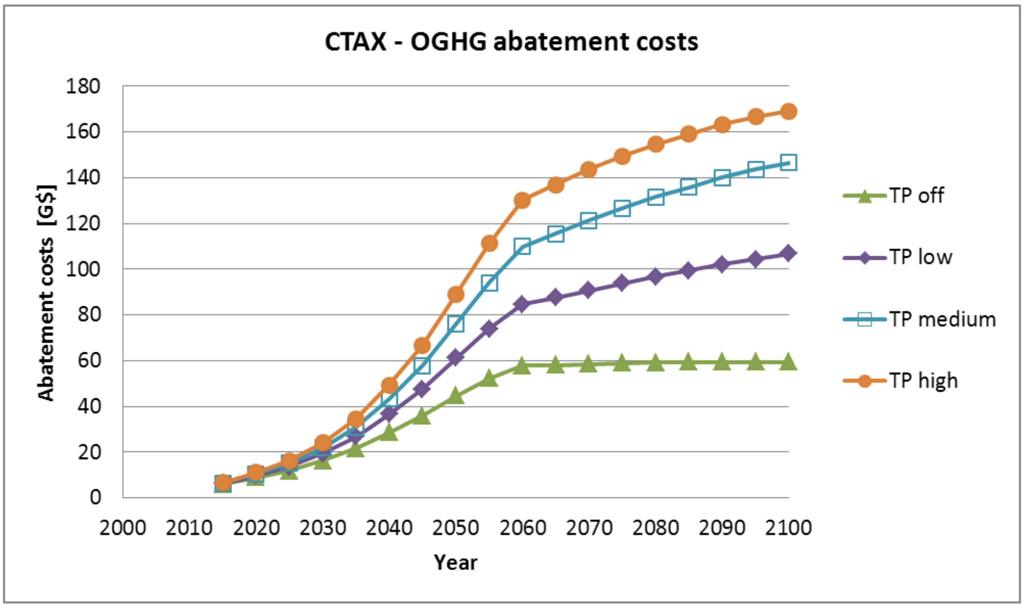

Figure 24 – CTAX: OGHG abatement costs.

This is due to the combination of a series of factors:

1. as shown in Figure 2, OGHG baseline emissions grow in the first part of the century, and then remain substantially constant in the second half;
2. as shown in Figure 14, the normalized abatement has an almost identical evolution, as it grows in the first half of the century, reaching 1 in 2050 ÷ 2060 (depending on cases) and then keeping this upper bound level until the end of the analyzed period;
3. the imposition of the technical progress factor makes the maximum available abatement grow linearly over time, according to the relevant scenario path.

The result is that in the first half of the century, the actual abated emissions, and thus costs, considerably increase because of the combined growth of the aforementioned three factors. After the mid-century, baseline emissions and the normalized abatement being constant, the overall behavior depends on the evolution of the TP only: that is why in the TP off case costs remain constant as well (no TP evolution is present), while in the other cases they grow according to the TP growth (moderately in the TP low case, heavily in the TP high one).

Dividing these values by the abated emissions, one can obtain the equivalent price of the "OGHG carbon dioxide", i.e. the OGHG carbon price (Figure 25).

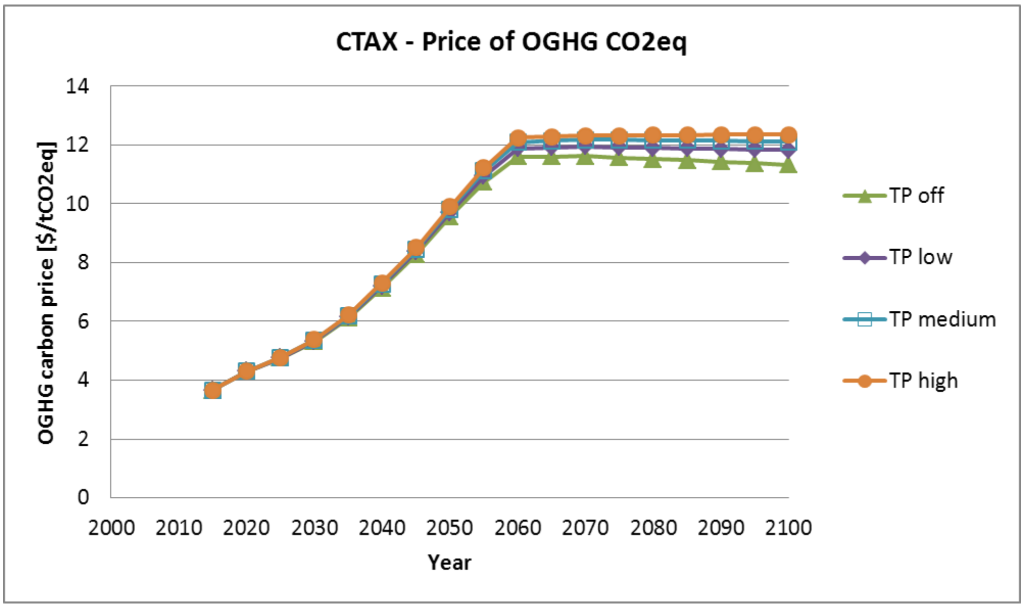

Figure 25 – CTAX: price of OGHG-equivalent carbon dioxide.

However, as one can easily infer from the absolute values shown in the chart, the impact of the OGHG abatement costs on the whole policy ones is quite negligible, as observable in Figure 26, which reports the discounted GDP losses associated to each scenario (discount factor = 5%). The impact of the policy on the CO_2-related world, visible in the CO_2 only case, is 0.58%, while the OGHG abatement accounts for 0.01 ÷ 0.02% only, so it has almost no impact on the whole policy cost: indeed, it is sufficient to compare the OGHG carbon price shown above with the carbon tax. The TP high case, thus, results the most expensive one, even if this is repaid by a more effective emission abatement (summarizing: -90 ppmCO_2eq, -0.67 W/m^2, -0.38°C in 2100 with respect to the CO_2 only case).

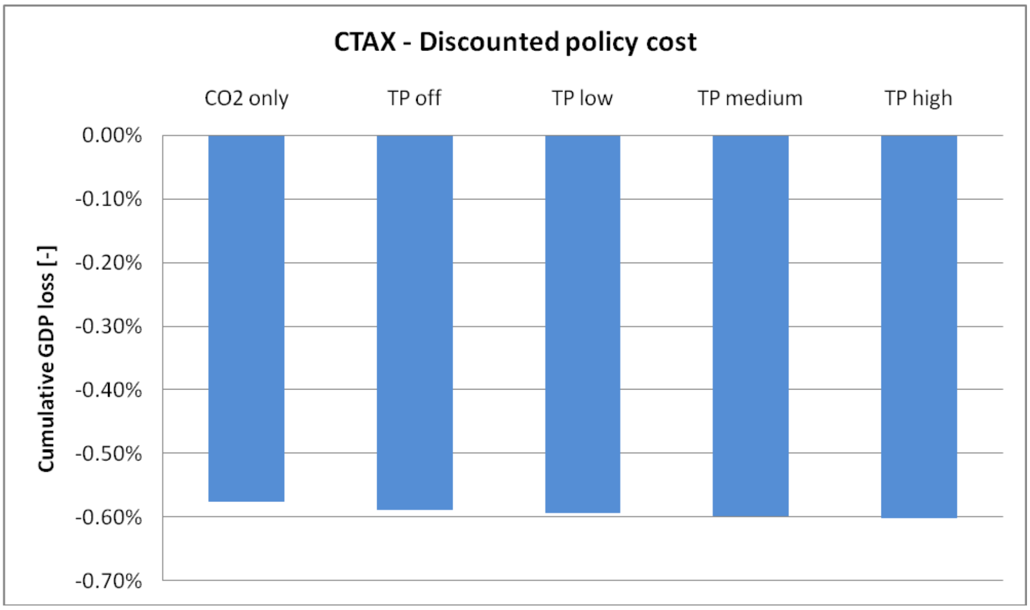

Figure 26 – CTAX: discounted policy cost.

Discounted policy costs are a performing indicator but they do not provide any information about the inter-temporal distribution of costs, which is finally shown in Figure 27: the evolution is almost identical in the various cases, and grows contextually to the carbon tax, up to about 3% in 2100.

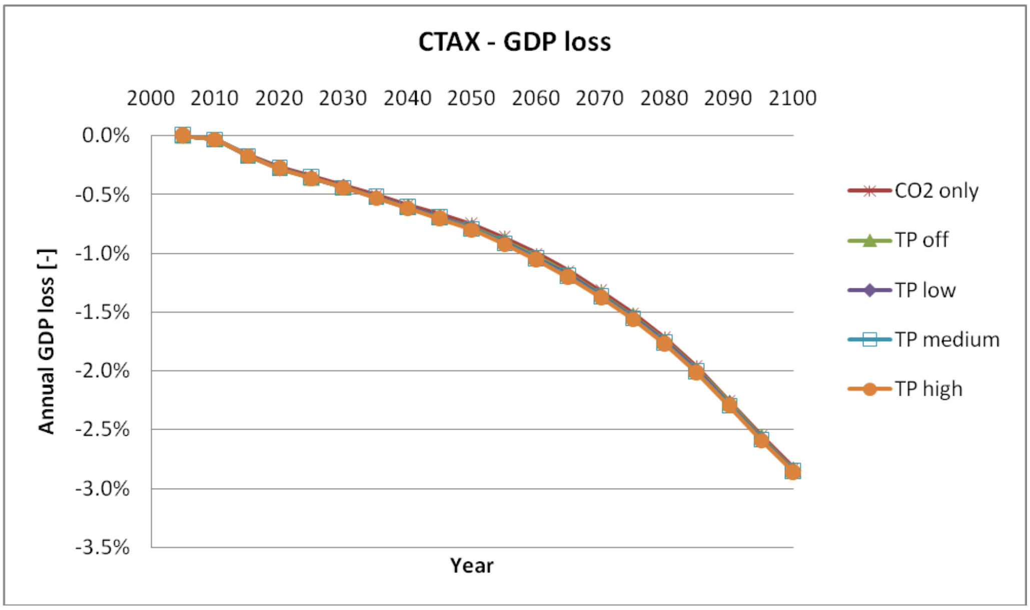

Figure 27 – CTAX: annual policy cost.

5.2 Stabilization 535

Figure 28 and Figure 29 respectively show global OGHG emissions and the cumulative ones over the century, expressed in relative terms with respect to the BaU case, for the Stabilization 535 scenario. As one can see, results are very similar to those obtained in the Carbon Tax case (Figure 12 and Figure 13).

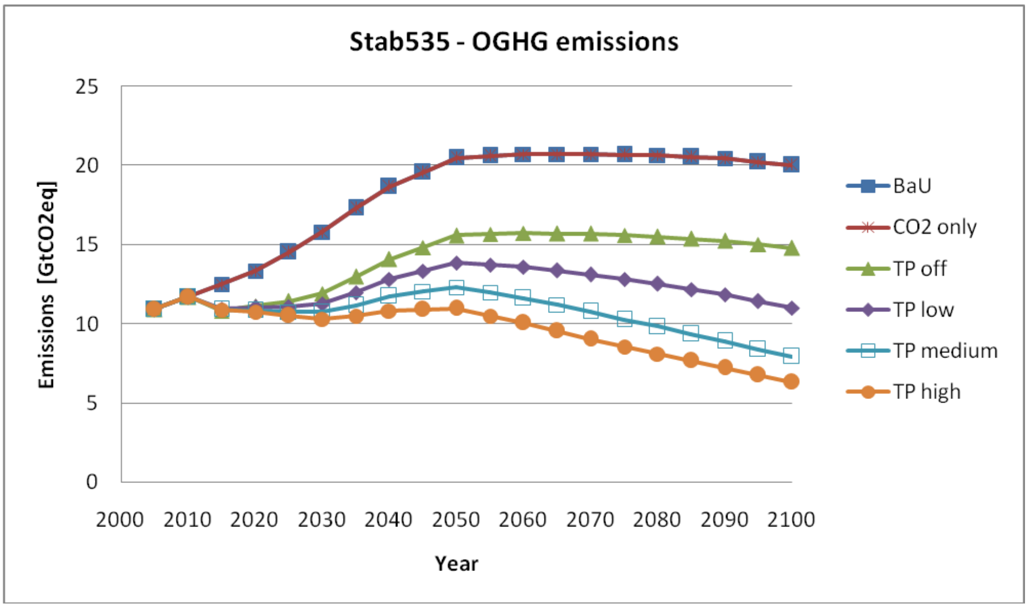

Figure 28 – Stab535: OGHG emissions.

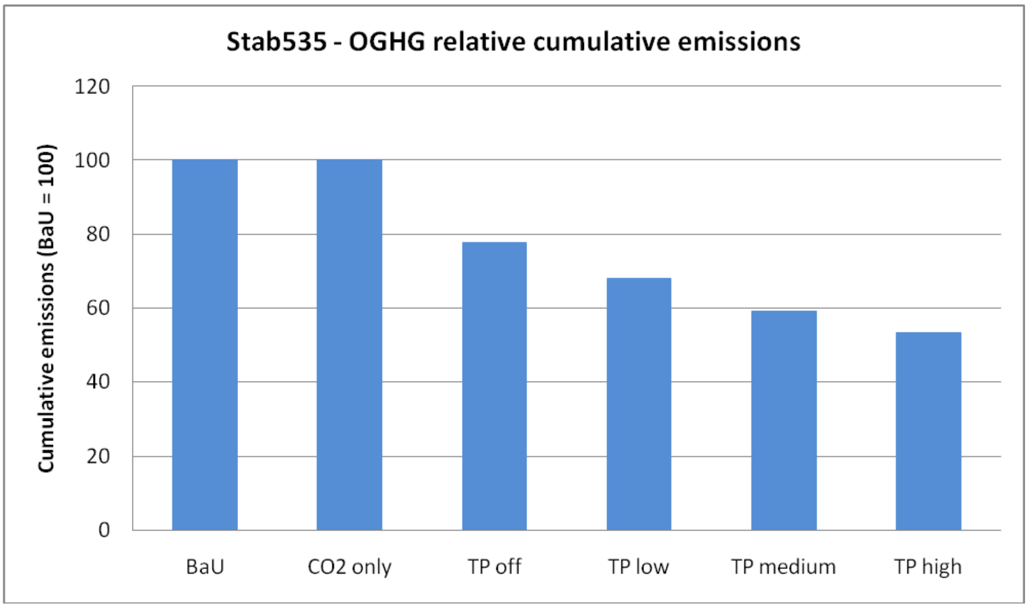

Figure 29 – Stab535: OGHG relative cumulative emissions.

Such a result relies on the evolution of the normalized abatement over time, which is indeed very similar to the CTAX case, as one can see in Figure 30 (again, methane for the EASIA region is taken as a reference, replicating the behavior of all other gases and regions), as there is a strong increase in the first decades, and a subsequent maintaining of the upper bound level for the rest of the century.

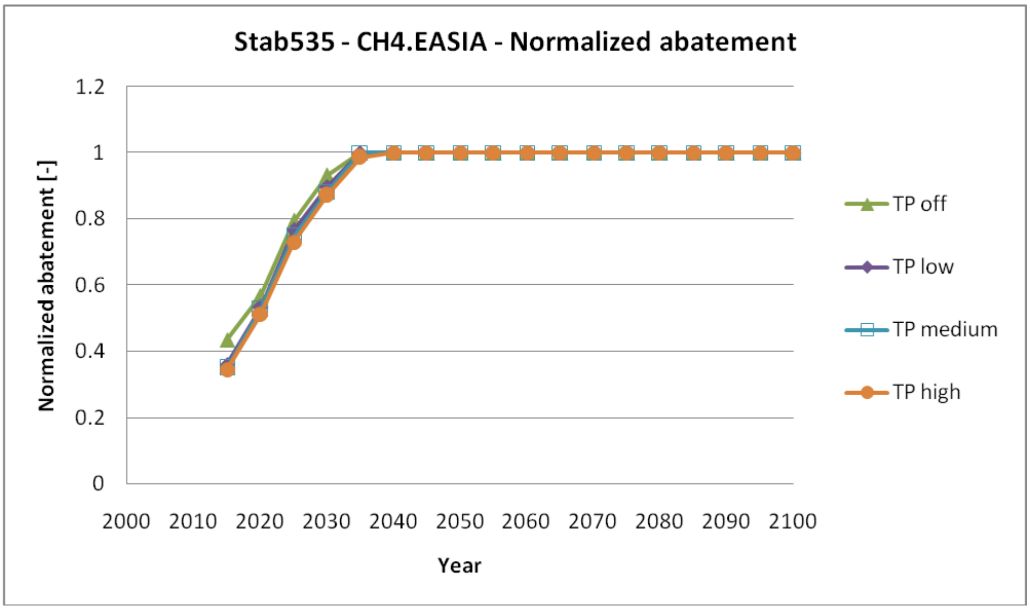

Figure 30 – CTAX: evolution of ABAT for methane in EASIA region for all TP scenarios.

Nevertheless, there are two important differences as well: firstly there are different curves for the various scenarios, though very similar (in fact there is no mathematical reason why they should be equal now), and secondly the upper bound is reached well before than in the other case (2035 against 2060), thus demonstrating that this policy scenario is more stringent than the previous one, as already discussed.

It has already been explained also that the rationale which stand behind this policy scenario is well different than before. Now, in fact, carbon dioxide and OGHGs do not belong to two separate worlds on which the carbon tax is separately applied like before, but they both concur in respecting the emission constraint which is relevant for the entire set of greenhouse gases. This chart shows that, apart from the initial transient phase where the emission caps are not so stringent, OGHG abatement is preferred to the carbon dioxide one, being more convenient that the latter, as one may have inferred by the previous results and as will be shown further on.

As the logics of the policy scenario has changed, CO_2 and total GHG emission progresses have changed as well. In fact, if in the CTAX case carbon dioxide emissions were equal in all TP scenarios, and GHG ones only depended on the non-CO_2 gases behavior, now total GHG emissions are identical across the cases, being subject to the same overall constraint, while CO_2 ones are scaled according to the OGHG abatement potentials (Figure 32 and Figure 31).

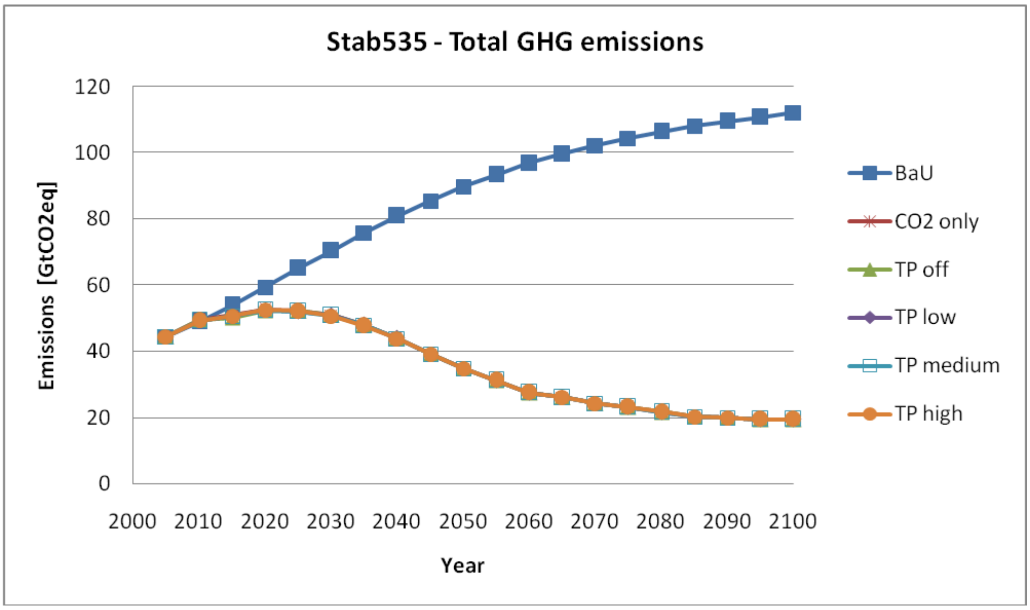

Figure 31 – Stab535: total GHG emissions.

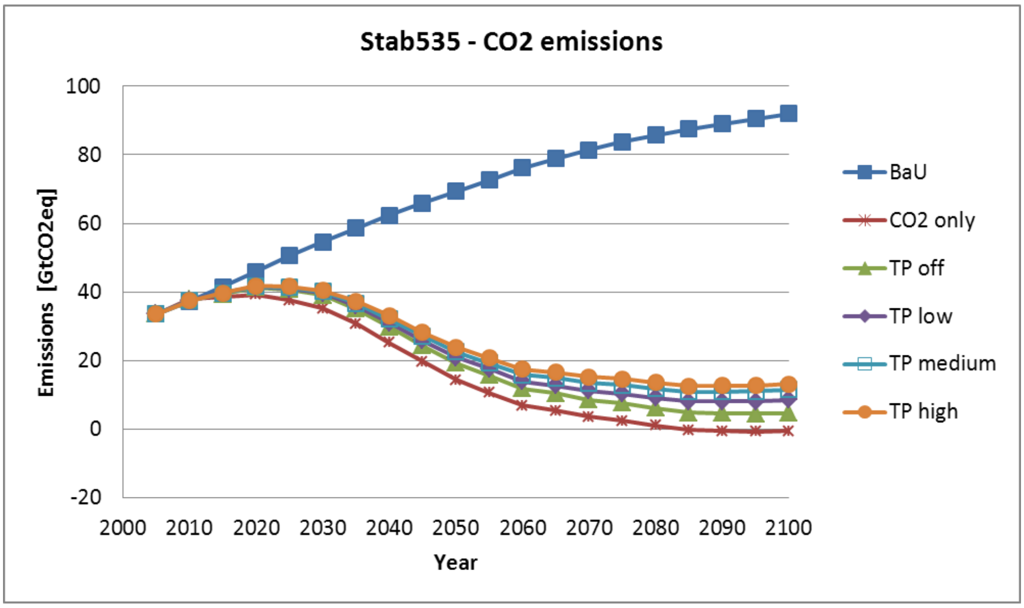

Figure 32 – Stab535: CO_2 emissions.

The stringency of the scenario, especially with respect to the CTAX case, is well clear observing the evolution of the GHGs, which reach 20 $GtCO_2eq$ yearly emissions in 2100 (-83% with respect to BaU), whereas the outcome in the CTAX case was 36 $GtCO_2eq$ in the TP high case and 49 $GtCO_2eq$ in the CO_2 only one. The importance of the OGHG abatement potential is clearly shown in Figure 32: if the TP high scenario takes place, CO_2 emissions of about 13 $GtCO_2$ are still allowed in 2100, while if no OGHG abatement is performable (CO_2 only case), carbon dioxide emissions must even be slightly negative (which is feasible thanks to the deployment of biomass-fired plants coupled with CCS devices: the emitted carbon dioxide is thus "doubly abated" both planting new biomass and sequestrating it).

The evolution of carbon dioxide and of all greenhouse gases concentration naturally reflects the emissions behavior as it has been described above. Therefore total GHG concentration has the same evolution across the scenarios and converges to 535 $ppmCO_2eq$ in 2100, as required by the emission cap (Figure 33), which means a 160 $ppmCO_2eq$-increase with respect to 2005 values (i.e. some +40%, whereas in the BaU case it would roughly triplicate); on the other hand, CO_2 concentrations (Figure 34) jointly grow up to 450 ÷ 470 ppm in 2050 and then decline, more rapidly in the CO_2 only case (395 ppm in 2100, essentially the 2005 level), as the abatement burden is up to carbon dioxide, and almost imperceptibly in the TP high case (453 ppm in 2100).

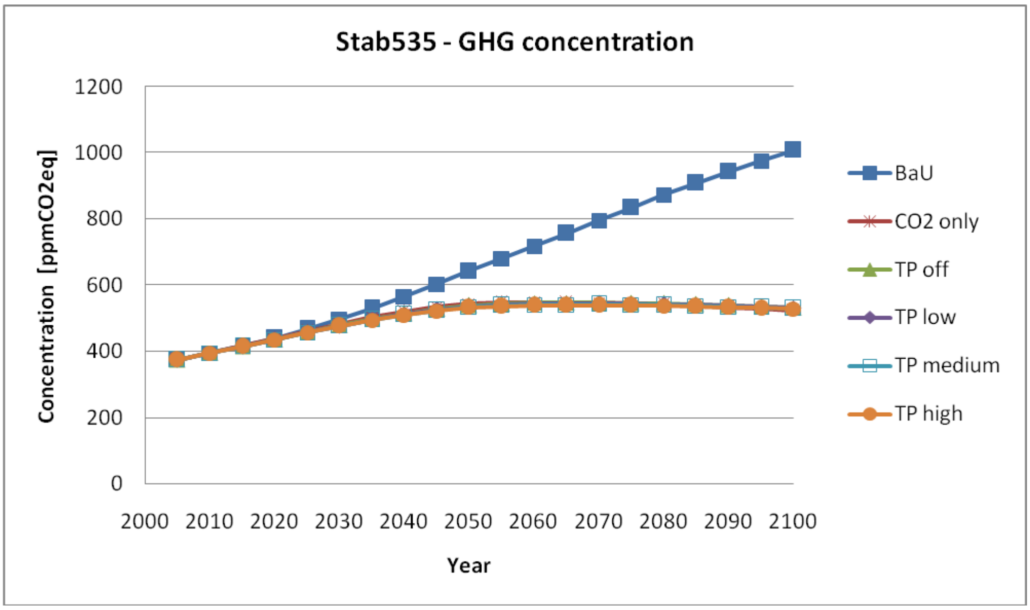

Figure 33 – Stab535: total GHG concentration.

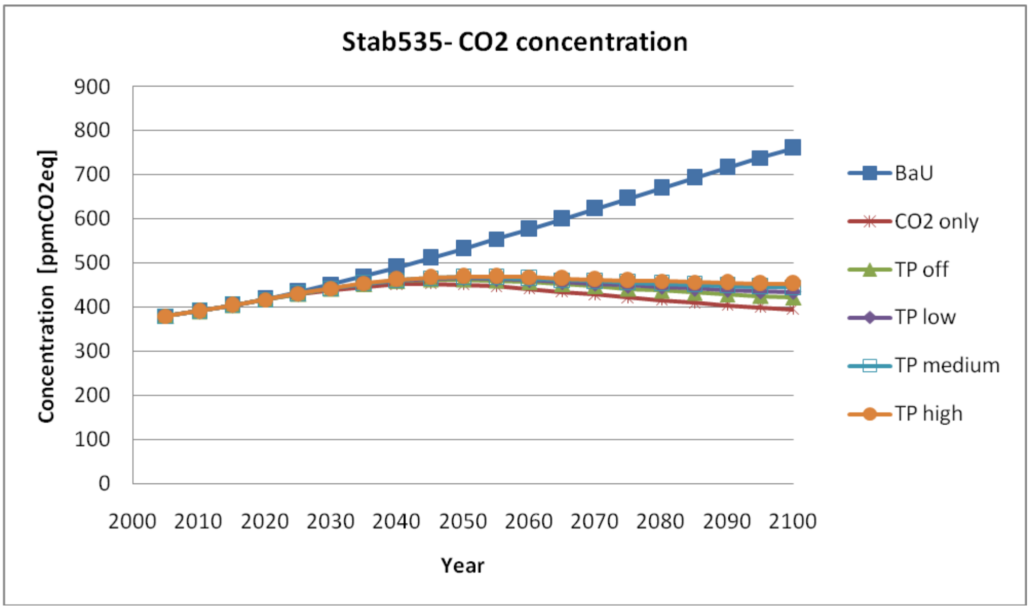

Figure 34 – Stab535: CO_2 concentration.

The GHG emission path being constant across scenarios, radiative forcing in 2100 will be equal as well, short of computational differences, and in particular is estimated to be about 3.5 W/m^2 (Figure 35), exactly half of the projected BaU value (6.97 W/m^2). It is evident how the non-CO_2 share (and especially the methane one) declines passing from the CO_2 only case, where OGHGs account for 46% of the whole forcing, to the TP high one, where they just represent 26% of the total, with a concomitant growth of the CO_2 share.

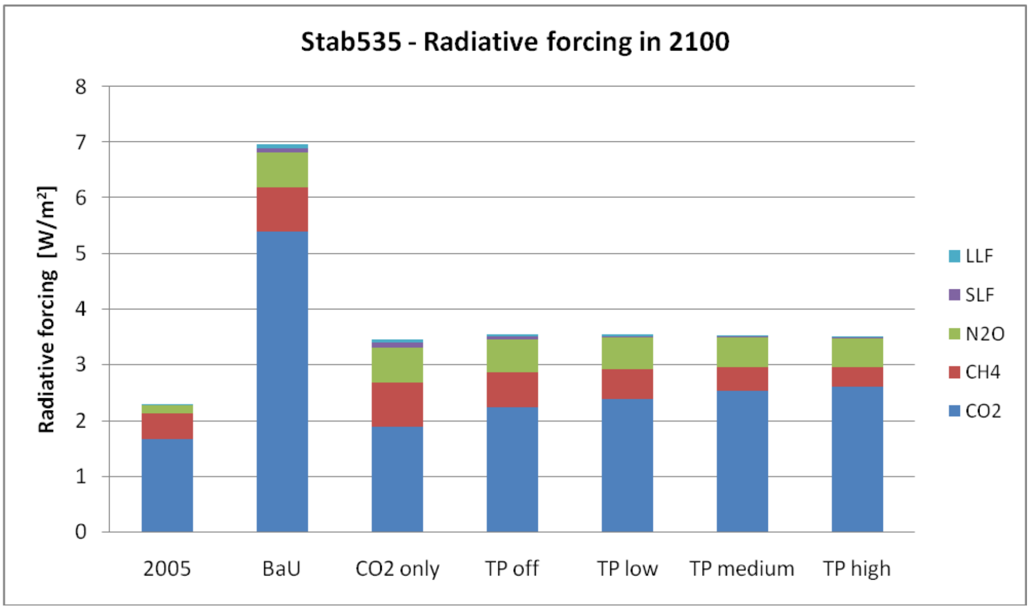

Figure 35 – Stab535: radiative forcing in 2100.

The resulting temperature increase with respect to the preindustrial level (Figure 36) is equal to 2.4°C. This value is well below the peak which would be achieved in the Business-as-Usual case (4.2°C), but is still higher than the already mentioned 2°C-threshold (which in fact is supposed to be met stabilizing GHG concentration at 450 ppmCO_2eq [1]).

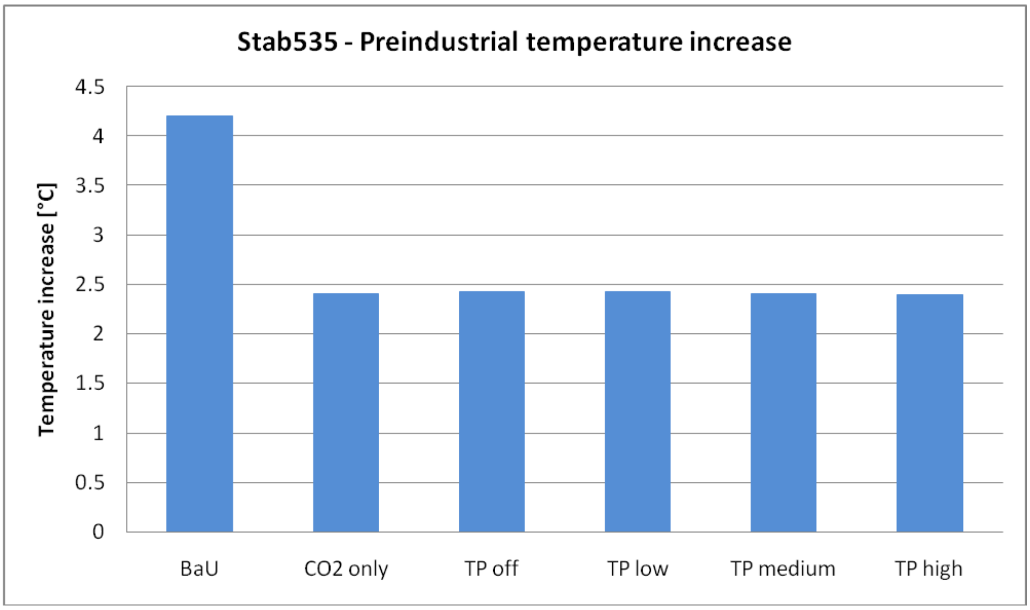

Figure 36 – Stab535: temperature increase with respect to the preindustrial age.

OGHG abatement costs (Figure 37) show a behavior which is in line with the CTAX results, as predictable analyzing the very similar evolution of the normalized abatement.

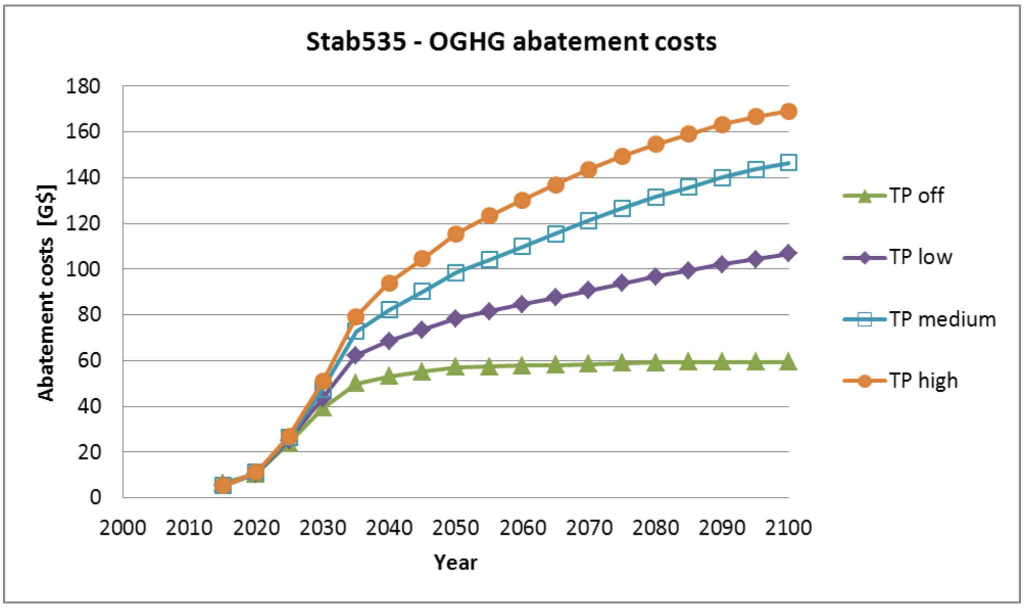

Figure 37 – Stab535: OGHG abatement costs.

Analogously, the equivalent price of the "OGHG carbon dioxide", i.e. the OGHG carbon price, has the same progress (Figure 38).

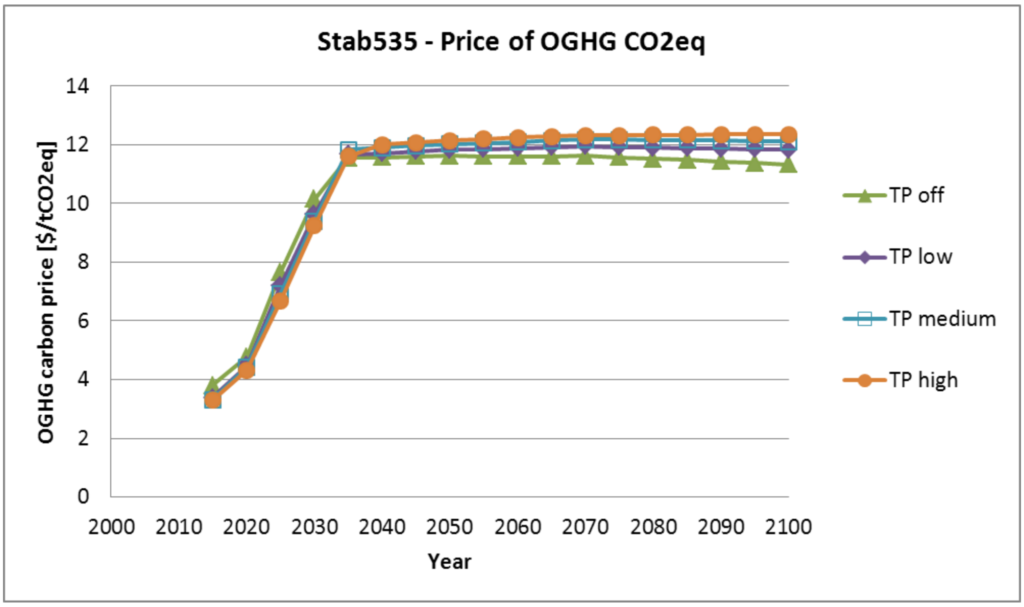

Figure 38 – Stab535: price of OGHG-equivalent carbon dioxide.

Differently from the CTAX case, the discounted cumulative GDP loss considerably varies across scenarios (again, 5% discount rate is assumed), and in particular it diminishes from 3.2% in the CO_2 only case to 1.6% in the TP high one, as shown in Figure 39. This result clearly demonstrates how convenient abating OGHGs rather than carbon dioxide to meet the emission cap is, at least with the adopted working hypotheses: if the whole burden is refered to carbon dioxide only, the global cost will be about 50% higher than allowing for OGHG abatement even neglecting any progress in the maximum abatment share (i.e. TP off case), and about twofold than that obtained with the highest TP increase path represented by the TP high case.

The resulting carbon price stresses this concept: if OGHG abatement is taken into account, the carbon price grows over the century up to about 1000 ÷ 1500 $/tCO_2eq$ in 2100 (precisely, from 765 $/tCO_2eq$ in the TP high case to 1747 $/tCO_2eq$ in the TP off one), while it leaps up to 4000 $/tCO_2eq$ if the policy is all born by carbon dioxide: looking at the prices shown in Figure 38, it is evident why if OGHG abatement is allowed, then it is completely performed, dramaticaly contributing to lower the resulting carbon price.

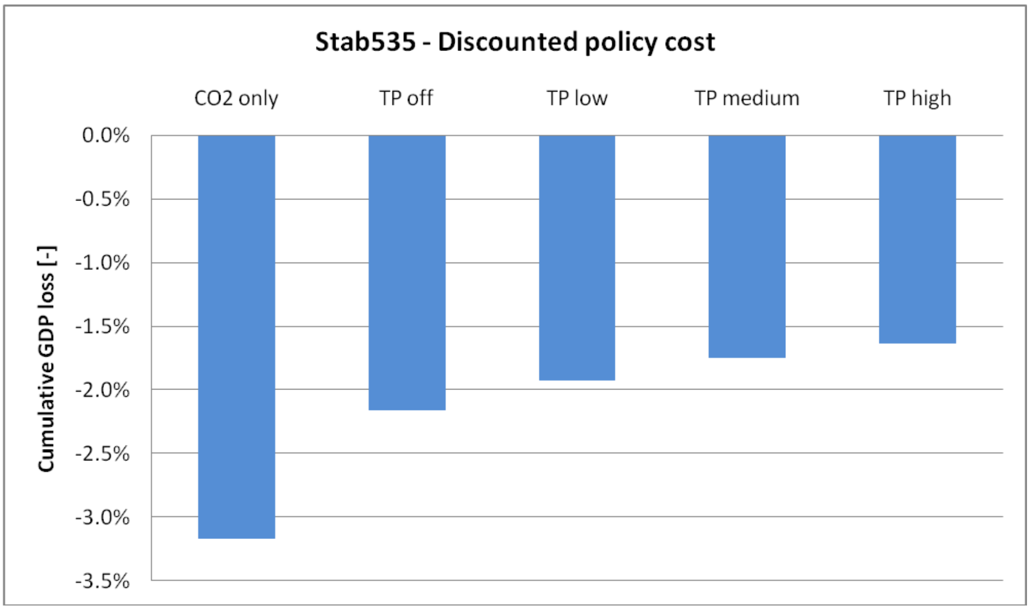

Figure 39 – Stab535: discounted policy cost.

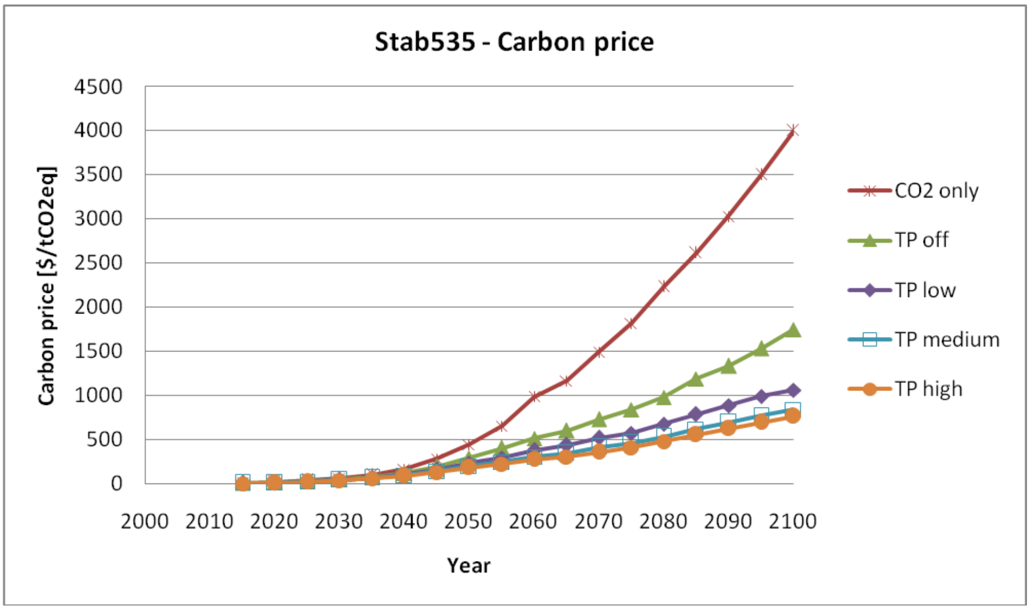

Figure 40 – Stab535: carbon price.

Finally, for the sake of completeness, Figure 41 reports the disaggregated annual GDP loss evolution over the century, showing in particular its severe growth up to 11% in 2100 in the CO_2 only case, while in the TP cases the final datum remains comprised between the range 4.2 ÷ 7.1%.

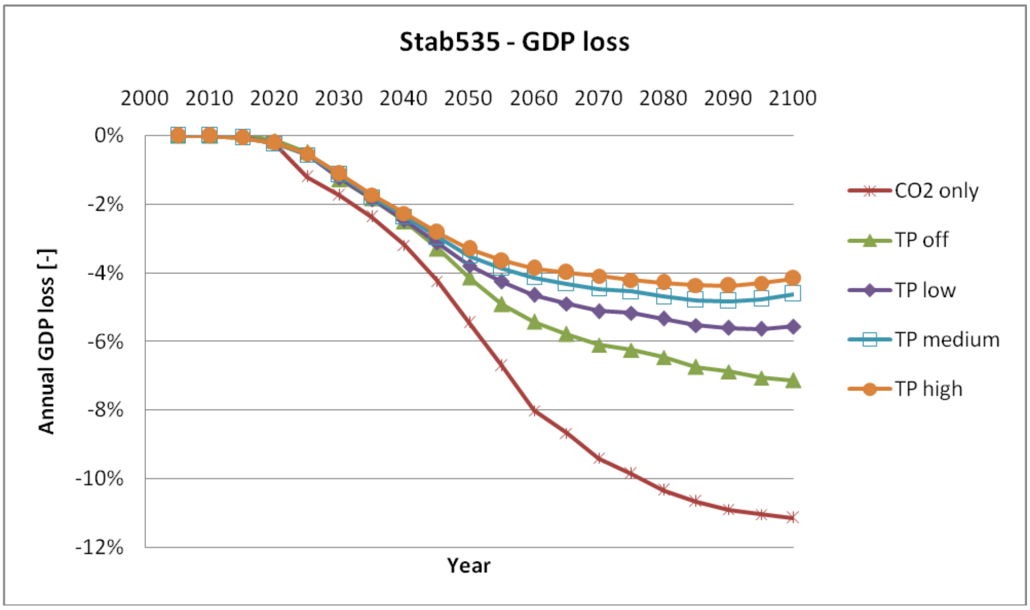

Figure 41 – Stab535: annual policy cost.

6 Conclusions

Non-CO_2 greenhouse gases concur in a major way in producing the global warming phenomenon, as they are responsible of 27% of the present radiative forcing and are expected to account for 23% in 2100 under a Business-as-Usual scenario. Their abating is thus of paramount importance to meet ambitious climate objectives.

As a consequence, it is mandatory for Integrated Assessment Models to take them into account and to properly model their abatement. A widely used approach consists in adopting marginal abatement cost curves, exogenously fixed analogously to the baseline emissions, which describe the abatement potentials and the relative costs. An endogenous modeling, in fact, would be very complicated, as it would imply taking into account a great number of sectors and sources within the model. Nevertheless, MAC evolution over time is an awkward aspect, as it is difficult to forecast the evolution of OGHG abatement potentials over time.

The main objective of this work has precisely been to perform, using the WITCH code, a sensitivity analysis of the climatic and economic impacts attainable allowing for MAC evolution over time according to different technical progress factors, which represent a multiplicative factor of the maximum allowable abatement potential. In particular five technical scenarios have been considered: i) no OGHG abatement (CO_2 only), ii) abatement without technical progress (TP off), abatement with a technical progress factor which roughly

iii) doubles (TP low) iv) triples (TP medium) v) quadruples (TP high) in 2100. All these cases have been run under two policy scenarios, Carbon Tax (where a carbon tax, whose value exponentially increases from 7 $/tCO_2eq$ in 2015 to 500 $/tCO_2eq$ in 2100, is applied to emissions) and Stabilization 535 (where emissions are constrained in order to achieve a 535 $ppmCO_2eq$ concentration of GHGs in 2100), always comparing results with the Business-as-Usual case.

The main outcome of the analysis is that, with the marginal abatement cost curves adopted in this work (taken from an EPA report), abating OGHGs is normally very convenient, as the abatement costs are much lower than those related to carbon dioxide abatement. This implies that the optimal abatement is often equal to the maximum available level, and thus the evolution over time of this upper bound, modeled by the various TP, is a fundamental factor, which justifies such an analysis.

If the Carbon Tax policy is deployed, extensive OGHG abatement, with almost no impact on policy costs, allows reaching better environmental results. With the tax adopted in this work, -90 $ppmCO_2eq$ of GHG concentration, -0.67 W/m^2 of radiative forcing, -0.38°C of pre-industrial temperature increase in 2100 are achieved in the TP high case with respect to the CO_2 only one (in absolute terms: 675 $ppmCO_2eq$, 4.82 W/m^2 and 3.15°C in 2100 in the former). On the other hand, if a Stabilization 535 scenario (more stringent than the previous one) is considered, climatic targets are obviously the same in all TP cases (3.5 W/m^2 and 2.4°C as 2100 radiative forcing and pre-industrial temperature increase), but the higher TP, the higher OGHG abatement and the lower carbon dioxide one, which results in a strong impact on policy costs (overall discounted GDP loss passes from 3.2% in the CO_2 only case to 1.6% in the TP high one), again confirming the general convenience in cutting non-CO_2 gas emissions. The abatement potential data and the TP hypotheses are such that the cumulative OGHG emissions over the century practically halve with respect to the baseline ones.

For the sake of completeness, it must be specified that the TP high scenario has eventually been implemented in WITCH, as 2010 abatement potentials, which are not huge especially for some gases, are supposed to grow considerably over the century (see Figure 9 and Figure 10 for comparison).

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