From Copenhagen to Durban and the quest for sustainable levels of GHG concentrations

Socrates Kypreos and Antti Lehtila

Energy Economics Group, Paul Scherrer Institut, Villigen, Switzerland

Technical Research Centre – VTT, Finland

e-mail: socrates.kypreos@gmail.com **Submission code: 4f149285180c9**

Abstract: The COP17 in Durban South Africa, has approved a deal to negotiate and arrange by 2015, a global binding commitment to reduce GHGs starting from 2020 onwards. COP17 also extended the Kyoto Protocol for a second period after 2012 and confirmed the commitment of COP16 for the green carbon fund supporting DCs. However, the success on climate change mitigation will depend on the modalities for the extension of the protocol after 2020. The legitimate question of concern refers to the appropriate level of GHG reduction that would be inline with UNFCCC Art. 2. We try to answer this question applying a parametric analysis with gradually stringent cumulative and global emission bounds applied in a special version of MERGE hard-linked with the TIMES-MACRO model of USA able to analyze technological details of the end-use markets. This model assumes endogenous learning defining the cost development of technology as endogenous and path dependent model property. Low generating cost of advanced carbon-free technologies for power generation, hydrogen and synthetic fuel production in respect to the conventional competitors is a prerequisite for the analysis of global warming and for defining the economic implications of a new climate protocol. Finally, the study estimates the cost of carbon mitigation and concludes that timing is a critical issue to sustain global warming below 2 °C as the new Kyoto protocol has a narrow time-window for balancing the lost opportunity to act earlier.

Acknowledgement: *The kind support of the IEA-ETSAP project for model development enhancing the ETSAP tools and its first application presented herein is appreciated.*

1. Introduction

The Copenhagen Conference of Parties COP15, as endorsed by the COP16 in Cancun, proposed the so-called Copenhagen Accord (CA) aiming to combat global warming with differentiated reduction targets of greenhouse gas emissions and by mobilizing resources supporting adaptation and carbon-free technology in developing countries (DCs). Unfortunately, both Conferences failed to fulfill the main goal of the United Nations Convention on Climate Change, namely a binding and global extension to the Kyoto Protocol to combat global warming. The recent (December 2011) outcome of COP17 that took place in Durban, South Africa was again unable to establish a legally binding global commitment. Instead a deal was approved to negotiate and to arrange by 2015 the initiation of such legal entity from 2020 onwards. Also COP17 approved to extend the Kyoto protocol for a second period after 2012, e.g., without an implementation gap and to initiate the green carbon fund as approved by COP16. Nevertheless, as the final outcome on mitigation depends on the modalities for the extension of the protocol after 2020, the legitimate question is which levels of GHG reduction would be sufficient to serve as a Post-Kyoto policy framework aiming ***to stabilize GHGs concentration at levels that would prevent dangerous anthropogenic interference with the climate system*** (UNFCCC Art. 2).

Also, as such agreement will start will global commitments after 2020, while the Kyoto protocol is not supported by significant countries like USA, Canada and eventually Japan and Russia, it is justified to question if it is not already too late to sustain global warming below 2°C with a significant probability. This is especially the case, in a period following the economic recession of 2008, where governments and markets become increasingly hesitant to mitigate global warming and support a post Kyoto globally binding agreement. On the other hand, the signs of temperature change in the atmosphere and the oceans are increasing.

These are the overarching questions we are trying to answer initiating the production of some fist results of importance. We apply in the analysis a special version of MERGE linked with the TIMES-MACRO model of USA, both being well known and established models for integrated assessment and mitigation studies. The reason for special emphasis given to USA is the need to analyze the technological details (i.e., by including explicitly the end-use markets not available in MERGE) and the economic implications of a climate agreement for USA together with the competition of advanced carbon free technologies in this sensitive market.

A significant study that helps our analysis to quantify the probability to sustain global warming below 2°C is the work published in Nature (Meinshausen 2009). This study, based on comprehensive probabilistic analysis, claims that cumulative emissions up to 2050 are robust indicators of the probability that twenty-first century warming will not exceed 2° C relative to pre-industrial temperatures. Limiting cumulative CO2 emissions over 2000–50 to 1,000 Gt CO2 yields a 25% probability of warming exceeding 2° C—and a limit of 1,440 Gt CO2 yields a 50% probability—given a representative estimate of the distribution of climate system properties. Therefore these results serve as an acceptable and authoritative approach to define cumulative targets for our analysis and are shown in Table 1.

Table 1 Probabilities of exceeding 2 °C

	Indicators	**Emissions**	**Probability of exceeding 2°C**	
Scenario Name	**Cumulative CO2**		**Range***	**Illustrative Default****
50 percent	Cumulative CO2 emissions 2000-50	1437 GtCO2	29-70%	50%
33 percent	Cumulative CO2 emissions 2000-50	1158 GtCO2	16-51%	33%
25 percent	Cumulative CO2 emissions 2000-50	1000 GtCO2	10-42%	25%
20 percent	Cumulative CO2 emissions 2000-50	886 GtCO2	8-37%	20%

* Range reflecting the various climate sensitivity distributions (with one exception)
** Illustrative example with a set of assumptions defined by Meinshausen et al. (2009)

In order to initiate the analysis we need to quantify first the carbon emission reduction targets up to 2020 for the extension of the Kyoto protocol after 2012 for the Annex B regions of the protocol and the expectations for the non-Annex B regions. A first quantification of emission levels by 2020 is summarized in Table 2 and it is defined based on the Copenhagen pledges and some extra assumptions compiled by Lamriet et al. (2010). Then, by postulating global constrained levels of cumulative carbon emissions in agreement with the conclusions of Mainshausen (Nature 2009) we aim to assess the feasibility and implications of the Durban COP17 outcome. In our analysis we apply cumulative constraints while simultaneously take care that at least the global target of CO2 emissions by 2020 remains below the level of 10 GtC. Then, by increasing gradually the stringency of this cumulative constraint and giving to the model the flexibility to efficiently reduce emissions between 2010 and 2020 following the stringency of this constraint, we assess the associated probability to restrict temperature change below 2 °C post industrial, by investigating the level of cumulative emissions in the period between 2000 to 2050.

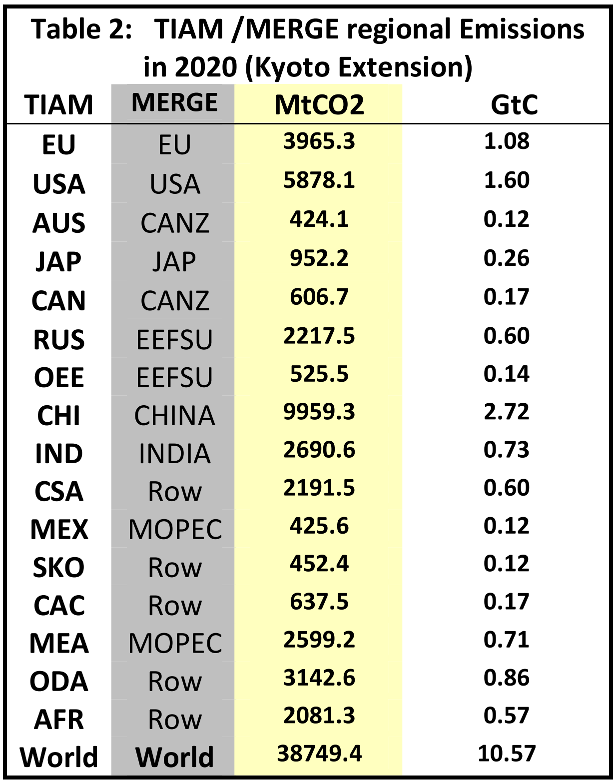

Table 2: TIAM /MERGE regional Emissions in 2020 (Kyoto Extension)

TIAM	MERGE	MtCO2	GtC
EU	EU	**3965.3**	**1.08**
USA	USA	**5878.1**	**1.60**
AUS	CANZ	**424.1**	**0.12**
JAP	JAP	**952.2**	**0.26**
CAN	CANZ	**606.7**	**0.17**
RUS	EEFSU	**2217.5**	**0.60**
OEE	EEFSU	**525.5**	**0.14**
CHI	CHINA	**9959.3**	**2.72**
IND	INDIA	**2690.6**	**0.73**
CSA	Row	**2191.5**	**0.60**
MEX	MOPEC	**425.6**	**0.12**
SKO	Row	**452.4**	**0.12**
CAC	Row	**637.5**	**0.17**
MEA	MOPEC	**2599.2**	**0.71**
ODA	Row	**3142.6**	**0.86**
AFR	Row	**2081.3**	**0.57**
World	**World**	**38749.4**	**10.57**

2 The Baseline

The baseline development is based on the assumptions made in the EU project ADAM, Edenhofer et al.(2010), fine-tuned with the baseline scenario development generated by the TIMER model (Van Vuuren, et al. (2006), Magné, et al, (2010)) for that project. The baseline excludes any consideration of damages and climate policies. This refers to the regions of EU, Eastern Europe and former Soviet Union (EESU), China, India, Japan, CANZ (Canada, Australia and New Zeeland), MOPEC (Mexico and Opec) and the rest of the world (ROW). USA which is the ninth world region of the model is analyzed based on assumptions made by the IEA-ETSAP TIAM project (Loulou and Lambriet 2008).

In the baseline, electricity production increases, as consequence of population and economic growth and the moderate improvement in energy intensity, from 21.2 PWh in 2005 up to 78.2 PWh per year by 2050, while the primary energy use increases from 418 EJ to 976 EJ per year by 2050. Existing fossil fuel-based thermal plants are progressively phased out and replaced initially by a combination of coal, NGCC and IGCC plants, and then coal and IGCC, owing to its relatively high efficiency and low fuel cost (supported by learning-by-doing). Next to IGCC, wind turbines followed by nuclear reactors are the most competitive power generation systems. Wind power complements the power supply up to 27% of overall electricity generation. Primary energy is mainly provided by coal followed by renewable energy forms, complimented by gas and oil. As a consequence, energy related carbon emissions reach a level of 14 GtC in 2050 and the atmospheric concentration becomes 545 ppmv for CO2 and 642 ppmv for all Kyoto gases. This moderate increase of GHGs in the atmosphere is due to the LbD and LbS model formulation that reduces the specific investment cost as function of experience applied in all scenarios as standard modeling option and results to high penetration for wind already in the baseline case.

Next we select different emission reduction targets to further reduce carbon emissions and restrict temperature change to acceptable levels, e.g., the 2°C target of the European Parliament (European Commission 2007) with different probabilities of exceeding this target. The model reduces also the emissions of other GHGs based on marginal abatement curves.

3. Global emission budgets, concentrations and marginal costs

We want to present the level of emission reduction, the probabilities to exceed the 2 °Celsius of post-industrial warming, the implied global carbon taxes and the economic implications for USA and other world regions in respect to the baseline developments.

3.1 Global emission budgets

As explained before, Table 1 gives the cumulative emission budgets associated with 20%, 25%, 33% and 50 % probability of exceeding 2°C of warming. In order to set the scene for the analysis we need to define first the emissions between 2010 and 2020 and then to impose either global cumulative constraints that correspond to the cumulative emissions of Table 1 or annual budgets in agreement with the cumulative constraints and operate with a policy scenario as e.g., a Cap and Trade (C&T) case. We do not follow the annual specification of global emissions to allow for efficient solutions with a maximum flexibility in meeting the global and cumulative constraint assumed. All scenarios are estimated with a descriptive utility discount rate of 3 percent.

Figure 1 illustrates the emission levels estimated with the MERGE&TIMES-USA model when cumulative constrained budgets are imposed for the period 2020-2060 that correspond to the four emission budgets discussed before. Notice that the model is fixing global emissions in the year 2010 but is free to select optimal pathways and emission reductions in the period from 2010-2020 in order to satisfy the cumulative emission budgets corresponding to Table 1. As consequence of this flexibility, the more stringent the cumulative bound the less the emissions in the period around 2020 which should be interpreted that a Kyoto extension policy is initiated by 2015 where the signatory countries are determined to combat global warming as of satisfying the probability in discussion for not exceeding global warming above the 2°C. Clearly this approach is not forcing the global emission profiles to necessarily satisfy the sustainability targets of Table 1. Another possibility would have been to fix emissions for 2020 to the emissions corresponding to Table 2 that is defined assuming the adoption of the Copenhagen pledges but this results to quite high levels of emissions making it difficult to satisfy the sustainability targets.

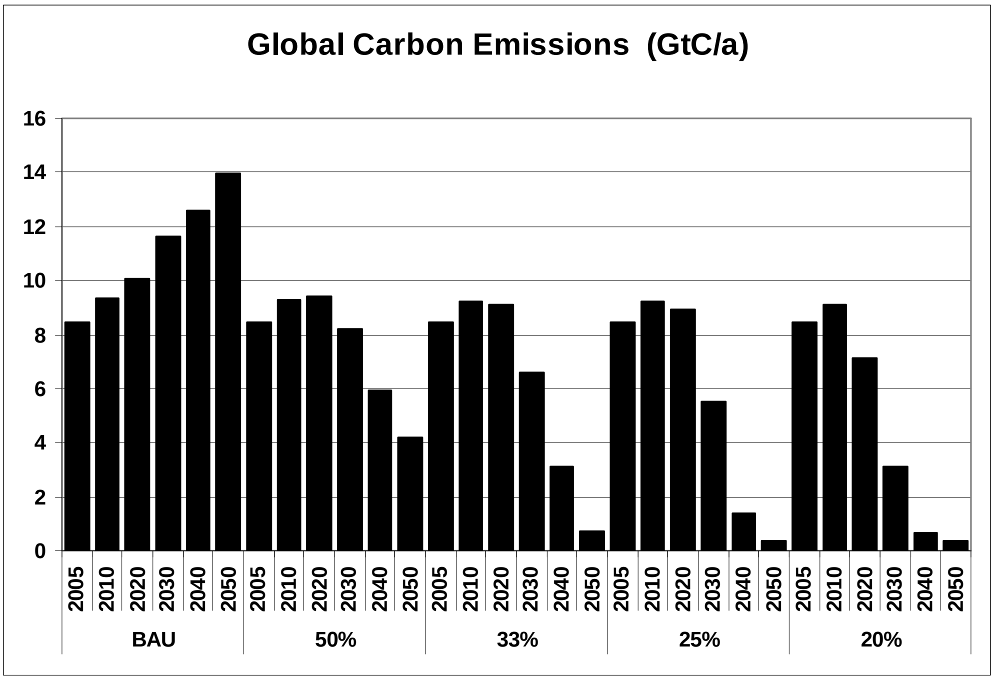

Fig. 2: Annual Carbon Emissions estimated for the Baseline (BAU) and under the imposed global and cumulative budgets with 50%, 33%, 25% and 20 % probability of exceeding 2°C.

Table 3: Estimated Carbon Emissions in GtCO2/a and the associated probability to exceed 2 °Celsius

2010	2020	2030	2040	2050	2000-2050	probability
GtCO2/a	GtCO2/a	GtCO2/a	GtCO2/a	GtCO2/a	GtCO2	Obtained in%
37.69	41.18	46.93	49.94	54.96	2174	NA
37.40	38.39	34.17	26.03	18.85	1597	**60**
37.14	37.14	28.38	15.22	5.79	1352	**45**
37.11	36.67	24.38	8.32	4.58	1232	**37**
36.74	30.18	15.14	5.79	4.69	1048	**28**

Examining the column of cumulative emissions between 2000-2050 of Table 3 (estimated by applying the trapezoidal rule for the shown emission level 2010-2050, and by adding 330 $GtCO_2$ for the period of 2000-2010) we confirm the expected implication that the required cumulative emission targets are now associated with higher probabilities to exceed the 2 ° Celsius as the expected decision to introduce mitigations actions and undertake global and binding commitments are delayed. The probabilities given in Table 3 are estimated applying the probabilities and cumulative emissions levels of table 2 via interpolation. We realize that the probability to exceed 2°C varies now between 60% and 28% instead of 50% and 20%. This in a first interpretation is not awkward situation but there are two basic drawbacks remaining:

1) The associated shadow prices become high once we approach probability levels of around 30% as shadow prices reach levels of 700-1000 $/t of carbon (Fig. 3).
2) The estimated emissions in 2020 is a result of optimization but such a performance for the extended Kyoto protocol requires a substantial mobilization in the global level in order to reduce by 2020 emissions to the levels estimated in the model (i.e., about 20% below the global CO2 emissions in 2010).

3.2 Emissions and Concentrations

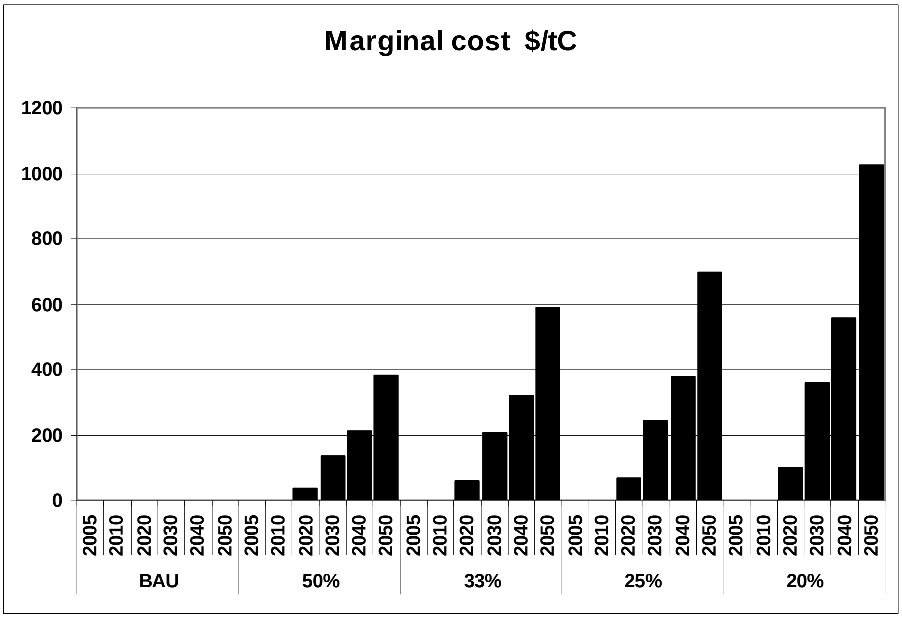

Fig. 3: Marginal cost of carbon control estimated in MERGE&TIMES-USA model under global and cumulative emission budgets from 2020 to 2060 that correspond to the emission profiles shown in Figure 1 for different probabilities of exceeding 2°C of warming.

Figure 3 presents the tax levels corresponding to the imposed cumulative constraints. This emission profiles for the low probability cases indicates significant reductions for the year 2020 already which needs the initiation of policies by the year 2015. The stringency of actions depends on the stringency of the imposed constraint. As in reality there is no such political will to initiate actions now the 20% probability case is optimistic and instead a stabilization of emission profiles for the period 2010-2020 is a more realistic expectation.

Comparing emission levels and the corresponding marginal control cost of carbon we conclude that MERGE & TIMES-USA model is flexible in reducing carbon emissions at almost zero levels but at high shadow prices. Another conclusion illustrated in Figure 4 is the low atmospheric concentration of the Kyoto gases obtained in the case with the lower probability is around 400 ppmv while the equivalent CO2 concentration of all GHGs remains in the level of 510 ppmv.

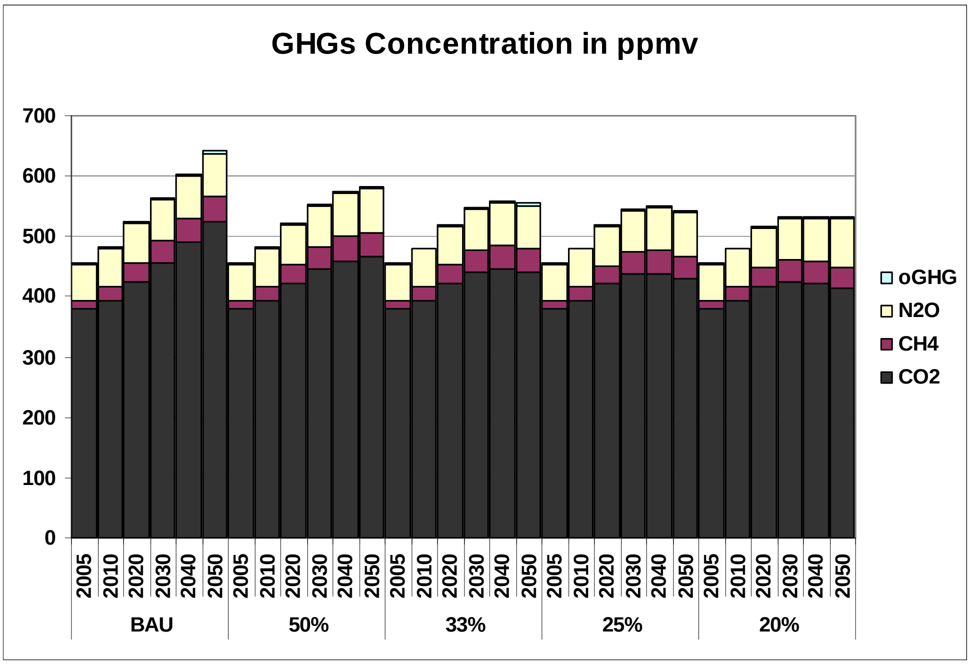

Fig. 4: Atmospheric concentrations given in ppmv of Kyoto GHGs in CO2 equivalent as estimated with MERGE&TIMES-USA under global and cumulative emission budgets for different probabilities of exceeding 2°C of warming.

3.3 GDP and economic burden by region

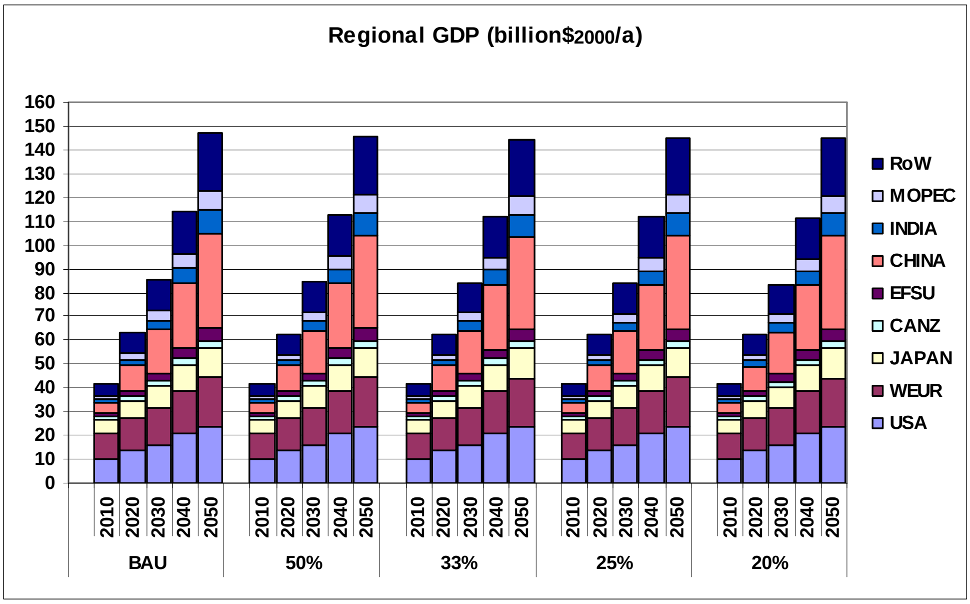

Fig. 5: GDP by region and time for the cases analyzed.

One has difficulties to recognize the differences in terms of GDP development due to the cumulative carbon constraint as the overall and maximum cumulative difference is 1.4 percent for the most stringent emission reduction case. But the regional impacts are significant for some world regions as e.g. for the oil exporting countries.

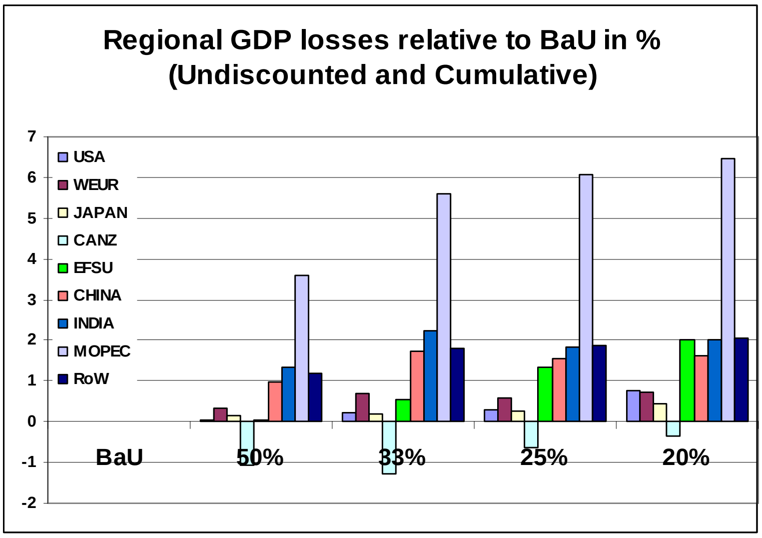

Fig. 5: Regional cumulative and undiscounted GDP losses by region for the cases analyzed relative to BaU in percent.

This figure defines the GDP loss for the period of analysis but in undiscounted prices. The cumulative constraint on total CO2 emissions defines efficient solutions across time, and regions and even other Kyoto GHG gases are reduced following the marginal cost pricing, but is not evaluating any compensation measures like in the case of Cap & Trade policies to counter balance these losses. The cost for DCs is high with a maximum appearing for the OPEC regions as not only exports and fossil fuel use are reduced but as a consequence their prices are also falling. The cost for the industrialized world is moderate with CANZ having a net benefit mainly due to production of unconventional oil (tar sands) and exports of synthetic fuels. This explains why the DCs are reluctant to join a globally binding protocol without compensation measures. Notice that the global undiscounted GDP net losses of the global economic output for the period of analysis are trivial (1.2% to 1.4%) while the benefits of reduced local pollutions (less fossil fuel use) and reduced temperature change are not assessed in the analyses.

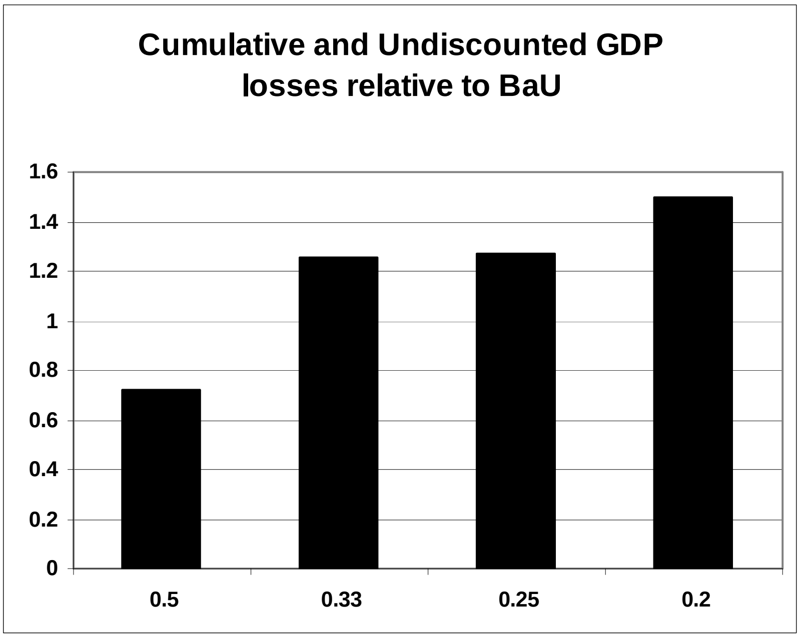

Fig. 6: Global cumulative and undiscounted GDP losses for the cases analyzed relative to BAU (in percent)

3.4 Primary energy and power generation

This section presents the primary energy consumption and power generation by the different levels of the global and cumulative constraints applied. We have already realized (Fig. 2 and Fig. 3) that the strong emission reduction obtained for the 20% probability case has a rather high marginal cost of around 1000 $ per ton of Carbon. This indicates (when comparing with similar studies) a deficit in terms of sufficient measures to control carbon emissions and explains the strong degree of energy conservation in terms of primary energy consumption shown by Fig. 7.

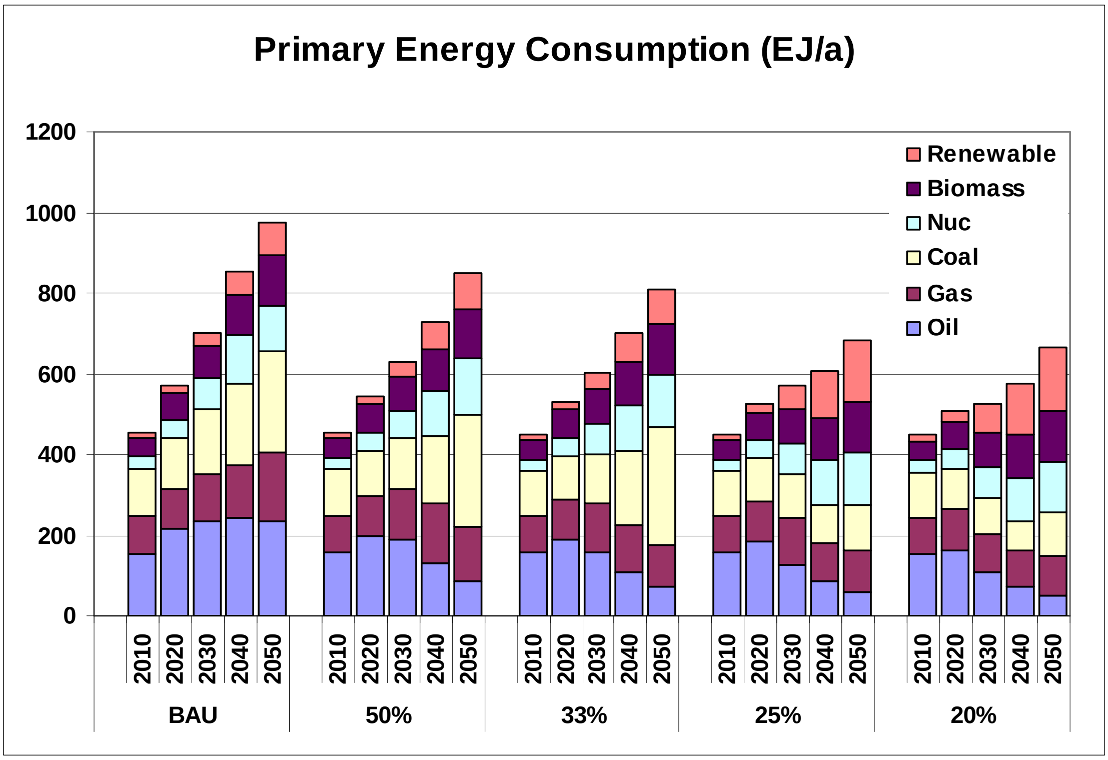

Fig. 7: Global Primary Energy Consumptions for the cases analyzed and in comparison to BAU

The impact of the carbon constraint to the primary energy consumption (PEC) levels shows a significant reduction in energy use equivalent to 1/3 of the PEC of the baseline for the 25% and the 20% probability cases. Also the use of oil is below 10% of the total primary consumption while the absolute and relative levels of coal are around 100EJ or

1/6th of total primary energy. Gas is also reduced but to a lesser extend. Consequently the market shares of renewable, biomass and nuclear are increased over baseline.

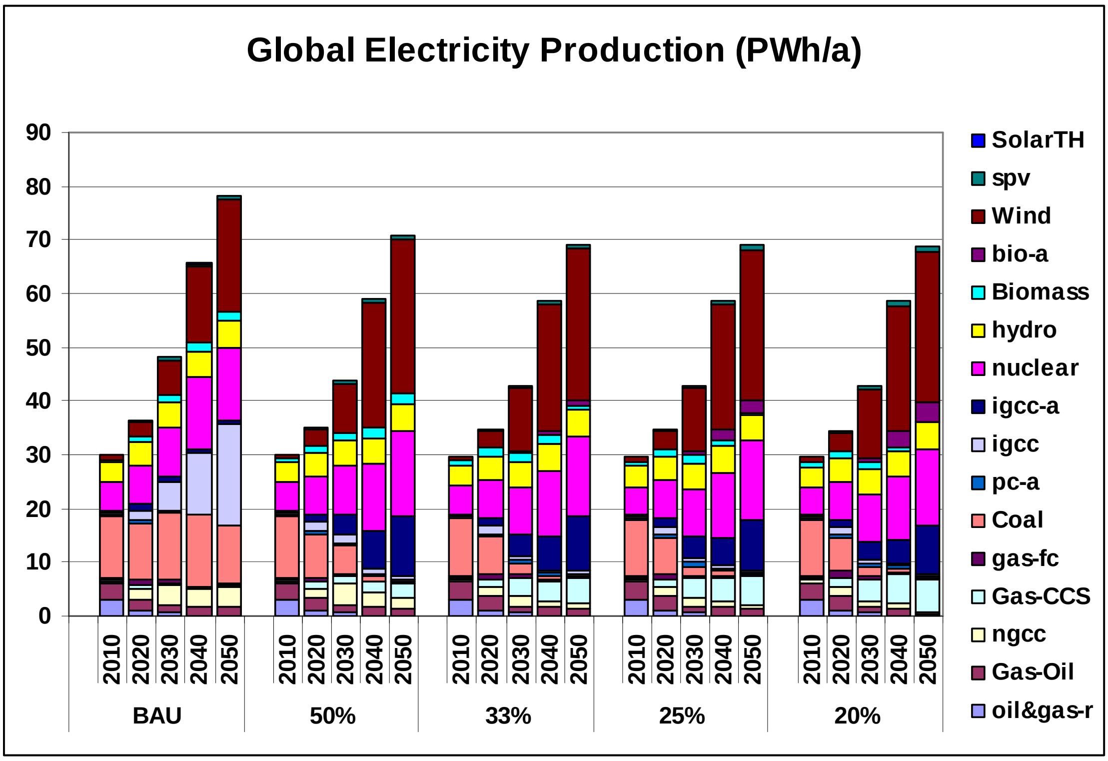

Fig. 8: Global electricity production for the cases analyzed and in comparison to BAU

The impact of the carbon constraint to the level of electricity production is around 10 PWh/a or about 12% reduction relative to baseline but the structural change of power generation is significant as carbon free options are becoming mature and dominate the market while the production level of electricity is almost independent of the stringency of the carbon constraint. Winners are wind energy, nuclear energy and coal use based on IGCC and gas combined cycle GCC both with CCS options.

4. Specific results for the US

The previous sections introduced a global and binding carbon constraint in the energy system that is acting as driving force of the technological change needed to take place in a carbon constrained world and explains the economic implications of that constraint together with the probability to restraint post-industrial temperature changes below 2 ° Celsius. The last part of this report will explain the implications of global policies on the national level developments consistent with the global policy constraint.

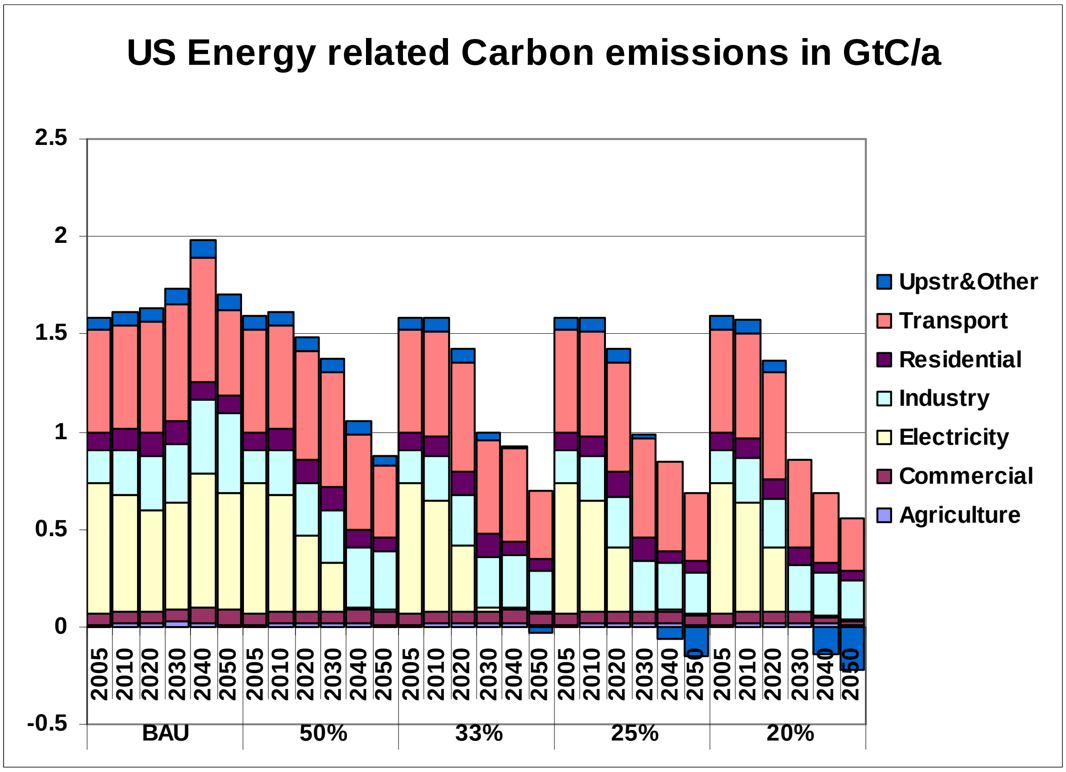

Fig. 9: US electricity production for the cases analyzed and in comparison to BAU

The reduction of carbon emissions in USA follows the general pattern that appears on the global level where Industry and transport sectors are less efficient to reduce emissions as in relation with the power generation sector where carbon emissions are totally eliminated.

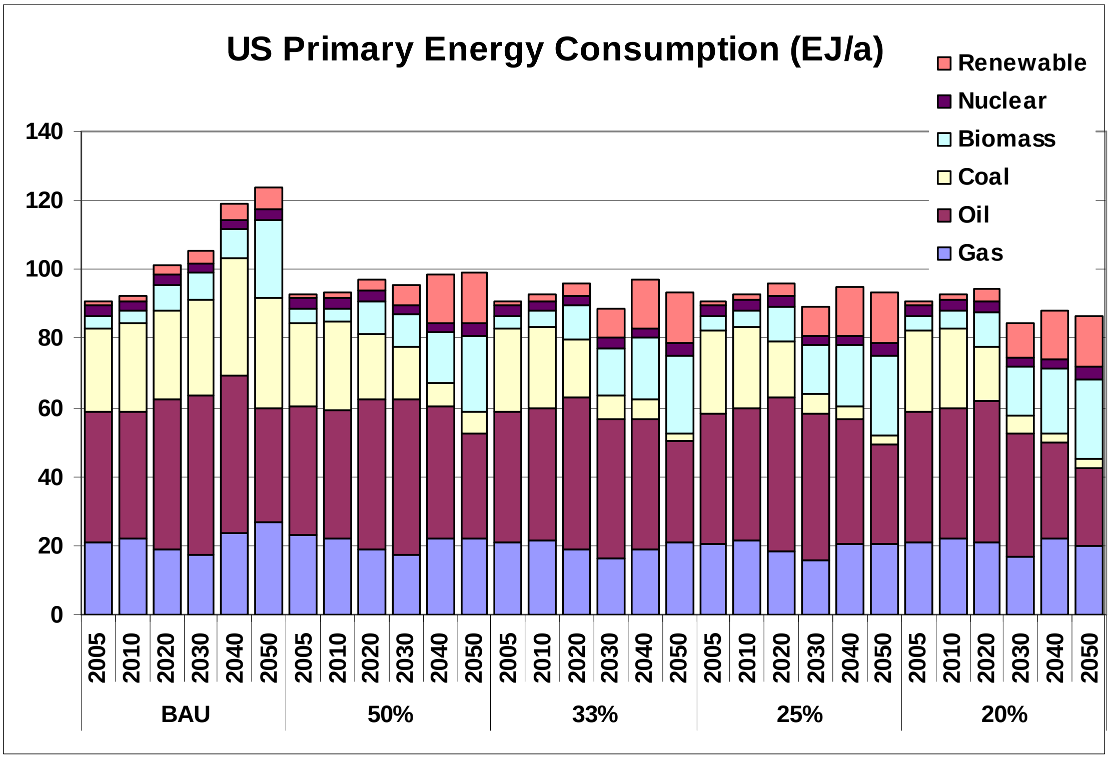

Fig. 10: US Primary energy consumption for the cases analyzed and in comparison to BAU

Similar behavior appears in the US PEC which is increased by 1/3rd in the baseline case but remains almost stabilized in the carbon constrained cases. The other important conclusion is related to the structural changes in primary energy use as indicated by the total elimination of direct coal use substituted by biomass and other renewable. Gas and oil products continue to supply significant fractions of PEC.

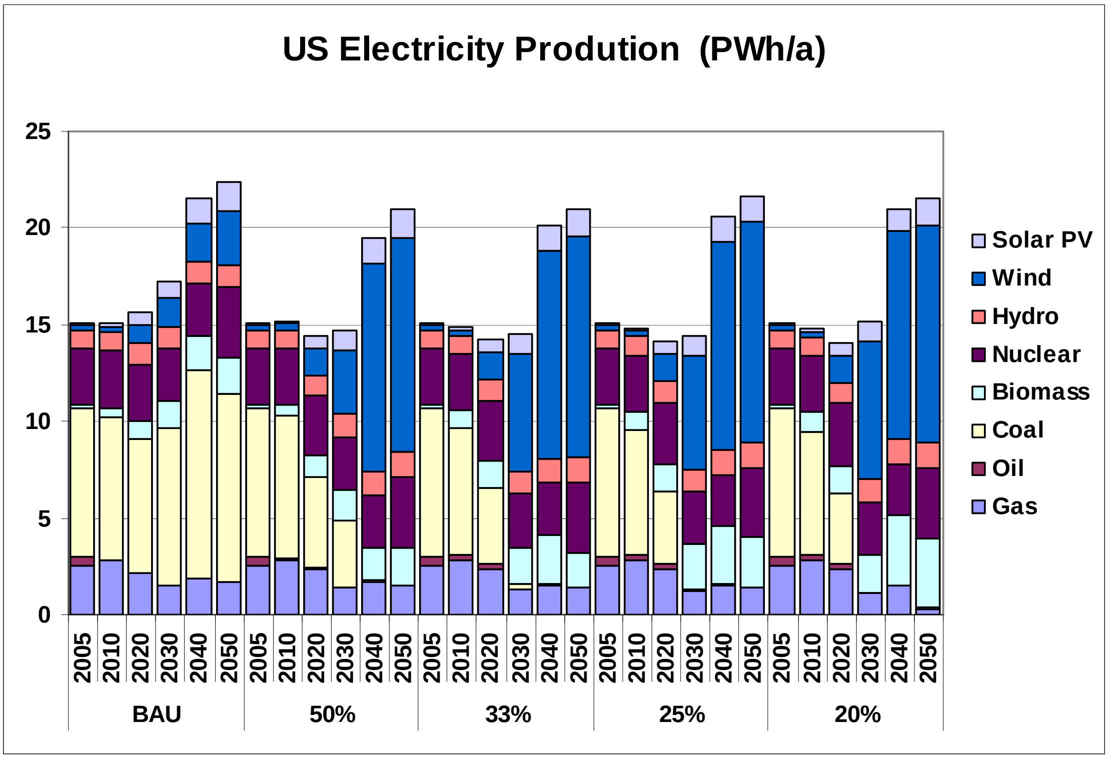

Fig. 11: US Electricity generation for the cases analyzed and in comparison to BAU

Again in the power generation sector coal is substituted mainly by wind followed by biomass and nuclear. Solar PV options are also introduced in the last two decades of analysis. Wind covers more than 50% of electricity generation and this is asking for investments in smart grids. As consequence of all these changes power generation becomes carbon free in USA.

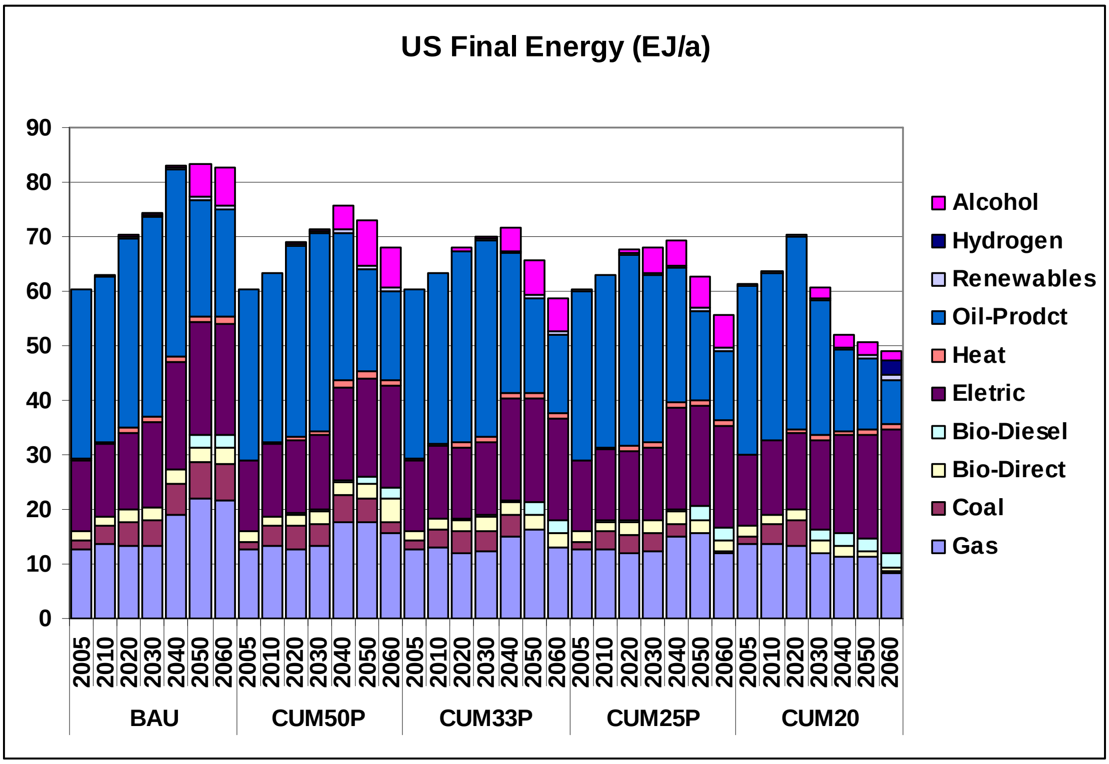

Fig. 12: US Electricity generation for the cases analyzed and in comparison to BAU

Here the share of electricity, alcohol fuels and bio-diesel contributes to the reduction of oil products while the overall consumption is first increased up to 2020 and when the carbon constrained becomes active is either stabilized or is significantly reduced (CUM20%) mainly due to the use of efficient devices and electric heat pumps and methanol/ethanol cars but also due to consumers behavior that reduce significant the demand for energy services. The assumed elasticity of substitution for USA is ESUB=0.5.

5. Conclusions

As the last UN COP failed to arrange a global and binding agreement to reduce GHG emissions other than to postpone the initiation of such agreement after 2020, it is justified to question the feasibility to sustain global warming below 2℃ and if instead, a more pragmatic target should be followed. The present study derives conclusions on the feasibility to restrict global warming below 2° Celsius, the associated economic impact by world region and the importance of carbon free technologies like wind, solar PV and biomass based systems and low-carbon systems with IGCC and GTCC, systems with CCS and their competition in respect with conventional fossil systems.

- The study concludes that is always feasible to sustain global warming below 2℃ explaining that is not yet very late as we have a time window to successfully implement the appropriate measures. However, already now the associated probabilities to sustain temperature change below 2 ℃ are becoming worse, while this window of opportunity is becoming narrow. Further delays with make the goal of 2 ℃ post-industrial warming an impossible task. Obviously other moderate targets can be satisfied at lower cost although at higher risks due to climate change.
- Although some carbon-free technologies like wind and advanced nuclear systems are competitive and contribute to the reduction of carbon emissions already in the baseline, other systems like advanced carbon capture and sequestration options based on coal and natural gas for power generation and solar PV need the introduction of taxes or other instruments to become competitive.
- Synthetic fuel production and advanced power generation based on biomass with CCS options have negative carbon emissions and become one of the key future technological options to mitigate carbon emissions but for the moment they need policy support to become mature.
- Conservation options in the building sector and in the transportation together with efficiency improving end-use options are contributing to the reduction of carbon emissions. This is indicated by the stabilization of final energy use for USA although the economic activity assumes a significant growth.
- Finally, although the net GDP reduction on the global level remains below 1.4% the impact of the carbon constraint is DCs and oil/gas exporting regions is significant asking for compensation measures. This could be obtained by Cap & trade policies, the carbon transfer fund for renewable and by regional differentiation of carbon emission policies in the early

decades based on the expected economic developments and the potential mitigation options across the world regions.

6. Appendix: The GMTM-USA model

A flexible formulation of E3 models for Integrated Assessment is used to derive conclusions on national GHGs mitigation policies in respect with global commitments and policies. This is done linking together the TIMES-MACRO (TM) model of USA, (Remme, 2005) rich in technological details, with the MERGE model of the remaining world regions. This modeling approach enlarges the options given in evaluating the regional and technological details for significant world regions while simultaneously being consistent with global developments in terms of resource use, climate constraints, trade of fuels, and the endogenous treatment of technological change needed to efficiently control climate change. The Global MERGE and TIMES (GMTM) model is a modelling framework aiming to design national energy and environmental policies under consistent international boundary conditions. The approach is placing national policy visions within an international context of world developments with the scope to define consistent and optimal national energy policies and visions that take into consideration the global boundaries of resource use, environmental constraints and path-dependent technological change and learning. The link will maximize the global welfare while ranking the technological options needed to achieve the set of normative constraints imposed. This method will allow for an endogenous and path -and- policy dependent ranking of technological options.

The first version of such hybrid models, that become available at late nineties, (Kypreos, IEA-ETSAP meeting in 1988, Berlin, Germany) has been developed together with Alan Manne and Gary Goldstein, and was one of the early efforts going into the direction of regionalized hybrid models on the global scale based on the integration of simplified macroeconomic growth models linked with detailed bottom-up engineering models. In the mean time, a series of different well known models become available like the MERGE model of A. Manne and R. Richels, a 6 region GMM model (Barreto, 1998) to be concluded with the development of the 15-16 region ETP (IEA/OECD) and TIAM models (R. Loulou and M. Lambriet, 2008) all functioning either as hybrid models (i.e., MERGE) or as regionalized but global models based on partial equilibrium algorithms (i.e., all others). Finally, the link of TIAM with the applied general equilibrium model GEMINI (Bernard and Vielle, 2003) should be understood as cutting edge development work in climatic change modeling, as it combines detailed engineering models with applied general equilibrium models focusing on sectoral economic impacts. However, the development work described herein is less ambitious but is unique as it applies a NLP formulation in Energy-Economy and Environment (E3), with endogenous learning focusing on the macro-economic implications of either energy related or environmental related policies

A1: The Energy/Economy/Environment (E3) Hybrid Techno-Economic Model

For simplicity, only the basic model structure related to the global trade and the link between the demand and supply will be given here.

The objective of the model is to maximize the utility function (discounted and weighted sum of regional utilities (δ is the time preference rate), that subjects to regional and global constraints.

$$U = W_r \cdot \sum_{t=0}^{t=T} \ln C_t \cdot e^{-\delta \cdot t}$$

The weights of the objective functions W_r are the Negishi weights. The weights are normalized and adjusted in an iterative approach according to the inverse of the marginal utility of regional income such that the discounted trade per region and time is balanced. Negishi has shown that in such a case the obtained solution is Pareto optimal, e.g., it redistributes new wealth and not the existing one (Negishi, 1972)

A2: Regional constraints

The link between the macroeconomic model and the energy supply model is obtained through the variables that represent energy services and the annualized energy system cost. The production function relates the input of primary production factors to the gross output of the economy. In the TIMES-MACRO (TM) formulation we have capital C, labor L, and energy services D, as primary production factors. In MERGE energy is disaggregated to electric E, and non-electric inputs NE, i.e., a very similar structure as both models are based on a concept formulated by Alan Manne (Manne and Richels, 2004, Manne and Wene, 200x).

$$Y_t = \langle a \cdot K_t^{\rho\alpha} \cdot L_t^{\rho(1-\alpha)} + \sum_m b_m \cdot D_{mt}^{\rho} \rangle^{1/\rho}$$ **TIMES-MACRO region**

$$Y_{rt} = \langle a_r \cdot K_{rt}^{\rho_r \alpha_r} \cdot D_{rt}^{\rho_r(1-\alpha_r)} + \sum_m b_{mr} \cdot D_{mrt}^{\rho_r} \rangle^{1/\rho_r}$$ **MERGE** regions

The economic output Y is distributed among consumption C, investments I, and the energy cost EC, while the national accounts are balanced assuming the net exports $\mathbf{XTR_{nmr}}$ of a numeraire good, a composite commodity of all non-energy sectors:

$$Y = C + I + EC + XTR_{nmr}$$

GDP is defined as the sum of consumption C, investments I, and the net experts of all traded goods and services.

The capital formation function (per time and region) takes into account the capital depreciation rate $\boldsymbol{\delta_k}$ and the new investments (petty-clay model).

$$K_t = (1 - \delta_k) \cdot K_{t-1} + I_t$$

The demand constraints relate the adjusted demands (due to the autonomous efficiency improvement **aeei**) to the model energy flows related to the demand for energy services:

$$\sum_{\forall X_j \subseteq D_i} X_{jt} \geq D_{mt} \cdot e^{-aeei_d \cdot \Delta t}$$ Sum of all demand devices that satisfy demand D_m, (TM)

$$\sum_j PE_{jrt} = E_{rt} e^{-aeei_{PE} \cdot \Delta t}$$ Sum of electricity production per technology j, (MERGE)

$$\sum_i PNE_{irt} = N_{rt} e^{-aeei_{PNE} \cdot \Delta t}$$ Sum of non-electric energy per technology i, (MERGE)

Energy system cost: In MERGE, a simplified way to present the model is to say that energy cost accounts for the annualized production costs of electric **PE**, and non-electric **PN** energy, using the corresponding unit cost, i.e., **ce** for the electric and **cn** for the non-electric energy. Conventional energy taxes **taxe** and **taxne**, carbon taxes tax_{CO2} and the transaction costs $\mathbf{csttrn_g}$ of exported good minus the tax revenues are also included.

$$EC = \sum_j PE_j \cdot ce_j + \sum_i PN_i \cdot cne_i + taxe \cdot E \cdot e^{-aeei_E \cdot \delta t} + taxne \cdot N \cdot e^{-aeei_{NE} \cdot \delta t} +$$
$$\sum_g csttrn_g \cdot EXP_g + E_{CO2} \cdot tax_{CO2} - TAXREV + QP$$

The exact model formulation for MERGE is given by Magne et als (2010). The model introduces a quadratic cost penalty function **QP**, for technologies that penetrate the market above normal rates. Similar **QP** functions are also introduced in the TM model.

CO2 emission balance per region and time for Cap & Trade.

The sum of carbon emissions in a region r and time t, due to electricity production and non-electric energy use (i.e., energy activity times specific emissions per unit of activity), and the direct use of fossil fuels in the end-use sectors, minus the net exports of fossil fuels **EX**, must be greater or equal to the initial endowments **IE** of emissions rights, minus the net exports of emission certificates $XTR_{crt,t,r}$.

$$\sum_{k \in Electrictech} PE_{k,r,t} \cdot se_k \cdot HTRate_k + \sum_{n \in NE} PN_{n,r,t} \cdot sn_n / eta_n + DirFOS_{f,r.t} sn_f - \sum_{i \in fossil} EX_{i,r,t} \cdot se_i \geq IE_{r,t} - XTR_{crt,t,r}$$

A3: Global constraints

Global trade balance per time and product **g**: $\sum_r XTR_{r,g,t} = 0.0$

The dual of this constraint defines the price of traded products. Other constraints refer to the production, depletion and use of energy resources, mainly hydrocarbons.

The sequential optimization algorithm introduced by Thomas Rutherford in 1992 adjusts the Negishi weights per iteration. The first solution assumes weights proportional to economic production and defines a set of marginal costs for the traded products. The weights are then adjusted using the marginal cost of the trade balance and the inverse of the marginal utility function, e.g., Consumption, to get a Pareto optimal equilibrium solution. The normalization of the (shadow) prices for the traded goods is done by using the marginal cost of the numeraire good for the year 2005, $\pi_{g,t} = \pi_{g,t} / \pi_{nmr,2005}$. The weights $\mathbf{W_r}$, are defined such that the cumulative trade balance per region is satisfied.

7. References:

Barreto, L. and S. Kypreos (2004), “Endogenizing R&D and Market Experience in the "Bottom-Up" Energy-Systems ERIS Model”, Technovation 24(8), 615-629.

Bernard A. Vielle M. Measuring the Welfare Cost of Climate Change Policies: A Comparative Assessment Based on the Computable General Equilibrium Model GEMINI-E3. Environmental Modeling & Assessment, 8(3):199-217, 2003.

Edenhofer, O., Knopf, B., Barker, T., Baumstark, L., Bellevrat, E., Chateau, B., Criqui, P., Isaac, M., Kitous, A., Kypreos, S., Leimbach, M., Lessmann, K., Magne, B., Scrieciu, S., Turton, H., van Vuuren, D. (2010). The economics of low stabilisation: exploring its implications for mitigation costs and strategies. Energy Jounal 31 (Special Issue 1 on The Economics of Low Stabilization), pp. 11-48, ISSN: 0195-6574.

European Commission (2007). Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions - Limiting global climate change to 2 degrees Celsius - The way ahead for 2020 and beyond. (COM (2007) 2)

Hansen, J., M. Sato, P. Kharecha, D. Beerling, R. Berner, V. Masson-Delmotte, M. Pagani, M. Raymo, D. L. Royerm and J. C. Zachos (2008). “Target Atmospheric CO2: Where Should Humanity Aim?” The Open Atmospheric Science Journal 2: 217-231.

Kypreos, S. (2007). A MERGE model with endogenous technological change and the cost of carbon stabilization, Energy Policy 35(11), 5327-36.

Loulou, R. & Labriet, M. 2008. ETSAP-TIAM: the TIMES integrated assessment model. Part I: Model structure. Computational Management Science 5(1), p. 7-40.

Loulou, R. & Labriet, M. 2008. ETSAP-TIAM: the TIMES integrated assessment model. Part II: mathematical formulation. Computational Management Science 5(1), p. 41-66.

Magné, B., Kypreos, S, Turton, H. (2010). Technology options for low stabilization pathways with MERGE. In Edenhofer, Knopf, Leimbach, Bauer (Eds) Special Issue in the Energy Journal (The economics of low stabilization), pp. 83-107, ISSN: 0195-6574.

Manne, A., Wene, C.-O. (). MARKAL-MACRO

Manne, A., Richels, R. (2004a). MERGE: An Integrated Assessment Model for Global Climate Change. (http://www.stanford.edu/group/MERGE/biblio.htm)

Manne, A., Richels, R. (2004b). The impact of learning-by-doing on the timing and costs of CO2 abatement, Energy Economics 26(4), 603-619.

Negishi, T. (1972), General Equilibrium Theory and International Trade. North-Holland Publishing Company, Amsterdam.

Meinshausen, M., Meinshausen, N., William Hare, W., Raper, S., Frieler, K., Knutti, R., Frame, D., Allen, M., (2009) Greenhouse-gas emission targets for limiting global warming to 2 ℃. Nature Vol 458, 30 April 2009, doi:10.1038/nature08017

Remme, U. & Blesl, M. 2006. Documentation of the TIMES-MACRO model. IEA Energy Technology Systems Analysis Programme.

http://www.iea-etrap.org/web/Docs/MACRO_Draft_010206.pdf

Rogner, H. (1997). “An assessment of world hydrocarbon resources”. Annual Review of Energy and the Environment, 22: 217-262.

U.S. Geological Survey (2000). World Petroleum Assessment 2000 – Description and Results. U.S. Department of the Int. U.S.

US DOE (US Department Of Energy) (2004). International Energy Annual: US DOE.

UN-FCCC/CP/2009/L.7, Copenhagen Accord, 18 December 2009

Van Vuuren, D. P., B. van Ruijven, et al. (2006). TIMER 2: Model description and application. Integrated modelling of global environmental change. An overview of IMAGE 2.4. A. F. Bouwman, T. Kram and K. Klein Goldewijk. Bilthoven, The Netherlands, Netherlands Environmental Assessment Agency (MNP), 39-59