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Marginal Abatement Curves in the Energy-System GMM Model

Report to the

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1. Introduction

The consideration of non-CO_2 greenhouse gases (GHG) is an important aspect when examining cost-effective strategies for mitigation of global climate change (e.g. Manne and Richels, 2000, 2003; Reilly *et al.*, 1999, 2003). Although CO_2 is the most significant contributor to climate change, other GHGs play also an important role, in particular due to the fact that they are associated with a much more potent greenhouse effect in the atmosphere than CO_2. Including non-CO_2 GHGs may have noticeable effects on the costs and composition of mitigation strategies. Thus, they represent an important component when it comes to enhance the degree of flexibility of climate-change mitigation strategies.

There are several possibilities for considering the effects of non-CO_2 GHG abatement in a "bottom-up" modeling framework. One of them is the explicit inclusion of abatement technologies, an approach that has been followed by Rao and Riahi (2004) and Delhotal *et al.*, (2004), among others. The second approach is the use of aggregate marginal abatement curves (MACs), built on the basis of assessment of abatement technologies.

Following the work of Manne and Richels (2000, 2003) for the MERGE model and Turton and Barreto (2004) for the ERIS model, we incorporate marginal abatement curves for two main non-CO_2 greenhouse gases, namely methane (CH_4) and nitrous oxide (N_2O), considering both energy-related and non-energy-related sources, into the Global, Multi-regional MARKAL model (GMM). GMM is a global, five-region, "bottom-up" energy-system model developed and applied at the Paul Scherrer Institute (PSI) in Switzerland (Barreto, 2001; Barreto and Kypreos, 2004; Rafaj *et al.*, 2004a,b). The model is part of the MARKAL family of models, a group of "bottom-up", perfect-foresight, energy-system optimization models that allows a detailed representation of energy supply and end-use technologies (Fishbone and Abilock, 1981, 1983; Loulou *et al.*, 2004).

This approach uses the regional marginal abatement curves for non-CO_2 GHGs estimated by U.S EPA (2003). By incorporating MACs for these non-CO_2 GHGs, the context for the examination of energy-technology strategies in the GMM model is substantially improved. Although we have restricted the implementation of methane and nitrous oxide in the GMM model, the approach is general enough as to consider MACs for other GHGs.

The remainder of this document is organized as follows. Section 2 presents a detailed description of the approach followed here for the representation of MACs. Section 3 presents details of the incorporation of the MACs into the GMM model. The changes to the RMARKAL code are presented in Appendix 1.

2. Description of the approach

2.1. Definition of baseline emissions

Following US EPA (2003), the categories considered in this analysis are as follows: CH_4 emissions from coal, oil and gas production, solid waste management and manure management, N_2O emissions from adipic and nitric acid production. Baseline emissions must be defined for these different sources of emissions. Baseline emissions can be endogenous if they are linked to a model variable or exogenous if they are specified from sources external to the model. In this formulation, energy-related methane emissions from coal, oil and gas production are endogenous to the model. Emissions from other sources are exogenous to the model.

Other sources of CH_4 (enteric fermentation and rice paddies) and N_2O (soils) emissions are also considered exogenously. However, since no MACs are specified for them in the US EPA study (2003), they are treated here as non-abatable emissions. It must be noticed that these sources of emissions currently represent a large fraction of the total emissions of these non-CO_2 gases worldwide (Reilly *et al.*, 2003), but, uncertainties still abound regarding the potential, costs and feasibility of implementation of those measures.

2.2. Definition of marginal abatement curves

The marginal abatement curves (MACs) are given to the model as stepwise curves relating abatement costs and abatement potentials. These abatement potentials are given either as absolute potentials, e.g. in tons of the respective GHG or carbon-equivalent, or in relative terms (e.g. percentage) of a given baseline. In what follows, it is assumed that the abatement potentials are given as a fraction of the baseline and that emissions from non-CO_2 GHG are expressed in terms of carbon-equivalent (C-eq) emissions using the 100-years global warming potentials (GWP) reported by IPCC (2001), namely 21 for CH_4 and 310 for N_20.[1] Correspondingly, abatement costs are given in US$/ton C-eq.

The abatement potentials have been derived on the basis of considerations of availability, reduction efficiency and technical and economic applicability of the different abatement options (Delhotal *et al*., 2003). Abatement potentials per price step, region, and GHG are specified for a reference time period, here chosen as 2010. We did not consider no-regrets options in this specification. That is, all MACs were shifted upwards such that abatement costs are always positive. Abatement potentials for other periods are computed using the so-called technical-progress multipliers (tm). These multipliers represent the fact that abatement technologies may improve over time, thus increasing the abatement potential achievable at a given cost. The multipliers allow extrapolating the MACs beyond 2010, the reference year.

[1] The use of global warming potentials (GWPs) has been criticized in the literature because they do not constitute an adequate "exchange rate" between GHGs (O'Neill, 2000; Manne and Richels, 2000; Fuglestvedt *et al.,* 2003). Specifically, they fail to capture a number of physical and chemical interactions between GHGs and differences in their persistence in the atmosphere, among others. Also, they lack an economic rationale. However, the use of alternative, economic indices proposed in the literature, which rely mostly on the monetization of damages due to climate change, has not been possible so far given the huge uncertainties that currently surround the assessment of climate damages (Reilly *et al*., 2003).

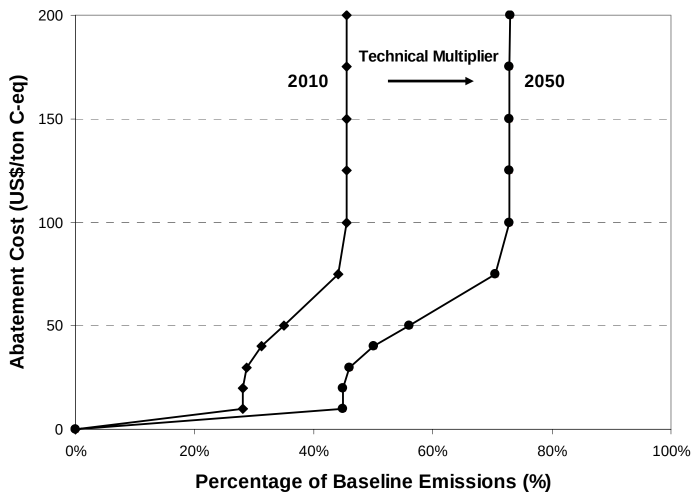

Figure 1: Illustration of the effect of technical multipliers to shift marginal abatement curves out into future periods.

It has to be recognized that these multipliers provide only a rudimentary way to represent technical change in non-CO_2 abatement options and that this takes place only exogenously (i.e. it does not depend on the amount of cumulative abatement). Moreover, at this point their choice is somewhat arbitrary and dependent on the modeler's judgment. Delhotal *et al.* (2003) have proposed a methodology for shifting MACs into the future on the basis of technology assessment for individual technologies, but figures are not yet available for multiple regions and/or sectors.

2.3. Computation of abatement and remaining emissions

In what follows, we describe the basic equations of the MAC formulation in the GMM model. The following notation is used here for sets, parameters and variables:

Sets

GHG:	GHG emissions category
ERGHG:	Energy-related GHG emissions (a subset of GHG)
NERGHG:	Non-energy-related GHG emissions (a subset of GHG)
MSTEP:	Step of the MAC
REG:	Region
TP:	Time period

Parameters

$abtpref_{GHG,REG,TP}$:	Abatement potential for the reference period (percentage)
$abatepot_{GHG,REG,TP}$:	Abatement potential for other periods (percentage)
$bline_{NERHG,REG,TP}$:	Exogenous baseline emissions for non-energy-related GHGs
$tm_{GHG,REG,TP}$:	Technical multipliers
$gr_{GHG,REG,TP}$:	Growth rate
Δt:	Period length
GWP_{GHG}:	Global Warming Potential of a given GHG

Variables

$EMGHG_{GHG,REG,TP}$: GHG emissions per GHG category, region and time period
$EREM_{ERGHG,REG,TP}$: Baseline energy-related GHG emissions per ERGHG category, region and time period
$ABATE_{GHG,REG,TP}$: Abatement per GHG category, region and time period
$CEQEM_{REG,TP}$: Carbon-equivalent emissions (CO_2+CH_4+N_2O)

The abatement potentials for time periods beyond the reference period (in our case 2010) are defined as the abatement potential for the reference period multiplied by the corresponding technical-progress multipliers:

$$abatepot_{GHG,REG,TP} = tm_{GHG,REG,TP} * abtpref_{GHG,REG,TP} \quad (1)$$

The baseline energy-related emissions ($EREM_{ERGHG,REG,TP}$) are computed as a function of the related activity variables in the model (in this case CH4 emissions from coal, oil and gas production). Notice that the corresponding emission coefficients may be reduced over time if, for instance, a reduction of leakage in pipelines is assumed.

The amount of abatement per period, region and sector is constrained to (for energy-related and non-energy-related emissions respectively):

$$ABATE_{ERGHG,MSTEP,REG,TP} \leq abatepot_{ERGHG,MSTEP,REG,TP} * EREM_{ERGHG,REG,TP} \quad (2)$$

$$ABATE_{NERGHG,MSTEP,REG,TP} \leq abatepot_{NERGHG,MSTEP,REG,TP} * bline_{NERGHG,REG,TP} \quad (3)$$

The resulting energy-related emissions are computed as the endogenous baseline emissions minus the corresponding abatement as follows:

$$EMGHG_{ERGHG,REG,TP} = EREM_{ERGHG,REG,TP} - \sum_{MSTEP} ABATE_{ERGHG,MSTEP,REG,TP} \quad (4)$$

Similarly, the resulting non-energy-related emissions are computed as the exogenous baseline emissions minus the corresponding abatement:

$$EMGHG_{NERGHG,REG,TP} = bline_{NERGHG,REG,TP} - \sum_{MSTEP} ABATE_{NERGHG,MSTEP,REG,TP} \quad (5)$$

The carbon-equivalent (C-eq) emissions are computed as:

$$CEQEM_{REG,TP} = \sum_{GHG} GWP_{GHG} * EMGHG_{GHG,REG,TP} \quad (6)$$

In order to avoid abrupt changes in non-CO_2 emissions as a result of cost-effective abatement, we have introduced a maximum growth constraint for the abatement of non- CO_2 GHGs. This constraint also reflects the fact that, in reality, abatement technologies will experience a diffusion process that takes time and, thus, their abatement potential cannot be tapped fully at once.

$$\sum_{MSTEP} ABATE_{GHG,REG,TP} \leq \left[\sum_{MSTEP} ABATE_{GHG,REG,TP-1} \right] * (1+gr)^{\Delta t} \; (7)$$

3. Implementation into the GMM model

For the implementation of marginal abatement curves (MACs) into the GMM model, the following elements are required:

- Definition of baseline emissions (exogenous, endogenous)[2]
- Definition of marginal abatement curves (steps, costs, abatement potentials)
- Computation of abatement and remaining emissions
- Computation of carbon-equivalent (C-eq) emissions
- Definition of multi-regional trade of C-eq emissions

The MACs are given to the GMM model as stepwise curves relating abatement costs (normally given as C-eq prices) and abatement potentials. These abatement potentials are given as absolute potentials, e.g. in tons of C-eq, or in relative terms (fraction or %) of a given baseline. In what follows, it is assumed that the MACs are specified only for CH_4 and N_2O, the two main non-CO_2 GHGs, but the formulation is general enough to be extended to other gases. Energy-related and non-energy-related sources of these two gases have been considered here. It is assumed that the abatement potentials are given as a fraction of the baseline and that emissions from non-CO_2 GHG are expressed in terms of C-eq emissions. The MACs have to be chosen for a given discount rate.

3.1. Sets

3.1.1 Set defining steps for the marginal abatement curves

SET MSTEP

/ 1*11 /

3.1.2 Set defining the non-CO_2 GHGs to be considered

SET GHG

/CH4COA, CH4GAS, CH4OIL, CH4SWM, CH4MAN, N2ONI, N2OADI/

Where:

CH4COA: CH4 from coal production
CH4GAS: CH4 from gas production
CH4OIL: CH4 from oil production
CH4SWM: CH4 from solid waste management

[2] We refer here to endogenous baseline emissions when they are linked to a model variable. Exogenous baseline emissions are specified from sources external to the model.

CH4MAN: CH4 from manure management
N2ONI: N2O from nitric acid production
N2OADI: N2O from adipic acid production

These are the categories for which the US EPA (2003) provides MACs

3.1.3 Set defining the energy-related GHGs, namely CH_4 from coal, oil and gas production. These GHGs have endogenous baseline emissions.

SET ERGHG(GHG)

/ CH4COA, CH4GAS, CH4OIL /

3.1.4 Set defining the non-energy-related GHGs (i.e. CH_4 from solid waste management and manure management and N_2O from adipic and nitric acid production). For these sources an exogenous baseline is considered in this approach

SET NERGHG(GHG)

/ CH4SWM, CH4MAN, N2ONI, N2OADI/

3.1.5 Set defining other sources of non-abateable GHGs (i.e. for which MACs are not specified)

SET GHGOS

/ CH4OS, N2OOS/

Where

CH4OS CH_4 emissions from enteric fermentation and rice paddies
N2OOS N_2O emissions from soils

3.1.6 Set defining total C-eq emissions (i.e. CO_2+CH_4+N_2O)

SET CEQ / CEQ /

3.1.7 Set mapping the GHG categories to C-eq emissions

SET GHGTOCEQ(GHG,CEQ)

/ CH4COA.CEQ, CH4GAS.CEQ, CH4OIL.CEQ, CH4SWM.CEQ, CH4MAN.CEQ, N2ONI.CEQ, N2OADI.CEQ /

In principle, more than one element could be declared in SET CEQ. If so, the GHGs categories could be associated to different C-eq subgroups.

3.1.8 Other sets

SET REG Regions

SET TP Time period

SET SEP(SRC,ENT,P) Supply Steps

SET ENV 'Environmental Indicators'

Three additional regional environmental indicators have been added to account for CH_4 emissions from oil, coal and gas production.

```
C4O 'CH4 from oil             '
C4C 'CH4 from coal            '
C4G 'CH4 from gas             '
```

Set defining the sub-set of environmental indicators related to CH_4 emissions

SET ENV1(ENV) 'Environmental Indicators'

```
/
 C4O 'CH4 from oil             '
 C4C 'CH4 from coal            '
 C4G 'CH4 from gas             '
 /
```

The pollutants C4O, C4C and C4G should be added to the set ENV in the *.dd file for the computation of energy-related CH_4 emissions (from oil, coal and gas production respectively). C4C should be defined both for lignite and coal resources.

SET G_TRADE(*)

The C-eq emissions (CEQ) should be added to the set of commodities being traded

These are standard sets in MARKAL

3.1.9 Set mapping the regional environmental indicators (ENV) associated to regional energy-related CH4 emissions to the ERGHG set

SET ETOERGHG(ENV1,REG,ERGHG)

```
/
C4C.ASIA.CH4COA
C4G.ASIA.CH4GAS
C4O.ASIA.CH4OIL
C4C.EEFSU.CH4COA
C4G.EEFSU.CH4GAS
C4O.EEFSU.CH4OIL
C4C.LAFM.CH4COA
C4G.LAFM.CH4GAS
C4O.LAFM.CH4OIL
C4C.OOECD.CH4COA
```

C4G.OOECD.CH4GAS
C4O.OOECD.CH4OIL
C4C.NAM.CH4COA
C4G.NAM.CH4GAS
C4O.NAM.CH4OIL
/

3.2. Parameters

3.2.1 Reference abatement potentials

The abatement potentials of both energy-related (ER) and non-energy-related (NER) non-CO_2 GHG emissions must be specified.

Table ABTPREF_R(GHG,MSTEP,REG)

Abatement potential per price step, region, and GHG (defined in relative terms to the baseline) for a reference time period (i.e. 2010). An example is given below.

These potentials could also be specified as a function of time but that would require a number of additional tables. The assumption here is that they are specified for 2010 and potentials for other periods would be computed by the model using the technical-progress multipliers below.

	NAM	OOECD	EEFSU	ASIA	LAFM
CH4COA.1	0.665	0.602	0.790	0.842	0.680
CH4COA.2	0.860	0.618	0.790	0.842	0.855
CH4COA.3	0.860	0.618	0.790	0.842	0.855
CH4COA.4	0.860	0.618	0.790	0.842	0.855
CH4COA.5	0.860	0.618	0.790	0.842	0.855
CH4COA.6	0.860	0.618	0.790	0.842	0.855
CH4COA.7	0.860	0.618	0.790	0.842	0.855
CH4COA.8	0.860	0.618	0.790	0.842	0.855
CH4COA.9	0.860	0.618	0.790	0.842	0.855
CH4COA.10	0.860	0.618	0.790	0.842	0.855
CH4COA.11	0.860	0.618	0.790	0.842	0.855

3.2.2 Technical-progress multipliers

Table ABTM_R(GHG,REG,YEAR) Technical progress multipliers for abatement curves per GHG, region and time period.

These multipliers represent the fact that the abatement potential may increase along the time horizon due to technological progress in the mitigation options. They are necessary because the MACs from US EPA are defined only for the years 2010 and 2020. The multipliers allow extrapolating the MACs for other periods (beyond 2010 if reference potentials, ABTPREF_R, are given for this year). However, since the potentials are defined as a fraction of the baseline in our approach, the technical multipliers should not allow potentials to be larger than 1 (as fraction, or, in other words 100%)

One can define a conservative abatement potential setting the technical-progress multipliers to 1. That is, assuming that the abatable fraction does not increase in time.

3.2.3 Total abatement potentials per time period

The total abatement potentials per time period, region and GHG are defined as (given in relative terms, i.e. percentage or fraction):

```
ABATEPOT_R(GHG,MSTEP,REG,TP)=ABTM_R(GHG,
REG,TP)*(ABTPREF_R(GHG,MSTEP,REG)-ABTPREF_R(GHG,MSTEP-
1,REG));
```

This formulation implies that the reference abatement potentials ABTPREF_R (GHG, MSTEP, REG) are given by the user in a cumulative way. That is, if for the first segment a potential of 30% that can be abated at 10$/ton C-eq is given and for the second segment a potential of 50% is specified, which can be abated at 20 $/ton C-eq, this means that 20% (i.e. 50%-30%) of emissions can be abated at 20 $/ton C-eq.

To avoid abatement of emissions beyond the baseline emissions the following expression is necessary

```
ABATEPOT_R(GHG,MSTEP,REG,TP) =
 min(ABATEPOT_R(GHG,MSTEP,REG,TP), 1);
```

Use 1 if the coefficient ABATEPOT_R is defined as fraction. If it is defined as a percentage, then the 1 above should be changed to 100.

3.2.4 Abatement cost steps

Table ABATCOST_R(MSTEP,GHG) "abatement costs in US$/ton C eq"

The abatement costs for each MAC step, i.e. the carbon-equivalent prices being used in the curve definition. The table below is an example given in US$/ton C-eq using the steps provided by the US EPA (2003) study.

Table ABATCOST_R(MSTEP, GHG) "abatement costs in US$/ton C-eq"

	CH4COA	CH4GAS	CH4OIL	CH4SWM	CH4MAN	N2ONI	N2OADI
1	10	10	10	10	10	10	10
2	20	20	20	20	20	20	20
3	30	30	30	30	30	30	30
4	40	40	40	40	40	40	40
5	50	50	50	50	50	50	50
6	75	75	75	75	75	75	75
7	100	100	100	100	100	100	100
8	125	125	125	125	125	125	125
9	150	150	150	150	150	150	150
10	175	175	175	175	175	175	175
11	200	200	200	200	200	200	200

;

3.2.5 Exogenous baseline for non-energy-related GHG with MACs

For the sources of non-CO_2, non-energy-related GHG for which a MAC is defined (i.e. those belonging to the NERGHG set).

BLINE_R(NERGHG,REG,YEAR) baseline emissions (C-eq) per GHG, region, time period

Since our approach assumes that the emissions are given in terms of C-eq, in case they are defined originally in tons of CH_4 or N_2O, global warming potentials (GWP) should be used to convert them.

The US EPA study provides baselines only up to the year 2020. Therefore, they must be extrapolated to other periods assuming a given growth rate.

	1990	2000	2010	2020	2030	2040	2050
CH4SWM.NAM	69.28	67.31	67.17	59.61	58.56	55.64	52.73
CH4SWM.OOECD	50.53	44.76	43.43	45.98	42.44	40.94	39.44
CH4SWM.EEFSU	35.98	31.15	29.25	30.76	27.40	25.64	23.89
CH4SWM.ASIA	27.16	41.80	59.58	84.02	100.23	119.07	137.90
CH4SWM.LAFM	41.12	49.96	62.35	78.50	89.12	101.57	114.02

3.2.6 Exogenous baseline emissions for non-energy-related, non-abateable GHGs (without MACs)

Non-CO_2 GHG emissions from other sources for which a MAC is not specified are by definition non-abatable. However, they are necessary for comprehensiveness in reporting total C-eq emissions. Therefore, baseline emissions should also be defined for these sources as well.

BLINEOS_R(GHGOS, REG, YEAR) baseline emissions (C-eq), GHGOS, region, time period

3.2.7 Coefficients for CH_4 emissions from oil, gas and coal production

These coefficients can be included in the following table in the *.dd file, where the coefficients for other pollutants such as CO_2 are computed.

TABLE ENV_TACT(ENV,TCH,YEAR)

The CH_4 specific emissions (in ton C-eq/GJ or a similar unit) are defined separately for oil, gas and coal production to facilitate the computation of the corresponding energy-related baseline emissions below.

3.3. Variables

POSITIVE VARIABLES

R_ABATE(GHG,MSTEP,REG,TP) abatement per GHG, price step, region and time period.

R_EREM(GHG,REG,TP) Energy-related baseline GHG emissions, region, time period

R_EMGHG(GHG,REG,TP) Energy-related GHG emissions per region and time period (i.e. baseline minus abatement)

R_CEQEM(REG,TP) Regional C-eq emissions (CO2+CH4+N2O)

R_CEQGLOEM(TP) Global C-eq emissions (CO2+CH4+N2O)

3.4. Equations

MR_EMGHG1(ERGHG,REG,TP) annual energy-related ghg emissions
MR_EMGHG2(NERGHG,REG,TP) annual non-energy-related ghg emissions
MR_EREMGHG(ERGHG,REG,TP) annual energy-related baseline ghg emissions
MR_CEQEM (REG,TP) annual carbon eq. emissions (CO2+CH4+N2O) per region
MR_CEQGLOEM(TP) annual global carbon eq. emissions (CO2+CH4+N2O)
MR_ABPOT1(ERGHG,MSTEP,REG,TP) abatement for energy-related GHGs
MR_ABPOT2(NERGHG,MSTEP,REG,TP) abatement - non-energy related GHGs
MR_GTRDCEQ(TP,CEQ) Global trade of C-eq emissions
MR_PGTRDCEQ(%3TP,CEQ) Global trade of C-eq emissions - positive exports

3.4.1 Abatement for energy-related (endogenous baseline) non-CO_2 GHGs

MR_ABPOT1(ERGHG,MSTEP,REG,TP)..R_ABATE(ERGHG,MSTEP,REG,TP) =L= ABATEPOT_R(ERGHG,MSTEP,REG,TP)*R_EREM(ERGHG,REG,TP);

3.4.2 Abatement for non-energy-related (exogenous baseline) non-CO_2 GHGs

MR_ABPOT2(NERGHG,MSTEP,REG,TP)..R_ABATE(NERGHG,MSTEP,REG,TP) =L= ABATEPOT_R(NERGHG,MSTEP,REG,TP)*BLINE_R(NERGHG,REG,TP);

3.4.3 Annual energy-related baseline non-CO_2 GHG emissions per region and fuel (oil, coal, gas)

MR_EREMGHG(ERGHG,REG,TP)..

R_EREM(ERGHG,REG,TP) =E=

SUM(ENV1$(ETOERGHG(ENV1,REG,ERGHG)), R_EM(REG,TP,ENV1));

3.4.4 Energy-related annual non-CO_2 GHG emissions per region, time period

MR_EMGHG1(ERGHG,REG,TP)..R_EMGHG(ERGHG,REG,TP)=E=

R_EREM(ERGHG,REG,TP)

- SUM(MSTEP, R_ABATE(ERGHG,MSTEP,REG,TP));

3.4.5 Non-energy-related annual non-CO_2 GHG emissions per region and time period

```
MR_EMGHG2(NERGHG,REG,TP)..R_EMGHG(NERGHG,REG,TP) =E=

BLINE_R(NERGHG,REG,TP)

               - SUM(MSTEP, R_ABATE(NERGHG,MSTEP,REG,TP));
```

3.4.6 Annual C-eq emissions (CO_2+CH_4+N_2O) per region and time period

```
MR_CEQEM(REG,TP)..R_CEQEM(REG,TP)=G=      SUM(GHG,R_EMGHG(GHG,REG,TP))+
SUM(GHGOS, BLINEOS_R(GHGOS, REG,TP))

* plus CO2 emissions (check this)

+ %4EM(%5TP,%2"COX")

* plus trade of C-eq emissions

+ SUM(CEQ, R_NTXTRD(REG,TP,CEQ));
```

3.4.7 Global annual C-eq emissions (CO_2+CH_4+N_2O) per time period

```
MR_CEQGLOEM(TP)..R_CEQGLOEM(TP)=E=SUM(REG,R_CEQEM(REG,TP));
```

3.4.8 Global trade of C-eq emissions

```
MR_GTRDCEQ(TP,CEQ) ..
  SUM(REG,MMSCALE_R(REG) * R_NTXTRD(REG,TP,CEQ) * REG_XCVT(REG,CEQ) )
=E=
  0;

* Additional constraint for global trade of C-eq emissions

MR_PGTRDCEQ(REG,TP,CEQ)$TRD_COST(CEQ) ..
  R_NTXTRD(REG,TP,CEQ) =L= R_EXPTRD(REG,TP, CEQ)
 ;
```

3.4.9 Changes to the objective function

The objective function. i.e. total discounted system costs, is modified to reflect the costs of the non-CO_2 abatement. That is, a term of the following form is added (MMEQPRIC.INC):

```
+SUM(REG,SUM(TP,PRI_DF_R(REG,TP)*(SUM((MSTEP,GHG),
ABATCOST_R(MSTEP,GHG)*R_ABATE(GHG,MSTEP,REG,TP)))))
```

Where PRI_DF is the discount factor:

```
PRI_DF(TP) =
   SUM(ALLORD$(ORD(ALLORD) LE NYRSPER), (1 + DISCOUNT) ** (1 -
ORD(ALLORD))) /
   ((1 + DISCOUNT) ** (- STARTYRS + NYRSPER * (ORD(TP) - 1)));
```

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5. Appendix 1. The MAC Code in RMARKAL

In this section the changes to the RMARKAL code necessary for the implementation of the MACs are presented. Files where changes were made are renamed and called separately to run the model.

5.1 File MMEQMAC.ML

This file contains the main equations related to the MACs. It is called in MMEQUAMAC.REG

```
*=============================================================*
*  MMEQMAC.ML Marginal Abatement Curves
*    %1 - equation name prefix 'EQ' or 'MS' or 'MR'
*    %2 - SOW indicator => '' or 'SOW,' or ''
*    %3 - coef qualifier => '' or '' or '_R'
*    %4 - variable/coef prefix => '' or 'S_' or 'R_'
*    %5 - REGional indicator => '' or '' or 'REG,'
*    %6 - regional scaling => '' or '' or '(REG)'
*    %7 - loop control set => 'TPTCH(TP,TEG)' or 'TPNTCH(TP,SOW,TEG)' or
'TPTCH_R(REG,TP,TEG)'
*    %8 - loop control qualifier for REG => '' or '' or '$ENV_R(REG,ENV)'
*==============================================================*
*$ONLISTING

* Energy-related baseline non-CO2 GHG emissions per region and fuel (oil, coal,
gas)

%1_EREMGHG(ERGHG,%5TP)..

%4EREM(ERGHG,%5TP) =E=

SUM(ENV1$(ETOERGHG(%2ENV1,%5ERGHG)), %4EM(%5TP,%2ENV1));

* Abatement for energy-related (endogenous baseline) non-CO2 GHGs

%1_ABPOT1(ERGHG,MSTEP,%5TP)..%4ABATE(ERGHG,MSTEP,%5TP) =L=
ABATEPOT%3(ERGHG,MSTEP,%5TP)*%4EREM(ERGHG,%5TP);

* Abatement for non-energy-related (exogenous baseline) non-CO2 GHGs

%1_ABPOT2(NERGHG,MSTEP,%5TP)..%4ABATE(NERGHG,MSTEP,%5TP)
=L= ABATEPOT%3(NERGHG,MSTEP,%5TP)*BLINE%3(NERGHG,%5TP);


* Energy-related annual non-CO2 GHG emissions per region, time period

%1_EMGHG1(ERGHG,%5TP)..%4EMGHG(ERGHG,%5TP)=E=
```

```
%4EREM(ERGHG,%5TP)

        - SUM(MSTEP, %4ABATE(ERGHG,MSTEP,%5TP));

* Non-energy-related annual non-CO2 GHG emissions per region and time period

%1_EMGHG2(NERGHG,%5TP)..%4EMGHG(NERGHG,%5TP) =E=

BLINE%3(NERGHG,%5TP)

        - SUM(MSTEP, %4ABATE(NERGHG,MSTEP,%5TP));

* Annual C-eq emissions (CO2+CH4+N2O) per region and time period

* %1_CEQEM (%5TP)..%4CEQEM(%5TP)=E=
SUM(NERGHG, %4EMGHG(NERGHG,%5TP))+
SUM(ERGHG,%4EREM(ERGHG,%5TP))+ SUM(GHGOS,
BLINEOS%3(GHGOS, %5TP))

%1_CEQEM (%5TP)..%4CEQEM(%5TP)=E=
SUM(GHG, %4EMGHG(GHG,%5TP))+ SUM(GHGOS,
BLINEOS%3(GHGOS, %5TP))

* plus CO2 emissions (check this)

+ SUM(TPSEP%3(%5TP, SEP)$ENV_S%3(%5"CO2", SEP), TENV_SEP%3(%5TP,
SEP, "CO2") * %4TSEP(%5TP, %2SEP))

* plus trade of C-eq emissions

+ SUM(CEQ,%4NTXTRD(%5TP,CEQ));

* Global annual C-eq emissions (CO2+CH4+N2O) per time period

%1_CEQGLOEM(TP)..%4CEQGLOEM(TP)=E=SUM(%5%4CEQEM(%5TP));

*LB*, April 2004 (PSI)

* Global trade of C-eq emissions

%1_GTRDCEQ(TP,CEQ) ..
  SUM(%5MMSCALE%3%6 * %4NTXTRD(%5TP,CEQ) *
REG_XCVT(%5CEQ) )
=E=
  0;

* Additional constraint for global trade of C-eq emissions

%1_PGTRDCEQ(%5TP,CEQ)$TRD_COST(CEQ) ..
  %4NTXTRD(%5TP,CEQ) =L= %4EXPTRD(%5TP, CEQ)
```

;

*$OFFLISTING

5.2 File MMEQPRIMAC.ML

In this file, the discounted costs of non-CO2 abatement are included in the objective function. This file is called in MMEQUAMAC.REG

```
*==============================================================*
*  MMEQPRICMAC.ML PRICE for MACs
*    %1 - equation name prefix 'EQ' or 'MS' or 'MR'
*    %2 - SOW indicator => '' or 'SOW,' or ''
*    %3 - coef qualifier => '' or '' or '_R'
*    %4 - variable/coef prefix => '' or 'S_' or 'R_'
*    %5 - REGional indicator => '' or '' or 'REG,'
*    %6 - regional scaling => '' or '' or '(REG)'
*    %7 - loop control/variable ref set => '' or '(SOW)' or '(REG)'
*    %8 - N indicator in stochastic sum sets => '' or 'NN' or ''
*    %9 - SON, sum controller for stochastics => '' 'SON,' ''
*==============================================================*
*$ONLISTING
* Costs of Non-CO2 abatement

+ SUM(REG, SUM(TP, PRI_DF%3(%5TP)*(SUM((MSTEP,GHG),
ABATCOST%3(MSTEP,GHG)*%4ABATE(GHG,MSTEP,%5TP)))))

* + SUM(REG, SUM(TP, PRI_DF%3(%5TP)*(SUM((MSTEP,GHG),
NYRSPER*ABATCOST%3(MSTEP,GHG)*%4ABATE(GHG,MSTEP,%5TP)))))


*$OFFLISTING
```

5.3 File MMEQUAMAC.ML

This file declares the equations related to the MACs. It is called in MMEQUAMAC.REG

```
*==============================================================*
*LB* MACs
* %1 - EQ, MS, MR
* %2 - '', ALLSOW, ''
* %3 - '', '', 'REG,'
* called from MMEQUA.INC/MS/REG
*==============================================================*

%1_EMGHG1(ERGHG,%3TP)       annual energy-related ghg emissions
%1_EMGHG2(NERGHG,%3TP)      annual non-energy-related ghg emissions
%1_EREMGHG(ERGHG,%3TP)      annual energy-related baseline ghg emissions
```

%1_CEQEM (%3TP)   annual carbon eq. emissions (CO2+CH4+N2O) per region
%1_CEQGLOEM(TP)   annual global carbon eq. emissions (CO2+CH4+N2O)
%1_ABPOT1(ERGHG,MSTEP,%3TP) abatement for energy-related non-co2 GHGs
%1_ABPOT2(NERGHG,MSTEP,%3TP) abatement for non-energy related non-co2 GHGs
%1_GTRDCEQ(TP,CEQ)   Global trade of C-eq emissions
%1_PGTRDCEQ(%3TP,CEQ)   Global trade of C-eq emissions - positive exports

5.4 File MMEQUAMAC.REG

In this file MMEQUAMAC:ML and MMEQMAC.ML are called. This file is called in REG_MGMAC.REG

```
*LB* Marginal Abatement Curves
$IF '%MAC%' == 'YES' $BATINCLUDE MMEQUAMAC.ML 'MR' '' 'REG,'

*=============================================================*
*MAC*   Marginal Abatement Curves - MACs - LB                *
*=============================================================*
$IF '%MAC%' == 'YES' $BATINCLUDE MMEQMAC.ML  MR '' '_R' 'R_' 'REG,' '(REG)' ' ' '$ENV_R(REG,ENV)'
```

5.5 File MMCOEFMAC.ML

In this file the abatement potentials are defined and set to be at most 100% of the baseline emissions. This file is called in REG_MGMAC.REG and RUN_REGMAC.REG.

```
*****************************************************************
*LB* MACs parameters*
*****************************************************************

$ IF NOT '%ETL%' == 'YES' $GOTO NOMIP

ABATEPOT_R(GHG,MSTEP,REG,TP)=ABTM_R(GHG, REG,TP)*ABTPREF_R(GHG,MSTEP,REG);

ABATEPOT_R(GHG,MSTEP,REG,TP) = min(ABATEPOT_R(GHG,MSTEP,REG,TP), 1);

$LABEL NOMIP
```

5.6 File MMINITMAC.REG

In this file the parameters and sets for the MACs are initialized. This file is called in REG_INIMAC.REG

```
*LB* MACs parameters and sets
```

```
SET ENV1_R(REG,*);
SET MSTEP                        / EMPTY /;
SET GHG                          / EMPTY /;
SET ERGHG(GHG)                   / EMPTY /;
SET NERGHG(GHG)                  / EMPTY /;
SET GHGOS                        / EMPTY /;
SET ETOERGHG(ENV1,REG,ERGHG)        / EMPTY.EMPTY.EMPTY /;
SET CEQ                          / EMPTY /;
SET GHGTOCEQ                     / EMPTY.EMPTY /;


PARAMETER ABTPREF_R(GHG,MSTEP,REG)      / EMPTY.EMPTY.EMPTY 0
/;
PARAMETER ABTM_R(GHG,REG,YEAR)          / EMPTY.EMPTY.EMPTY 0 /;
PARAMETER ABATEPOT_R(GHG,MSTEP,REG,YEAR)  /
EMPTY.EMPTY.EMPTY.EMPTY 0 /;
PARAMETER ABATCOST_R(MSTEP, GHG)         / EMPTY.EMPTY 0 /;
PARAMETER BLINE_R(NERGHG, REG, YEAR)        / EMPTY.EMPTY.EMPTY
0 /;
PARAMETER BLINEOS_R(GHGOS, REG, YEAR)        /
EMPTY.EMPTY.EMPTY 0 /;
```

5.7 File REG_INIMAC.REG

This file is called in REG_INIMAC.BAT

```
$ONLISTING
$PHANTOM EMPTY
* REG_INIT.REG get the base stuff loaded into the empty multi-region workfile
$INCLUDE MMINIT.INC
$INCLUDE MMINITMAC.REG
```

5.8 File REG_INIMAC.BAT

```
call gams reg_inimac.reg idir=\RMARKAL s=_initreg
```

5.9 File MMSETREMAC.REG

This file is called in REG_MGMAC.REG

```
ENV1_R('%2',ENV1)$ENV(ENV1)                  = YES;
```

5.10 File MMSETMAC.INC

In this file the SETS related to the MACS implementation are initialized. This file is called in REG_MGMAC.REG

```
*LB* MACs sets
```

```
SET MSTEP                    / EMPTY /;
SET GHG                      / EMPTY /;
SET ERGHG(GHG)               / EMPTY /;
SET NERGHG(GHG)              / EMPTY /;
SET GHGOS                    / EMPTY /;
SET CEQ                      / EMPTY /;
SET GHGTOCEQ(GHG,CEQ)        / EMPTY.EMPTY /;

* SET ETOERGHG(ENV,REG,ERGHG)        / EMPTY.EMPTY.EMPTY /;
```

5.11 File MMVARSMAC.ML

Declaration of MAC-related variables. This file is called in MMVARSMAC.REG

```
*==================================================================*
*LB* MACs variables              *
* %1 - '', S_, R_
* %2 - '', 'ALLSOW,' ''
* %3 - '', '', 'REG,'
* called from MMVARS.INC/MS/REG
*==================================================================*

POSITIVE VARIABLES

R_ABATE(GHG,MSTEP,REG,TP)
R_EREM(GHG,REG,TP)
R_EMGHG(GHG,REG,TP)
R_CEQEM(REG,TP)
R_CEQGLOEM(TP)
```

5.12 File MMVARSMAC.REG

This file is called in REG_MGMAC.REG

```
*==================================================================*
*MAC* Marginal Abatement Curves - LB                              *
*==================================================================*
$IF '%MAC%' == 'YES' $BATINCLUDE MMVARSMAC.ML '' '' ''
```

5.13 File MODELMAC.ML

With this file the MAC-related equations are included in the RMRK model. This file is called in MODELMAC.REG

```
*==================================================================*
*LB* MACs model, April, 2004
*   %1 - EQ, MS, MR
*==================================================================*

   %1_EMGHG1
```

```
   %1_EMGHG2
   %1_EREMGHG
   %1_CEQEM
   %1_CEQGLOEM
   %1_ABPOT1
   %1_ABPOT2
   %1_GTRDCEQ
   %1_PGTRDCEQ
```

5.14 File MODELMAC.REG

This file calls MODELMAC.ML. It is called in REG_MGMAC.REG

```
$IF '%MAC%' == 'YES' $BATINCLUDE MODELMAC.ML MR
```

5.15 File CLEARMAC.REG

This file is called in REG_MGMAC.REG

```
*==============================================================*
* MACs
*===============================================================
*
$IF NOT '%MAC' == 'YES' $GOTO NOMAC

  OPTION CLEAR = ENV1;
  OPTION CLEAR = MSTEP;
  OPTION CLEAR = GHG;
  OPTION CLEAR = ERGHG;
  OPTION CLEAR = NERGHG;
  OPTION CLEAR = GHGOS;
  OPTION CLEAR = ETOERGHG;
  OPTION CLEAR = ABTPREF_R;
  OPTION CLEAR = ABTM_R;
  OPTION CLEAR = ABATEPOT_R;
  OPTION CLEAR = ABATCOST_R;
  OPTION CLEAR = BLINE_R;
  OPTION CLEAR = BLINEOS_R;
  OPTION CLEAR = CEQ;
  OPTION CLEAR = GHGTOCEQ;

$LABEL NOMAC
```

5.16 File REG_MGMAC.REG

```
$ INCLUDE MMSETSMAC.INC
$ INCLUDE MMVARSMAC.REG
$ INCLUDE MMEQUAMAC.REG
$ INCLUDE MODELMAC.REG
$ BATINCLUDE CLEARMAC.REG 'YES'
```

5.17 File REG_SOLMAC.REG

This file is called in RUN_SOLV.REG

```
*MAC* initial control parameters must be reset
$ SET MAC 'YES'

* clear out the base declarations in preparation for reports
$ BATINCLUDE CLEARMAC.REG 'NO'
```

5.18 File REG_SOLV.BAT

```
call gams run_regmac.reg idir1=\RMARKAL r=_nextreg s=_lastreg ps=99999 scrdir
= c:\
```

5.19 File RUN_REGMAC.REG

```
*MAC*
$SET MAC 'YES'

$ INCLUDE TRADE.REG
$IF '%MAC%' == 'YES' $ INCLUDE GHG.DD
$IF '%MAC%' == 'YES' $INCLUDE MMCOEFMAC.ML
```

5.20 File RUN_SOLV.REG

```
$ INCLUDE TRADE.REG
$ INCLUDE GHG.DD

$ BATINCLUDE REG_SOLMAC.REG GMARKAL SOLVE
```

5.21 File TRADE.REG

This file includes the parameters related to the trade of C-eq emissions and bounds on C-eq emissions. This file is called in RUN_REGMAC.REG and RUN_SOLV.REG

```
* list of ENC/ENV commodities to be traded globally
 SET      G_TRADE(*)
        /
         CEQ

PARAMETER TRD_FROM(*)
        /
         CEQ 3

 PARAMETER TRD_COST(*)
        / COX .001
         CEQ .001
```

```
/;
```

* Bounds on trade of C-eq permits, e.g., When bounding trade to zero you EXCLUDE trade!

```
*  R_NTXTRD.FX(REG,TP,'CEQ')=0;

 PARAMETER REG_XCVT(REG,*)
      /
       ASIA.CEQ 1
       LAFM.CEQ 1
       NAM.CEQ 1
       EEFSU.CEQ 1
       OOECD.CEQ 1

/;

*LB* Bounds on C-eq emissions, April, 2004, PSI

 R_CEQEM.UP("NAM","1990")=2094.0438;
 R_CEQEM.UP("NAM","2000")=2409.3106;
 R_CEQEM.UP("NAM","2010")=2731.3149;
 R_CEQEM.UP("NAM","2020")=3012.0179;
 R_CEQEM.UP("NAM","2030")=2500.;
 R_CEQEM.UP("NAM","2040")=2500.;
 R_CEQEM.UP("NAM","2050")=2500.;
```

5.22 File GHG.DD

This file is called in RUN_REGMAC.REG and RUN_SOLV.REG

```
        SET  MSTEP     'MAC STEP'
         /   1*11      /

        SET  GHG  'Non-CO2 GHG'
         /   CH4COA, CH4GAS, CH4OIL, CH4SWM, CH4MAN, N2ONI, N2OADI/

       SET   ERGHG(GHG)  'energy-related endogenous GHG'
          /  CH4COA, CH4GAS, CH4OIL/

    SET   NERGHG(GHG)  'non-energy-related GHG'
          /  CH4SWM, CH4MAN, N2ONI, N2OADI /

        SET  GHGOS  'Other sources Non-CO2 GHG'
         /   CH4OS, N2OOS/

        SET  CEQ
         /
         CEQ
         /

     SET  GHGTOCEQ(GHG,CEQ)

         / CH4COA.CEQ, CH4GAS.CEQ, CH4OIL.CEQ, CH4SWM.CEQ, CH4MAN.CEQ,
N2ONI.CEQ, N2OADI.CEQ /
```

```
SET ETOERGHG(ENV1,REG,ERGHG)

/

C4C.ASIA.CH4COA
C4G.ASIA.CH4GAS
C4O.ASIA.CH4OIL
C4C.EEFSU.CH4COA
C4G.EEFSU.CH4GAS
C4O.EEFSU.CH4OIL
C4C.LAFM.CH4COA
C4G.LAFM.CH4GAS
C4O.LAFM.CH4OIL
C4C.OOECD.CH4COA
C4G.OOECD.CH4GAS
C4O.OOECD.CH4OIL
C4C.NAM.CH4COA
C4G.NAM.CH4GAS
C4O.NAM.CH4OIL

/

*         TABLE ENV_TSEP(ENV,SRC,ENT,P,YEAR)
*                      1990     2000     2010     2020     2030     2040     2050
*  C4O.MIN.OIL.1      0.0200                                        0.0200
*  C4C.MIN.COA.1       0.354                                         0.354
*  C4G.MIN.NG1.1       0.187                                         0.094

*         TABLE TENV_ACT_R(REG,YEAR,PRC,ENV1)
*

      TABLE ABTPREF_R(GHG,MSTEP,REG)

* input as fraction

              NAM    OOECD   EEFSU   ASIA   LAFM
CH4COA.1       0.665  0.602   0.790   0.842  0.680
CH4COA.2       0.860  0.618   0.790   0.842  0.855
CH4COA.3       0.860  0.618   0.790   0.842  0.855
CH4COA.4       0.860  0.618   0.790   0.842  0.855
CH4COA.5       0.860  0.618   0.790   0.842  0.855
CH4COA.6       0.860  0.618   0.790   0.842  0.855
CH4COA.7       0.860  0.618   0.790   0.842  0.855
CH4COA.8       0.860  0.618   0.790   0.842  0.855
CH4COA.9       0.860  0.618   0.790   0.842  0.855
CH4COA.10      0.860  0.618   0.790   0.842  0.855
CH4COA.11      0.860  0.618   0.790   0.842  0.855

*             NAM    OOECD   EEFSU   ASIA   LAFM
CH4GAS.1       0.168  0.229   0.236   0.281  0.194
CH4GAS.2       0.185  0.239   0.275   0.281  0.212
CH4GAS.3       0.185  0.248   0.276   0.287  0.243
CH4GAS.4       0.187  0.258   0.277   0.313  0.264
CH4GAS.5       0.188  0.290   0.313   0.350  0.303
CH4GAS.6       0.273  0.343   0.345   0.441  0.402
CH4GAS.7       0.326  0.387   0.367   0.455  0.441
CH4GAS.8       0.347  0.393   0.378   0.455  0.447
CH4GAS.9       0.362  0.394   0.378   0.455  0.447
CH4GAS.10      0.362  0.399   0.378   0.455  0.448
CH4GAS.11      0.362  0.413   0.379   0.456  0.457
```

*	NAM	OOECD	EEFSU	ASIA	LAFM
CH4OIL.1	0.000	0.103	0.070	0.000	0.214
CH4OIL.2	0.179	0.174	0.259	0.266	0.348
CH4OIL.3	0.226	0.179	0.259	0.266	0.348
CH4OIL.4	0.226	0.179	0.259	0.266	0.348
CH4OIL.5	0.226	0.179	0.259	0.266	0.348
CH4OIL.6	0.226	0.179	0.259	0.266	0.348
CH4OIL.7	0.226	0.179	0.259	0.266	0.348
CH4OIL.8	0.226	0.179	0.259	0.266	0.348
CH4OIL.9	0.226	0.179	0.259	0.266	0.348
CH4OIL.10	0.226	0.179	0.259	0.266	0.348
CH4OIL.11	0.226	0.179	0.259	0.266	0.348

*	NAM	OOECD	EEFSU	ASIA	LAFM
CH4SWM.1	0.230	0.448	0.421	0.395	0.332
CH4SWM.2	0.315	0.465	0.443	0.486	0.421
CH4SWM.3	0.474	0.527	0.507	0.513	0.475
CH4SWM.4	0.474	0.542	0.529	0.513	0.529
CH4SWM.5	0.545	0.567	0.529	0.513	0.529
CH4SWM.6	0.636	0.577	0.529	0.513	0.529
CH4SWM.7	0.692	0.625	0.595	0.622	0.595
CH4SWM.8	0.692	0.697	0.697	0.658	0.595
CH4SWM.9	0.740	0.720	0.835	0.728	0.618
CH4SWM.10	0.790	0.722	0.873	0.786	0.665
CH4SWM.11	0.790	0.790	0.873	0.880	0.734

*	NAM	OOECD	EEFSU	ASIA	LAFM
CH4MAN.1	0.000	0.034	0.000	0.033	0.027
CH4MAN.2	0.000	0.043	0.005	0.033	0.027
CH4MAN.3	0.000	0.048	0.005	0.033	0.036
CH4MAN.4	0.000	0.048	0.005	0.033	0.036
CH4MAN.5	0.000	0.048	0.005	0.033	0.036
CH4MAN.6	0.000	0.056	0.005	0.068	0.060
CH4MAN.7	0.012	0.084	0.034	0.143	0.060
CH4MAN.8	0.012	0.098	0.055	0.159	0.162
CH4MAN.9	0.012	0.101	0.059	0.159	0.162
CH4MAN.10	0.041	0.126	0.059	0.159	0.185
CH4MAN.11	0.071	0.130	0.059	0.172	0.185

*	NAM	OOECD	EEFSU	ASIA	LAFM
N2ONI.1	0.889	0.862	0.889	0.889	0.889
N2ONI.2	0.889	0.889	0.889	0.889	0.889
N2ONI.3	0.889	0.889	0.889	0.889	0.889
N2ONI.4	0.889	0.889	0.889	0.889	0.889
N2ONI.5	0.889	0.889	0.889	0.889	0.889
N2ONI.6	0.889	0.889	0.889	0.889	0.889
N2ONI.7	0.889	0.889	0.889	0.889	0.889
N2ONI.8	0.889	0.889	0.889	0.889	0.889
N2ONI.9	0.889	0.889	0.889	0.889	0.889
N2ONI.10	0.889	0.889	0.889	0.889	0.889
N2ONI.11	0.889	0.889	0.889	0.889	0.889

*	NAM	OOECD	EEFSU	ASIA	LAFM
N2OADI.1	0.960	0.960	0.960	0.960	0.960
N2OADI.2	0.960	0.960	0.960	0.960	0.960
N2OADI.3	0.960	0.960	0.960	0.960	0.960
N2OADI.4	0.960	0.960	0.960	0.960	0.960
N2OADI.5	0.960	0.960	0.960	0.960	0.960
N2OADI.6	0.960	0.960	0.960	0.960	0.960

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N2OADI.7        0.960   0.960   0.960   0.960  0.960
N2OADI.8        0.960   0.960   0.960   0.960  0.960
N2OADI.9        0.960   0.960   0.960   0.960  0.960
N2OADI.10       0.960   0.960   0.960   0.960  0.960
N2OADI.11       0.960   0.960   0.960   0.960  0.960

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          TABLE ABTM_R(GHG,REG,YEAR)
                    1990    2000    2010    2020    2030    2040    2050
  CH4COA.NAM        0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4COA.OOECD      0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4COA.EEFSU      0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4COA.ASIA       0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4COA.LAFM       0.00    0.00    1.00    1.00    1.00    1.00    1.00

  CH4GAS.NAM        0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4GAS.OOECD      0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4GAS.EEFSU      0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4GAS.ASIA       0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4GAS.LAFM       0.00    0.00    1.00    1.00    1.00    1.00    1.00

  CH4OIL.NAM        0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4OIL.OOECD      0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4OIL.EEFSU      0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4OIL.ASIA       0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4OIL.LAFM       0.00    0.00    1.00    1.00    1.00    1.00    1.00

  CH4SWM.NAM        0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4SWM.OOECD      0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4SWM.EEFSU      0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4SWM.ASIA       0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4SWM.LAFM       0.00    0.00    1.00    1.00    1.00    1.00    1.00

  CH4MAN.NAM        0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4MAN.OOECD      0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4MAN.EEFSU      0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4MAN.ASIA       0.00    0.00    1.00    1.00    1.00    1.00    1.00
  CH4MAN.LAFM       0.00    0.00    1.00    1.00    1.00    1.00    1.00

  N2ONI.NAM         0.00    0.00    1.00    1.00    1.00    1.00    1.00
  N2ONI.OOECD       0.00    0.00    1.00    1.00    1.00    1.00    1.00
  N2ONI.EEFSU       0.00    0.00    1.00    1.00    1.00    1.00    1.00
  N2ONI.ASIA        0.00    0.00    1.00    1.00    1.00    1.00    1.00
  N2ONI.LAFM        0.00    0.00    1.00    1.00    1.00    1.00    1.00

  N2OADI.NAM        0.00    0.00    1.00    1.00    1.00    1.00    1.00
  N2OADI.OOECD      0.00    0.00    1.00    1.00    1.00    1.00    1.00
  N2OADI.EEFSU      0.00    0.00    1.00    1.00    1.00    1.00    1.00
  N2OADI.ASIA       0.00    0.00    1.00    1.00    1.00    1.00    1.00
  N2OADI.LAFM       0.00    0.00    1.00    1.00    1.00    1.00    1.00
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  TABLE ABATCOST_R(MSTEP, GHG) 'abatement costs in US$/ton C-eq'

      CH4COA   CH4GAS   CH4OIL   CH4SWM   CH4MAN   N2ONI   N2OADI
  1   10       10       10       10       10       10      10
  2   20       20       20       20       20       20      20
  3   30       30       30       30       30       30      30
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  4    40      40      40      40      40      40      40
  5    50      50      50      50      50      50      50
  6    75      75      75      75      75      75      75
  7    100     100     100     100     100     100     100
  8    125     125     125     125     125     125     125
  9    150     150     150     150     150     150     150
  10   175     175     175     175     175     175     175
  11   200     200     200     200     200     200     200
;

  TABLE BLINE_R(NERGHG,REG,YEAR)
* in MtCE for GWP-CH4 23 and N2O 296
               1990     2000     2010     2020     2030     2040     2050
 CH4SWM.NAM       69.28    67.31    67.17  59.61    58.56    55.64   52.73
 CH4SWM.OOECD     50.53    44.76    43.43  45.98    42.44    40.94   39.44
 CH4SWM.EEFSU     35.98    31.15    29.25  30.76    27.40    25.64   23.89
 CH4SWM.ASIA      27.16    41.80    59.58  84.02    100.23   119.07          137.90
 CH4SWM.LAFM      41.12    49.96    62.35  78.50    89.12    101.57  114.02

 CH4MAN.NAM       10.09    12.72    14.31    16.19    18.30    20.28    22.27
 CH4MAN.OOECD     16.10    15.22    15.52    16.53    16.24    16.40    16.56
 CH4MAN.EEFSU     9.35     6.85     7.78     8.75     7.96     7.87     7.78
 CH4MAN.ASIA      14.91    19.76    23.00    27.45    31.49    35.58    39.66
 CH4MAN.LAFM      7.88     8.60     10.92    13.96    15.48    17.54    19.59

 N2ONI.NAM        0.00              5.67     6.19  6.81     7.36     7.94    8.51
 N2ONI.OOECD      0.00              11.15    12.17 12.78    13.66    14.47   15.29
 N2ONI.EEFSU      0.00              1.20     1.34  1.41     1.53     1.64    1.75
 N2ONI.ASIA       0.00     8.90     9.77  10.74     11.64    12.56  13.48
 N2ONI.LAFM       0.00              0.54     0.61     0.69     0.77     0.84    0.92

 N2OADI.NAM       0.00     2.30     2.85     3.76     4.43     5.16     5.88
 N2OADI.OOECD     0.00     4.53     4.94     5.19     5.55     5.88     6.21
 N2OADI.EEFSU     0.00     0.49     0.54     0.57     0.62     0.67     0.71
 N2OADI.ASIA      0.00     4.92     5.99     6.62     7.55     8.40     9.25
 N2OADI.LAFM      0.00     1.52     1.85     2.05     2.33     2.60     2.86


  TABLE BLINEOS_R(GHGOS,REG,YEAR)
* in MtCE for GWP-CH4 23 and N2O 296
               1990     2000     2010     2020     2030     2040     2050
 CH4OS.NAM        58.18    59.10    65.18    68.95    72.45    76.29    80.13
 CH4OS.OOECD      99.70    92.57    94.64    98.55    96.02    95.88    95.74
 CH4OS.EEFSU      86.92    65.71    73.11    80.33    73.42    72.18    70.95
 CH4OS.ASIA       404.61   475.76   531.52   584.54   648.00   707.55   767.11
 CH4OS.LAFM       239.77   275.83   346.60   436.41   489.82   555.88   621.95

 N2OOS.NAM        103.42   118.08   125.80   133.01   144.20   153.85   163.50
 N2OOS.OOECD      101.33   104.82   112.76   120.31   126.02   132.51   138.99
 N2OOS.EEFSU      73.61    57.62    69.43    84.31    82.22    86.61    91.00
 N2OOS.ASIA       270.97   338.59   379.40   429.77   483.99   535.71   587.43
 N2OOS.LAFM       219.63   246.69   299.55   383.30   423.26   477.65   532.03


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