TIMES Version 3.8 User Note

TIMES-Macro: Decomposition into Hard-Linked LP and NLP Problems

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Foreword

This User Note contains the documentation for the implementation and usage of the TIMES-Macro modeling features of the TIMES model generator, with a special focus on the new implementation introduced in TIMES v3.4.0, which is based on decomposing the overall problem into linear and nonlinear sub-problems.

The document is divided into four chapters. Chapter 1 contains a short introduction, and Chapter 2 presents a simplified description of the mathematical formulations, on which the implementations of the Macro variants are based. Chapter 3 contains the description of the GAMS implementation of the new elements, along with the input parameters, variables, and equations that have been added to the TIMES model generator. Finally, Chapter 4 constitutes a brief User's Reference Manual for the Macro modeling features in TIMES.

The work has been carried out by Socrates Kypreos (PSI), who was responsible for the mathematical formulations, decomposition algorithm and economic theory behind the implementation, and Antti Lehtilä (VTT), who completed the actual implementation written in the GAMS modeling language. The work has been financially supported by ETSAP.

This documentation is a supplement to the complete documentation of the TIMES model generator.

Contents

1. INTRODUCTION

This document presents an updated documentation on the linkage of the energy systems model TIMES with the single-sector general equilibrium model Macro, leading to the merged model TIMES-MACRO. The Macro model maximizes an inter-temporal utility function for a single representative producer-consumer agent in each region. The purpose of the TIMES-Macro facility is the integrated modeling of macro-economic impacts within the TIMES framework.

The Macro-features of TIMES are thus intended for modelers who wish to evaluate various energy and environmental policies with respect to their general macro-economic implications. In particular, such integrated macro-economic modeling capabilities may be of interest for evaluating the economic impacts of long-term climate policies on different countries and regions.

The original approach for linking TIMES with Macro (see Remme & Blesl 2006) was very similar to the linkage of the MARKAL model with the Macro model (see Manne & Wene 1992, Kypreos 1996, Loulou, et. al. 2004). Even a large part of the MARKAL code that was related to the Macro model was used as the basis for the original formulation of TIMES-Macro.

The more recent approach is based on decomposition, whose adoption for TIMES was proposed by S. Kypreos in 2006 (Kypreos 2006). The new implementation makes it possible to use the Macro facility even for large multi-regional energy system models.

As indicated above, the Macro modeling facilities currently include the following two different variants:

- Standard TIMES-Macro: the original implementation approach
- TIMES-MSA: decomposed Macro Stand-Alone implementation

The standard TIMES-Macro has been thoroughly documented earlier (Remme & Blesl 2006). Therefore, the present updated documentation focuses on the more recent decomposition approach, and on the differences between these two alternative Macro variants with respect to the mathematical formulation and usage.

2. MATHEMATICAL FORMULATION

2.1 The Standard TIMES-Macro Formulation

2.1.1 Basic formulation

The basic formulation of the original TIMES-Macro implementation comprised the core TIMES model along with the following Macro-specific equations (1)–(9):

$$Max\ U = \sum_{t=1}^{T-1} dfact_t \cdot \ln(C_t) + \frac{dfact_{T-1} \cdot (dfactcurr_{T-1})^{\frac{d_{T-1}+d_T}{2}}}{1-(dfactcurr_T)^{\frac{d_{T-1}+d_T}{2}}} \cdot \ln(C_T) \tag{1}$$

$$Y_t = C_t + INV_t + EC_t \tag{2}$$

$$Y_t = \left(akl \cdot K_t^{kpvs \cdot \rho} \cdot l_t^{(1-kpvs)\rho} + \sum_k b_k \cdot DEM_{t,k}^{\rho} \right)^{\frac{1}{\rho}} \tag{3}$$

$$K_{t+1} = tsrv_t \cdot K_t + \frac{1}{2}(d_t \cdot tsrv_t \cdot INV_t + d_{t+1} \cdot INV_{t+1}) \tag{4}$$

$$K_T \cdot (growv_T + depr) \le INV_T \tag{5}$$

$$DET_{t,k} = aeeifac_{t,k} \cdot DEM_{t,k} \tag{6}$$

$$EC_t = AESC_t + \left[optional\ quadratic\ penalty\ function \right] \tag{7}$$

$$aeeifac_{t,k} = \prod_{\tau=1}^{t} (1 - ddf_{\tau,k})^{\frac{d_t+d_{t+1}}{2}} \tag{8}$$

$$l_1 = 1 \quad \text{and} \quad l_{t+1} = l_t \cdot (1 + growv_t)^{\frac{d_t+d_{t+1}}{2}} \tag{9}$$

where
- C_t: annual consumption in period t (variable)
- Y_t: annual production in period t (variable)
- K_t: total capital in period t (variable)
- INV_t: annual investments in period t (variable)

- $DEM_{t,k}$: annual demand in Macro for commodity k in period t (variable)
- $DET_{t,k}$: annual demand in TIMES for commodity k in period t (variable)
- EC_t: annual energy system costs in Macro in period t (variable)
- $AESC_t$: annual energy system costs in TIMES in period t (variable)
- $aeeifac_{t,k}$ autonomous energy efficiency impr. for demand k in period t
- akl: production function constant
- b_k: demand coefficient for demand commodity k
- d_t: duration of period t in years
- $ddf_{t,k}$ demand decoupling factor in period t (calibration parameter)
- $depr$: depreciation rate
- $dfact_t$: utility discount factor for period t
- $dfactcurr_t$: annual discount rate for period t
- $growv_t$: labour growth rate in period t (calibration parameter)
- $kpvs$: capital value share
- l_t: annual labor growth index in period t
- $tsrv_t$: capital survival factor between periods t and $t+1$
- ρ: elasticity of substitution constant
- T: number of periods in the model horizon

2.1.2 Differences compared to the original TIMES-Macro formulation

For the purposes of making the standard TIMES-Macro fully comparable and consistent with the Macro decomposition method, in the updated TIMES code only a few small changes have been made to the original formulation presented above:

1. The objective function (1) has been revised by introducing period-wise multipliers pwt_t, representing period-length-dependent weights in the utility function. These multipliers are applied exactly in the same way as the $dfact_t$ multipliers. The multipliers are all 1 if all period lengths are equal to each other.
2. The last term in the objective function (1) has been revised. This last term represents the geometric sum of the utility in an infinite time horizon starting from the last model period, leading to a larger value of the utility discount factor (see Remme & Blesl 2006). However, in many analyses such a larger weight on the last period might distort the model results (e.g. when the policy target is to reduce cumulative emissions within the original model horizon), and therefore the utility discount factor for the last term, $dfact_T$, has been parameterized according to a user-defined multiplier $arbm$ defining the number of terms in the geometric sum.
3. The annual energy system cost relation (7) has been revised by introducing an additional constant term amp_t on the right hand side (see explanation below).

The purpose of the new period multipliers pwt_t is to correct the original formulation in cases where the period lengths are not equal, which apparently was not taken into account in the original formulation that was inherited from MARKAL. The multipliers are automatically set to be proportional to the period lengths.

The generalization into the handling of the last period has been made by introducing a new input parameter *arbm*, which has a default value of 1000 in the standard Macro formulation. The default value thus corresponds to the last period being repeated 1000 times, which is reasonably close to the original infinite horizon assumption.

In TIMES, the investment and fixed costs of past investments and residual capacities are often left unaccounted in the model, by leaving the corresponding cost parameters unspecified. In these cases the annual energy system costs would be unreasonably low in the first model periods, and would only gradually reach the levels that correspond to the true full annual costs of the system. While this causes no problems in the partial equilibrium mode, it tends to some cause distortions in the Macro formulation, because the production is defined as the sum of the GDP and the annual energy system costs. In order to alleviate such distortions, the new parameter amp_t has been introduced, which represents the unaccounted portion of the annual costs in the first periods. This parameter is automatically estimated by the new MSA calibration mode, according to a user-specified heuristic growth parameter (see section 3.2.1 below). It can thus be controlled by the user and also turned off when desired. When using the original Macro calibration procedure, this parameter is ignored (it has zero values).

In summary, only very small modifications have been made to the standard Macro formulation. If the model has equal period lengths and the original calibration procedure is used, the new updated formulation is almost fully equivalent to the original one, the only difference being that the infinite horizon assumption has been replaced by assuming the last period repeated only 1000 times.

2.1.3 Calibration Procedure

The purpose of the calibration procedure for the standard TIMES-Macro formulation is to estimate the calibration parameters $growv_t$ and $ddf_{t,k}$ mentioned above. The calibration is based on the following algorithm (the original algorithm is unchanged):

1. Solve the Baseline scenario using the standard TIMES LP formulation;
2. Calculate initial *ddf* factors from the demand levels, undiscounted demand prices and the user-defined growth projection;
3. Write the calculated initial estimates for the calibration parameters and annual energy cost data from the solution into a file DDF.DD;
4. Solve the Baseline scenario using the Macro formulation, using the estimated calibration parameters and other Macro input data;
5. Re-calculate updated *ddf* factors and updated labor growth rates *growv* from the new demand levels, new undiscounted demand prices, and the realized growth in production and GDP; write the updated calibration parameters and annual energy cost data into the file DDF.DD;
6. If the error in demands is less than tolerance, stop, otherwise continue from step 4.

See the documentation of TIMES-Macro for more details about the calibration algorithm (Remme & Blesl 2006).

2.2 The Macro Stand-Alone Formulation (MSA)

For the new Macro stand-alone formulation the original Macro formulation had to be generalized to support multiple regions. In the multi-regional case the model is solved by maximizing the Negishi-weighted sum of regional utilities, iterating between the stand-alone TIMES-Macro model (TMSA) and the standard TIMES LP model. The TMSA model explicitly considers only the trade of the numéraire good, as the trade in all energy products is defined in the TIMES LP model.

The formulation of the stand-alone Macro implementation, which is used in the decomposition approach, can be written by the following equations (10)–(19) (assuming that the *arbm* multiplier for the last period is 1):

$$Max\ U = \sum_{t=1}^{T}\sum_{r} nwt_r \cdot pwt_t \cdot dfact_{r,t} \cdot \ln(C_{r,t}) \tag{10}$$

$$Y_{r,t} = C_{r,t} + INV_{r,t} + EC_{r,t} + NTX\,(nmr)_{r,t} \tag{11}$$

$$Y_{r,t} = \left(akl_r \cdot K_{r,t}^{kpvs_r \cdot \rho_r} \cdot l_{r,t}^{(1-kpvs_r)\rho_r} + \sum_{k} b_{r,k} \cdot DEM_{r,t,k}^{\rho_r} \right)^{\frac{1}{\rho_r}} \tag{12}$$

$$K_{r,t+1} = tsrv_{r,t} \cdot K_{r,t} + \frac{1}{2}(d_t \cdot tsrv_{r,t} \cdot INV_{r,t} + d_{t+1} \cdot INV_{r,t+1}) \tag{13}$$

$$K_{r,T} \cdot (growv_{r,T} + depr_r) \leq INV_{r,T} \tag{14}$$

$$DET_{r,t,k} = aeeifac_{r,t,k} \cdot DEM_{r,t,k} \tag{15}$$

$$EC_{r,t} = qa_{r,t} + \sum_{k} qb_{r,t,k} \cdot (DET_{r,t,k})^2 + amp_{r,t} \tag{16}$$

$$\sum_{r} NTX\,(trd)_{r,t} = 0 \qquad \forall\,\{t,trd\} \tag{17}$$

$$aeeifac_{r,t,k} = \prod_{\tau=1}^{t}(1 - ddf_{r,\tau,k})^{\frac{d_t + d_{t+1}}{2}} \tag{18}$$

$$l_{r,1} = 1 \ \ \text{and} \ \ \ l_{r,t+1} = l_{r,t} \cdot (1 + growv_{r,t})^{\frac{d_t + d_{t+1}}{2}} \tag{19}$$

where
- $C_{r,t}$:   annual consumption in period t (variable)
- $Y_{r,t}$:   annual production in period t (variable)
- $K_{r,t}$:   total capital in period t (variable)
- $INV_{r,t}$:   annual investments in period t (variable)
- $DEM_{r,t,k}$:   annual demand in Macro for commodity k in period t (variable)
- $DET_{r,t,k}$:   annual demand in TIMES for commodity k in period t (variable)
- $EC_{r,t}$:   annual energy system costs in Macro in period t (variable)
- $NTX(trd)_{r,t}$:   annual net exports of commodity trd in period t (variable)
- akl_r :   production function constant
- $amp_{r,t}$:   constant cost term related to past investments in period t
- $b_{r,k}$:   demand coefficient for demand commodity k
- $aeeifac_{r,t,k}$ autonomous energy efficiency improvement
- d_t :   duration of period t in years
- $ddf_{r,t,k}$ demand decoupling factor (calibration parameter)
- $depr_r$:   depreciation rate
- $dfact_{r,t}$:   utility discount factor for period t
- $growv_{r,t}$:   growth rate in period t (calibration parameter)
- $kpvs_r$:   capital value share
- $l_{r,t}$:   annual labor growth index in period t
- nwt_r :   Negishi weight for region r
- pwt_t :   weight multiplier for period t
- $qa_{r,t}$:   constant term of the quadratic supply cost function
- $qb_{r,t,k}$:   coefficient for demand k in the quadratic supply cost function
- $tsrv_{r,t}$:   capital survival factor between periods t and $t+1$
- ρ_r :   elasticity of substitution constant
- T :   number of periods in the model horizon

The primary differences in the formulation compared to the standard TIMES-Macro formulation are the following:

1. The use of the Negishi weights in the objective function (10) when the model is multi-regional;
2. The inclusion of the trade in the numeraire good *NTX(nmr)* in the production function (11);
3. The introduction of the trade balances (17);
4. The replacement of the full TIMES LP cost accounting by quadratic supply-cost functions for each demand commodity (16).

The quadratic supply-cost functions can be easily constructed from the annual energy system costs $AESC_{r,t}$ and undiscounted marginal prices $P_{r,t,k}$ for each demand k:

$$qb_{r,t,k} = \frac{P_{r,t,k}}{2 \cdot DET_{r,t,k}} \quad \text{and} \quad qa_{r,t} = AESC_{r,t} - \sum_k qb_{r,t,k} \cdot DET_{r,t,k}^2 \qquad (20)$$

2.3 The Standard TIMES LP Formulation

The second part of the decomposed model, the standard TIMES LP model, uses the standard TIMES formulation, which can be written in short as follows (see the main TIMES documentation, Part I):

$$Min \ NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} \bullet ANNCOST(r,y) \tag{21}$$

$$A \cdot x = b \quad and \quad x \geq 0 \tag{22}$$

where:
- NPV : net present value of all energy system costs
- $YEARS$: the set of years within the model horizon
- $REFYR$: reference year for discounting
- $d_{r,y}$: discount factor for region r in year y
- $ANNCOST(r,y)$ annual energy system cost in region r and year y
- A : coefficient matrix for all other model equations
- x : vector of all model variables
- b : RHS constant vector for all other model equations
- R : number of internal regions in the model

For a comprehensive treatment of the standard TIMES LP formulation, see the documentation (Loulou et al. 2005).

In order to make the LP formulation more analogous with the Macro objective function, the objective function of the standard TIMES LP formulation can be rewritten in terms of period-wise average annual costs and period-specific discount factors, as follows:

$$Min \ NPV = \sum_{r=1}^{R} \sum_{t=1}^{T} pvf_{r,t} \bullet AESC(r,t) \tag{23}$$

where:
- $pvf_{r,t}$: present value factor for period t in region r
- $AESC(r,t)$: annual energy system costs in region r and period t
- T : number of periods t in the model horizon

2.4 The Decomposition Algorithm

2.4.1 Algorithm for Baseline Calibration

In both of the Macro formulations, the use of the Macro mode for evaluating policy scenarios requires that the demand decoupling factors (DDF) and labor growth rates have first been calibrated with the Baseline scenario and corresponding GDP growth projections. The core part of the calibration procedure is the updating of the demand decoupling factors and labor growth rates between successive iterations of the calibration algorithm.

In the TIMES-MSA implementation, all the basic mathematical formulas for updating the demand decoupling factors and labor growth rates are fully equivalent to those in the standard TIMES-Macro formulation, and are therefore omitted here. The reader is advised to consult the original documentation (Remme & Blesl 2006) for the details on those parts. The overall algorithm for calibrating the Baseline is given below.

- **Step 1: Solve the Baseline TIMES-LP model:**
  a) $Min\ ObjZ = \sum_{r,t} pvf_{r,t} \cdot AESC_{r,t}$

  b) Calculate Quadratic Supply-cost Functions QSF for the demands

- **Step 2: Solve the stand-alone MACRO model (MSA):**
  a) Calculate new DDF factors and labor growth rates
  b) Solve $MaxU = \sum_{r,t} pwt_t \cdot dfact_{r,t} \cdot \ln(Y_{r,t} - INV_{r,t} - EC_{r,t})$

  c) If max. error in demands and GDP are above tolerance, go to Step 2a

- **Step 3: If multi-regional, iterate MSA with Negishi weights**
  a) Calculate initial Negishi weights nwt_r

  b) Solve MSA with the modified objective:
  $$MaxU = \sum_{r,t} nwt_r \cdot pwt_t \cdot dfact_{r,t} \cdot \ln(Y_{r,t} - INV_{r,t} - EC_{r,t} - NTX(nmr)_{r,t})$$

  c) Calculate new nwt_r, and if difference is above tolerance, update the DDF factors and labor growth rates, and go back to Step 3b

- **Step 4: Write final calibration parameters into a DD file**

Remark: The procedure for updating the DDF factors and labor growth rates between successive steps is exactly similar to that in the standard TIMES-Macro. See the TIMES-Macro documentation for further details on the update procedure (Remme & Blesl 2006).

2.4.2 Algorithm for Policy Scenarios

The main purpose of using TIMES-Macro is, of course, in running policy scenarios. The multiregional TIMES-MSA model is solved by maximizing the Negishi weighted sum of regional utilities while we iterate between the two models on the Negishi weights and demand levels in all periods, until they converge. The decomposition algorithm employed in TIMES-MSA for the policy scenarios can be outlined as follows:

- Step1: Solve the Policy Scenario TIMES-LP model:

  a) Minimize the partial equilibrium LP objective function:
  $$Min \ ObjZ = \sum_{r,t} pvf_{r,t} \cdot AESC_{r,t}$$
  b) Calculate the Quadratic Supply-cost Functions (QSF). Read the calibrated *ddf* and labor growth factors from the DD file that was saved when the calibration run was terminated.

- Step 2: Solve TMSA (with Negishi loop if multi-regional)

  a) Calculate initial Negishi weights nwt_r
  b) Maximize the total utility:
  $$U = \sum_{r,t} nwt_r \cdot pwt_t \cdot dfact_{rt} \cdot \ln(Y_{rt} - INV_{rt} - EC_{rt} - NTX(nmr)_{rt})$$
  c) Calculate the new nwt_r and if difference is above tolerance, go to Step 2b
  d) If error in demand levels below tolerance go to Step 3
  e) Update the LP demands according to the MSA results and then resolve the standard TIMES model LP using the *ObjZ* objective
  f) Calculate new QSF and go back to Step 2b

- Step 3: Calculate all model results and finish

The initial Negishi weights are set as being proportional to the regional output share. To balance for inter-temporal trade deficits we need to properly adjust the weights in an iterative approach following the sequential optimization algorithm of Rutherford (1992). As the global net exports, per traded product *trd*, are balanced to zero at each time period, we can use the dual of this constraint to define the price of traded products. The weights are adjusted using the normalized price of the traded products and the trade excess and the inverse of the marginal regional utility i.e.,

$$NW_r = \sum_{t,trd} \pi_{trd,t} \cdot NTX_{r,t,trd} + \sum_{t} \pi_{nmr,t} \cdot C_{r,t} \quad \text{with} \quad nwt_r = NW_r / \sum_r NW_r$$

According to Rutherford, if the weights are inversely-proportional to the marginal utility per region, the solution is Pareto optimal.

2.5 Integration of Climate Impacts

2.5.1 Modifications to the MSA Formulation

The MSA implementation allows also considering market and non-market damage from climate impacts. These impacts have been implemented basically in the same way as in Merge (Warren & al. 2006, Manne 2004). The inclusion of these climate impacts is optional, and when activated, the Equations (10) and (11) are modified as follows:

$$Max\ U = \sum_{t=1}^{T} \sum_{r} nwt_r \cdot pwt_t \cdot dfact_{r,t} \cdot \ln(ELF_{r,t} \cdot C_{r,t}) \tag{24}$$

$$Y_{r,t} = C_{r,t} + INV_{r,t} + EC_{r,t} + MD_{r,t} + NTX(nmr)_{r,t} \tag{25}$$

In addition, the following additional equations are needed for defining the non-market and market damages, respectively:

$$ELF_{r,t} = \left(1 - \left(\frac{DT_t}{catt_r}\right)^2\right)^{hsx_{r,t}} \tag{26}$$

$$MD_{r,t} = \left[mdl_r \cdot \frac{DT_t}{reftemp} + mdq_r \cdot \left(\frac{DT_t}{reftemp}\right)^2\right] \cdot potgdp_{r,t} \tag{27}$$

where
- $C_{r,t}$:   annual consumption in period t (variable)
- $Y_{r,t}$:   annual production in period t (variable)
- $INV_{r,t}$:   annual investments in period t (variable)
- $EC_{r,t}$:   annual energy system costs in Macro in period t (variable)
- $NTX(trd)_{r,t}$:   annual net exports of commodity trd in period t (variable)
- $ELF_{r,t}$:   economic loss factor for non-market damage (variable)
- $MD_{r,t}$:   annual market damage (variable)
- DT_t :   temperature change (variable)
- $catt_r$:   catastrophic temperature change in region r
- $dfact_{r,t}$:   utility discount factor for period t
- mdl_r :   linear coefficient for market damage
- mdq_r :   quadratic coefficient for market damage
- nwt_r :   Negishi weight for region r
- $potgdp_{r,t}$:   potential GDP in period t
- pwt_t :   weight multiplier for period t
- $reftemp$:   reference temperature change

The temperature change variables shown above in Equations (26) and (27) could, in principle, be directly fixed on the basis of the LP solution, because in TIMES we already have a linearized climate module, which includes the temperature change variables. Alternatively, we could include a climate module in MSA and fix its emission variables.

On should note that Equation (24) can be rewritten in the following augmented form:

$$Max\ U = \sum_{t=1}^{T} \sum_{r} nwt_r \cdot pwt_t \cdot dfact_{r,t} \cdot \ln(C_{r,t}) +$$
$$\sum_{t=1}^{T+X} \sum_{r} nwt_r \cdot pwt_t \cdot dfact_{r,t} \cdot \ln(ELF_{r,t}) \tag{28}$$

This augmented formula shows that the non-market damages can be considered independently of the main objective function, because the ELF variables depend only on the temperature change. They can thus be consistently included in the objective function also for any longer time-horizon extended to $T+X$, if the corresponding temperature change estimates are available for some extended periods. The TIMES model generator does, indeed, include an option for extending the climate equations beyond the model horizon by using extrapolated emission trajectories. The impacts of the longer-term damages can thus be taken into consideration in a cost-benefit analysis, without having to extend the time-horizon of the LP problem unnecessarily too far into the future.

Therefore, as explained below in Section 2.5.2, the full TIMES climate module (Loulou & al. 2010) is included in the MSA sub-model when damages from climate change are modeled. In addition, all the linearized forcing functions are updated during the master iterations to reflect the levels and slopes obtained with accurate non-linear functions.

2.5.2 Modifications to the LP Formulation

In the basic formulation of Equations (26)–(27) above, the damage is a function of temperature change. In order to derive the marginal damage caused by emissions in the MSA sub-model, we also need the climate equations describing the development of concentrations, forcing, and temperature change as a function of emissions. For this purpose, the full TIMES climate module is included in the MSA sub-model, when the damages from climate change are considered. During the master iterations, all the linearized forcing functions can be updated according to the non-linear functions.

In the final optimal solution of the integrated TIMES-MACRO-MSA model, the marginal loss from the emissions in the MSA sub-model should be equal to the marginal loss from reducing emissions in the energy system LP sub-model. In order to reach this condition, we can fix the emission variables in the MSA sub-model to the values obtained from the LP solution, and subsequently pass the undiscounted marginal cost equivalent of the marginal damage from emissions, as obtained from the MSA sub-model, and use these as damage costs for the emissions in the LP sub-model.

The modified LP formulation can thus be written as follows:

$$Min\ NPV = \sum_{r=1}^{R}\sum_{t=1}^{T} pvf_{r,t} \bullet \big(AESC(r,t) + EM_{k}(r,t) \cdot mdm_{k}(t)\big) \tag{29}$$

where:
- $pvf_{r,t}$:   present value factor for period t in region r
- $AESC(r,t)$:   annual energy system costs in region r and period t
- $EM_{k}(r,t)$:   annual emissions of type k in region r and period t
- $mdm(t)$:   marginal damage cost from emissions of type k in period t
- T :   number of periods t in the model horizon

2.5.3 Modifications to the Overall Algorithm

The modified overall decomposition algorithm can be summarized as follows:

- Step1: Solve the Policy Scenario TIMES-LP model:

    a) Minimize the partial equilibrium LP objective function:
    $$Min\ ObjZ = \sum_{r,t} pvf_{r,t} \cdot \big(AESC_{r,t} + EM_{r,t,k} \cdot mdm_{t,k}\big)$$
    b) Calculate the Quadratic Supply-cost Functions (QSF). Read the calibrated *ddf* and labor growth factors from the DD file produced in the calibration.

- Step 2: Solve TMSA (with Negishi loop if multi-regional)

    a) Calculate initial Negishi weights nwt_r
    b) Update all forcing functions, and fix the MSA emissions to the LP solution
    c) Maximize the total utility:
    $$U = \sum_{r,t} nwt_r \cdot pwt_t \cdot dfact_{rt} \cdot \big(\ln(Y_{rt} - INV_{rt} - EC_{rt} - MD_{rt} - NTX(nmr)_{rt}) + \ln(ELF_{rt})\big)$$
    d) Calculate the new nwt_r and if difference is above tolerance, go to Step 2c
    e) If error in demand levels is below tolerance then STOP and finish
    f) Update the LP demands and damage costs for emissions from the MSA results, and then resolve the TIMES LP model using the *ObjZ* objective
    g) Calculate new QSF and go back to Step 2b.

An alternative approach that could also have been applied is based on using MAC curves. From any given LP solution with emission constraints, we could derive quadratic MAC curves for emissions abatement, and add these cost functions to the energy system costs in MSA, making sure that the annual energy system costs remain valid by adjusting the constant terms. In this approach, the emission variables would thus not be fixed to the LP solution, but the MSA sub-model would instead derive new estimates for the optimal emission abatement levels in order to reduce damage from climate change. Doing some test model runs has indeed verified that these two approaches lead to identical results.

3. GAMS IMPLEMENTATION

3.1 Overview

As discussed in Section 2, a new implementation of TIMES-Macro based on a decomposition approach has been incorporated into TIMES. In general, the TIMES-Macro facility can be useful, for example, for analyzing the macro-economic implications of long-term climate policies. And the new implementation based on decomposition, TIMES-MSA, makes it possible to use this facility even for large multi-regional models. In this section the main elements of the TIMES-MSA implementation are described.

3.2 Parameters

3.2.1 Input parameters

The input parameters that are available in the standard TIMES-Macro and decomposed TIMES-MSA formulations are listed in Table 1. All the input parameters of the original implementation of TIMES-Macro are unchanged (see Remme & Blesl 2006), and most of

Table 1. Input parameters for the TIMES-Macro modeling facilities.

Parameter	Description
TM_ARBM	Arbitrary multiplier for the last period replication
TM_DEFVAL(item)	Default values for regional Macro constants
TM_DEPR(r)	Depreciation rate (percentage)
TM_DMTOL(r)	Lower bound factor for the demand variables
TM_ESUB(r)	Elasticity of substitution
TM_GDP0(r)	GDP in the first period
TM_GR(r,y)	Projected annual GDP growth in per cent
TM_HSX(r,t)	Hockey-stick exponent for non-market damage
TM_IVETOL(r)	Investment and energy cost upper bound tolerance
TM_KGDP(r)	Initial capital to GDP ratio
TM_KPVS(r)	Initial capital value share in all production factors
TM_MDTL(r)	Linear coefficient for market damage
TM_MDTQ(r)	Quadratic coefficient for market damage
TM_SCALE_CST	Scaling factor for cost units
TM_SCALE_NRG	Scaling factor for the demand units
TM_SCALE_UTIL	Scaling factor for the utility function
TM_QFAC(r)	Switch for market penetration penalty function *
TM_EXPBND(r,y,p)	Market Penetration Cutoff for Applying Cost Penalty *
TM_EXPF(r,y)	Annual percent expansion factor *

* Available only in standard TIMES-Macro (not in TIMES-MSA)

them are available in both standard TIMES-Macro and TIMES-MSA. There are only five new input parameters, which are discussed in more detail below:

1. The parameter **TM_ARBM** can be used for specifying the multiplier for the last period in both the standard TIMES-Macro formulation and in the decomposition-based TMSA formulation. This multiplier specifies the number of terms in the geometric sum, where the objective component corresponding to the last period is replicated further into the future. In the original TIMES-Macro, the multiplier was infinite, corresponding to the infinite horizon assumption (see Remme & Blesl 2006). However, in the new formulation the multiplier is required to be a finite number.

   - The default value is 1000 in the standard TIMES-Macro formulation. For example, if the length of the last period is 10 year, this would correspond to 10,000 years further into the future.
   - The default value is 1 in the decomposed TMSA formulation, meaning that the model accounting horizon is by default equal to that in the standard TIMES LP formulation.

2. The parameter **TM_DEFVAL(item)** can be used for defining default values for the regional Macro constant input parameters when using the decomposed TMSA formulation. The items and the constants for which it can be used are the following:

   - DEPR: default value for TM_DEPR(r); standard default = 5
   - ESUB: default value for TM_ESUB(r); standard default = 0.25
   - KGDP: default value for TM_KGDP(r); standard default = 2.5
   - KPVS: default value for TM_KPVS(r); standard default = 0.25
   - DMTOL: default value for TM_DMTOL(r); standard default = 0.5
   - IVETOL: default value for TM_IVETOL(r); standard default = 0.5
   - ESC: default value for cost escalation factor (see explanation below).
   - REFTEMP: default value for the reference temperature of climate damage
   - REFLOSS: default value for the consumption loss at reference temperature

   The cost escalation factor **ESC** mentioned above, which can be defined by using the specification **TM_DEFVAL('ESC')**=<value>, controls the heuristic estimation of the unaccounted costs related to past investments in the first periods. These unaccounted costs may often be considerable in TIMES models, due to the investments and fixed costs of the existing capacities being left unspecified. The **ESC** factor gives the maximum expected escalation in the total annual energy system costs, beyond the GDP growth rate. The default value for this factor has been set at 1.028, corresponding to 2.8% annual cost escalation. By setting this factor at a high value, e.g. 2.0, the user can effectively remove the application of the heuristic additional cost term $amp_{r,t}$ described above in section 2.1.2. Note that the internal parameter $amp_{r,t}$ is estimated only by the MSA calibration mode (CSA), and it is not available when using the original TIMES-Macro calibration (it is assumed to be zero).

The reference temperature constant, REFTEMP, can be used for defining the reference temperature change, which is used for calculating the $catt_r$ parameter in Equation (26) and directly in Equation (27). The default value is 2 (°C).

The reference loss constant, REFLOSS, can be used for defining the reference loss in consumption, which is used for calculating the $catt_r$ parameter in Equation (26). The default value is 0.02 (2%).

3. The parameter TM_HSX(r,t) can be used for defining the so-called hockey-stick parameter for non-market damage (see Eq. (26)). The parameter value should be in the range [0,1]. There is no default value for this parameter.

4. The parameter TM_MDTL(r) can be used for defining a linear coefficient for market damage (see Eq. (27)). The parameter value should be in the range [0,1]. There is no default value for this parameter.

5. The parameter TM_MDTQ(r) can be used for defining a quadratic coefficient for market damage (see Eq. (27)). The parameter value should be in the range [0,1]. There is no default value for this parameter.

When including non-market damage from climate change in the MSA formulation by using the parameter TM_HSX, the internal parameter $catt_r$ represents a catastrophic temperature change, at which the entire regional production would be wiped out (see Equation (26)). It is calculated from the REFTEMP and REFLOSS parameters as follows (see Manne 2004):

$$catt_r = \left(\frac{reftemp^2}{refloss} \right)^{0.5} \tag{30}$$

For more details on the other input parameters, which are all unchanged with respect to the original implementation, the reader is advised to consult the original documentation of TIMES-Macro (Remme & Blesl 2006).

3.2.2 Reporting parameters

Some new Macro-specific results attributes have been implemented into TIMES, and these are available both when using the MSA and when using the standard TIMES-MACRO formulation. Within the TIMES code and for importing into VEDA-BE, these result attributes are all grouped under a single result parameter. In TIMES, the name of the parameter is **TM_RESULT(item,reg,year)**, which in VEDA-BE appears under the name Var_Macro.

The Macro-specific result attributes are the following:

- GDP-REF – Baseline GDP projection by region and period
- GDP-ACT – Actualized GDP in scenario by region and period
- PRD-Y – Annual Macro production by region and period
- CON-C – Annual Macro consumption by region and period
- INV-I – Annual Macro investments by region and period
- ESCOST – Annual energy system costs by region and period
- GDPLOS – GDP loss in per cent (policy runs)

In addition, most of the standard results parameters are also available when running scenarios with either of the Macro formulations. Only some results related to the standard TIMES objective function are omitted.

3.3 Variables

The variables used in the standard TIMES-Macro formulation are essentially unchanged. The reader is advised to consult the original TIMES-Macro documentation for more details on the implementation of the variables (Remme & Blesl 2006).

The decomposed MSA implementation of TIMES-Macro introduces closely similar sets of variables, which are listed and briefly described in Table 2 above. Most of these variables are fully equivalent to the corresponding variables in the standard TIMES-MACRO implementation (see Remme & Blesl 2006). The only new variables introduced in TIMES-MSA are the trade variables VAR_NTX(r,t,trd), which are free variables representing the net exports of traded commodity *trd* from region *r* in period *t*, and the climate damage variables VAR_CDM(r,item,y).

Table 2. Variables in the MSA formulation of TIMES-Macro.

Variable	Description
VAR_UTIL	The objective variable representing total cumulative utility
VAR_C(r,t)	Variable representing annual economy consumption
VAR_Y(r,t)	Variable representing annual economy production
VAR_K(r,t)	Variable representing capital
VAR_INV(r,t)	Variable representing annual investments
VAR_D(r,t,com)	Variable representing annual Macro demand of commodity *com*
VAR_DEM(r,t,com)	Variable representing annual TIMES demand of commodity *com*
VAR_SP(r,t,com)	Artificial variable for scaling shadow price of demand
VAR_EC(r,t)	Variable representing annual TIMES energy system costs
VAR_NTX(r,t,trd)	Variable representing trade in commodity *trd*
VAR_CDM(r,item,y)	Variable representing annual climate damage of type *item*

3.4 Equations

The equations defined in the standard TIMES-Macro formulation remain essentially unchanged. The reader is advised to consult the original TIMES-Macro documentation for more details on the implementation of the equations (Remme & Blesl 2006).

The equations introduced in the MSA implementation of TIMES-Macro are listed and briefly described below in Table 3. Most of these equations are fully equivalent to the corresponding equations in the standard TIMES-MACRO implementation (see Remme & Blesl 2006). The only new equations introduced in TIMES-MSA are the trade balance equations EQ_TRDBAL(t,trd), which require that the sum of net exports over all regions is zero for all traded commodities *trd* and periods *t*, and the climate change damage equations EQ_CCDM(r,item,y).

The objective function, the production function and energy cost equations are, of course, somewhat different in TIMES-MSA as compared to the standard TIMES-Macro formulation. These differences have already been described in Sections 2.2 and 2.5.

Finally, when damages from climate change are considered (see Section 2.5), also the TIMES **Climate Module** (see Loulou & al. 2010) is almost fully included in MSA. All the Climate Module equations for concentrations, forcing and temperature change are then included unchanged in MSA. Consequently, also all the variables referred to in these equations are included in the MSA formulation. The temperature change variables DT_t mentioned in Equations (26) and (27) thus refer to the corresponding VAR_CLIBOX variables in the Climate Module. The emission variables are fixed to the LP solution, as described in Section 2.5.

Table 3. Equations in the MSA formulation of TIMES-Macro.

Equation	Description
EQ_UTIL	The Macro objective function defining the total utility maximized
EQ_CONSO(r,t)	Equation defining annual economy consumption
EQ_PROD_Y(r,t)	Equation defining annual economy production
EQ_DD(r,t,com)	Demand decoupling equation for demand commodity *com*
EQ_MCAP(r,t)	Capital dynamics equation
EQ_TMC(r,t)	Terminal condition for investment in last period
EQ_IVEQBND(r,t)	Bound on the sum of investment and energy costs
EQ_ESCOST(r,t)	Annual energy system cost equation
EQ_TRDBAL(t,trd)	Trade balance equation for traded commodity *trd*
EQ_CCDM(r,item,y)	Equation defining annual market and non-market damages

4. USER'S REFERENCE

4.1 Using the Standard TIMES-Macro Mode

4.1.1 Calibration

In both of the Macro formulations, the evaluating of policy scenarios requires that so-called demand decoupling factors (DDF) and labor growth rates have first been calibrated with the Baseline scenario and corresponding GDP growth projections. The calibration produces a file containing the calibrated parameters, which must then be included in the subsequent policy scenarios to be evaluated.

When using the standard TIMES-Macro facility (the original approach), the Baseline calibration can be carried out in two ways

- Using the original calibration procedure based on the standard TIMES-Macro formulation; or
- Using the new calibration procedure based on the decomposed formulation.

For basic details on using the original calibration procedure, see the original documentation (Remme & Blesl 2006). However, note that a small change has been made into the implementation: In the new versions of TIMES, the file containing the updated DDF factors and labor growth rates (DDFNEW.DD) is now always automatically generated directly after each of the TIMES-Macro NLP runs, and so the use of the old routine **ddfnew.gms** can be completely omitted. Otherwise the calibration procedure remains identical to the original one.

The new calibration procedure based on the decomposed formulation can be used instead of the old procedure even when the aim is to use the standard TIMES-Macro formulation for the subsequent policy runs. The new calibration can be activated by using the following switch:

```
$  SET MACRO CSA        ! Activate MSA in calibration mode
```

In both calibration methods, the only required Macro input parameters are the following:

- TM_GDP0(r) :   GDP in base year (currency units)
- TM_GR(r,y) :   GDP growth projection (per cent / a)

All the other Macro input parameters have pre-defined default values, as described above in Section 3.2.1. The default values are overridden by any user-specified values, which should thus be defined whenever appropriate.

The CSA calibration procedure produces a file MSADDF.DD, which contains the calibrated parameters. This file is automatically included in subsequent TIMES-Macro

policy runs started in the same GAMS working directory, unless some other DDF file has been already included in the RUN file.

4.1.2 Policy evaluation

When using the standard TIMES-Macro facility (the original approach), the policy analysis mode can be activated by using the following switch:

    $ SET MACRO YES   ! Activate TIMES-Macro

In addition, the user should make sure that the DD file containing the calibrated DDF factors and labor growth rates is either included explicitly in the RUN file, or this file is located in the current working directory and has the name MSADDF.DD. The latter is automatically the case if the calibration has been previously done with the CSA calibration procedure, which creates the file MSADDF.DD (see above).

4.2 Using the Decomposed TIMES-Macro Mode

4.2.1 Calibration

In both of the Macro formulations, the evaluating of policy scenarios requires that so-called demand decoupling factors (DDF) and labor growth rates have first been calibrated with the Baseline scenario and corresponding GDP growth projections. The calibration produces a file containing the calibrated parameters, which must then be included in the subsequent policy scenarios to be evaluated.

The new calibration procedure based on the decomposed formulation can be activated by using the following switch:

    $ SET MACRO CSA   ! Activate MSA in calibration mode

The only required Macro input parameters that must be defined are the following:

- TM_GDP0(r) :   GDP in base year (currency units)
- TM_GR(r,y) :   GDP growth projection (per cent / a)

All the other Macro input parameters have pre-defined default values, as described above in Section 3.2.1. The default values are overridden by user-specified values, which should thus be defined whenever appropriate.

Additionally, the user can optionally activate updating of the general discount factors applied in the standard TIMES formulation during the calibration. This can be accomplished by using the following switch:

    $ SET OBJANN YES   ! Activate discount factor updating (optional)

The updating of the general discount factors causes the discount factors applied in the standard TIMES formulation to be converged towards those in the MSA formulation (i.e. the present value of the annual costs in different periods, measured by the impact of the costs on the objective function, will follow the same trajectory). However, one should note that the updating of the discount factors may be useful only when validating the MSA results against the standard TIMES-Macro formulation.

The CSA calibration procedure produces a file MSADDF.DD, which contains the calibrated parameters. This file is automatically included in subsequent MSA policy runs started in the same GAMS working directory.

4.2.2   Policy evaluation

The new decomposed TIMES-Macro formulation (MSA) can be activated by using the following switch:

    $ SET MACRO MSA   ! Activate MSA in policy analysis mode

In the policy-analysis mode, all the relevant Macro parameters are already included in the DD file containing the calibration parameters, and therefore no Macro parameters are actually required to be defined in the other input data files when doing the policy runs.

The user should make sure that the DD file containing the calibration parameters (produced by a preceding calibration run), is located in the current working directory and has the name MSADDF.DD. That is automatically the case if the calibration has been previously done in the same working directory with the CSA calibration procedure (see above).

4.2.3   Cost-benefit analysis of climate change impacts

Cost-benefit analysis of climate change impacts can be carried out by including damages from climate change in the MSA formulation. The damages are divided into market and non-market damages (see Warren & al. 2006, Marcucci & Turton 2012).

Market damages can be activated simply by specifying the coefficients TM_DMTL(r) and/or TM_DMTQ(r) for them, where TM_DMTL defines linear damage coefficients and TM_DMTQ quadratic damage coefficients. One can define only either of them, or both, depending on the damage formula desired to be used (Warren & al. 2006). The reference temperature *reftemp* used in the formula can be defined by the TM_DEFVAL parameter, and has the default value of 2 (°C).

Non-market damages can be activated by specifying the TM_HSX(r,y) parameter, which defines the hockey-stick parameter *hsx*. The catastrophic temperature change *catt* used in the formulation is derived from the REFTEMP and REFLOSS parameters, which can both be defined by TM_DEFVAL parameter.

The damages from climate change, as formulated in TIMES-MSA, can be included only in the policy evaluation mode. Note that when including them, the TIMES damage costs must also not be disabled, i.e. one should not use the setting $SET DAMAGE NO.

According to one of the authors (Socrates Kypreos), in order to obtain substantial impacts from climate change damage in the model, one needs to run it with a very low utility discount rate. However, in TIMES-MACRO there is no direct input parameter for defining the utility discount rate. The utility discount rate is calculated from the capital to GDP ratio, capital value share and depreciation rate parameters, as well as from the projected GDP growth. One might thus suggest instead to experiment with a very low depreciation rate.

4.3 Specification of Input Parameters

The following Table 4 lists the available user-input parameters. The following indexes are used in the index domain of the parameters:

Index	Meaning	Index	Meaning
r	Region	c	Commodity
datayear	Year of data specified	s	Timeslice
p	Process	item	Macro constant name

Table 4: Input parameters for TIMES-MSA

Input parameter (Indexes)[1]	Related parameters[2]	Units / Ranges & Default values & Default inter-/extrapolation[3]	Instances[4] (Required / Omit / Special conditions)	Description	Affected equations or variables[5]
TM_ARBM		• Dimensionless • [1, INF); default value: 1000 (standard) or 1 (MSA)	• None	Time multiplier for the last period in the Macro objective function	• EQ_UTIL
TM_DEFVAL (item)	TM_DEPR TM_DMTOL TM_ESUB TM_IVETOL TM_KGDP TM_KPVS	• See the corresponding regional parameter	• Item can be one of DEPR, DMTOL, ESUB, IVETOL, KGDP, KPVS, ESC, REFTEMP, REFLOSS • Overridden by the regional parameter if specified	Default values for various other Macro constants	• See the corresponding regional parameter
TM_DEPR (r)		• Percentage points • [0, 100]; default value: 5	• Typically chosen to be equal or close to the discount rate G_DRATE in TIMES	Depreciation rate	• EQ_UTIL • EQ_TMC
TM_DMTOL (r)	TM_IVETOL	• Fraction • (0, 1]; default value: 0.5	• None	Lower bound for demand c as a fraction of the base year demand	• VAR_D
TM_ESUB (r)		• Dimensionless • (0, 1]; default value: 0.25	• Typically between 0.2 and 0.5	Elasticity of substitution	• EQ_PROD_Y

---

[1] The first row contains the parameter name, the second row contains in brackets the index domain over which the parameter is defined.

[2] This column gives references to related input parameters or sets being used in the context of this parameter as well as internal parameters/sets or result parameters being derived from the input parameter.

[3] This column lists the unit of the parameter, the possible range of its numeric value [in square brackets] and the inter-/extrapolation rules that apply.

[4] An indication of circumstances for which the parameter is to be provided or omitted, as well as description of inheritance/aggregation rules applied to parameters having the timeslice (**s**) index.

[5] Equations or variables that are directly affected by the parameter.

Input parameter (Indexes)[1]	Related parameters[2]	Units / Ranges & Default values & Default inter-/extrapolation[3]	Instances[4] (Required / Omit / Special conditions)	Description	Affected equations or variables[5]
TM_GDP0 (r)	TM_GR	• Macro cost units • [0, INF), default value: none	• Required for all internal regions modeled • Must be scaled to Macro cost units according to TM_SCALE_CST	Initial GDP in the first model period	• EQ_PROD_Y
TM_GR (r,datayear)	TM_GDP0	• Percentage • [0, 100]; default value: none • Default i/e: standard	• Required for all regions modeled	Projected annual growth in GDP in percentage points, by period	• EQ_PROD_Y • VAR_Y
TM_HSX (r,datayear)	TM_MDTL TM_MDTQ	• Exponent • [0,1], default value: none	• None	Hockey-stick parameter for non-market damage	• EQ_CCDM
TM_IVETOL (r)	TM_DEMTOL	• Dimensionless • [0, 1]; default value: 0.5	• None	Defines an upper bound on investments and annual energy costs	• EQ_IVECBND
TM_KGDP (r)	TM_KPVS	• Dimensionless • (0, INF); default value: 2.5	• None	Initial capital-to-GDP ratio in first period	• EQ_MCAP
TM_KPVS (r)	TM_KGDP	• Fraction • (0, 1); default value: 0.25	• None	Share of capital in the sum of all production factors in first period	• EQ_PROD_Y • VAR_Y
TM_MDTL (r)	TM_MDTQ	• Dimensionless • [0,1]	• None	Coefficient for linear damage per GDP	• EQ_CCDM
TM_MDTQ (r)	TM_MDTL	• Dimensionless • [0,1]	• None	Coefficient for quadratic damage per GDP	• EQ_CCDM

Input parameter (Indexes)[1]	Related parameters[2]	Units / Ranges & Default values & Default inter-/extrapolation[3]	Instances[4] (Required / Omit / Special conditions)	Description	Affected equations or variables[5]
TM_SCALE_CST	TM_SCALE_NRG	• Dimensionless • (0, INF); default value: 0.001	• None	Scaling factor for energy system costs	• EQ_ESCOST
TM_SCALE_NRG	TM_SCALE_CST	• Dimensionless • (0, INF); default value: 1	• None	Scaling factor for demands	• EQ_DD
TM_SCALE_UTIL		• Dimensionless • (0, INF); default value: 0.001	• None	Scaling factor for utility	• EQ_UTIL

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