Energy Technology Systems Analysis Programme

Documentation of the TIMES-MACRO model

DRAFT Version

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1. Introduction

This document describes the linkage of the energy systems model TIMES with the one-sectoral general equilibrium model MACRO leading to the merged model TIMES-MACRO. The approach of linking TIMES and MACRO is very similar to the linkage of the MARKAL model, the ancestor of TIMES, with the MACRO model (see /Manne and Wene 1992/, /Kypreos 1997/, /Loulou, et. al. 2004/). A great part of the MARKAL code related to the MACRO model has been used as basis for the TIMES formulation.

In the following chapter a simplified formulation of the MACRO model and the general concept of linking TIMES with MACRO are presented. Chapter 3 serves as reference guide for TIMES-MACRO. It gives an overview of the user input parameters for building a as well as internal parameters of the GAMS implementation. The equations and associated variables of the MACRO model are also presented there. Details on the derivation of some coefficients of the MACRO equations, information on bounds and starting values for the MACRO variables as well as an overview of the reporting parameters are also given in Chapter 3. The routines for calibrating the TIMES-MACRO model are described in Chapter 4 followed by a short description of running the TIMES-MACRO model (Chapter 5) and a discussion on some solution issues (Chapter 6).

2. Concept of the TIMES-MACRO model

The TIMES-MACRO model is a result of linking the bottom-up energy systems model TIMES with the top-down model MACRO. Bottom-up models as TIMES describe the energy sector in technology-rich way, but ignore the interdependencies of the energy sector with the remaining economy. On the other hand top-down models as MACRO, which depict the economic relationships of the entire economy, enable one to study the interconnections between economic development and energy demand. Since this is done on a more aggregate level, detailed technology related information cannot be derived from top-down models. To circumvent the shortcomings present in the two modeling approaches, several developments have been undertaken to extend the methodology in the corresponding other direction, i.e., technological detail has been added to top-down models (see e.g. /Böhringer 1998/, /Böhringer and Rutherford 2005/) and information on the interconnection of the energy sector with the remaining economy has been added to bottom-up models (see e.g. /Manne and Wene 1992/). The latter approach is the basis of the TIMES-MACRO model presented here. The concept of the MACRO model and its linkage with the TIMES model will be presented in this section. For detailed information on the TIMES model the reader is referred to the model documentation (/Loulou, et. al. 2005/).

The MACRO model, which can be characterized as a single-sector, optimal growth dynamic inter-temporal general equilibrium model, maximizes the national (regional) utility. The utility is a logarithmic function of the consumption of a single generic consumer. The industry sectors outside of the energy sector are presented by the production function of a single representative industry sector. Inputs for the production are labor, capital and energy. The energy demand is covered by the energy sector, which is represented by the TIMES model. Part of the annual production is used to cover the costs for energy demand. The other part can be used for investments in the capital stock or for consumption by the households. Thus, the linkage between the MACRO model and the TIMES model is established in two directions: the TIMES model provides the costs of the energy demand to the MACRO model, while in the other direction the MACRO model determines the energy demand being input factor for the TIMES model. The linkage of the two models is shown in Figure 1.
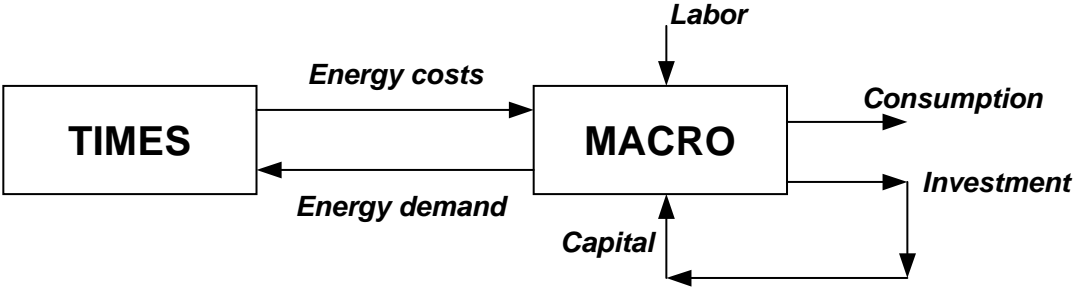
Figure 1:   Concept of the linkage for a single-region TIMES-MACRO model

Government is not represented in the TIMES-MACRO model. The approach implemented so far works only for a single-regional model. The equilibrium of the single-regional model is characterized by a maximum of the region's utility or welfare and can be computed by solving a non-linear programming (NLP) problem. In a multi-regional context, each region seeks to maximize its utility. The regions are linked through trade in goods. The calculation of the equilibrium for a multi-regional model is much more complex. Approaches to find solutions for multi-regional problems are presented for MARKAL-MACRO in /Büeler 1997/. An alternative solution route is to separate MACRO from the energy part and to solve the overall problem in an iterative way.

2.1. Basic formulation of the MACRO model

To describe the general ideal of the MACRO model its basic mathematical formulation is given by the equations (1) – (6)[1]:

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

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

$$Y_t = \left(akl \cdot K_r^{kpvs \cdot \rho} \cdot l_t^{(1-kpvs)\rho} + \sum_{dm} b_{dm} \cdot DEM\_M_{t,dm}^{\rho} \right)^{1/\rho} \tag{3}$$

$$l_1 = 1 \quad \text{and} \quad l_{t+1} = l_t \cdot \left(1 + growv_t\right)^{\frac{d_t+d_{t+1}}{2}} \tag{4}$$

$$K_{t+1} = tsrv_t \cdot K_t + \frac{1}{2}\left(d_t \cdot tsrv \cdot INV_t + d_{t+1} \cdot INV_{t+1}\right) \tag{5}$$

$$K_T \cdot \left(growv_T + depr\right) \leq INV_T \tag{6}$$

with the model variables

C_t: annual consumption in period t,

$DEM\_M_{t,dm}$: annual energy demand in MACRO for commodity dm in period t,

Y_t: annual production in period t,

INV_t: annual investments in period t,

EC_t: annual energy costs in period t,

K_t: total capital in period t

and the exogenously determined parameters

akl: production function constant,

b_{dm}: demand coefficient,

d_t: duration of period t in years,

$depr$: depreciation rate,

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[1] The concrete implementation in the TIMES-MACRO model differs in some points, e.g. the consumption variable in the utility function is substituted by equations (2) and (3). The exact formulation as implemented in TIMES is given further below in Chapter 3.

$dfact_t$:	utility discount factor,
$dfactcurr_t$:	annual discount rate,
$growv_t$:	growth rate in period t,
$kpvs$	capital value share,
l_t:	annual labor index in period t,
ρ:	substitution constant,
T:	period index of the last period,
$tsrv_t$:	capital survival factor between two periods.

The objective function (1) of the MACRO model is the maximization of the discounted utility. The utility is defined through the consumption C_t of the households. A logarithmic utility function has been chosen, instead of a linear one, to avoid "bang-bang" solutions related to linear functions. Due to the concave nature of the utility function the additional utility of consumption is decreasing with increasing consumption (diminishing marginal utility). To measure the utility, consumption and not GDP (gross domestic product) has been selected, since GDP contains in addition to consumption investments. The discount factor of the last period has a larger impact. It is assumed that the utility of the last period will be valid for the infinite time horizon after the last model period leading to a larger value of the discount factor. The derivation of the discount factors is discussed in Section 3.4.1.

The production function (3) is a nested, constant elasticity of substitution (CES) function with the input factors capital, labor and energy. The production input factors labor l_t and capital K_t form an aggregate A_{KL}, in which both can be substituted by each other represented by a Cobb-Douglas function. Then, the aggregate of the energy services and the aggregate of capital and labor can substitute each other.

The elasticity of substitution between the aggregate of capital and labor on the one side and energy on the other side is the ratio between the relative change in the quotient of two production factors and the relative change in their prices. For the production factors energy E and the aggregate of capital and labor A_{KL} the elasticity of substitution has the general form:

$$\sigma = \frac{\partial \left(\dfrac{A_{KL}}{E} \right) \Big/ \dfrac{A_{KL}}{E}}{\partial \left(\dfrac{P_{KL}}{P_E} \right) \Big/ \dfrac{P_{KL}}{P_E}}) = \frac{\partial \ln(A_{KL}/E)}{\partial \ln(P_{KL}/P_E)} \tag{7}$$

with

σ: elasticity of substitution,

A_{KL}:   aggregate of capital and labor,

E: energy,

P_{KL}:   price for the production factor aggregate of capital and labor,

P_E: price for the production factor energy.

For Western European economies the elasticity of substitution has been estimated to be in the range of 0.2 to 0.5 /Läge 2001/. The lower the value of the elasticity of substitution the closer is the linkage between economic growth and increase in energy demand. For homogenous production functions with constant scale of returns[2] the substitution constant ρ in Eqn. (3) is directly linked with the user-given elasticity of substitution σ by the expression $\rho = 1 - 1/\sigma$.

The capital value share *kpvs* describes the share of capital in the sum of all production factors and has to be specified by the user. For OECD economies, *tm_kpvs_r* typically lies in the range from 0.2 to 0.3. The parameter *akl* is the level constant of the production function. The parameters *akl* and b_{dm} of the production are determined based on the results from a TIMES model run without the MACRO module (see Section 3.4.3).

Equation (2) describes how the annual production Y_t spent. The consumers, who want to maximize their utility over the model horizon, can decide whether they want to spend the production for consumption in the current period or whether they want to use use Y_t for investments, which can be used for future consumption. In addition, the production has to cover the costs for the production of energy EC_t.

The production factor labor (Eqn. (4)) is modeled has efficiency indicator having a value of 1 for the first period. It is not an endogenous model variable in MACRO, but specified exogenously by the labor growth rate $growv_t$. The increase in the production factor labor can be caused by an increase in population but also by efficiency improvements in the productivity. The efficiency improvements can be interpreted as a form of technical progress. This type of efficiency improvement, which is only subject to the production factor labor, is called Harrod-neutral or labor augmenting technical progress. It should be noted that the

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[2] A production function is called homogenous of degree *r*, if multiplying all production factors by a constant scalar leads λ to an increase of the function by λ^r:

$$Y = f(K,L)$$
$$\lambda^r Y = f(\lambda K, \lambda L)$$

If $r = 1$, the production function is called linearly homogenous and leads to constant returns of scale.

exogenously specified labor growth rate $growv_t$ is only a potential growth rate, the real GDP growth rate is calculated endogenously by the model. The purpose of the calibration routine described in Section 4 is to adjust the labor growth rates $growv_t$ in such a way that a user-specified GDP growth rate (input parameter tm_gr) is matched.

The capital dynamics equations (5) describes the capital stock in the current period K_{t+1} based on the capital stock in the previous period and on investments made in the current and the previous period. Depreciation leads to a reduction of the capital. This effect is taken into account by the capital survival factor $tsrv_t$. It describes the share of the capital or investment in period t that still exists in period $t+1$. It is derived from the depreciation rate $depr$ using the following expression:

$$tsrv_t = (1 - depr)^{\frac{(d_{t+1} + d_t)}{2}} \tag{8}$$

Expression (8) calculates the capital survival factor for a period of years beginning with the end of the middle year m_t and ending with the end of the year m_{t+1}. The duration between these two middle years equals the duration $\frac{d_{t+1} + d_t}{2}$. Then, a mean investment in period t is calculated by weighting the investments in t and $t+1$ with the respective period duration: $1/2(d_t \cdot tsrv \cdot INV_t + d_{t+1} \cdot INV_{t+1})$.

For the first period it is assumed that the capital stock grows with the labor growth rate of the first period $growv_0$. Thus, the investment has to cover this growth rate plus the depreciation of capital. Since the initial capital stock is given and the depreciation and growth rates are exogenously, the investment in the first period can be calculated beforehand:

$$INV_0 = K_0 \cdot (depr + growv_0) \tag{9}$$

Since the model horizon is finite, one has to ensure that the capital stock is not fully exhausted which would maximize the utility in the model horizon. Therefore a terminal condition (6) is added, which guarantees, that also after the end of the model horizon a capital stock for the following generations exists. It is assumed that the capital stock grows with the labor growth rate $growv_T$. This is coherent with the last term of the utility function.

2.2. Linkage of the TIMES and MACRO model

As shown in Figure 1 the TIMES model and the MACRO model are connected by two flows of information: the annual energy costs calculated by the TIMES model are passed to the MACRO model, whereas in the opposite direction the demand for energy determined by the MACRO model is given as input information to the TIMES model. Eqn. (10) links the MACRO energy demand $DEM\_M_{t,dm}$ with the energy demand $DEM\_T_{t,dm}$ in the TIMES model.

$$DEM\_T_{t,dm} = aeeifac_{t,dm} \cdot DEM\_M_{t,dm} \tag{10}$$

The energy demand effective in the TIMES model can be lower than the energy requirement of the MACRO model due to demand reductions, which are caused by autonomous energy efficiency improvements and which are not already captured in the energy sector of the TIMES model. These efficiency improvements are captured by the autonomous energy efficiency improvement factor $aeeifac_{t,dm}$. It is determined in a calibration procedure described in Chapter 4.

The costs EC_t for covering the energy demand determined by the MACRO model are calculated by the TIMES model as costs $COST\_T_t$:

$$COST\_T_t + \frac{1}{2} qfac \sum_{p} \frac{cstinv_{t,p}}{expf_t \cdot capfy_p} \cdot XCAP_{t,p}^2 = EC_t \tag{11}$$

with

$COST\_T_t$:   annual undiscounted energy system costs of the TIMES model,

$XCAP_{t,p}$:   Penalized capacity expansion for technology p in period t exceeding a predefined tolerable expansion,

EC_t: costs for the production factor energy in the MACRO model,

$qfac$:   trigger to activate penalty term (0 for turning-off penalty, 1 for using penalty term),

$cstinv_{t,p}$:   specific annualized investment costs of technology p in period t,

$capfy_p$:   maximum level of capacity for technology p,

$expf_t$:   tolerable expansion between two periods.

To slow down the penetration a quadratic penalty term has been added on the left hand side of Eqn. (11). The variable $XCAP_{t,p}$ is the amount of capacity exceeding a predefined expansion level expressed by the expansion factor $expf_t$ and is determined by the following equation:

$$CAP_{t+1,p} \leq (1 + expf_t) \cdot CAP_{t,p} + XCAP_{t+1,p} \qquad (12)$$

with

$CAP_{t,p}$:   total installed capacity of technology p in period t.

As long as the total installed capacity in period $t+1$ is below $(1 + expf_t) \cdot CAP_{t,p}$ no penalty costs are applied. For the capacity amount $XCAP_{t+1,p}$ exceeding this tolerated capacity level penalty costs are added to the regular costs of the TIMES model in Eqn. (11).

Since the quadratic term in Eqn. (11) introduces a nonlinear term for each technology and period, it may cause solution problems for large models and is hence replaced in the current implementation of TIMES, as in MARKAL, by a linear approximation (see Section 3.3.6 for details).

2.3. Calibration of a TIMES-MACRO model

2.3.1. Initial values

Based on macroeconomic statistics the MACRO variables for the first period can be estimated. When the initial GDP, the capital-to-GDP value *kgdp*, the depreciation rate *depr* and the potential growth rate *growv* are given, the initial capital stock K_0, the initial investment I_0, the initial consumption C_0, the initial production Y_0 can be calculated. The energy demand vector of the MACRO model is set equal to the demand vector of the stand-alone TIMES model for the first period. The calculation of these initial values is described in more detail in Section 3.4.2.

2.3.2. Parameters of the production function

For the production function (Eqn. (3)) the substitution constant ρ, the capital value share *kpvs*, the level constant *akl* and the demand coefficients b_{dm} have to be provided.

The substitution constant ρ is based on the elasticity of substitution σ by the expression $\rho = 1 - 1/\sigma$. The elasticity of substitution for the production factor energy is difficult to

obtain. For Western European economies the elasticity of substitution has been estimated to be in the range of 0.2 to 0.5 /Läge 2001/. A high value indicates a higher substitution reaction to price changes, while the opposite is true for low values. Hence, /Loulou, et. al. 2004/ argue that for energy system models having a detailed representation of the end-use sectors with energy substitution and saving options, the elasticity of substitution should be in the lower range, while for models with a limited representation of the end-use sectors the flexibility to substitute energy by the aggregate and labor should be higher, which is expressed by a larger value for the elasticity of substitution.

With the partial derivative of the production function with respect to the energy demands dm the demand coefficients b_{dm} can be estimated by solving the partial derivates for the b_{dm} coefficients:

$$\frac{\partial VAR\_Y_t}{\partial VAR\_D_{t,dm}}\bigg|_{t=0} = pref_{0,dm} = \left(\frac{Y_0}{DEM\_M_{0,dm}}\right)^{1-\rho} b_{dm} \tag{13}$$

The prices $pref_{0,dm}$ are obtained from a stand-alone TIMES model run as the undiscounted shadow prices of the demand commodities in the first period. Since the first period(s) are usually used for calibrating the energy system model, the shadow prices in these periods are usually degenerated due to an overdetermined equation system. Therefore, it is advised to take the shadow prices of a following undisturbed period. After the calculation of b_{dm}, the level constant akl can be computed from the production function for the initial period.

2.3.3. Calibration routine

The purpose of the calibration routine is twofold. First, it should determine the autonomous energy efficiency improvement factor $aeeifac_{t,dm}$ of Eqn. (10) in such a way that the values of the TIMES demand variables $DEM\_T_{r,t,dm}$ match the exogenously specified demand parameters $com\_proj_{t,dm}$ of the stand-alone TIMES model. As a result of this calibration step the results in the energy system part of the linked TIMES-MACRO model are identical to the ones when running the stand-alone TIMES model. Secondly, the calibration routine should calculate the labor growth rates $growv_t$ such that user-specified GDP growth rates tm_gr are matched.

3. Reference Guide for TIMES-MACRO

This chapter serves as reference guide for TIMES-MACRO. It gives an overview of the user input parameters (Section 3.1.1) for building a as well as internal parameters of the GAMS implementation (Section 3.1.2). Then the equations and associated variables (Section 3.2, 3.3) of the MACRO model are presented. Details on the derivation of some coefficients of the MACRO equations (Section 3.4), information on bounds and starting values for the MACRO variables (Section 3.5) as well as an overview of the reporting parameters (Section 3.6) are also given.

3.1. Parameters of the TIMES MACRO model

In this chapter the parameters used in the MACRO model are described. One can distinguish between user-input parameters, which are provided by the user, and internal parameters, which are derived internally based on the user-input parameters within the GAMS code of the MACRO module. The utility discount factors in the objective function are an example for internal parameters.

To distinguish the parameters relevant for the MACRO model from the parameters of the TIMES model, the MACRO related parameters have the suffix "$tm\_$". The MACRO parameters also have a regional index, although the current implementation does not work for multi-regional models[3]. The regional index was however added for programming reasons, since almost every parameter in TIMES is assigned to a region.

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[3] If the current TIMES-MACRO model is run with a multi-regional model, the sum of the utility of all regions will be maximized. The equations of the MACRO model will be generated for each region. No trade will be considered.

3.1.1. User-input parameters

The following Table 1 lists the possible user-input parameters. If not stated otherwise, all these parameters have to be provided by the user to run a TIMES-MACRO model properly. The following indexes are used in the index domain of the parameters:

- r: region,
- t: period/milestoneyear,
- dm: demand commodity,
- p: process.

Table 1: TIMES-MACRO user-input parameters

Input parameter (Indexes)[4]	Related parameters[5]	Units / Ranges & Default values & Default inter-/extrapolation[6]	Instances[7] (Required / Omit / Special conditions)	Description	Affected equations or variables[8]
tm_ddatpref (r,dm)		• TIMES cost unit/TIMES demand unit • [open]; default value: none • Default i/e[9]: none	• Determined by TIMES model run without MACRO; otherwise it has to be provided by the user. • Provided for each demand commodity.	Shadow price of demand commodity *dm* in first period.	•

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

[5] 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.

[6] 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.

[7] 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.

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

[9] Abbreviation i/e = inter-/extrapolation

Input parameter (Indexes)[4]	Related parameters[5]	Units / Ranges & Default values & Default inter-/extrapolation[6]	Instances[7] (Required / Omit / Special conditions)	Description	Affected equations or variables[8]
tm_ddf (r,t,dm)	tm_aaeifac, tm_aaeiv	• Percent • [(-100) – (+100)]; default value: none • Default i/e: none	• Determined in calibration routine; otherwise it has to be provided by the user. • Provided for each demand commodity.	Demand decoupling factor for demand *dm* in period *t*.	• EQ_DD
tm_depr (r)	tm_fact, tm_dfactcurr	• Percent • [0-100]; default value: none • Default i/e: none	• Typically choosen to be equal or near the discount rate g_drate in TIMES	Depreciation rate.	• EQ_TMC
tm_dmtol (r)		• Fraction • [0-1]; default value: none • Default i/e: none	•	Provides lower bound on the demand variable.	•
tm_ec0 (r)	tm_y0	• MACRO cost units • [open]; default value: none • Default i/e: none	•	Annual energy system costs in first period expressed in MACRO cost units.	•
tm_esub (r)	tm_rho	• Fraction • [0-1]; default value: none • Default i/e: none	•	Elasticity of substitution (typically between 0.2 and 0.5).	• EQ_UTIL

Input parameter (Indexes)[4]	Related parameters[5]	Units / Ranges & Default values & Default inter-/extrapolation[6]	Instances[7] (Required / Omit / Special conditions)	Description	Affected equations or variables[8]
tm_expbnd (r,t,p)	tm_captb	• Units of capacity • [open]; default value: none • Default i/e: none	• To be provided when the market penetration penalty function should be used.	Maximum expansion bound for capacity; used for the cumulated capacity bound tm_captb, above which the penalty is to be applied for new investments in a technology.	• EQ_COSTNRG
tm_expf (r,t)		• Percent • [0-100]; default value: none • Default i/e: none	• To be provided when the market penetration penalty function should be used. • Internally converted from annual percentage values to period-wise fractions.	Allowed annual capacity expansion factor.	• EQ_COSTNRG • EQ_MPEN
tm_gdp0 (r)	tm_k0, tm_y0	• MACRO cost units • [open]; default value: none • Default i/e: none	•	Gross domestic product in first period.	•
tm_gr (r,t)	tm_growv	• Percent • [open]; default value: none • Default i/e: none	• It holds the user-defined GDP growth rate and is constant during the calibration procedure, whereas the parameter tm_growv is adjusted throughout the calibration procedure.	Projected annual GDP growth in period *t*.	•

Input parameter (Indexes)[4]	Related parameters[5]	Units / Ranges & Default values & Default inter-/extrapolation[6]	Instances[7] (Required / Omit / Special conditions)	Description	Affected equations or variables[8]
tm_growv (r,t)	tm_l, tm_growv	• Percent • [open]; default value: none • Default i/e: none	• The labor growth rate is adjusted in the calibration procedure such that the GDP growth calculated by TIMES-MACRO matches the user-defined growth rate tm_gr.	Annual labor growth rate in period *t*.	• EQ_TMC
tm_ivetol (r)		• Fraction • [0-1]; default value: none • Default i/e: none	•	Used as upper bound on the investment and energy in equation EQ_IVECBND; also provides lower bound for the capital variable.	• EQ_IVECBND
tm_kgdp (r)	tm_dfactcurr	• Fraction • [Open]; default value: none • Default i/e: none	•	Capital-to-GDP value in first period.	•
tm_kpvs (r)	tm_dfactcurr	• Fraction • [Open]; default value: none • Default i/e: none	•	Share of capital in the sum of all production factors in first period.	•
tm_qfac (r)		• Switch • [0 or 1]; default value: 0 • Default i/e: none	• If a value of 1 is provided, the market penetration cost penalty function is applied.	Switch for market penetration penalty function.	• EQ_COSTNRG

Input parameter (Indexes)[4]	Related parameters[5]	Units / Ranges & Default values & Default inter-/extrapolation[6]	Instances[7] (Required / Omit / Special conditions)	Description	Affected equations or variables[8]
tm_scale_util		• Fraction • [0.001 or 1]; default value: none • Default i/e: none	•	Utility scaling parameter and indicator.	• EQ_UTIL
tm_scale_cst		• MACRO cost unit/TIMES cost unit • [open]; default value: none • Default i/e: none	•	Cost scaling parameter from TIMES costs to MACRO costs.	•
tm_scale_nrg		• MACRO demand unit/TIMES demand unit • [0.001 or 1]; default value: none • Default i/e: none	•	Demand scaling parameter from TIMES demand commodity units to MACRO demand units.	•

3.1.2. Internal parameters

The internal parameters, which are calculated internally within the MACRO module of the TIMES-MACRO model, are listed in Table 2.

Table 2:   TIMES-MACRO internal parameters

Input parameter (Indexes)	Related parameters	Units / Ranges & Default values & Default inter-/extrapolation	Instances (Required / Omit / Special conditions)	Description	Affected equations or variables
par_gdp (r,t)		• MACRO cost units • [open]; default value: none • Default i/e: none	• Result parameter.	Result parameter for GDP.	•
par_grgdp (r,t)		• Percent • [open]; default value: none • Default i/e: none	• Result parameter.	Annual GDP growth rate.	•
par_gry (r,t)		• Percent • [open]; default value: none • Default i/e: none	• Result parameter.	Annual growth rate for production.	•
par_mc (r,t,dm)		• TIMES cost unit/TIMES demand unit • [open]; default value: none • Default i/e: none	• Result parameter.	Undiscounted marginal cost for demand commodity.	•

Input parameter (Indexes)	Related parameters	Units / Ranges & Default values & Default inter-/extrapolation	Instances (Required / Omit / Special conditions)	Description	Affected equations or variables
par_y (r,t)		• MACRO cost unit • [open]; default value: none • Default i/e: none	• Result parameter.	Annual production.	•
tm_adder (r,t,dm)		• TIMES demand units • [open]; default value: none • Default i/e: none	•	Demand decoupling adder.	• EQ_DD
tm_aeeifac (r,t,dm)	tm_aeeiv	• TIMES demand units/MACRO demand units • [open]; default value: none • Default i/e: none	•	Period-wise autonomous energy efficiency and demand coupling factor.	• EQ_DD
tm_aeeiv (r,t,dm)	tm_aeeifac	• TIMES demand units/MACRO demand units • [open]; default value: none • Default i/e: none	•	Annual autonomous energy efficiency and demand coupling factor.	• EQ_DD
tm_akl (r)	tm_b	• Fraction • [open]; default value: none • Default i/e: none	•	Production function constant.	• EQ_UTIL
tm_asrv (r,t)	tm_tsrv	• Fraction • [open]; default value: none • Default i/e: none	•	Annual capital survival factor.	•

Input parameter (Indexes)	Related parameters	Units / Ranges & Default values & Default inter-/extrapolation	Instances (Required / Omit / Special conditions)	Description	Affected equations or variables
tm_b (r,dm)	tm_akl	• Fraction • [open]; default value: none • Default i/e: none	•	Coefficient of energy demand variable in production function.	• EQ_UTIL
tm_c0 (r)		• MACRO demand units • [open]; default value: none • Default i/e: none	•	Consumption in first period.	•
tm_cap (r,p)		• Capacity units • [open]; default value: none • Default i/e: none	•	Upper bound parameter for market penetration variables $VAR\_XCAPP_{r,t,p}$, $VAR\_XCAPP1_{r,t,p}$.	•
tm_captb (r,p)	tm_expbnd	• Capacity units • [open]; default value: none • Default i/e: none	•	Cumulative quadratic capacity level for process p beyond which the penalty function is applied.	• EQ_COSTNRG
tm_cstinv (r,t,t,p)		• TIMES cost unit/Capacity unit • [open]; default value: none • Default i/e: none	•	Annualized investment costs of process p in period t.	• EQ_COSTNRG
tm_d0 (r,dm)		• MACRO demand unit • [open]; default value: none • Default i/e: none	•	Energy demand in first period.	•

Input parameter (Indexes)	Related parameters	Units / Ranges & Default values & Default inter-/extrapolation	Instances (Required / Omit / Special conditions)	Description	Affected equations or variables
tm_ddf_dm (r,t,dm)		• Fraction • [open]; default value: none • Default i/e: none	• Used in the demand calibration of a TIMES-MACRO model.	Exogenous energy demand of TIMES model (com_proj) normalized to demand in first period.	• EQ_DD
tm_ddf_mc (r,t,dm)		• TIMES cost unit/TIMES demand units • [open]; default value: none • Default i/e: none	• Used in the demand calibration of a TIMES-MACRO model.	Undiscounted shadow price of demand commodities *dm* in period *t*.	• EQ_DD
tm_ddf_pref (r,dm)	tm_ddf_mc	• TIMES cost unit/TIMES demand units • [open]; default value: none • Default i/e: none	• Used in the demand calibration of a TIMES-MACRO model.	Undiscounted shadow price of demand commodities *dm* in first period.	• EQ_DD
tm_ddf_sp (r,t,dm)	tm_ddf_mc	• Fraction • [open]; default value: none • Default i/e: none	• Used in the demand calibration of a TIMES-MACRO model.	Undiscounted shadow price of demand commodities *dm* normalized to demand in first period.	• EQ_DD
tm_ddf_y (r,t,dm)	tm_yr	• Fraction • [open]; default value: none • Default i/e: none	• Used in the demand calibration of a TIMES-MACRO model.	Period-wise production growth rate based on $tm\_yr_{r,t}$.	• EQ_DD

Input parameter (Indexes)	Related parameters	Units / Ranges & Default values & Default inter-/extrapolation	Instances (Required / Omit / Special conditions)	Description	Affected equations or variables
tm_dfact (r,t)	tm_dfactcurr	• Fraction • [open]; default value: none • Default i/e: none	•	Period-wise utility discount factor.	• EQ_UTIL
tm_dfactcurr (r,t)	tm_dfact	• Fraction • [open]; default value: none • Default i/e: none	•	Annual utility discount factor.	• EQ_UTIL
tm_growvn (r,t)		• Fraction • [open]; default value: none • Default i/e: none	• Used in the calibration of a TIMES-MACRO model.	New calculated GDP growth from the results of a TIMES-MACRO run.	•
tm_iv0 (r)		• MACRO cost unit • [open]; default value: none • Default i/e: none	•	Investment in capital stock in first period.	•
tm_k0 (r)		• MACRO cost unit • [open]; default value: none • Default i/e: none	•	Capital stock in first period.	•
tm_l (r,t)	tm_growv	• Fraction • [open]; default value: none • Default i/e: none	•	Annual labor index in period *t*.	•
tm_rho (r)	tm_esub	• Fraction • [open]; default value: none • Default i/e: none	•	Substitution constant.	•

Input parameter (Indexes)	Related parameters	Units / Ranges & Default values & Default inter-/extrapolation	Instances (Required / Omit / Special conditions)	Description	Affected equations or variables
tm_tsrv (r,t)	tm_asrv	• Fraction • [open]; default value: none • Default i/e: none	•	Period-wise capital survival factor.	•
tm_y0 (r)		• MACRO cost unit • [open]; default value: none • Default i/e: none	•	Annual production in first period.	• EQ_IVECBND
tm_yr (r,t,dm)	tm_ddf_y	• Fraction • [open]; default value: none • Default i/e: none	•	Annual production growth rate.	•

3.2.   Variables of the TIMES MACRO model

In the MACRO module additional variables to the ones of the TIMES model are used. These variables are listed in Table 3.

Table 3:   TIMES-MACRO variables

Variable (Indexes)	Variable description
VAR_UTIL	Utility variable to be maximized
VAR_C (r,t)	Annual consumption in period t
VAR_D (r,t,dm)	Annual energy demand in MACRO for commodity c in period t
VAR_Y (r,t)	Annual production in period t
VAR_INV (r,t)	Annual investments in period t
VAR_EC (r,t)	Annual energy cost in period t in the MACRO model
VAR_K (r,t)	Total capital in period t
VAR_DEM (r,t,c)	Annual demand in TIMES for demand commodity c in period t
VAR_OBJCOST (r,t)	Annual energy system cost in year t in the TIMES model
VAR_SP (r,t,dm)	Artificial variable for calculation marginal costs of demand commodities
VAR_XCAP (r,t,p)	Market penetration bound variables
VAR_XCAPP (r,t,p)	Market penetration bound variables
VAR_XCAPP1 (r,t,p)	Market penetration bound variables
VAR_XCAPP2 (r,t,p)	Market penetration bound variables

3.3. Equations of the MACRO model

In the following the equations of the MACRO model and the equations needed to link the TIMES and MACRO model are presented in detail. Table 4 gives an overview of the equations of the MACRO model.

Table 4: Equations of the MACRO model

Equation (Indexes)	Equation description	Document section
EQ_UTIL	Utility function	3.3.1
EQ_MCAP (r,t)	Capital dynamics equation	3.3.2
EQ_TMC (r,t)	Terminal condition for investments in last period	3.3.3
EQ_DD (r,t,c)	Demand decoupling equation	3.3.4
EQ_IVECBND (r,t)	Bound on the sum of investment and energy	3.3.5
EQ_COSTNRG (r,t)	Annual cost of energy	3.3.6
EQ_MPEN (r,t,p)	Variable definition for market penetration cost penalty function	3.3.7
EQ_XCAPBD (r,t,p)	Defines the capacity part, to which the market penetration cost penalty function is applied, as the sum of three variables, which have in the penalty function increasing cost coefficients	3.3.8

3.3.1. Objective function

The optimization goal in the economy is the maximization of the utility VAR_UTIL.

$$Max \ \ VAR\_UTIL \tag{14}$$

Definition of utility

The utility is defined as the discounted sum of the consumption $VAR\_C_{r,t}$ of the households:

EQ_UTIL

$$\frac{VAR\_UTIL}{scale\_fac} = \sum_{r,t} \left(tm\_dfact_{r,t} \cdot \log VAR\_C_{r,t} \right) \tag{15}$$

$$\begin{array}{l} scale\_fac = 1000 \text{ if } tm\_scale\_util = 0.001 \\ scale\_fac = 1000 \cdot \log 1000 \text{ if } tm\_scale\_util = 1 \end{array} \tag{16}$$

with the utility discount factor $tm\_dfact_{r,t}$. The calculation of the utility discount factor is described in Section 3.4.1.

The MACRO model describes a one-sectoral and one-regional economy. The relationship between production $VAR\_Y_{r,t}$ and the input factors capital $VAR\_K_{r,t}$, labor $tm\_l_{r,t}$ and energy demand $VAR\_D_{r,t,c}$ is described by the CES (constant elasticity of substitution) production function (14):

$$VAR\_Y_{r,t} = \left(tm\_akl_r \cdot VAR\_K_{r,t}^{tm\_kpvs_r \cdot tm\_rho_r} \cdot tm\_l_{r,t}^{(1-tm\_rho_r) \cdot tm\_kpvs_r} + \sum_{dm} tm\_b_{r,dm} \cdot VAR\_D_{r,t,dm}^{tm\_rho_r} \right)^{1/tm\_rho_r} \tag{17}$$

with

tm_akl_r :   production function constant,

tm_kpvs_r capital value share,

tm_rho_r :   substitution constant,

$tm\_l_{r,t}$:   annual labor index in period t,

$tm\_b_{r,dm}$:   demand coefficient.

The production input factors labor $l_{r,t}$ and capital $VAR\_K_{r,t}$ form an aggregate, in which both can be substituted by each other represented by a Cobb-Douglas function. Then, the aggregate of the energy services and the aggregate of capital and labor can substitute each other.

The production function level constant tm_akl_r and the demand coefficients $tm\_b_{r,dm}$ are calculated based on the results of a stand-alone TIMES model run. Their calculation is described in Section 3.4.3. The capital value share tm_kpvs_r describes the share of capital in the sum of all production factors and has to be specified by the user. For OECD economies, tm_kpvs_r typically lies in the range from 0.2 to 0.3. The substitution constant tm_rho_r is based on the elasticity of substitution tm_esub_r in the following way:

$$tm\_rho_r = 1 - \frac{1}{tm\_esub_r} \qquad (18)$$

The input factor labor is exogenously specified as an efficiency indicator being 1 in the first period and increasing with the potential growth rate $tm\_growv_{r,t}$:

$$tm\_l_{r,0} = 1 \quad \text{and} \quad tm\_l_{r,t+1} = tm\_l_{r,t} \cdot \left(1 + tm\_growv_{r,t}\right)^{\frac{d_t + d_{t+1}}{2}} \qquad (19)$$

with
$d_t:$ duration of period t in years.

The households can use the output $VAR\_Y_{r,t}$ for consumption $VAR\_C_{r,t}$ in the current period or for investments $VAR\_INV_{r,t}$, which lead to higher consumption in future periods. In addition, the households have to cover the energy costs $VAR\_EC_{r,t}$ for the energy consumed in the production function. The usage of the annual output is therefore described by the following equation:

$$VAR\_Y_{r,t} = VAR\_C_{r,t} + VAR\_INV_{r,t} + VAR\_EC_{r,t} \qquad (20)$$

With equations (14) and (17) the annual consumption is described by the following equation:

$$VAR\_C_{r,t} =$$

$$\left[\begin{array}{l} tm\_akl_{r,t} \cdot \left(VAR\_K_{r,t}^{\,(tm\_kpvs_r \cdot tm\_rho_r)} \cdot tm\_l_{r,t}^{\,(1-tm\_kpvs_r) \cdot tm\_rho_r} \right) \\ + \\ \sum_{dm} \left(tm\_b_{r,dm} \times VAR\_D_{r,t,dm}^{\,tm\_rho_r} \right) \end{array} \right]^{1/tm\_rho_r} - VAR\_INV_{r,t} - VAR\_EC_{r,t} \quad (21)$$

This term is inserted into Eqn. (15) to define the annual utility. Thus, the only non-linear equation of the TIMES-MACRO model is the objective function.

3.3.2. Capital dynamics equation

The capital dynamics equations describes the capital stock in the current period $VAR\_K_{r,t+1}$ based on the capital stock in the previous period and on investments made in the current and the previous period.

$EQ\_MCAP_{r,t+1} \ \forall \ t \in 1..T-1$

$$VAR\_K_{r,t+1} = tm\_tsrv_{r,t} \cdot VAR\_K_{r,t} + \frac{1}{2}\left(d_t \cdot tm\_tsrv_r \cdot VAR\_INV_{r,t} + d_{t+1} \cdot VAR\_INV_{r,t+1} \right) \qquad (22)$$

The capital survival factor $tm\_tsrv_{r,t}$ describes the share of the capital or investment in period t that still exists in period $t+1$. It is calculated from the depreciation rate tm_depr_r using the following expressions:

$$tm\_asrv_r = 1 - \frac{tm\_depr_r}{100} \qquad (23)$$

$$tm\_tsrv_{r,t} = tm\_asrv_r^{\frac{(d_{t+1}+d_t)}{2}} \qquad (24)$$

The term (23) corresponds to an annual capital survival factor, while term (24) calculates the capital survival factor for a period of years beginning with the end of the middle year m_t and ending with the end of the year m_{t+1}. The duration between these two middle years equals the duration $\frac{d_{t+1}+d_t}{2}$. Then, a mean investment in period t is calculated by weighting the investments in t and $t+1$ with the respective period duration $1/2\left(d_t \cdot tm\_tsrv_r \cdot VAR\_INV_{r,t} + d_{t+1} \cdot VAR\_INV_{r,t+1} \right)$.

For the first period it is assumed that the investment covers the depreciation of capital stock plus the growth rate (25). Since the initial capital stock is given and the depreciation and growth rates are exogenously, the investment in the first period can be calculated beforehand and is therefore implemented as parameter (26).

$$VAR\_INV_{r,0} = VAR\_K_{r,0} \cdot \left(tm\_depr_r + tm\_growv_{r,0} \right) \qquad (25)$$

$$tm\_iv0_r = tm\_k0_r \cdot \left(tm\_depr_r + tm\_growv_{r,t1} \right) \qquad (26)$$

3.3.3. Terminal condition for investment in last period

Since the model horizon is finite, one has to ensure that the capital stock is not fully exhausted which would maximize the utility in the model horizon. Therefore a terminal condition Eqn. (27) is added that guarantees that also after the end of the model horizon a capital stock for the following generations exists. It is assumed that the capital stock grows with the labor growth rate $growv_{r,T}$, which means that the investment has been high enough to cover this growth as well as the depreciation of the existing capital stock.

$EQ\_TMC_{r,T}$

$$VAR\_K_{r,T} \cdot \left(tm\_growv_{r,T} + tm\_depr_r\right) \Big/ 100 \quad \leq \quad VAR\_INV_{r,T} \qquad (27)$$

3.3.4. Demand decoupling equation

The demand decoupling equation links for each demand commodity the energy demand of the MACRO model $VAR\_D_{r,t,dm}$ with the energy demand $VAR\_DEM_{r,t,dm}$ entering the TIMES model. Thus, the TIMES demand parameter $COM\_PROJ_{r,t,dm}$, by which the energy demand is exogenously specified in a stand-alone TIMES model, is replaced by the demand variable $VAR\_DEM_{r,t,dm}$. The factor $tm\_aeeifac_{r,t,dm}$ allows for demand reductions, which are caused by autonomous energy efficiency improvements and which are not already captured in the energy sector of the TIMES model. The period-wise factor $tm\_aeeifac_{r,t,dm}$ is based on the annual autonomous energy efficiency improvement factor $tm\_aeeiv_{r,t,dm}$ and the demand decoupling factor $tm\_ddf_{r,t,c}$ (see expressions (29) and (30)). The demand decoupling factor is determined in a calibration routine of the TIMES-MACRO model which is described in detail further below.

$$EQ\_DD_{r,t,dm} \ \forall \ t \in 1..T$$

$$VAR\_DEM_{r,t,dm} = \frac{1}{tm\_scale\_nrg} \cdot \left(tm\_aeeifac_{r,t,dm} \cdot VAR\_D_{r,t,dm} + tm\_adder_{r,t,dm} + VAR\_SP_{r,t,dm} \right)$$

(28)

$$tm\_aeeifac_{r,t+1,dm} = tm\_aeeifac_{r,t,dm} \cdot \left(1 - tm\_aeeiv_{r,t+1,dm} \right)^{\frac{d_t + d_{t+1}}{2}}$$

(29)

$$tm\_aeeiv_{r,t,c} = \frac{tm\_ddf_{r,t,c}}{100}$$

(30)

The parameter $tm\_adder_{r,t,dm}$ has been adopted from the MARKAL-MACRO formulation. It is used there to iteratively solve a MARKAL_MACRO model (so-called "Adder Procedure"). In TIMES this procedure has not been implemented yet. The variable $VAR\_SP_{r,t,dm}$ is a dummy variable, which is fixed to a value of zero. Its reduced costs are used in the calculation of the marginal costs for the demand commodities (see Chapter 3.6).

3.3.5. Bound on the sum of investment and energy

This constraint puts an upper bound on the annual investment and energy costs based on the initial production and labor growth. With the user-supplied parameter tm_ivetol_r the magnitude of the upper bound can be adjusted.

$EQ\_IVECBND_{r,t} \ \forall \ t \in 2..T$

$$VAR\_INV_{r,t} + VAR\_EC_{r,t} \leq tm\_y0_r \cdot tm\_l_{r,t}^{tm\_ivetol_r} \tag{31}$$

3.3.6. Annual cost of energy

The equation links the annual energy cost $VAR\_OBJCOST_{r,t}$ of the TIMES model with the energy costs variable $VAR\_EC_{r,t}$ of the MACRO model. The MACRO energy costs can be increased by a penalty term to dampen a too rapid penetration of technologies. In the original MACRO formulation the penalty term was the quadratic function $VAR\_XCAP^2_{r,t,p}$ with $VAR\_XCAP_{r,t,p}$ determined by equation (35) below. To keep the constrained part of the MACRO model linear (only the utility function is nonlinear) the variable $VAR\_XCAP_{r,t,p}$ is approximated by the sum of three variables ($VAR\_XCAPP1_{r,t,p}$, $VAR\_XCAPP2_{r,t,p}$, $VAR\_XCAPP3_{r,t,p}$) with an increasing cost coefficient as penalty in equation (32). These three variables are defined in equation (36) below.

$EQ\_COSTNRG_{r,t}$

$VAR\_OBJCOST_{r,t} \cdot tm\_scale\_cst$

$+$

$$\sum_{p \in rtp_{r,t,p} \wedge tm\_captb_{r,p}} \left(\begin{array}{l} \dfrac{1}{2} \cdot tm\_qfac_r \cdot tm\_cstinv_{r,t,t,p} \cdot \\[2mm] \dfrac{tm\_captb_{r,p}}{tm\_expf_{r,t}} \left(VAR\_XCAPP_{r,t,p} + 6 \cdot VAR\_XCAPP1_{r,t,p} + 12 \cdot VAR\_XCAPP2_{r,t,p} \right) \end{array} \right)$$

$=$

$VAR\_EC_{r,t}$

$$(32)$$

The expansion factor $tm\_expf_{r,t}$ describes the tolerable, normal expansion between two periods. The user gives an annual expansion factor, which is converted into a period-wise expansion factor using the following calculation routine:

$h\_expf_{r,t} := tm\_expf_{r,t}$

$$tm\_expf_{r,t} := \left(1 + \frac{h\_expf_{r,t}}{100}\right)^{\frac{d_t}{2}} \cdot \left(1 + \frac{h\_expf_{r,t+1}}{100}\right)^{\frac{d_{t+1}}{2}} \tag{33}$$

The parameter $tm\_captb_{r,p}$ gives the cumulative capacity level beyond which the penalty is applied. It is defined as the sum of the maximum expansion bounds $tm\_expbnd_{r,t,p}$ specified by the user:

$$tm\_captb_{r,p} = \sum_{t \in rtp_{r,t,p}} tm\_expbnd_{r,t,p} \tag{34}$$

The factor tm_qfac_r is used to activate the penalty cost function. When it equals its default value of zero, the penalty cost function is not used. The modeler has to specify a value greater zero to activate the penalty cost function.

The internal parameter $tm\_cstinv_{r,t,t,p}$ corresponds to the specific annualized investment costs of technology p in its construction period t.

3.3.7. Variable definition for market penetration cost penalty function

The constraint is only generated when the cost penalty function in equation (32) is activated by tm_qfac_r. The constraint decomposes the capacity expansion between two periods into two terms: the first term denotes the tolerated, normal capacity increase given by $tm\_expf_{r,t}$, while penalty costs are applied to the installation of additional capacity $VAR\_XCAP_{r,t+1,p}$.

$$EQ\_MPEN_{r,t+1,p} \quad \forall\, t \in 1..T - 1 \wedge tm\_captb_{r,p} \wedge tm\_qfac_r$$

$$VAR\_CAP_{r,t+1,p} \leq tm\_expf_{r,t} \cdot VAR\_CAP_{r,t,p} + VAR\_XCAP_{r,t+1,p} \tag{35}$$

3.3.8. Market penetration cost penalty function, quadratic approximation

This equation defines the part of the capacity increase $VAR\_XCAP_{r,t+1,p}$ to which penalty costs are applied as the sum of three variables. These three variables have increasing cost coefficients in equation (32), so that thus a quadratic cost penalty function is approximated by a linear expression. The equation is only generated when the user provides a value greater zero for the parameter tm_qfac_r.

$$EQ\_XCAPBD_{r,t,p} \quad \forall\, t \in 1..T - 1 \wedge tm\_captb_{r,p} \wedge tm\_qfac_r \tag{36}$$

$$VAR\_XCAP_{r,t+1,p} = VAR\_XCAPP_{r,t+1,p} + VAR\_XCAPP1_{r,t+1,p} + VAR\_XCAPP2_{r,t+1,p}$$

3.4. Precalculations

Several precalculations have to be done before starting a TIMES-MACRO model run. In the GAMS code these calculations are contained in the file *ppmain.tm*. In the following the different calculation steps are elaborated in more detail.

3.4.1. Utility discount factor

The annual discount factor of the utility function is calculated in the following way

$$tm\_dfactcurr_{r,t} = 1 - \left(\frac{tm\_kpvs_r}{tm\_kgdp_r} - \frac{tm\_depr_r}{100} - \frac{tm\_growv_{r,t}}{100} \right) \tag{37}$$

with

tm_kpvs_r: capital value share,

tm_kgdp_r: initial capital-to-GDP value,

tm_depr_r: depreciation rate in %,

$tm\_growv_{r,t}$: growth rate in period t in %.

The capital value share tm_kpvs_r denotes the share of capital in the sum of all production factors. The first quotient in (37) thus divides the portion of the GDP that is caused by the production factor capital by the initial capital stock tm_kgdp_r. Hence, this term can be regarded as a rate of return on capital. The other two terms in the expression in brackets in (34) express that the rate of return on capital is reduced by the depreciation of capital and by the growth in production factor labor. The depreciation rate is typically chosen to be equal or near the general discount rate *g_drate* of TIMES.

For all periods but the last one, the period-wise discount factor *tm_dfact* is expressed by

$$tm\_dfact_{r,0} = 1$$
$$tm\_dfact_{r,t} = tm\_dfact_{r,t-1} \cdot tm\_dfactcurr_{r,t-1}^{\frac{d_{t-1}+d_t}{2}} \quad \forall\, t \in 1...T-1 \tag{38}.$$

The discount factor of the last period has a larger impact. It is assumed that the utility of the last period will be valid for the infinite time horizon after the last model period leading to a larger value of the discount factor (formula uses an infinite geometric sequence $\sum_{n=0}^{\infty} q^n = 1/1 - q$):

$$tm\_dfact_{r,T} = \frac{tm\_dfact_{r,T-1} \cdot tm\_dfactcurr_{r,T-1}^{\frac{d_{T-1}+d_T}{2}}}{1 - tm\_dfactcurr_{r,T}^{\frac{d_{T-1}+d_T}{2}}}$$ (39).

3.4.2. Initial values

Since economic relationships exist between some of the quantities in the first period, not all of them have to be provided by the modeler for calibration, but are calculated using the following expressions:

$$tm\_k0_r = tm\_kgdp_r \cdot tm\_gdp0_r$$ (40)

$$tm\_iv0_r = tm\_k0_r \cdot (tm\_depr_r + tm\_growv_{r,t1})$$ (41)

$$tm\_c0_r = tm\_gdp0_r - tm\_iv0_r$$ (42)

$$tm\_y0_r = tm\_gdp0_r + tm\_ec0_r$$ (43)

$$tm\_d0_{r,dm} = tm\_scale\_nrg \cdot com\_proj_{r,0,dm}$$ (44)

It is assumed that the capital stock is increasing with the growth rate plus a compensation for the depreciation of the capital stock. This leads to the initial investments tm_iv0_r in expression (41). The initial consumption tm_c0_r equals initial GDP minus investments (see expression (42)), while production tm_y0_r equals initial GDP plus costs for energy. The initial energy demand in the MACRO model $tm\_d0_{r,dm}$ is set equal to the energy demand of the TIMES model $com\_proj_{r,0,dm}$ taking into account the scaling factor tm_scale_nrg.

3.4.3. Coefficients of the production function

The value of the substitution constant tm_rho_r is directly obtained from $tm\_rho_r = 1 - 1/tm\_esub_r$. The latter parameter, the elasticity of substitution between the production factors labor, capital and the energy aggregate, cannot be found directly, first of all because it relates to the elasticity of energy demand services, and their quantities and prices are not available from statistics, unlike final energy uses. Secondly, it is an aggregate governing the reaction of all demands to changes in their prices and thereby necessarily a compromise. It is recommended to vary tm_esub_r and analyze the results before deciding on a 'best guess'. Realistic ranges are thought to be between 0.2 and 0.5. The higher end estimates are more appropriate for models in which end-use demand sectors are modeled in TIMES with little detail and/or have limited opportunities for energy conservation or substitution. In that case the technological response to higher prices inside TIMES is relatively small, and the econometric response should contribute more to the overall demand reaction. Vice versa, if a

large number of technological response options are present in TIMES, tm_esub_r should be at the lower end so as not to overestimate the combined demand response.

The parameters $b_{r,dm}$ and tm_akl_r of the production function are calculated based on information for the first period. The partial derivative of the production $VAR\_Y_{r,0}$ with respect to the energy demand $VAR\_D_{r,0,dm}$ in the first period equals the reference price of the energy demand $tm\_ddatpref_{r,dm}$ (corrected by the scaling factors tm_scale_cst and tm_scale_nrg):

$$\left. \frac{\partial VAR\_Y_{r,t}}{\partial VAR\_D_{r,t,dm}} \right|_{t=0} = tm\_ddatpref_{r,dm} \cdot \frac{tm\_scale\_cst}{tm\_scale\_nrg} = \left(\frac{VAR\_Y_{r,0}}{VAR\_D_{r,0,dm}} \right)^{1-\rho} tm\_b_{r,dm} \tag{45}$$

Solving for $tm\_b_{r,dm}$ yields:

$$tm\_b_{r,dm} = \frac{tm\_ddatpref_{r,dm} \cdot \dfrac{tm\_scale\_cst}{tm\_scale\_nrg}}{\left(\dfrac{tm\_y0_r}{tm\_d0_{r,dm}} \right)^{1-\rho}} \tag{46}$$

The reference prices $tm\_ddatpref_{r,dm}$ are equated to the shadow prices of the demands obtained from a TIMES model run without the MACRO part. To obtain meaningful results from a TIMES-MACRO run, the evolution of the shadow prices of the demands over time of should be smooth. Sharp spikes or drops of the shadow prices in the first periods of the model may be caused by calibrating to energy statistics. One should avoid that the shadow price of one of the commodities becomes zero in one of the periods. This situation occurs when production of a commodity exceeds its demand, which may be caused by lower bounds on preceding technologies in the process chain linked to the demand commodity. Hence, in case that the demand shadow prices look ill-behaved, one should check also the commodity prices of preceding commodities in the RES linked to the demand commodity. Having identified the commodity where the perturbances occur the first time, when can check the constraints on the technologies producing the commodity, e.g. for the said lower bounds. Distortions in the shadow prices may also be caused by user constraints, e.g. quotas or market shares, which are not valid for the entire model horizon, but are introduced at a specific period. Prices may change drastically between the last period without user constraint and the first period for which the user constraint is enforced. Independently, of running TIMES-MACRO it is worthwhile to analyze the shadow prices of commodities and constraints, since they may help to identify faults in the model or to improve it. For example bounds or constraints (e.g. market shares) intended only for calibrating the first periods are by mistake kept for future periods

limiting the flexibility of the model when new policies, e.g. GHG reduction targets, are introduced.

Knowing $tm\_b_{r,dm}$ the production function constant tm_akl_r can be definite by solving the production function (11) in the initial period for tm_akl_r:

$$tm\_akl_r = \frac{tm\_y0_r{}^{tm\_rho_r} - \sum_{dm} tm\_b_{r,dm} \cdot tm\_d0_{r,dm}{}^{tm\_rho_r}}{tm\_k0_r{}^{tm\_kpvs_r \cdot tm\_rho_r}} \tag{47}$$

3.4.4. Further precalculations

These calculation expressions have already been explained above in the context of the description of the equations. Therefore, the expressions are listed here for the sake of completeness. More information on them can be found in the equation section by using the formula number in brackets as reference.

$$tm\_l_{r,t+1} = tm\_l_{r,t} \cdot \left(1 + tm\_growv_{r,t}\right)^{\frac{d_t + d_{t+1}}{2}} \tag{19}$$

$$tm\_asrv_r = 1 - \frac{tm\_depr_r}{100} \tag{23}$$

$$tm\_tsrv_{r,t} = tm\_asrv_r{}^{\frac{d_{t+1} + d_t}{2}} \tag{24}$$

$$tm\_aeeifac_{r,t+1,dm} = tm\_aeeifac_{r,t,dm} \cdot \left(1 - tm\_aeeiv_{r,t+1,dm}\right)^{\frac{d_t + d_{t+1}}{2}} \tag{29}$$

$$h\_expf_{r,t} := tm\_expf_{r,t}$$
$$tm\_expf_{r,t} := \left(1 + \frac{h\_expf_{r,t}}{100}\right)^{\frac{d_t}{2}} \cdot \left(1 + \frac{h\_expf_{r,t+1}}{100}\right)^{\frac{d_{t+1}}{2}} \tag{33}$$

$$tm\_captb_{r,p} = \sum_{t \in rtp_{r,t,p}} tm\_expbnd_{r,t,p} \tag{34}$$

3.5. Variable bounds and starting values

The energy demand, investment and capital variables are fixed to initial values, which have either been provided by the user or have been internally derived.

$$VAR\_D_{r,0,dm,FX} = tm\_d0_{r,dm} \qquad (48)$$

$$VAR\_INV_{r,0,FX} = tm\_iv0_r \qquad (49)$$

$$VAR\_K_{r,0,FX} = tm\_k0_r \qquad (50)$$

Based on the labor index growth $tm\_l_{r,t}$ starting values for the investment and capital variables are calculated with the intention to improve the performance of the solving the problem:

$$VAR\_INV_{r,t} = tm\_iv0_r \cdot tm\_l_{r,t} \qquad (51)$$

$$VAR\_K_{r,t} = tm\_k0_r \cdot tm\_l_{r,t} \qquad (52)$$

With the help of the two input parameters tm_dmtol_r and tm_ivetol_r lower bounds for the demand and capital variables are calculated to reduce the feasible domain of the optimization process (see (53), (54)). If these lower bounds should reach these lower bounds in the optimal solution, the bounds should be further reduced. If the bounds are already relatively low, this might be an indicator that there might be another problem in the input data of the model.

$$VAR\_D_{r,t,dm} \geq tm\_dmtol_r \cdot tm\_d0_{r,dm} \qquad (53)$$

$$VAR\_K_{r,t} \geq tm\_k0_r \cdot tm\_l_{r,t}^{tm\_ivetol_r} \qquad (54)$$

The dummy variable $VAR\_SP_{r,t,dm}$, which occurs in the demand decoupling equation $EQ\_DD_{r,t,dm}$, is fixed to a value of zero:

$$VAR\_SP_{r,t,dm} = 0 \qquad (55)$$

The two market penetration variables $VAR\_XCAPP_{r,t,p}$ and $VAR\_XCAPP1_{r,t,p}$, which are used in the linear approximation (36) of the cost penalty term in the demand decoupling equation, are bounded by a maximum value. This maximum value corresponds to the cumulative expansion bound beyond which the cost penalty is applied.

$$VAR\_XCAPP_{r,t,p} \leq tm\_captb_{r,p} \tag{56}$$

$$VAR\_XCAPP1_{r,t,p} \leq tm\_captb_{r,p} \tag{57}$$

3.6. TIMES-MACRO specific reporting parameters

Several parameters are calculated for reporting purposes after each TIMES-MACRO run. Some of them are also used in the calibration routine described further below.

Annual production:

$$par\_y_{r,t} = \left(tm\_akl_r \cdot VAR\_K.L_{r,t}^{tm\_kpvs_r \cdot tm\_rho_r} \cdot tm\_l_{r,t}^{(1-tm\_rho_r) \cdot tm\_kpvs_r} + \sum_{c \in dem_{r,c}} tm\_b_{r,c} \cdot VAR\_D.L_{r,c,t}^{tm\_rho_r} \right)^{1/tm\_rho_r}$$
(58)

Annual GDP:

$$par\_gdp_{r,t} = par\_y_{r,t} - VAR\_EC.L_{r,t}$$
(59)

Annual production growth rate between the periods t and t+1:

$$tm\_yr_{r,t} = 100 \cdot \left(\frac{par\_y_{r,t+1}}{par\_y_{r,t}}^{\frac{1}{(d_t+d_{t+1})/2}} - 1 \right)$$
(60)

Annual GDP growth rate between the periods t and t+1:

$$par\_grgdp_{r,t} = 100 \cdot \left(\frac{par\_grgdp_{r,t+1}}{par\_grgdp_{r,t}}^{\frac{1}{(d_t+d_{t+1})/2}} - 1 \right)$$
(61)

The marginal cost for providing the TIMES energy demand of commodity *dm* is calculated the following way[10]:

$$tm\_ddf\_mc_{r,t,dm} = -\frac{VAR\_SP.M_{r,t,dm}}{EQ\_COSTNRG.M_{r,t}} \cdot \frac{tm\_scale\_nrg}{tm\_scale\_cst}$$
(62)

The reduced costs $VAR\_SP.M_{r,t,dm}$ describe here the change in utility, when the energy demand is increased by one unit. The shadow price $EQ\_COSTNRG.M_{r,t}$ of the cost balancing equation specifies the change in utility when the costs are changed by one unit. Hence, it can be considered as a conversion factor between utility and energy system costs (which is valid, however, only for one specific solution). The two scaling factors *tm_scale_nrg* and *tm_scale_cst* are needed to convert the MACRO cost and energy units to TIMES units.

---

[10] Since the shadow price information is needed in a calibration routine of the TIMES-MACRO model (see below), which determines the so-called demand decoupling factors, the parameter name of the shadow prices for the demand commodities $tm\_ddf\_mc_{r,t,dm}$ contains the abbreviation *ddf*.

The following three calculation steps (63)-(66) are needed for the calibration routine of the TIMES-MACRO model described further below. In this calibration routine the TIMES-MACRO model is iteratively solved several times. After each model run a new labor growth rate $tm\_growvn_{r,t}$ is calculated by adjusting the previous growth rate $tm\_growv_{r,t}$ by the difference between the projected GDP growth rate $tm\_gr_{r,t}$ and the actual GDP growth rate in the model run. The projected growth rate $tm\_gr_{r,t}$ equals the growth rate $tm\_growv_{r,t}$ initially provided by the user. Since it is overwritten by calculation step (62), it is saved as parameter $tm\_gr_{r,t}$.

$$tm\_growvn_{r,t} = tm\_growv_{r,t} + tm\_gr_{r,t} - par\_gdp_{r,t} \qquad (63)$$

$$tm\_growvn_{r,T} = tm\_gr_{r,T} \qquad (64)$$

$$tm\_growv_{r,t} = tm\_growvn_{r,t} \qquad (65)$$

The annual system costs of the middle year of the first period tm_ec0_r are also updated in the calibration process:

$$tm\_ec0_r = VAR\_OBJCOST.L_{r,0} \cdot tm\_scale\_cst \qquad (66)$$

For the calibration routine some of the results are saved in the text file *ddfnew.dd*, namely, $tm\_growv_{r,t}$, $tm\_ddf\_mc_{r,t,dm}$, $tm\_yr_{r,t}$ and tm_ec0_r.

4. Calibrating a TIMES-MACRO model

The purpose of the calibration is twofold: first, it should determine the so-called demand decoupling factors $tm\_ddf_{r,t,c}$ of the demand decoupling equation (28) in such a way that the values of the TIMES demand variables $VAR\_DEM_{r,t,dm}$ match the exogenously specified demand parameters $com\_proj_{r,t,dm}$, secondly, the calibration routine should calculate the labor growth rates such that the user-specified GDP growth rates are matched. As a result of the calibration the results in the energy system part of the linked TIMES-MACRO model are identical to the ones when running the stand-alone TIMES model. This is not surprising since one goal of the calibration is to match the endogenous demand of the TIMES-MACRO model with the exogenous demand vector of the stand-alone TIMES model. The results of the calibrated model serve then as reference scenario to analyze the impacts, e.g. change in GDP, which are caused by adding policy constraints or measures not present in the reference scenario to the model.

As mentioned already in Section 3.4.3 it is utmost important to check the behavior of the shadow prices of the demand commodities. Abrupt changes of the prices between adjacent periods should be avoided. Causes for shadow prices dropping to zero have to be eliminated before entering the calibration process, since zero values will cause a division by zero error in the course of the calibration routine.

Figure 2 gives an overview of the calibration procedure. Based on the model run of a stand-alone TIMES model the calibration routine **DDFNEW0** calculates an initial set of ddf factors and marginal costs for the demand commodities. With this input information the TIMES-MACRO model is run. The reporting routine after this run (see Chapter 3.6) provides new labor growth rates, new shadow prices and the production growth rates. These parameters are used in the calibration routine **DDFNEW** to determine a new set of ddf factors $tm\_ddf_{r,t,c}$. With these new dff factors and the new labor growth rates a new TIMES-MACRO model run is started and the results are again processed in the calibration routine **DDFNEW**. This sequence of alternately running the TIMES-MACRO model and the calibration routine continues, until the demand calculated by TIMES-MACRO ($VAR\_DEM_{r,t,dm}$) sufficiently matches the exogenously specified demand ($com\_proj_{r,t,dm}$) and until the GDP growth rate determined by TIMES-MACRO ($par\_grgdp_{r,t}$) matches the user-specified GDP projection ($tm\_gr_{r,t}$). The number of iterations in the calibration routine can be flexibly adjusted by the modeler. For example, the modeler can specify first 5 iterations, inspect the solution and can then, if the routine has not converged yet, perform further calibration iterations in addition to the 5 already done.
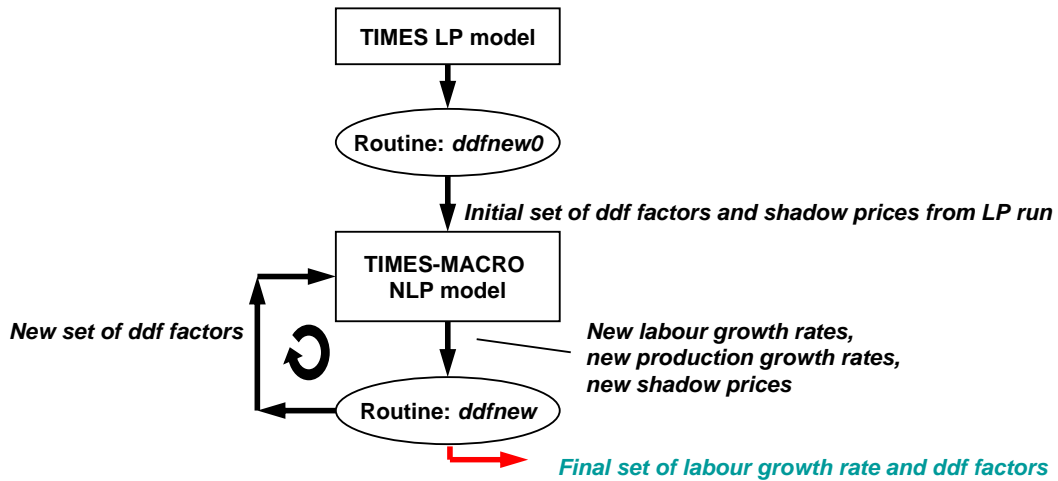
Figure 2: Overview of the calibration procedure of a TIMES-MACRO model

In the following the contents of the two calibration routines *ddfnew0* and *ddfnew* are described in more detail.

4.1. DDFNEW0

The results of a stand-alone TIMES model run serve as input for the calibration routine *ddfnew0* (technically the save/restart file of the TIMES are read by the routine). In addition, two other files are used as input for the calibration routine *ddfnew0*: the file *gr.dd*, which contains the elasticity of substitution tm_esub_r and the projected GDP growth rates tm_gr_r, and the file *macro.dd*, which contains the user-specified input parameters related to the MACRO extension (see Figure 4 below).

Based on the results of the TIMES-LP run the routine *ddfnew0* determines:
- the annual energy system costs tm_ec0_r,
- the marginal costs of the demand commodities of the first period $tm\_ddatpref_{r,dm}$
- and the ddf factors $tm\_ddf_{r,t,dm}$.

The annual undiscounted energy system costs equal the result parameter $tot\_objv_{r,0}$ of the TIMES-LP run adjusted by the cost scaling factor:

$$tm\_ec0_r = tot\_objv_{r,0} \cdot tm\_scale\_cst \tag{67}$$

The marginal costs of the demand commodities dm in the initial period are derived from the shadow prices of the commodity balances $EQG\_COMBAL.M_{r,0,dm,s}$ or $EQE\_COMBAL.M_{r,0,dm,s}$, respectively.

$$tm\_ddatpref_{r,dm} = \sum_{s \in com\_ts_{r,dm,s}} g\_yrfr_{r,s} \frac{\left(EQG\_COMBAL.M_{r,0,dm,s} + EQE\_COMBAL.M_{r,0,dm,s}\right)}{vda\_disc_{r,0}} \quad (65)$$

The first shadow price $EQG\_COMBAL.M$ is used, when the commodity balance is of type $\geq$, while the latter $EQE\_COMBAL.M$ refers to commodity balances of strict equality. $vda\_disc_{r,t}$ is an internally discount factor in TIMES converting annual undiscounted costs in period-wise discounted ones. The parameter $g\_yrfr_{r,s}$ equals the duration of the timeslice s expressed as the fraction of a year.

The normalized shadow prices for the demand commodities $tm\_ddf\_sp_{r,t,dm}$, the normalized demand $tm\_ddf\_dm_{r,t,dm}$ and the period-wise GDP growth projection $tm\_ddf\_y_{r,t}$ are calculated according to equations (69)-(72). These internal parameters are used in the estimation of the demand decoupling factors $tm\_ddf_{r,t,dm}$.

$$tm\_ddf\_sp_{r,t,dm} = \frac{\sum_{s \in com\_ts_{r,dm,s}} g\_yrfr_{r,s} \frac{\left(EQG\_COMBAL.M_{r,t,dm,s} + EQE\_COMBAL.M_{r,t,dm,s}\right)}{vda\_disc_{r,t}}}{tm\_ddatpref_{r,0,dm}} \quad (69)$$

$$tm\_ddf\_dm_{r,t,dm} = \frac{com\_proj_{r,t,dm}}{com\_proj_{r,0,dm}} \quad (70)$$

$$tm\_ddf\_y_{r,0} = 1 \quad (71)$$

$$tm\_ddf\_y_{r,t} = tm\_ddf\_y_{r,t-1} \cdot \left(1 + \frac{tm\_yr_{r,t-1}}{100}\right)^{(d_{t-1}+d_t)/2} \quad (72)$$

The demand decoupling factors are calculated according to the formulas (73) and (74). A detailed derivation of these expressions can be found in /Kypreos 1996/.

$$tm\_ddf_{r,0,dm} = 0 \quad (73)$$

$$tm\_ddf_{r,t,dm} = 100 \cdot \left\{ 1 - \left[\frac{\dfrac{tm\_ddf\_dm_{r,t,dm}}{tm\_ddf\_y_{r,t} \cdot tm\_ddf\_sp_{r,t,dm}{}^{-tm\_esub_r}}}{\dfrac{tm\_ddf\_dm_{r,t-1,dm}}{tm\_ddf\_y_{r,t-1} \cdot tm\_ddf\_sp_{r,t-1,dm}{}^{-tm\_esub_r}}} \right]^{\frac{tm\_rho_r-1}{d_{t-1}} \cdot tm\_rho_r} \right\} \tag{74}$$

The labor growth rate $tm\_growv_{r,t}$, which has to be specified exogenously in expression (19), is initially set equal to the GDP projection:

$$tm\_growv_{r,t} = tm\_gr_{r,t} \tag{75}$$

The new parameters tm_ec0_r, $tm\_growv_{r,t}$, $tm\_ddf_{r,t,dm}$ and $tm\_ddatpref_{r,dm}$ are written into the text file *ddf.dd*. This file serves as input in the following TIMES-MACRO run (see Figure 2) and contains in addition other user-input parameters needed to run TIMES-MACRO (see Table 1).

4.2. DDFNEW

The calibration routine **DDFNEW** takes the results of a previous TIMES-MACRO run to calculate a new set of demand decoupling factors $tm\_ddf_{r,t,dm}$. The results of the model run are contained in the file *ddfnew.dd* ($tm\_growv_{r,t}$, $tm\_ddf\_mc_{r,t,dm}$, $tm\_yr_{r,t}$, tm_ec0_r). In addition, the file *gr.dd*, which contains the elasticity of substitution tm_esub_r and the projected GDP growth rate tm_gr_r, is read by the calibration routine. This file has to be provided only once by the user for running a TIMES-MACRO model and is not altered in the calibration process or during the model run.

In a similar way as in the calibration routine **DDFNEW0**, the normalized period-wise GDP growth projection $tm\_ddf\_y_{r,t}$, the normalized marginal costs of the demand commodities $tm\_ddf\_sp_{r,t,dm}$ and the normalized demand projection $tm\_ddf_{r,t,dm}$ are used to calculate a new set of demand decoupling factors $tm\_ddf_{r,t,dm}$:

$$tm\_ddf\_y_{r,0} = 1 \tag{76}$$

$$tm\_ddf\_y_{r,t} = tm\_ddf\_y_{r,t-1} \cdot \left(1 + \frac{tm\_gr_{r,t-1}}{100} \right)^{(d_{t-1}+d_t)/2} \tag{77}$$

$$tm\_ddatpref_{r,dm} = tm\_ddf\_mc_{r,0,dm} \tag{78}$$

$$tm\_ddf\_sp_{r,t,dm} = \frac{tm\_ddf\_mc_{r,t,dm}}{tm\_ddatpref_{r,dm}} \tag{79}$$

$$tm\_ddf\_dm_{r,t,dm} = \frac{com\_proj_{r,t,dm}}{com\_proj_{r,0,dm}} \tag{80}$$

$$tm\_ddf_{r,0,dm} = 0 \tag{81}$$

$$tm\_ddf_{r,t,dm} = 100 \cdot \left\{ 1 - \left[\frac{\dfrac{tm\_ddf\_dm_{r,t,dm}}{tm\_ddf\_y_{r,t} \cdot tm\_ddf\_sp_{r,t,dm}^{-tm\_esub_r}}}{\dfrac{tm\_ddf\_dm_{r,t-1,dm}}{tm\_ddf\_y_{r,t-1} \cdot tm\_ddf\_sp_{r,t-1,dm}^{-tm\_esub_r}}} \right]^{\frac{tm\_rho_r - 1}{d_{t-1}} \cdot tm\_rho_r} \right\} \tag{82}$$

The resulting new demand decoupling factors and the shadow prices of the demand commodities in the first period are saved in the text file *ddf.dd*. In addition, this file contains the required input parameters needed to run TIMES-MACRO (see Table 1).

4.3.   Running the calibration routine

The calibration routine is started by calling a batch file. An example of this batch file is displayed in Figure 3. First, the TIMES model is optimized without the MACRO extension by calling GAMS with the run-file *eu25_lp.run*. Afterwards, the calibration routine *ddfnew0.gms* is executed. In the first iteration the TIMES-MACRO model is optimized by calling GAMS with the run-file *eu25_nlp.run* followed by a call of the calibration routine *ddfnew.gms*.

The output file *ddfnew.dd* and the listing file *eu25_nlp.lst* generated by the TIMES-MACRO run and the output file *ddf.dd* of the calibration routine are copied with a modified file name containing the iteration number. Thus, they can be inspected later by the modeler. The further iterations proceed in the same way. In the example in Figure 3 five calibration iterations are performed. After the last iteration, the modeler can compare in the GDX file *eu25_nlp.gdx* the demand calculated by TIMES-MACRO ($VAR\_DEM_{r,t,dm}$) with the exogenously specified demand ($com\_proj_{r,t,dm}$) as well as the GDP growth rate determined by TIMES-MACRO ($par\_grgdp_{r,t}$) with the user-specified GDP projection ($tm\_gr_{r,t}$). If both parameters sufficiently match the exogenously specified numbers, the calibration is finished. Otherwise, more calibrations steps can be performed by adding further iterations in the batch file and commenting out the previous content in the batch file.

```
* Stand-alone TIMES run
call gams eu25_lp.run gdx=eu25_lp idir1=times1.3.8 s=GAMSSAVE\_lastrun

* Calibration routine DDFNEW0
call gams ddfnew0.gms idir1=times1.3.8 r=GAMSSAVE\_lastrun

* Iteration 1
call gams eu25_nlp.run gdx=eu25_nlp idir1=times1.3.8 s=GAMSSAVE\_lastrun
call gams ddfnew.gms idir1=times1.3.8 r=GAMSSAVE\_lastrun FW=1
if exist ddf.dd copy ddf.dd ddf_1.dd
if exist ddfnew.dd copy ddfnew.dd ddfnew_1.dd
if exist eu25_nlp.lst copy eu25_nlp.lst eu25_nlp_1.lst

* Iteration 2
call gams eu25_nlp.run gdx=eu25_nlp idir1=times1.3.8 s=GAMSSAVE\_lastrun
call gams ddfnew.gms idir1=times1.3.8 r=GAMSSAVE\_lastrun FW=1
if exist ddf.dd copy ddf.dd ddf_2.dd
if exist ddfnew.dd copy ddfnew.dd ddfnew_2.dd
if exist eu25_nlp.lst copy eu25_nlp.lst eu25_nlp_2.lst

* Iteration 3
call gams eu25_nlp.run gdx=eu25_nlp idir1=times1.3.8 s=GAMSSAVE\_lastrun
call gams ddfnew.gms idir1=times1.3.8 r=GAMSSAVE\_lastrun FW=1
if exist ddf.dd copy ddf.dd ddf_3.dd
if exist ddfnew.dd copy ddfnew.dd ddfnew_3.dd
if exist eu25_nlp.lst copy eu25_nlp.lst eu25_nlp_3.lst

* Iteration 4
call gams eu25_nlp.run gdx=eu25_nlp idir1=times1.3.8 s=GAMSSAVE\_lastrun
call gams ddfnew.gms idir1=times1.3.8 r=GAMSSAVE\_lastrun FW=1
if exist ddf.dd copy ddf.dd ddf_4.dd
if exist ddfnew.dd copy ddfnew.dd ddfnew_4.dd
if exist eu25_nlp.lst copy eu25_nlp.lst eu25_nlp_4.lst

* Iteration 5
call gams eu25_nlp.run gdx=eu25_nlp idir1=times1.3.8 s=GAMSSAVE\_lastrun
call gams ddfnew.gms idir1=times1.3.8 r=GAMSSAVE\_lastrun FW=1
if exist ddf.dd copy ddf.dd ddf_5.dd
if exist ddfnew.dd copy ddfnew.dd ddfnew_5.dd
if exist eu25_nlp.lst copy eu25_nlp.lst eu25_nlp_5.lst
```

Figure 3:   Example of a batch file for calibrating a TIMES-MACRO

To run the calibration routine the modeler has to provide two files: the file *macro.dd* containing the input data needed for the MACRO model and the file *gr.dd* containing the projected GDP growth rate and the elasticity of substitution. The content of these files is shown in Figure 4 and Figure 5.

```
TM_KGDP(R)          = 2.5;
TM_KPVS(R)          = 0.25;
TM_DEPR(R)          = 5;
TM_GROWV(R,T)       = 2;
TM_GDP0(R)          = 8.629736;
TM_SCALE_UTIL       = 0.001;
TM_SCALE_CST        = 0.000001;
TM_SCALE_NRG        = 0.001;
TM_IVETOL(R)        = 0.5;
TM_DMTOL(R)         = 0.9;
```

Figure 4:   Content of the file *macro.dd*

Currently, the code is organized in such a way that the file *gr.dd* has to be in the TIMES source code directory.

```
* Elasticity of substitution
PARAMETER TM_ESUB(R)
/
EU25    0.25
/
* MACRO Projected Annual GDP Growth
PARAMETERS TM_GR(R,ALLYEAR)
/
EU25.1990       2.00
EU25.1995       2.00
EU25.2000       2.00
EU25.2005       2.00
EU25.2010       2.00
EU25.2015       2.00
EU25.2020       2.00
EU25.2025       2.00
EU25.2030       2.00
/
```

Figure 5:   Content of the file *gr.dd*

Figure 6 summarizes the structure of the calibration process. The GAMS routines or model runs are shown as rectangles, whereas the input files needed for the GAMS jobs or created by them are displayed as ellipses.
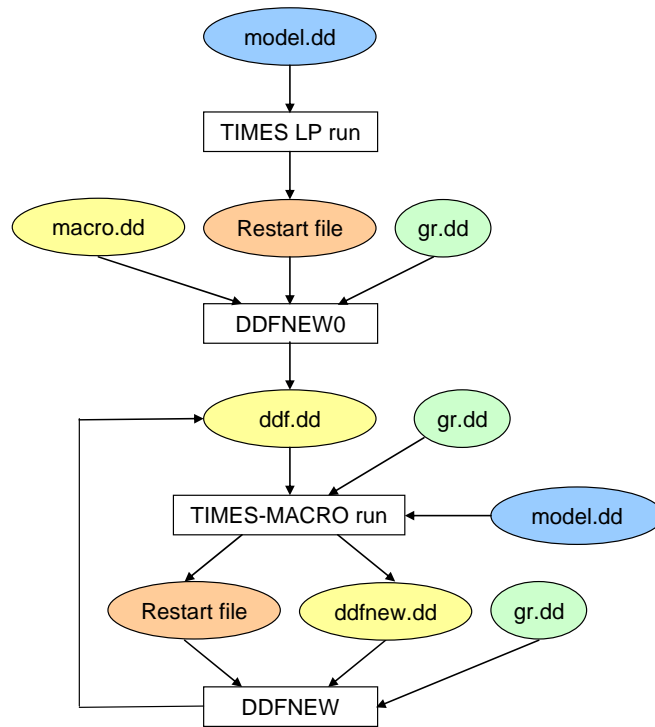
Figure 6:   File structure of the calibration process

5. Running a TIMES-MACRO model

A TIMES-MACRO model can be run in two ways: after a calibration and without any calibration. In the first case the *ddf.dd* file created by the calibration routine and the *gr.dd* file (see Figure 5) are needed. The *gr.dd* file must be located in the TIMES source code directory. If the TIMES-MACRO model should be run without using the full calibration routine, the modeler can perform only the first step of the calibration by running the TIMES-LP model and the routine **DDFNEW0**, which provides the initial shadow prices for the demand commodities together with a first estimate for the demand decoupling factors. The *ddf.dd* file created by the routine **DDFNEW0** can then be used to run the TIMES-MACRO model. Basically, in the batch file in Figure 3 the modeler only has to comment out the iteration part to run the model in this way. Alternatively, when the user does not want to use the calibration at all, the user has to create the *ddf.dd* file manually. The required contents of the *ddf.dd* file are shown in Figure 7. Generally, it is, however, recommended to use at least the calibration routine **DDFNEW0**, since it provides the user automatically with a set of shadow prices from the LP model run.

```
PARAMETERS   TM_EC0(R)
/
EU25                            1.079
/;
PARAMETERS TM_GROWV(R,T)
/
EU25      .1990                 1.612
EU25      .1995                 2.152
EU25      .2000                 1.975
EU25      .2005                 2.085
EU25      .2010                 1.941
EU25      .2015                 2.077
EU25      .2020                 1.809
EU25      .2025                 1.825
EU25      .2030                 2.000
/;
PARAMETERS TM_DDATPREF(R,C)
/
EU25      .D_COOKR       7.3370000
EU25      .D_COOLC       7.0160000
EU25      .D_COOLR       7.0570000
EU25      .D_ELCCM       6.3140000
.
.
.
/;
PARAMETERS TM_DDF(R,T,C)
/
EU25      .1990      .D_COOKR    0.0000000
EU25      .1990      .D_COOLC    0.0000000
EU25      .1990      .D_COOLR    0.0000000
EU25      .1990      .D_ELCCM    0.0000000
EU25      .1990      .D_ELCI     0.0000000
EU25      .1990      .D_ELCR     0.0000000
EU25      .1990      .D_H_I      0.0000000
EU25      .1990      .D_LTHCM    0.0000000
EU25      .1990      .D_LTHR     0.0000000
EU25      .1990      .DT_PKM     0.0000000
EU25      .1990      .DT_TKM     0.0000000
EU25      .1990      .J_GDPMB    0.0000000
EU25      .1990      .JN_GDPC    0.0000000
EU25      .1990      .JN_GDPG    0.0000000
EU25      .1990      .JN_GDPGS   0.0000000
EU25      .1990      .JN_GDPHF   0.0000000
EU25      .1990      .JN_GDPL    0.0000000
EU25      .1990      .JN_GDPN    0.0000000
EU25      .1995      .D_COOKR    2.7910422
.
.
.
/;

PARAMETERS   TM_KGDP(R)
/
EU25                            2.5000000
/;
PARAMETERS   TM_KPVS(R)
/
EU25                            0.2500000
/;
```

```
PARAMETERS  TM_DEPR(R)
/
EU25                           5.0000000
/;
PARAMETERS  TM_ESUB(R)
/
EU25                           0.2500000
/;
PARAMETERS  TM_GDP0(R)
/
EU25                           8.6297360
/;
SCALAR   TM_SCALE_UTIL
/
   0.0010000
/;
SCALAR   TM_SCALE_CST
/
   0.0000010
/;
SCALAR   TM_SCALE_NRG
/
   0.0010000
/;
PARAMETERS  TM_DMTOL(R)
/
EU25                           0.9000000
/;
PARAMETERS  TM_IVETOL(R)
/
EU25                           0.5000000
/;
```

Figure 7:   Content of the file *ddf.dd*

6. Solution issues

6.1. Reduction algorithm

When solving a TIMES-MACRO model it is recommended to use the internal reduction algorithm within TIMES. It reduces the number of equations and variables by various substitution and elimination steps. Since NLP solvers, as MINOS or CONOPT, in contrast do LP solvers do not contain a reduction algorithm, decreasing the model size already in TIMES helps to reduce the solution time of the NLP solver. The TIMES reduction algorithm in TIMES is activated by setting the dollar control switch REDUCE to YES in the run-file:

```
$ SET REDUCE        'YES'
```

6.2. Solver

One should try different NLP solvers, if available, to test which one solves the problem best. Since the only non-linear equation of the TIMES-MACRO model is the objective function, the MINOS solver, which is considered to work well with problems having few non-linear and many linear constraints, should be the first choice. One should note that two different solvers are available in MINOS: MINOS5 is the newer one, MINOS the older one. For some TIMES-MACRO models it has been observed that the older solver MINOS works better than the newer one. The solver can be set by adding the line

```
OPTION NLP = MINOS/MINOS5/CONOPT
```

in the top of the run file

6.3. Starting values

To reduce the solution time of NLP problems, it is usually helpful to provide starting values for the decision variables. By uncommenting the following two lines in the file *solve.mod*, which is found in TIMES source code directory, the results of previous model run can be used as starting values for the current run:

```
$gdxin   %RUN_NAME%.gdx
$load var_act var_flo var_ncap var_ire
```

The name of the GDX file with the result of the previous run must equal the name contained in the dollar control parameter RUN_NAME. It is specified in the run-file.

Literature

/Böhringer 1998/

Böhringer, C.: The Synthesis of Bottom-up and Top-down in Energy Policy modeling, Energy Economics 20 (1998), p. 233-248

/Böhringer and Rutherford 2005/

Böhringer, C., and Rutherford, T.F.: Integrating Bottom-Up into Top-Down: A Mixed Complementarity Approach, Discussion Paper No. 05-28, Centre for European Economic Research, 2005

/Büeler 1997/

Büeler, B. P.: Computing economic equilibria and its application to international trade of CO_2, Dissertation ETH Zürich, 1997

/Kypreos 1996/

Kypreos, S.: The MARKAL-MACRO model and the Climate Change. Paul Scherrer Institut, Department of General Energy, PSI Bericht 96-14, Villigen/Switzerland, 1996

/Läge 2001/

Läge, E.: Entwicklung des Energiesektors im Spannungsfeld von Klimaschutz und Ökonomie: Eine modellgestützte Analyse, Dissertation, Institut für Energiewirtschaft und Rationelle Energieanwendung, Universität Stuttgart, 2001.

/Loulou, et. al. 2004/

Loulou, R., Goldstein, G, Noble, K.: Documentation of the MARKAL family of models: Part II-MARKAL-MACRO, www.etsap.org, 2004

/Loulou, et. al. 2005/

Loulou, R., Remme, U., Kanudia, A., Lehtilä, A., Goldstein, G.: Documentation of the TIMES model, www.etsap.org, 2005

/Manne and Wene 1992/

Manne, A. S., and Wene, C.-O.: MARKAL-MACRO: A Linked model for Energy-Economy Analysis, Bookhaven national Laboratory, BNL-47161, 1992