ENERGY TECHNOLOGY SYSTEMS ANALYSIS PROGRAMME

TIMES Version 4.0 User Note

Residual Load Curves in TIMES

Authors:

Antti Lehtila
VTT, Finland

George Giannakidis
CRES, Greece

Kostas Tigas
CRES, Greece

Updated: May 1, 2017

Table of contents

1. Introduction

The Residual Load Curve modeling features of TIMES are intended for modelers who wish to improve the representation of non-dispatchable electricity generation in their energy system models, in particular, under a large scale penetration of intermittent renewable power supply.

In probabilistic production costing methodologies for dispatchable power plants, there is a wide use of Load Duration Curves (LDCs) or Equivalent Load Duration Curves (ELDCs) which are the basis of the relevant expansion planning methodologies. For large penetration of non-dispatchable electricity plants (wind, pv, run of river hydro and CHP) a similar methodology can be used and the essential problem to be resolved is to calculate the remaining load (residual load) for dispatchable units (thermal power and regulating hydro power).

Non-dispatchable electricity generation depends on weather and other random parameters and therefore has a strong stochastic nature. Input data required for probabilistic generation expansion planning require a thorough statistical analysis of non-dispatchable generation data combined with the relevant customer load data. Due to its nature as a long-term energy system modeling framework, TIMES is not very well suitable for stochastic generation expansion planning, but we can try to simulate the impacts of stochasticity on the system by using deterministic variation parameters that are statistically calibrated outside the model.

The new features can be useful for evaluating the impacts of the integration of large amounts of variable renewable generation on the electricity system. Such analyses could thus be utilized for giving an indication of the new investments that would be needed in various parts of the energy system under different future scenarios.

The specific residual load modeling features include the following components:

- Calculation of residual load curves by region and time period;
- Constraints ensuring that the technically imposed minimum levels of thermal generation are satisfied;
- Constraints for ensuring sufficient storage and peak capacity, taking into account the expected variations in the residual load and non-dispatchable generation.

2. MATHEMATICAL FORMULATION

2.1 Basic nomenclature

The mathematical formulations make use of a number of symbols, which are presented and briefly described in Table 1.

Table 1. Input parameters for the TIMES residual load modeling features.

Symbol	Description
L_j^{res}	Residual Load calculated in timeslice *j*
L_j^{cust}	Customer load (demand) at timeslice *j*, equal to the ratio of energy demand during timeslice *j* over the duration d_j of timeslice *j*
L_j^{exp}	Level of exported power during timeslice *j*, equal to the ratio of energy exported over the duration d_j of timeslice *j*
L_j^{loss}	Transmission power losses during timeslice *j*, equal to the ratio of energy losses over the duration d_j of timeslice *j*
L_j^{curt}	Power losses due to curtailment during timeslice *j*, equal to the ratio of energy curtailment over the duration d_j of timeslice *j*
P_j^{disp}	Level of dispatchable power output at timeslice *j*, equal to the ratio of energy produced by dispatchable units in timeslice *j* over the duration d_j of timeslice *j*
$P_j^{non\text{-}disp}$	Level of non-dispatchable power output at timeslice *j*, equal to the ratio of energy produced by non-dispatchable units in timeslice *j* over the duration d_j of timeslice *j*
$P_{j,k}^{non-disp}$	Total level of non-dispatchable power output in load category *LC*(*k*), at timeslice *j*
P_j^{wind}	Level of wind power output at timeslice *j*, equal to the ratio of energy produced by wind power in timeslice *j* over the duration d_j of timeslice *j*
P_j^{pv}	Level of PV power output at timeslice *j*, equal to the ratio of energy produced by PV in timeslice *j* over the duration d_j of timeslice *j*
P_j^{ror}	Level of run-of-river hydro power output at timeslice *j*, equal to the ratio of energy produced by run of river in timeslice *j* over the duration d_j of timeslice *j*
P_j^{chp}	Level of CHP power output at timeslice *j*, equal to the ratio of energy produced by CHP in timeslice *j* over the duration d_j of timeslice *j*
P_j^{stg}	Level of storage output at timeslice *j*, equal to the ratio of energy produced by storage in timeslice *j* over the duration d_j of timeslice *j*
P_j^{imp}	Level of imported power during time slice *j*, equal to the ratio of energy imported in timeslice j over the duration d_j of timeslice *j*
$P_j^{th\text{-}min}$	Minimum level of dispatchable thermal generation during timeslice *j*
$E_{i,j}$	Energy produced by technology *i* in time slice *j*
CAP_i	Nominal capacity of technology *i*

Symbol	Description
CAP_i^{stg}	Output capacity of storage technology *i*
$\boldsymbol{d_j}$	Duration of timeslice *j* (hours / year fraction)
$AF_{i,j}$	Maximum availability of technology *i* during timeslice j
$PAR\_THMIN_i^k$	Nominal technical minimum power level of technology *i*, according to specification method *k* (see details in next Section)
VAR_j^{res+}	Expected positive variation of residual load in timeslice *j*
VAR_j^{res-}	Expected negative variation of residual load in timeslice *j*
VAR_j^{k+}	Expected positive variation of non-dispatchable generation of type *k*

2.2 Formulation of Residual Load Equations

A summary of the RLDC equations implemented into TIMES is given below. Those marked with an asterisk **(*)** are the equations that are actually implemented in TIMES.

The total residual load in each timeslice *j* is defined as the total customer load, plus net exports and transmission losses, minus the total non-dispatchable generation. It can thus be written as follows:

$$\begin{aligned} L_j^{res} &= L_j^{cust} + L_j^{exp} + L_j^{loss} - P_j^{wind} - P_j^{pv} - P_j^{ror} - P_j^{chp} - P_j^{imp} \\ &= L_j^{cust} + L_j^{exp} + L_j^{loss} - P_j^{non\text{-}disp} - P_j^{imp} \end{aligned} \quad (1)$$

For the overall electricity load balance in each timeslice *j*, we may assume that the following equality holds:

$$P_j^{disp} + P_j^{non\text{-}disp} + P_j^{stg} + P_j^{imp} = L_j^{cust} + L_j^{stg} + L_j^{exp} + L_j^{loss} + L_j^{curt} \quad (2)$$

In the above, we have used the convention that any curtailment of intermittent renewable generation is to be included in the term $P_j^{non\text{-}disp}$ on the production side and in the term L_j^{curt} on the consumption side. From these two relations we can subsequently derive a more convenient formula for calculating the residual load in TIMES:

$$\Rightarrow \quad P_j^{non\text{-}disp} = L_j^{cust} + L_j^{stg} + L_j^{exp} + L_j^{loss} + L_j^{curt} - P_j^{disp} - P_j^{stg} - P_j^{imp} \quad (3)$$

$$\Rightarrow \quad L_j^{res} = P_j^{disp} + P_j^{stg} - L_j^{stg} - L_j^{curt} \quad (4)*$$

For the different load categories *LC(k)* corresponding to non-dispatchable generation, we can calculate the total level as follows:

$$P_{j,k}^{non-disp} = \sum_{i \in LC(k)} \frac{E_{i,j}}{d_j} \quad (5)*$$

Non-dispatchable power curtailment is usually closely related to the technical minimum of thermal power generation in the system. Therefore, we impose constraints on the thermal power generation that reflect these technical limits:

$$\frac{E_{i,j}^{th}}{d_j} \geq P_{i,j}^{th\text{-}min} \qquad \text{for each technology } i \tag{6*}$$

$$\sum_i P_{i,j}^{th\text{-}min} = P_j^{th\text{-}min} \tag{7*}$$

where:

$$\begin{aligned}
P_{i,j}^{th\text{-}min} &= PAR_THMIN_i^1 \cdot CAP_i && (PAR_THMIN_i^2 > 0) \\
P_{i,j}^{th\text{-}min} &= PAR_THMIN_i^2 && (PAR_THMIN_i^1 > 0) \\
P_{i,j}^{th\text{-}min} &= PAR_THMIN_i^3 \cdot \max_{s \in SEASON(j)} \left(\frac{E_{i,s}^{th}}{d_s} \right) && (PAR_THMIN_i^3 > 0)
\end{aligned} \tag{8*}$$

Here, $PAR\_THMIN_i^k$, k $\in\{1,2,3\}$ is an input parameter defining the minimum level of thermal generation of technology *i*, by using one of three alternative ways:

1) As a fraction of the nominal capacity
2) As an absolute minimum amount (expressed in the capacity units)
3) As a fraction of the maximum level of output in the season

Finally, we impose two capacity constraints to cope with the *variation* in the residual load. The first one defines the minimum available storage capacity in each timeslice j:

$$\sum_i AF_{i,j}^{stg} \cdot CAP_i^{stg} \geq P_j^{th\text{-}min} - (1 - VAR_j^{res-}) \cdot L_j^{res} + \sum_k VAR_j^{k+} \cdot P_{j,k}^{non-disp} \tag{9*}$$

Here $AF_{i,j}$ is an input parameter defining the availability factor of storage technology *i* by Timeslice, VAR_j^{res-} is the expected negative variation in the residual load, and VAR_j^{k+} is the expected positive variation in non-dispatchable generation of load category *k*. The categories *k* of the non-dispatchable variable generation to be considered separately can be defined by the user, and can include e.g. wind power, solar pv, and run-of-river hydro.

The second constraint defines the minimum dispatchable capacity in each timeslice j:

$$\sum_i AF_{i,j}^{disp} \cdot CAP_i^{disp} + \sum_i AF_{i,j}^{stg} \cdot CAP_i^{stg} \geq (1 + VAR_j^{res+}) \cdot L_j^{res} + \sum_k VAR_j^{k-} \cdot P_{j,k}^{non-disp} \tag{10*}$$

Here again, $AF_{i,j}$ is an input parameter defining the availability factor of technology *i* by Timeslice, VAR_j^{res+} is the expected positive variation in the residual load, and VAR_j^{k-} is the expected negative variation in non-dispatchable generation of type *k*. This equation can be considered supplementary to the peak equation, because its purpose is to ensure sufficient available peak load capacity.

2.3 Supplemental Remarks

2.3.1 Accounting Power Curtailment

Equation (9) above is meant to ensure that the system includes sufficient storage capacity, which is large enough to accommodate the power curtailment caused by any amount of $P_j^{th\text{-}min}$ being *in excess* of the residual load, or even more if non-zero variation parameters have also been specified. However, if the intermittent variable generation technologies have been modeled with upper bounds for their availability factors, power curtailment cannot actually be easily accounted in the TIMES model in a reliably way. In practice, if the thermal minimum generation would, indeed, tend to exceed the residual load, the model would be able adjust the output of non-dispatchable generation to a lower level, thereby increasing the residual load to match the thermal minimum. Therefore, if it is considered important that Equation (9) will fully ensure the indicated storage capacity, the user is suggested to use fixed availability factors for all intermittent wind and solar power.

According to Equation (9), the model would actually be prevented from optimizing between the losses due to power curtailment and investments into new storage, even with zero variation. However, if the possibility of optimizing between them should be maintained, the following alternative relaxed formulation may be suggested. First, define:

$$L_j^{res*} \;=\; L_j^{res} + L_j^{curt} \;=\; P_j^{disp} + P_j^{stg} - L_j^{stg}$$

Now, start with Equation (9) without the variation components, and add L_j^{curt} on the left hand side, in order to allow optimization between curtailment losses and storage capacity:

$$\sum_i AF_{i,j}^{stg} \cdot CAP_i^{stg} + L_j^{curt} \geq \; P_j^{th\text{-}min} - (L_j^{res*} - L_j^{curt})$$

Rearranging, and by adding the variation components back on the LHS we get:

$$\sum_i AF_{i,j}^{stg} \cdot CAP_i^{stg} \;\geq\; P_j^{th\text{-}min} - (1 - VAR_j^{res-}) \cdot L_j^{res*} + \sum_k VAR_j^{k+} \cdot P_{j,k}^{non-disp} \qquad (9)'$$

This alternative relaxed formulation has been implemented as on option in TIMES.

2.3.2 Imposing Minimum Levels of Thermal Generation

For the purposes of the Residual Load Curve equations, the minimum level of thermal generation would need to be imposed only on the aggregate level, because only the aggregate minimum level is referred to in equation (9). Therefore, in order to avoid increasing the model size by introducing a large number of process-wise constraints, one might consider imposing the constraints only at the aggregate level. Therefore, this simplified aggregate approach has also been implemented as an option into TIMES.

Using the aggregate level constraint can be usually expected to lead into total levels of dispatchable generation which is equal to those when using process-specific constraints. Only the mix of thermal generation would in such case be somewhat different in the two approaches. However, in some cases the process-specific constraints may also lead to an increase in the total level of thermal generation as compared to the aggregate approach.

3. GAMS IMPLEMENTATION

3.1 Overview

As discussed in Section 2, special facilities have been implemented into TIMES for the modeling of residual load curves in the electricity supply system. These features can be useful for analyzing the impacts of integrating large amounts of variable renewable generation on the electricity system.

3.2 Input Parameters

There are only three relevant input parameters that have been implemented for the residual load curve modeling features, and should be available for the user input in the user shell. All the new parameters have the prefix '**GR_**' in the GAMS code of the model generator. The parameters are discussed in more detail below:

1. The parameter **GR_VARGEN(r,s,lc,bd)** can be used for specifying the expected variation of load category *lc* in timeslice *s* and direction *bd* (where *bd* = lo/up).

   - The predefined load category **RL_DISP** must be used for defining the lower / upper variation for the residual load. For the load categories corresponding to non-dispatchable generation, the user can freely use any convenient category names. However, the predefined load category **RL_NDIS** can be used for all non-dispatchable generation not included in the other load categories defined for non-dispatchable generation.
   - The technologies belonging to the different load categories can be defined by using the **GR_THMIN** and **GR_GENMAP** parameters.
   - Defining at least one entry for the **GR_VARGEN** parameter is mandatory for activating the Residual Load Curve features.

2. The parameter **GR_THMIN(r,y,p)** can be used for defining the minimum level of thermal generation of process *p* in year *y*. It can be used (intermixingly) in three different ways, of which the first one mentioned below is the recommended method:

Table 2. Input parameters for the TIMES residual load curve modeling features.

Parameter	Description
GR_VARGEN(r,s,lc,bd)	Expected variation of load category *lc* in timeslice *s* and direction *bd* (*bd* = lo/up)
GR_THMIN(r,y,p)	Minimum level of thermal generation as a fraction of the nominal capacity of process *p* in year *y* (see text for options)
GR_GENMAP(r,p,lc)	Mapping of generation technology *p* to load category *lc*

- By specifying the fraction of the minimum level in timeslice *s* in proportion to the nominal capacity (valid range for **GR_THMIN** is in this case [0,1));
- By specifying the absolute level of the minimum thermal generation in timeslice *s*, in the capacity unit of the process (valid range for **GR_THMIN** is in this case [–INF,0]), such that the absolute level will be –**GR_THMIN**);
- By specifying the ratio of the maximum level of generation in the season to the minimum level of generation in the timeslice *s* (valid range for **GR_THMIN** is in this case [1,INF));

Note: The parameter **GR_THMIN** will automatically be used also for defining the processes to be included in the load category **RL_DISP**, i.e. dispatchable generation supplying the residual load. All processes that have **GR_THMIN** defined will thus be assumed in the RL_DISP load category, but additional processes can be included by using the parameter **GR_GENMAP**.

3. The parameter **GR_GENMAP(r,p,lc)** can be used for defining the mapping of generating technology p to load category *lc*, as follows:
   - The parameter should have the value 1;
   - Each generation process should be defined only into a single load category.
   - Note: This parameter is also used for in the TIMES grid modeling features for allocating generation to *unit types*, but that should not cause any problem.

See Section 4 for more details and advice on how to use the input parameters, with a concrete illustrative example.

3.3 Reporting Parameters

There are no reporting parameters related to the Residual Load modeling features at this time.

Table 3. New variables for the residual load curve modeling features in TIMES.

Variable	Description
VAR_RLD(r,t,s,lc)	The load level variables for load category *lc*, by region *r*, milestone year *t* and timeslice *s*.

3.4 Variables

There is only one sets of new variables introduced in the implementation of the residual load curve features, which is shown in Table 3. For other TIMES variables referred to in the equations, the user is referred to Chapter 4 of the TIMES Reference Manual for details on the variables of the model.

The variables **VAR_RLD(r,t,s,lc)** represent the total levels of the load in each of the load category *lc*. With *lc* = **RL-DISP**, the variables represent the residual load itself, and the with other load categories the variables represent the total levels of output in each set of non-dispatchable generation technologies (e.g. wind, solar, run-of-river, CHP), by model year and timeslice.

3.5 Equations

Below in Table 4 the six new equation sets related to the residual load curve modeling features are listed and briefly described. The equations include the defining equations for the residual load and other load categories, equations for ensuring sufficient storage and peak capacity, and the thermal minimum constraints described earlier in Section 2.2.

Note: The *bd* index in the **EQ_RL_TH*** equations is related to the option of using either the process-specific or aggregate approach for the minimum thermal generation levels.

Table 4. Equations for the residual load curve features in TIMES.

Equation	Description
EQ_RL_LOAD(r,t,s)	The equations defining the residual load in each timeslice *s*.
EQ_RL_NDIS(r,t,s,lc)	The equations calculating the level of non-dispatchable generation in load category *lc* and timeslice *s*.
EQ_RL_STCAP(r,t,s)	The equations ensuring sufficient storage capacity when the residual load is low.
EQ_RL_PKCAP(r,t,s)	The equations ensuring sufficient dispatchable generation capacity when the residual load is high.
EQ_RL_THBYP(r,t,p,s,bd)	The constraints for the minimum level of thermal generation by process *p* and timeslice *s*.
EQ_RL_THMIN(r,t,s,bd)	The equations defining the aggregate level of minimum thermal generation by timeslice *s*.

3.6 Changes in Model Generator Code

The implementation required only small modifications to the existing code and only one new component in the model generator source code. The new and modified code components are listed in Table 5.

The new source file, **resloadc.vda**, contains essentially all of the new code that has been implemented for the residual load curve modeling features. This file is automatically called from the files prep_ext.vda, coef.ext.vda and equ_ext.vda, if the parameter **GR_VARGEN** has been defined. Also the new variables and equations have been conditionally defined in this file.

Table 5. New and modified files in the TIMES model generator code.

Added file	Description
resloadc.vda	Declarations, preprocessing and equations for the RLDC features
Modified file	**Description of changes made**
initmty.vda	Declarations for the RLDC features
prep_ext.vda	Conditional calling of resloadc.vda for parameter interpolation
coef_ext.vda	Conditional calling of resloadc.vda for pre-processing
equ_ext.vda	Conditional calling of resloadc.vda for equation definitions
mod_ext.vda	Conditional additions for the model statement
*.rpt	(tbd)

4. User's Reference

4.1 Activating the Residual Load Curves

The residual load curve facility is automatically activated in TIMES whenever the **GR_VARGEN** parameter is specified for at least one load category in some region. The residual load modeling equations will be generated only for those regions that have some **GR_VARGEN** parameters specified. The equations will be generated for all projection years, i.e. for all Milestone years excluding the first one.

4.2 Defining Load Variations

The expected variations in the load levels can be defined with the **GR_VARGEN** parameter for each load category and timeslice, and for the lower and upper direction (LO/UP).

4.2.1 Load categories

The expected variation in the residual load should be specified by using the pre-defined load category **RL-DISP**. In addition, the user can define expected variations for the total outputs of any user-defined sets of non-dispatchable generation technologies, such as wind power, solar pv, and run-of-river hydro power technologies. The pre-defined load category **RL-NDIS** can additionally be used for defining the expected variations for all *other non-dispatchable generation* not included in the user-defined sets mentioned above.

The set of dispatchable generation technologies and any user-defined sets of non-dispatchable generation technologies must be defined by the user. The model generator will automatically assign all technologies that have the parameter **GR_THMIN** defined into the set of dispatchable generation technologies. Additional technologies can be included in this set by using **GR_GENMAP(r,p,'RL-DISP')** parameter entries.

For the sets of non-dispatchable generation technologies, any user-defined sets must be fully defined by the user, by using the **GR_GENMAP(r,p,lc)** parameters. However, the model generator will automatically assign all those generation technologies, which are neither in the set of dispatchable generation technologies nor in any of the user-defined sets of non-dispatchable generation technologies, into the set of *other non-dispatchable generation* (**RL-NDIS**). When defining the set members manually with the **GR_GENMAP** parameter, each generation technology should, of course, be categorized only into a single unique load category.

In summary, the names of the pre-defined load categories and the suggested names for the user-defined sets are the following:

- **RL-DISP** – residual load (predefined, dispatchable generation)
- **RL-NDIS** – residual non-dispatchable generation (pre-defined)

- **RL-WIND** – non-dispatchable wind power (user-defined)
- **RL-SOL** – non-dispatchable solar power (user-defined)
- **RL-ROR** – non-dispatchable run-of-river hydro power (user-defined)
- **RL-CHP** – non-dispatchable CHP power (user-defined)

4.2.2 Timeslices

In general, the expected load variation should be defined for all of the DAYNITE level timeslices. However, any timeslices on higher levels can be utilized as default values for the lower levels, and will be applied if no value is specified at the lower level. Therefore, one can easily, for example, define the same expected variation for all timeslices by defining the variation just for the ANNUAL timeslice.

4.2.3 Direction of variation

The variations can be specified in two directions, lower and upper (LO/UP). For the residual load, the lower variation represents the expected variation in the residual load in the downward direction, and the upper variation represents the expected variation in the upward direction. For the non-dispatchable load categories, the lower variation represents the expected variation in the total output of the category in the downward direction, and the upper variation represents the expected variation in the upward direction.

4.3 Defining Minimum Levels of Thermal Generation

As mentioned in Sections 2.2 and 3.2, the minimum level of thermal generation can be specified for each thermal technology in three alternative ways (1,2,3), which can also be used intermixingly, such that for some processes the minimum level is specified with option 1, for some other processes with option 2, and for yet some other processes with option 3.

The three alternative options for specifying the minimum level are the following:

1. By specifying the fraction of the minimum level in timeslice *s* in proportion to the nominal capacity (valid range for **GR_THMIN** is in this case [0,1));
2. By specifying the absolute level of the minimum thermal generation in timeslice *s*, in the capacity unit of the process (valid range for **GR_THMIN** is in this case [–INF,0]), such that the absolute minimum level will be –**GR_THMIN**);
3. By specifying the ratio of the maximum level of generation in the season to the minimum level of generation in the timeslice *s* (valid range for **GR_THMIN** is in this case [1,INF));

The first option is assumed to be the most commonly used method. The third option can be particularly useful if the technology can be dispatched on a seasonal basis, and may be shut down in some seasons. In such cases the minimum level of thermal generation should of course not be forced to be proportional to the capacity throughout the year.

In addition, the parameter **GR_THMIN** will be automatically utilized for defining the processes to be included in the load category **RL_DISP**, i.e. in dispatchable generation supplying the residual load. All processes that have **GR_THMIN** defined will thus be assumed to be in the **RL_DISP** load category. Additional processes can be included in this category by using the parameter **GR_GENMAP**.

4.4 Restricting periods considered for residual loads

The equations for the residual load curve representation are by default generated for all periods except the first period. However, an additional user option is available for restricting the periods to be considered for the residual load curve equations. The periods can be restricted by using the GR_VARGEN attribute, as follows:

- `GR_VARGEN(R,'ANNUAL','RL-TP',BD)` – defines the period range to be considered for residual load curves:
  - o BD=`LO`: defines the earliest period T to be considered, such that M(t) >= `GR_VARGEN(R,'ANNUAL','RL-TP','LO');`
  - o BD=`UP`: defines the latest period T to be considered, such that M(t) <= `GR_VARGEN(R,'ANNUAL','RL-TP','UP');`
  - o BD=`FX`: defines a single period to be considered, such that M(t) = `GR_VARGEN(R,'ANNUAL','RL-TP','FX').`

`'RL-TP'` is thus a reserved label for the time period ranges, which can only be used for this purpose.

4.5 Illustrative Example

Assume that we have the following generation technologies in the model:

- ECOAST – Coal condensing steam-electric
- EOILST – Oil condensing steam-electric
- EGASCC – Gas condensing combined cycle
- ENUCST – Nuclear condensing steam electric
- EPEKGT – Peak gas turbine
- EGASCHP – Gas-CHP combined cycle
- EWINON – Wind power onshore
- EWINOFF – Wind power offshore
- ESOLPV – Solar power PV
- EHYDROR – Hydro power run-of-river
- EHYDDAM – Hydro regulating power (dam)

The technical minimum levels of thermal generation can be defined by using the **GR_THMIN** parameter. Assume that the minimum level is 0.3 for coal-fired plant, 0.5 for nuclear, and 0.1 for oil and gas condensing plants, in proportion to the nominal capacity.

In addition, we have two other dispatchable technologies, EPEKGT and EHYDDAM, which must be defined as such, by using the **GR_GENMAP** parameter.

After the specifications mentioned above, the model generator will know that all the remaining technologies (wind, solar, run-of-river and CHP technologies) should be non-dispatchable technologies. However, we would like to define the variations for wind power and solar power separately. Therefore, we need to define the sets (load categories) **RL-WIND** and **RL-SOL**.

All these definitions can be accomplished with the following parameters:

Parameter	Indexes	Value	Parameter	Indexes	Value
GR_THMIN	RG.2010.ECOAST	0.3	GR_GENMAP	RG.EPEKGT.RL-DISP	1
GR_THMIN	RG.2010.EOILST	0.1	GR_GENMAP	RG.EHYDDAM.RL-DISP	1
GR_THMIN	RG.2010.EGASCC	0.1	GR_GENMAP	RG.EWINON.RL-WIND	1
GR_THMIN	RG.2010.ENUCST	0.5	GR_GENMAP	RG.EWINOFF.RL-WIND	1
			GR_GENMAP	RG.ESOLPV.RL-SOL	1

The model generator will now be able to define automatically that the remaining two technologies (EGASCHP and EHYDROR) should be in the predefined set **RL-NDIS**, which covers all unspecified non-dispatchable technologies.
Finally, we will define the expected variations for the four different load categories, by using the **GR_VARGEN** parameter. In this example we assume that the same variation may be applied to all timeslices, so that we need to specify the parameters at the ANNUAL level only. The following table shows an example specification (the numerical values for the variations are randomly chosen):

Parameter	Indexes	Value
GR_VARGEN	RG.ANNUAL.RL-DISP.LO	0.1
GR_VARGEN	RG.ANNUAL.RL-DISP.UP	0.1
GR_VARGEN	RG.ANNUAL.RL-WIND.LO	0.6
GR_VARGEN	RG.ANNUAL.RL-WIND.UP	0.3
GR_VARGEN	RG.ANNUAL.RL-SOL.LO	0.6
GR_VARGEN	RG.ANNUAL.RL-SOL.UP	0.4
GR_VARGEN	RG.ANNUAL.RL-NDIS.LO	0.05
GR_VARGEN	RG.ANNUAL.RL-NDIS.UP	0.05

4.6 Additional Options

In Section 2.3.2 it was mentioned that there is an option to relax the constraint for the storage capacity to allow optimization between power curtailment and storage in the zero variation case. This option can be activated by specifying any value X for the following parameter instance (for each region where it should be activated):

```
GR_VARGEN(r,'ANNUAL','RL-DISP','FX') = X;
```

In Section 2.3.2 it was also mentioned that there is an option to constraint the minimum thermal generation only on the aggregate level. This option can be activated for all regions by specifying any value X for the following parameter instance for any region:

```
GR_VARGEN(r,'ANNUAL','RL-THMIN','LO') = X;
```

4.7 Specification of Input Parameters

The following Table 6 lists the available user-input parameters. The **GR_VARGEN** parameter is required to be provided by the user to activate the residual load curve modeling features described here. The following indexes are used in the index domain of the parameters:

Index	Meaning	Index	Meaning
r	Region	s	Timeslice
datayear	Period / Milestone year	bd	Bound type (LO/UP)
p	Process	lc	Load category

Table 6: Input parameters for the TIMES Residual Load Modeling Features

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]
GR_VARGEN (r,s,lc,bd)	GR_GENMAP, GR_THMIN	• Dimensionless • [0, INF); default value: none • Default i/e[6]: none	• Required for each load category and timeslice for which load variations are to be accounted. • Period range to be considered can be restricted by using lc='RL-TP'.	Variation of the load in load category *lc* and timeslice *s*, as a proportion of the total load in that category, in direction *bd* (bd=lo/up)	• EQ_RL_STCAP, EQ_RL_PKCAP
GR_THMIN (r,datayear,p)	GR_VARGEN	• Relative or absolute value • (-INF, INF); default value: none • Default i/e: standard	• Required for each process to have a minimum thermal generation level defined • When specified as a fraction of nominal capacity the valid range is [0,1)	Level of minimum thermal generation of process *p* in timeslice *s*, usually as a fraction of the nominal capacity	• EQ_RL_THMIN, EQ_RL_THBYP
GR_GENMAP (r,p,lc)	GR_VARGEN	• Dimensionless • [0, 1] (usually 1); default value: none	• Required for dispatchable generation, for which GR_THMIN is not defined	Mapping of generation technologies to generation load categories.	• EQ_RL_LOAD, EQ_RL_NDIS

[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.
[6] Abbreviation i/e = inter-/extrapolation

5. REFERENCES

Chaviaropoulos, P., Rossis, K., Tentzerakis, S. & Foussekis, D. 2006. *Analysis of Wind Energy Generation Data and Development of Scenarios for the Penetration of Wind Energy into the Greek Interconnected Electricity Generation System*. Centre for Renewable Energy Sources and Energy Saving, on behalf of the Greek Regulatory Authority for Energy, CRES. WIND.RAE2A/06.

Loulou, R., Remme, U., Kanudia, A., Lehtilä, A. & Goldstein, G. 2005. *Documentation for the TIMES Model*. Energy Technology Systems Analysis Programme (ETSAP), April 2005. http://www.iea-etsap.org/web/Documentation.asp

Schenk, K.F., Misra, R.B., Vassos, S. & Wen, W. 1984. "A new Method for the Evaluation of Expected Energy Generation and Loss of Load Probability". IEEE Transactions on Power Apparatus and Systems, Vol. PAS-103, No. 2, 1984.

Tigas, K., Mantzaris, J., Giannakidis, G., Nakos, C. & Sakellaridis N. 2012. *Generation Expansion Planning under Wide-Scale RES Energy Penetration*. Energy Systems Analysis Lab. Centre for Renewable Energy Sources and Energy Saving. http://www.iea-etsap.org/web/Projects/Probabilistic%20generation%20expansion%20planning.pdf

Vassos, S., Tigas, K. & Mantzaris, J. 2009. *Probability Production Costing under wide-scale penetration of Renewable Energy Sources*. Center for Renewable Energy Sources and Energy Saving.