Energy Technology Systems Analysis Programme

Dispatching and unit commitment features in TIMES

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August 2016

Foreword

This report contains the full documentation on the implementation and application of the dispatching and unit commitment features in the TIMES modelling framework.

The report is divided into five chapters. Chapter 1 deals with the background of this extension. Chapter 2 gives an overview of unit commitment problem statement and its main features implemented in this extension. Chapter 3 includes the mathematical formulation and describes in detail the assumptions made during the design of the extension. Chapter 4 discusses the implementation of the extension in GAMS. Finally, Chapter 5 is the user's reference, presenting in detail the newly introduced input parameters and their usage.

This documentation may eventually also be inserted in the complete documentation of the TIMES model.

The authors wish to thank Dr. Uwe Remme from the International Energy Agency for providing useful material from earlier experimental work with unit commitment modelling in TIMES.

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1. INTRODUCTION

The Unit Commitment extension of TIMES is intended for modellers who wish to incorporate short-term operational decisions for power plants into long-term capacity expansion planning. For instance, the intermittency and high fluctuations of rapidly penetrated renewable energy technologies, i.e. wind and solar, requires the net load (total load minus load met by renewables) to be covered by flexible hydrothermal and storage options. In fact, the short-term operational constraints may significantly impact longer term investments. Therefore, the strategic investment decisions and the optimal roadmap of the power sector shall be also based on short-term power plant scheduling and dispatching and not only on long-term energy policies and strategic planning.

The incorporation of operational characteristics of power plants into long-term energy system models is a rather challenging task. To this end it is a common modelling practice not to consider operational constraints in large scale energy system models such as minimum stable generation levels, ramping rates, start-up costs, etc. Alternatively, current modelling practices include hybrid modelling frameworks combining long-term energy system models that optimise strategic investment decisions with short-term power and dispatch models that represent the hourly dynamics of the studied electricity system. This setting is based on an iterative process in which the strategic investment decisions made by the energy system model are verified by the short-term dispatch model. Although it may appeal computationally efficient, this approach can lead to inconsistent solutions because the investment decisions are not determined based on operational aspects of thermal units.

To overcome this shortcoming, the unit commitment extension of TIMES directly implements operational constraints of power plants into an energy system modelling framework. In this sense, this extension enables the integration of energy policy targets (e.g. CO_2 emission reduction targets, renewable energy penetration targets) and daily production scheduling. Although the literature is rich in formulating the standard Mixed Integer Programming (MIP) unit commitment problem, this formulation proved to be computationally prohibitive for the TIMES modelling framework. To this end, starting from this formulation, a number of alternative formulations were derived during this project ranging from linear basic formulation including the most common operational constraints such as minimum stable operation levels, ramping rates, minimum online/offline times and start-up/shut-down costs to more advanced linear formulations that provide the possibility of different start-up types according to the non-operational time after shutdown of a power plant and the flexibility to identify individual power plant units into TIMES.

Therefore, the aim of this extension is not merely to improve the strategic investment decisions made in the TIMES modelling framework by taking into account short-term power plant operational constraints and scheduling, but also to achieve this with the least possible overhead on the size of the model and the solution times. Although the implementation of the full set of the unit commitment features included in this extension may result in a considerable amount of additional equations, the linearized formulation adopted may still have substantially less impact on solution times. Thus the TIMES user has the option to select the set of the unit commitment features to be included into the model based on the trade-off between accuracy in the representation of the short-term operational constraints and solution times.

2. OVERVIEW OF THE INCLUDED FEATURES

Operational performances of power plants can be characterised via five general types of constraints:

1. ***Start-up time*** that represent the synchronisation of the generator to the grid frequency which are imposed in order to avoid thermal stress through extreme temperature and pressure differences within the components of a plant (in particular for classical base load power plants with attached steam cycles) and they are also affected by the non-operational time after shut-down
2. ***Ramping constraints*** describing the ability of the power plants to adjust production levels within a certain time interval, i.e. the speed of load level changes, in order also to reduce

thermal stress during the dispatching phase[1], or due to environmental regulations and electricity system requirements.

3. ***Minimum load level*** at which a power plant can be effectively operated in order to achieve a stable generation
4. ***Shut-down times*** which represent the desynchronization of the generator from the grid frequency and are also restricted by thermal stress in unit's components
5. ***Minimum online and offline times*** to sustain production and also avoid thermal stress.

Table 1 presents some indicative values of key operational constraints for selected technologies found in the literature.

Table 1: Indicative values of key operational constraints for selected technologies [1].

	Start-up time Hot/Warm/Cold	Ramping gradient %-Pn/min	Minimum load %-Pn	Minimum time Online/Offline
Nuclear	- / - / -	5-10	35-60	24-48 /24-48 h
Coal Supercritical	1 / 4 / 6 h	4-8	35-50	6-15 /6-15 h
Gas Combined Cycle	0.5-1.5 / 3 / 5 h	4-10	30-40	1-6 /1-6 h
Gas Open Cycle	<6 / 20 / 60 min	10-25	10-20	1-6 /1-6 h

The start-up constraints may be associated with start-up costs per unit of started capacity which can compose one of the following main factors: i) costs of start-up fuels, auxiliary electricity, chemicals and additional manpower required for unit start-up due to the synchronisation of the generator and due to the subsequent process of adjusting and controlling steam pressure and temperatures; ii) depreciation of the components exposed to wearing along with higher maintenance, overhaul capital expenditures, unit life shortening, and increased forced outage rates; iii) lost profits due to lower partial load efficiency of power plants when ramping. The ramping constraints also may be associated with additional costs per unit of load, on top of the fuel costs, reflecting the additional capital and maintenance costs of changing energy output of a plant.

Finally, the operation of a plant below the rated capacity typically reduces the efficiency and results in increased fuel consumption, emissions and fuel costs. As every power plant, independent of the exact technology, requires a certain amount of energy to keep the system running and thus synchronised, the share of this energy amount decreases with higher loads leading to higher efficiencies. Figure 1illustrates the relationship between the load, the efficiency loss and the overall efficiency for different types of power plants.

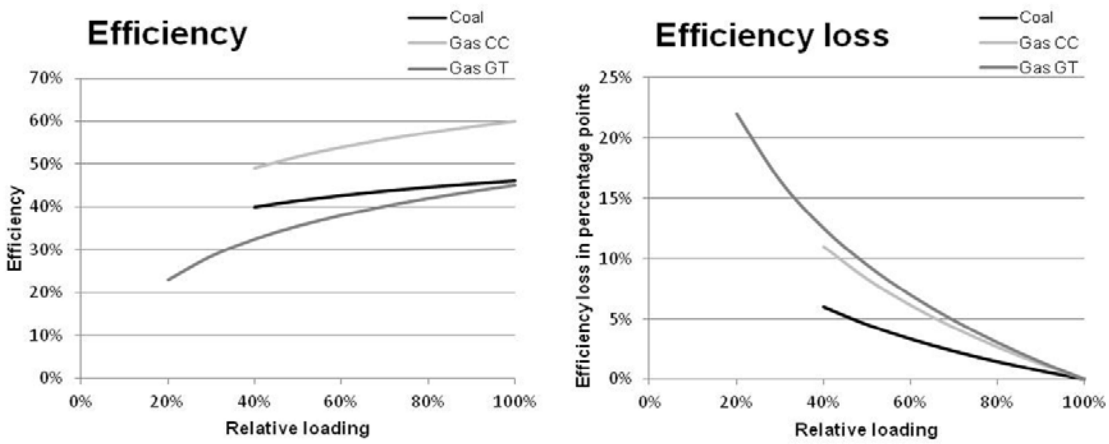


Figure 1: Efficiency loss and efficiency in part load operation [1].

[1] It is important to note that the ramping gradients depend on the investigated timeframe and the way the plant is operated.

The start-up, shut-down and ramping constraints can be associated with additional costs per unit of started capacity that can be taken into the optimisation. In addition, the efficiency of the thermal plants usually depends on the load level, and hence operating at a partial load it may result in efficiency losses, increased fuel consumption, emissions and fuel costs.

Following the relevant literature (see for example [2] – [7]) the full scale problem considered in this extension of TIMES can be formally stated as:

- For each region $r \in R$ the total planning horizon is split into a set of years $t \in T$, and each year is further delineated into a set of operating hours (time slices) $s \in ALL\_TS$. The time slices can be grouped into days, seasons, etc. by specifying a hierarchical time slice tree. In the tree time slice levels are identified, depending on the implemented hierarchy, $tsl \in \{\text{ANNUAL, SEASON,WEEKLY, DAYNITE}\}$. Each time slice is characterised by a duration, which is given as a fraction of the year $G\_YRFR_{r,s}$.
- In each region $r \in R$ a set of generating processes $p \in P$ can be installed. These can be existing processes or new candidates for the region and can be distinguish by a vintage $v \in V$. Although it is not necessarily a process to correspond to a discrete power plant, there is the flexibility to model individual power plants in two ways: **i)** the whole capacity of each process vintage is treated as a single unit, with the allowable sizes of new capacity units being optionally prescribed in advance, **ii)** the capacity of each process vintage can be internally divided into a number of "virtual units" that are sharing the same operational constraints, but the size of which is semi-continuous and greater than a specified minimum size. Both approaches have advantages and disadvantages, which are discussed in section 3.2.10.
- Three available start-up types $upt = \{hot, warm, cold\}$ can be considered for each process p based on its non-operational time (after being shut-down). There are specific time intervals, $ACT\_MAXNON_{r,v,p,upt}$, after which each process changes its standby condition from hot to warm and warm to cold. The start-up decision is discussed in more detail in section 3.2.2.
- After the determination of the appropriate start-up type, the synchronisation and soak phases follow respectively. These two phases are combined into a single phase, which we will call it start-up phase. The duration of the start-up phase, $ACT\_SDTIME_{r,v,p,upt,UP}$, depends on the chosen start-up type upt. During the start-up phase it is assumed that the power output of the process increases linearly until it reaches its minimum stable operation level $ACT\_MINLD_{r,v,p}$. It follows that the rate of increase of the output of the process for each start-up type upt is $var\_cap_{r,v,t,p} \cdot ACT\_MINLD_{r,v,p}/ACT\_SDTIME_{r,v,p,upt,UP}$ per hour, where $var\_cap_{r,v,t,p}$ is the available installed capacity of the process vintage v in period t. During the start-up phase start-up costs per unit of started capacity may apply, which they can be also differentiated by start-up type (e.g. costs can be higher if a power plant starts with a cold start-up, compared to a hot start-up). In addition, due to the process operation at partial load, efficiency losses can occur that result in increased fuel costs. These partial load efficiency losses can be modelled either as genuinely endogenous efficiencies, or as a penalty cost simulating the additional fuel cost at start-up phase. The start-up trajectories are discussed in detail in section 3.2.2 and the modelling of the partial load efficiency losses in section 2.2 and in section 3.2.7.
- After the completion of the start-up phase the process p enters into the dispatching phase. At this phase the power output of the process shall be above the minimum stable operation level and below of its maximum available capacity. The load of the process can be increased or decreased with respect to the ramping-up and ramping-down rates $ACT\_UPS_{r,v,p,s,UP}$ and $ACT\_UPS_{r,v,p,s,LO}$ respectively. Ramping costs $ACT\_CSTRMP_{r,v,p,UP/LO,cur}$ can be associated per capacity unit increased or decreased during the dispatching phase. In addition to ramping costs, partial load efficiency losses can also be considered. The dispatching phase is discussed in detail in section 3.2.5.
- The last operating phase of a process p is the desynchronization phase, or shut-down phase, which lasts $ACT\_SDTIME_{r,v,p,HOT,LO}$ hours. Before entering into the shut-down phase, the load of the process is set to be at the minimum stable operating level. Then the power output

is linearly decreased at the constant rate of $var\_cap_{r,v,t,p} \cdot ACT\_MINLD_{r,v,p}$ / $ACT\_SDTIME_{r,v,p,upt,LO}$ per hour, from the minimum stable operation level to zero. Similar to the start-up phase, shut-down costs related to per unit of started-up capacity and fuel costs related to partial load efficiency losses can occur in this phase too. The shut-down phase is discussed in detail in section 3.2.6.

- The start-up phase, the dispatching phase, and the shut-down phase comprise the operational phase of a process p, during which electricity is produced. In order to sustain the production levels usually the total operational time of a power plant must be greater or equal to a minimum online time $ACT\_TIME_{r,v,p,UP}$ after a start-up and the subsequent shutdown. In a similar way, in order to avoid for instance excessive thermal stress on power plant equipment, usually a minimum non-operational time $ACT\_TIME_{r,v,p,LO}$ is required between a shutdown and a start-up. These minimum online and offline times, which also characterise limitations in the flexibility of the power plants, are in principle no "hard" limits, but they can be considered as economic limits. They are discussed in detail in section 3.2.8.
- Finally, a governor constraint is the logical status of a power plant that prohibits the overlapping of the different operating phases. In each time slice the unit can be either started, or it can be dispatched, or it can be shut-down. The logic of the unit commitment is discussed in detail in section 3.2.1.

Figure 2 presents an example of the above described features, by assuming a process of installed capacity of 200 MW and maximum availability rate of 85%. This implies that the maximum started capacity is 170 MW. The minimum stable operation level is defined to be 20% of its installed capacity (or 40 MW). The start-up phase of the process needs 3h to be completed, during which the output of the unit increases linearly from 0 to 40 MW, i.e. the constant rate of increase is 40/3=13.33 MW per hour. During the dispatching phase the output of the process can be between 40 MW and 170 MW, and it is allowed to increase or decrease according to the specified ramp-up and ramp-down rates respectively. When the dispatching phase is completed, the output of the process is always equal to the minimum stable operation level before the shut-down phase starts. The shut-down phase of the process lasts also 3h, during which the power output of the process linearly decreases at a constant rate of 40/3=13.33 MW per hour from the minimum stable operation level of 40 MW to zero. During the operation of the power plant across all the three phases, start-up, dispatching and shut-down, fuel costs, start-up costs per unit of started capacity, shut-down costs per unit of started capacity, ramping costs and costs related to partial load efficiency losses occur, while at the same time electricity is produced and injected into the grid.

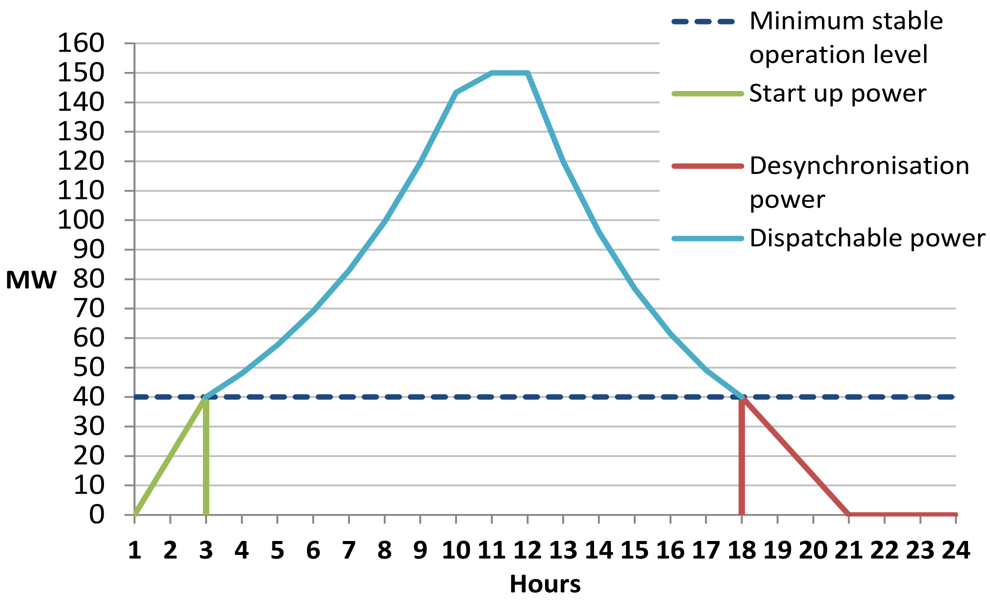


Figure 2: Operating stages of a thermal plant in the unit commitment problem.

2.1. Minimum stable operation level

Lower bounds for process availabilities are supported by TIMES, but imposing such bounds would force the technology to be operating unconditionally. In reality, for example power plant units can well be committed at least on a seasonal basis, some even on a daily basis. Start-ups and shut-downs of plant units should thus be allowed in the model, insofar as the associated additional costs are taken into account. However, for seasonal start-ups these costs might well be assumed to be included in the normal operating costs for power plants, and therefore seasonal start-ups could be assumed to occur without additional costs in TIMES. The input attribute for defining flexible lower bounds for process availabilities is $ACT\_MINLD_{r,v,p}$.

This parameter defines a lower bound for the process availability, like NCAP_AF(LO), but it also allows any fraction of the capacity to be offline during the season, such that the bound applies only to the fraction of the capacity that is online. The amount of capacity online is determined by TIMES according to the maximum operating level in each season. A simple example is illustrated in the figure below, where "Load" refers to the operating level in each time slice, in proportion to the total capacity. In commonly used terminology, the ACT_MINLD parameter can be interpreted as defining the minimum stable operation level for the process, below which the load can only be during the start-up and shut-down phases.

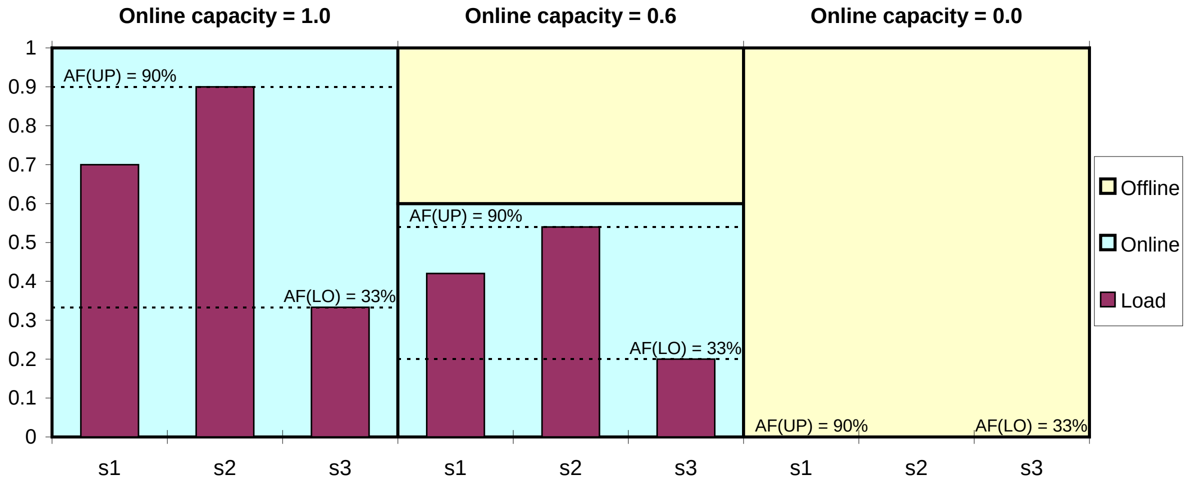


Figure 3: Illustration of the minimum stable operation level as a flexible lower bound.

This approach is generalized to cover all sub-annual time slice levels (SEASON, WEEKLY, DAYNITE), at the user's discretion. The associated (linearized) start-up costs can be included in the objective function according to the changes occurring in the offline capacity within any of the time slice cycles. Consequently, start-up costs can now be specified in TIMES for any process at these three time slice levels, and the impacts of start-ups can thus be modelled in an approximate way on all levels also under the linear formulation[2].

2.2. Partial load efficiency losses

The efficiency of the thermal plants usually depends on the load level, such that the efficiency is close to its maximum value only at load levels above e.g. 60%, or perhaps even only when approaching load levels of 100%. The current extension of TIMES allows the modelling of partial load efficiencies either as genuinely endogenous efficiencies, or as a penalty cost simulating the additional fuel cost at partial loads, depending on the user's choice.

[2] In reality, if there are only a few units that can be committed for the technology, the fraction of capacity online/offline should be highly discrete. However, if one can assume a large number of units for each technology, continuous fractions do not cause any major drawback in the linear approach. Nonetheless, accurate modelling of unit commitment and start up/shutdown costs would require discrete variables and thus a MIP approach.

2.2.1. Endogenous partial load efficiency losses

In general, the relationship efficiency and power output (load) of a power plant is non-linear as it has been illustrated in Figure 1. Modelling genuinely endogenous efficiencies requires an approximation of this non-linear relationship. Figure 4 below illustrates examples of efficiency curves that can be modelled with the approximation implemented in TIMES. It should be noted, though, that the endogenous modelling of partial load efficiencies requires that the process has its efficiency modelled through the *ACT_EFF* parameter (on the shadow side of the process).

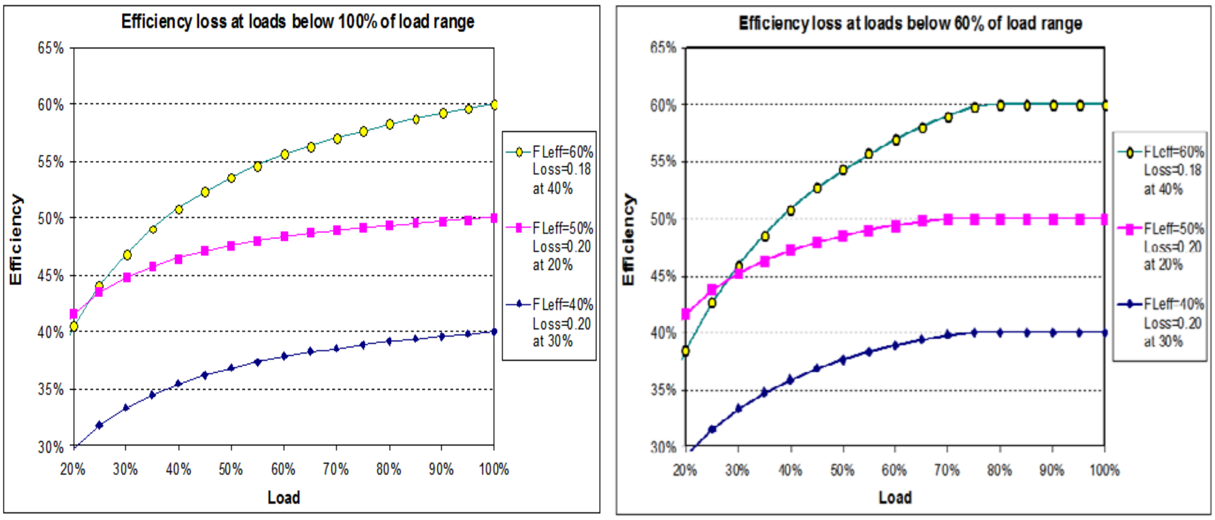


Figure 4: Illustrative partial load efficiencies assuming that efficiency losses occur at all load levels below 100%(left) and 60% (right) (FLeff = Full load efficiency).

The non-linear relationship of the efficiencies as a function of the load level, as illustrated in Figure 4, can be achieved through a linear approximation of a loss in activity that will result in increased fuel consumption. The linear approximation of the activity loss occurs between four key load levels, showed with different coloured dots in Figure 5:

a) the start-up load (blue dot)
b) the minimum stable operation load (red dot)
c) a load level above which no more efficiency losses are assumed to occur (green dot)
d) the shut-down load level (in Figure 5 it also corresponds to the blue dot for simplicity)

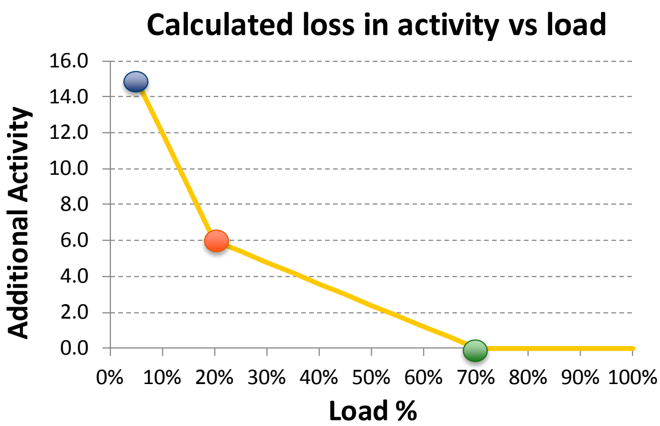


Figure 5: Linear trajectories of the losses in activity due to partial load efficiencies that result in increased fuel consumption between the start-up load (blue dot) and the minimum stable operation level (red to), and between the minimum stable operation level and the load above which no more activity losses are assumed to occur (green dot).

As shown in Figure 5, the loss of activity is proportional to the load between the four load levels. It is more pronounced during the start-up and shut-down phases (i.e. between the blue and the red dot in Figure 5) for reasons already discussed previously. The loss of activity is zero above the load level corresponding to the maximum load below which partial load efficiency losses occur (green dot). The loss of activity at the start-up load (blue dot) is calibrated in such a way that the resulting efficiency (i.e. the sum of the normal activity of the process and the loss in activity, divided by the fuel consumption) is equal to the specified efficiency for this load level. Then the activity loss is linearly decreased until the minimum operation load, where it is calibrated to be equal to the activity of the power plant. From this point onwards, the activity loss is linearly decreased to 0 until the load level above which no partial load efficiency losses occur.

Since the efficiency is an inverse relationship with activity it follows that the above linear approximation of activity losses will result in a non-linear relationship between efficiency and load, if the activity loss is taken into account in the fuel consumption equation. Figure 6 presents an indicative example of a non-linear function of efficiency vs. load resulted by the linear approximation of activity losses between the three load levels.

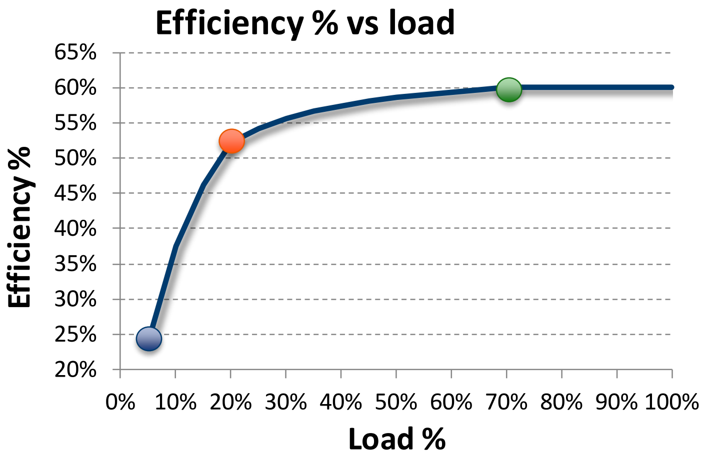


Figure 6: A non-linear relationship of efficiency versus power plant load; the dots represent selected efficiencies during the start-up phase (blue dot), the minimum stable operation level (red dot) and a load level above which no efficiency losses are assumed to occur (green dot); these selected efficiencies are used to approximate partial load efficiency losses in TIMES.

Numerical Example corresponding to Figure 5 ***and*** Figure 6***:***

The example assumes that:

- *The installed capacity of the process is 200 MW*
- *The minimum stable operation level is 20% or 40 MW*
- *The nominal efficiency at loads above 70% is 60% (full load efficiency)*
- *The incremental specific fuel consumption at minimum stable operation level is 15%, which implies that the efficiency at this partial load level is* $0.60/(1+0.15)=52.17\%$
- *The start-up load is 5% (or 10 MW) and the incremental fuel consumption due to partial load efficiency at this load level is 150%, which results in an efficiency of 24% at this load level*

Using the above data, the activity losses at the start-up load are 15 MWh, which results in a total activity of 25 MWh (10 MWh of the normal activity for this load level plus 15 MWh of the activity losses); this corresponds to a fuel consumption of $25/0.6=41.7$ *MWh, and the actual efficiency in the start-up level is therefore* $10/41.7=24\%$ *(which is exactly the efficiency provided by the user for the start-up load). Then the activity losses are linearly decreased to 6 MWh at the minimum stable operation level, which result in a total activity of 46 MWh (40 MWh of the normal activity plus 6 MWh of the activity losses); this leads to a fuel consumption of* $46/0.6=76.7$ *MWh which in turn implies an actual efficiency of* $40/76.7=52.17\%$ *(which is exactly the efficiency at this load level provided by the user). Finally, the activity losses are linearly decreased to zero at the load level of 70%, above which no efficiency losses are assumed to occur.*

2.2.2. Partial load efficiency losses as a penalty cost

The second alternative for modelling partial load efficiencies is to account them directly as a penalty cost per unit of activity into the objective function. The difference in this approach with the approach described in the previous section is that the calculated activity loss at the four key load levels (start-up load level, minimum stable operation level, shut-down load level, and load level above which no more partial load efficiency losses occur) does not result in increased fuel consumption. This implies that the activity-efficiency relationship of the process does not take into account the activity losses due to partial load efficiency, and the fuel consumption corresponds to the nominal efficiency of the process. Because of that, both the full load efficiency and the increase in fuel consumption must be embedded in the cost parameter when modelling the additional fuel costs caused by the increased fuel consumption. The penalty cost of the partial load efficiency losses is entered into the objective function, where it is multiplied by the sum of the activity losses and discounted to the base year.

The penalty cost approach is applicable only to power plants not modelled with the advanced unit commitment options (see Section 2.4). Its main advantage is that it can be used for any process, regardless of how the process efficiency has been modelled (i.e. it does not require the use of the ACT_EFF TIMES parameter for the definition of efficiency of a process). Another advantage of this approach is that the commodity balance equations are not affected by the introduction of partial load efficiency losses, and hence there is no need to alter the calibration of the model.

Numerical example:

For example, if we assume that the specific fuel consumption increases by 20% when the load is at its minimum operating level of 30% and the full load efficiency is 40% while the fuel price is 7 EUR/GJ , then the penalty costs are defined as $\mathrm{ACT\_CSTPL}_{\mathrm{r,v,p,cur}} = 7 \cdot 0.2/0.4 = 3.5$ *EUR/GJ for the increased fuel consumption at partial loads (7 EUR/GJ of additional fuel), by specifying the equivalent additional activity cost at the minimum operating level.*

Finally, it should be noted that in this approach the energy and emission equations are not affected by the reduced partial load efficiencies, but only the operating costs. This can lead to inconsistencies in the balances, which do not occur in the endogenous approach described in section 2.2.1. Hence, if completeness of the energy and emission balances is important, the endogenous efficiency approach should be used instead.

2.3. Ramping constrains, Start-up and Shut-down trajectories

Ramping constraints, which limit the capability of units to change production over short intervals of time, can also have an important impact on the short-term generation scheduling. In general, the power output of an electric unit is restricted by three kinds of ramp constraints:

1) Operating ramp constraints also known as ramp-up and ramp-down rate limits (or simply ramping constraints)
2) Start-up ramping constraint, which involves an increasing power trajectory
3) Shut-down ramping constraint, which involves a decreasing power trajectory

Although the ramping constraints can be formulated as linear functions of the change in load, the start-up and shut-down trajectories are usually non-linear. In addition, the start-up costs increase exponentially with the number of hours the unit has been offline. As these non-linear characteristics limit the explicit representation of the start-up costs and trajectories, a classification is often used in the literature: cold starts, warm starts and hot starts. These three start-up types are also used in the unit commitment extension.

The exponential function of the start-up costs, with respect to the start-up type, can be approximated through a discretised stepwise function as shown in Figure 7 below. However, such a stepwise approximation requires a MIP formulation with significant overhead not only to the solution time but also to the model size as well.

$$\delta_{p,s,t} \le \sum_{i=T^{SU}_{p,s}}^{T^{SU}_{p,s+1}-1} DN_{p,t-i}$$

$$\sum_{s} \delta_{p,s,t} = UP_{p,t}$$

$$\delta_{p,s,t} \in \{0,1\}$$

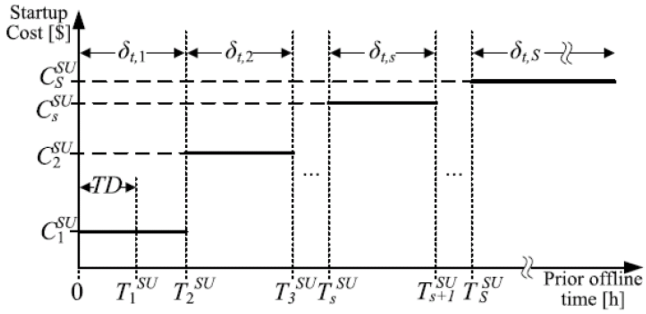


Fig. 1: Startup costs as a function of the unit's previous offline time.

Source: Morales-Espana et al. (2013).

Figure 7: Stepwise approximation of an exponential trajectory of start-up costs [7].

To avoid this, in the dispatching and unit commitment features extension of TIMES we assume that the power output increases linearly from the start-up load to the minimum stable operation level, but the duration of the start-up type depends on the standby condition of the power plant before its start-up. Hence, the power output from a cold start-up would require more time to reach the minimum stable operation level compared to a hot start-up, which in turn will result in increased fuel consumption, emission and fuel costs. In addition, the extension allows the flexibility to define start-up costs per unit of started capacity, which can be differentiated by start-up type. The rationale behind this approximation is to reduce the overhead in the model size and, consequently, in solution times.

2.4. Flexibility in selecting which features to include in a model

The dispatching features and unit commitment extension of TIMES offers the flexibility to the TIMES user to select a subset from the full set of features described in the previous section. In fact, based on the trade-off between an accurate representation of short-term operational constraints and overhead in model size and solution time, the TIMES user may select among three implementations.

2.4.1. Basic unit commitment option

This option implements a minimum subset of the unit commitment features described above. It uses a linearized formulation of dispatching, and it works best when each technology can be assumed to represent many units. Although it sacrifices accuracy in modelling short-term operational constraints, it has the advantage that the model stays at the Linear Programming space. This option has therefore the least impact among the three options offered on the model size and solution times. The subset of features included in this option is:

a. Start-up and shut-down capacities
b. Start-up and shut-down costs per unit of started capacity
c. Minimum stable operation level
d. Ramping rates and ramping costs at the dispatching phase per unit of started capacity
e. Minimum online and offline times
f. Partial load efficiency losses at the dispatching phase either as genuinely endogenous efficiencies or as a penalty cost
g. Limits on the number of start-up cycles within each full process time slice.

In the basic unit commitment option, it is assumed that the unit can reach its minimum stable operation level within the same time slice, in which it is turned on. Thus, in this option only the dispatching and offline states of a power plant are considered; in other words, the on-line state is equal to the dispatching state.

2.4.2. Advanced unit commitment option

This option includes all the main features of the basic unit commitment option and additionally offers:

a. Three different start-up types depending on the non-operational time of the unit: cold, warm and hot
b. Start-up times differentiated by start-up type, and shut-down times
c. Start-up costs per unit of started capacity differentiated by start-up type
d. Partial load efficiency losses at the start-up and shut-down phases as genuinely endogenous efficiencies; however, the penalty cost approach cannot be used for processes modelled using the advanced option

In the advanced unit commitment option, the start-up and shut-down phases are also modelled separately. Hence it considers the full operating cycle of a power plant in detail. This implies that it may result in overheads in both the model size and the solution times.

2.4.3. Discrete unit commitment option

This option includes all the features of the advanced unit commitment option and it additionally offers the modelling of individual process vintages consisting either of a single unit for each process vintage, or of multiple "virtual units" for each vintage. In the first approach, each individual unit can have different operational characteristics, but the full capacity of each vintage will be treated as a single unit. The second approach does also make the total online/offline capacity of each process vintage to behave in a discretised way, but the "virtual units" of each vintage share the same operational characteristics.

It turns out that among the three options offered, the discrete unit commitment options results in the highest accuracy in modelling short-term operational constraints, but at the same time the largest overhead in model size and solution times due to its MIP implementation. It is therefore up to the user to decide the most suitable option for implementing the dispatching and unit commitment features in his/her own instance of TIMES model, depending on the requirements of the performed analysis.

3. Mathematical formulation

3.1. Nomenclature

The mathematical formulation of basic and advanced unit commitment makes use of a number of symbols, which are briefly described in Tables 2, 3, 4 and 5.

Table 2: Basic set indexes used in the mathematical formulation of the unit commitment features extension in TIMES

Index	**Description**
$r \in R$	Region
$t \in T$	Time period
$p \in PRC$	Process
$v \in V$	Vintage
$ts, s, sl, ss \in ALL\_TS$	Time slice
$c \in COM$	Commodity
$cur \in CUR$	Currency
$tsl \in \{\text{ANNUAL, SEASON, WEEKLY, DAYNITE}\}$	Time slice level
$bd \in \{\text{LO, FX, UP}\}$	Bound, i.e. lower, fix, upper, none
$upt \in \{\text{HOT, WARM, COLD}\}$	Start-up type, i.e. hot, warm, or cold start-up, used in the advanced unit commitment formulation
$u \in U$	Set of new capacity units used for the discrete unit

	commitment formulation

Table 3: Other sets used in the mathematical formulation of the unit commitment features extension in TIMES

Set	Description
$PRC\_TSL(p)$	Process p time slice level
$TS\_GROUP(tsl)$	All the time slices s belonging to a time slice level tsl
$PRC\_TS(p)$	All timeslices on process p time slice operating levels
$C(s)$	Set of child time slices of time slice s in the time slice tree
$P(s)$	Set of parent time slice of time slice s in the time slice tree
$UPS(p)$	Set of time slices including the SEASON time slice and all time slices for which start-ups and shut-down costs are defined
$SUP(s)$	Set of time slices above time slice s in the time slice tree, but including s itself
$PL(p)$	Set of processes p for which endogenous partial load efficiency losses are modelled
$DPL\_TSL(p)$	Set of time slice levels in the time slice tree in which the process p can be dispatched
$DPL\_TS(p)$	Set of time slices in which the process p can be dispatched

Table 4: Parameter used in the mathematical formulation of the unit commitment features extension in TIMES

Parameter	Description
$AF\_MAX_{r,v,p,s}$	Maximum operating level of online capacity of process p, vintage v, in period t and in time slice s
$NCAP\_PASTI_{r.v,p}$	Capacity of process p installed in years v prior to the beginning of model horizon
$ACT\_MINLD_{r,v,p}$	Minimum operating level of online capacity of process p, vintage v
$CA_{r,p}$	Capacity to activity conversion parameter of process p
$Ctc_{r,v,t,p}$	Capacity transfer coefficient internally derived by TIMES
$G\_YRFR_{r,s}$	Duration of time slice s as fraction of a year in region r
$ACT\_UPS_{r,v,p,s,bd}$	Maximum ramp-up rate ($bd = \{\text{UP}\}$) or ramp-down rate ($bd = \{\text{LO}\}$) of online capacity of process p, vintage v, in time slice s
$ACT\_CSTUP_{r,v,p,tsl,cur}$	Start-up cost of capacity per unit of capacity of process p, vintage v, and in time slice level tsl; this parameter does not take into account different start up types of process p
$ACT\_CSTSD_{r,v,p,upt,bd,cur}$	Start-up cost of capacity per unit of capacity of process p, vintage v, and of start-up type upt
$ACT\_TIME_{r,v,p,bd}$	Minimum online (bd='UP') or offline (bd='LO') time for process p, vintage v
$ACT\_MCC_{r,v,p}$	Maximum number of start-up/shutdown cycles for process p, vintage v
$ACT\_LOSPL_{r,v,p,bd}$	Depending on bd: • bd='LO': defines the minimum operating level used for the partial load efficiency function • bd='FX': defines the proportional increase in specific fuel consumption at the minimum operating level used for the partial load efficiency function • bd='UP': defines the fraction of the feasible load range above the minimum operating level, below which the efficiency losses are assumed to occur. The bd='FX' parameter instances are used only when the partial load efficiency losses are endogenously modelled.

$ACT\_CSTPL_{r,v,p,cur}$	Defines the additional cost per activity at the minimum operating level, corresponding to the efficiency loss at that level
$ACT\_MAXNON_{r,v,p,upt}$	Maximum non-operational time after shut-down before start-up type upt
$ACT\_NON_{r,v,p,upt,bd}$	Auxiliary parameter for defining the bounds of the interval of non-operational time for each start-up type upt
$DP\_NON_{r,v,p,upt,bd}$	Auxiliary parameter for defining the length of the non-operational time intervals for each start-up upt.
$ACT\_SDTIME_{r,v,p,bd}$	Duration of start-up (bd = UP) and shut-down (bd = LO) phases in hours
$ACT\_LOSSD_{r,v,p,upt,bd}$	Efficiency losses at the start-up load ($bd = \{$UP$\}$) by start-up type, and efficiency losses at the shut-down load ($bd = \{$LO$\}$).
G_CYCLE_{tsl}	Number of cycles in an average year
$CEFF_{r,v,t,p,c,s}$	Commodity specific efficiency of commodity c, in process p, vintage v, in period t and time slice s
$ACT\_EFF_{r,v,t,p,cg,s}$	Commodity group efficiency of commodity group cg, in process p, vintage v, in period t and time slice s
$RS\_HR_{r,s}$	Parameter defining the middle hour of the hours belonging to timeslice s
$RS\_STGPRD_{r,s}$	Parameter referring to the number of cycles under the parent time slice of s (e.g. the number of days under the parent of a DAYNITE time slice).
$NCAP\_DISC_{r,v,p,u}$	Parameters for defining sizes of new capacity units u that can be added for process p, in region r, in period t.

Table 5: Variables used in the mathematical formulation of the unit commitment features extension in TIMES

Variable	Description
$var\_ncap_{r,v,p}$	The installed new capacity of a process p in period v
$var\_flo_{r,v,t,p,c,s}$	Consumption of the commodity c, from process p, vintage v, in period t and time slice s
$var\_ret_{r,v,t,p}$	The retired capacity of process p in period t and time slice s
$var\_cap_{r,v,t,p}$	Remaining installed capacity of a process p, in period t and time slice s
$var\_oncap_{r,v,t,p,s}$	Nominal online capacity of a process p, in period t and time slice s (defined as the residual between installed capacity and maximum offline capacity)
$var\_on_{r,v,t,p,s}$	Online capacity of a process p in period t and time slice s (genuine variable for online capacity used in the advanced unit commitment modelling)
$var\_act_{r,v,t,p,s}$	The activity of process p in period t and time slice s
$var\_off_{r,v,t,p,s}$	The offline capacity of process p, in period t and time slice s
$var\_mof_{r,v,t,p,s}$	The maximum offline capacity of process p, vintage v, in period t and time slice s, over time slice ts directly below time slice s
$var\_ups_{r,v,p,t,s}$	Start-up capacity of process p, vintage v, period t and time slice s
$var\_upt_{r,v,t,p,s,upt}$	Start-up capacity of process p, vintage v, period t and time slice s by start-up type upt
$var\_los_{r,v,t,p,s}$	Shut-down capacity of process p, vintage v, in period t and time slice s
$var\_pll_{r,v,t,p,s}$	Activity loss due to partial load efficiency of process p, vintage v, in period t and time slice s
$var\_udp_{r,v,t,p,s}$	Dispatched capacity of process p, vintage v, in period t and time slice s . It can be also considered as the gap between the minimum stable operation level and the maximum available capacity of process p, vintage v, in period t and time slice s.
$var\_ldc_{r,v,t,p,bd}$	Changes in load of the process during the dispatching phase; it holds the increase ($bd = \{$UP$\}$) or the decrease of the load ($bd = \{$LO$\}$) at the time slice s of process p, vintage v and period t
$var\_onind_{r,v,t,p,s,bd}$	Binary variable that indicates the status of the unit; when it is set to 1 the

	unit is online, while when it is set to 0 the unit is offline

3.2. Generic formulation of the unit commitment features

In order to improve the reading and the understanding the formulation of the unit commitment features is given at the DAYNITE time slice level. However, the equations are extended to cover time slices above the DAYNITE level as well, where this makes sense.

The following intermediate variables and parameters are introduced in the description of the formulation below, in order to improve its readability:

a) Remaining installed capacity of a process p, vintage v and in period t:

$$var\_cap_{r,v,t,p} = \left(var\_ncap_{r,v,p} + NCAP\_PASTI_{r,v,p} - var\_ret_{r,v,t,p}\right) \cdot Ctc_{r,v,t,p} \qquad \text{eq. 1}$$

If no vintages are considered for the process p, then the vintage index is omitted and in this case the capacity transfer coefficient is also not needed

b) Nominal online capacity of process p, vintage v, period t and time slice s:

$$var\_oncap_{r,v,t,p} = var\_cap_{r,v,t,p} - \sum_{ts \in SUP(s) \cap UPS(p)} var\_off_{r,v,t,p,s} \qquad \text{eq. 2}$$

c) Parameters for defining the interval of non-operational time for each start-up type in advanced unit commitment modelling only:

$$ACT\_NON_{r,v,p,upt,bd} = \begin{cases} ACT\_TIME_{r,v,p,LO}\ , \ upt \in \{\text{HOT}\} \text{ and } bd \in \{\text{LO}\} \\ ACT\_MAXNON_{r,v,p,upt}\ , \ bd \in \{\text{UP}\} \\ ACT\_MAXNON_{r,v,p,\text{"}HOT\text{"}},\ upt \in \{\text{WARM}\} \text{ and } bd \in \{\text{LO}\} \\ ACT\_MAXNON_{r,v,p,\text{"}WARM\text{"}},\ upt \in \{\text{COLD}\} \text{ and } bd \in \{\text{LO}\} \end{cases} \qquad \text{eq. 3}$$

In eq. 3 it is stated that the process p can start with a hot start-type from $ACT\_TIME_{r,v,p,LO}$ to $ACT\_MAXNON_{r,v,p,HOT}$ hours after shut-down, i.e. the hot state of an offline process holds for the time interval $[ACT\_TIME_{r,v,p,LO},\ ACT\_MAXNON_{r,v,p,\text{HOT}}\ ]$ hours after shutdown. Similarly, the warm state of an offline process p holds for the time interval $(ACT\_MAXNON_{r,v,p,\text{HOT}},\ ACT\_MAXNON_{r,v,p,\text{WARM}}\ ]$. And finally, the cold state of an offline process p will hold for the interval $(ACT\_MAXNON_{r,v,p,\text{WARM}},\ ACT\_MAXNON_{r,v,p,\text{COLD}}\ ]$.

Based on the parameter $ACT\_NON_{r,v,p,upt,bd}$, we may then define the following auxiliary parameter to use it in the basic and advanced unit commitment formulation:

$$DP\_NON_{r,v,p,upt,bd} = \begin{cases} ACT\_NON_{r,v,p,upt,UP} - ACT\_NON_{r,v,p,upt,LO}\ , bd \in \{\text{UP}\} \\ ACT\_NON_{r,v,p,upt,LO}\ ,\ bd \in \{\text{LO}\} \end{cases} \qquad \text{eq. 4}$$

According to eq. 4 the parameter $DP\_NON_{r,v,p,upt,UP}$ holds the length of the time interval after shutdown during which the process can start with start-up type upt. The parameter $DP\_NON_{r,v,p,upt,LO}$ holds the lower bound of the time interval during which the process can start with start-up type upt.

d) Counting the hours passed between two consecutive time slices:

Parameter $G\_YRFR_{r,s,}$ holds the duration of each time slice s, but for the unit commitment formulation is important to know how many hours have been passed between two consecutive time slices. At the same time, the parameter $RS\_STGRPRD_{r,s,}$ can be used for obtaining the number of cycles under the parent time slice of s (e.g. the number of days under the parent of a DAYNITE time slice). By combining these two parameters, it is possible to identify the middle hour of the set of hours represented via the time slice s, using the following algorithm:

z ← 0;

For each s,

f ← G_YRFR(r,s) / RS_STGPRD(r,s); RS_HR(r,s) ← z + f / 2; z ← z + f

The above sets the $RS\_HR_{r,s}$ parameter to hold the middle hour of the set of hours belonging to time slice s, equivalently to the following:

$$RS\_HR_{r,s} = \left(\frac{HourEnd(s) - HourStart(s)}{2}\right)/8760 \quad \text{eq. 5}$$

For example, if the time slice s spans between hours 14 and hours 18 then the $RS\_HR_{r,s}$ is set to be equal to 16. It follows from the above that the difference $RS\_HR_{r,s} - RS\_HR_{r,ts}$ for two consecutive time slices s and ts gives the hours passed between the two time slices.

3.2.1. Logic of the unit commitment problem and started capacity

A distinction shall be made between basic unit commitment formulation (which does not identify different start-up types) and advanced unit commitment formulation (which identifies different start-up types).

3.2.1.1. Basic unit commitment formulation

In the case that no different start-up types are modelled by the user then the start-up and shut-down capacities are related via the following four equations:

$$var\_ups_{r,v,t,p,s} - var\_los_{r,v,t,p,s} = var\_off_{r,v,t,p,s-1} - var\_off_{r,v,t,p,s} = 0 \quad \forall s \in UPS(p) \quad \text{eq. 6}$$

$$var\_mof_{r,v,t,p,P(s)} \geq var\_off_{r,v,t,p,s} \quad \forall s \in UPS(p) \quad \text{eq. 7}$$

$$\sum_{ts \in C(s)} var\_ups_{r,v,t,p,ts} \geq var\_mof_{r,v,t,p,s} \quad , \forall s \in \{\cup_{sl} P(sl) | sl \in UPS(p)\} \quad \text{eq. 8}$$

$$var\_cap_{r,v,t,p} + var\_off_{r,v,t,p,P(s)} + var\_udp_{r,v,t,p,(s)} = 0 \, , \forall s \in UPS(p) \quad \text{eq. 9}$$

The logic of the unit commitment problem is defined in eq. 6, by requiring that the capacity started-up minus the capacity shut-down in any time slice is equal to the difference in the offline capacity between the previous time slice and the current time slice. The next two equations, eq. 7 and eq. 8 implement the activity offline balance at higher time slice levels. The offline capacity in a time slice ts is set via eq. 7 to be the maximum offline capacity among all offline capacities at the time slices directly below ts. Furthermore, eq. 8 ensures that the sum of start-up capacities in each process time slice cycle is at least equal to the maximum offline capacity in that cycle. Finally, eq. 9 defines the dispatchable capacity at the parent slice level, as the difference between the installed capacity and the maximum offline capacity at this level.

3.2.1.2. Advanced unit commitment formulation

In the case that different start-up types are modelled, the start-up and shut-down capacities are given by the following equations:

$$var\_ups_{r,v,t,p,s} = \sum_{upt} var\_upt_{r,v,t,p,s,upt}\ ,\ \ \forall s \in DPL\_TS(p) \quad \text{eq. 10}$$

$$var\_ups_{r,v,t,p,s} - var\_los_{r,v,t,p,s} = var\_on_{r,v,t,p,s} - var\_on_{r,v,t,p,s-1}\ ,\ \ \forall s \in DPL\_TS(p), \quad \text{eq. 11}$$

In above, eq. 10 sets the start-up capacity of a process p to be equal to the capacity started with start-up type upt at the dispatching time slices of the process. Although the formulation of the equation does not explicitly state that the process should start with only one start-up type, this will hold in the cost minimisation process due to the different costs associated with each start-up type.

Finally, eq. 11 implements the logic of the unit commitment by requiring the difference in the online capacity between successive time slices to be equal to the difference between the started and shutdown capacity of the process.

3.2.2. Build-up of the started capacity and minimum stable operation level

As before a distinction shall be made between the basic unit commitment and advanced unit commitment formulation, since in the basic unit commitment formulation.

3.2.2.1. Basic unit commitment formulation

In the basic unit commitment formulation, there is not a distinct start-up phase. Rather it is assumed that the process can reach its minimum technical achievable electricity production within the same time slice in which is turned on. This implies that some excess ramp-up rates may occur when start-ups and shut-downs take place at the daily level.

The following equation, eq. 12, imposes the constraint of operating above the minimum technical level[3], by setting the activity in each time slice to be at least equal to the activity at the minimum stable operating level $ACT\_MINLD_{r,v,p}$.

$$var\_act_{r,v,t,p,s} \geq ACT\_MINLD_{r,v,p} \cdot var\_oncap_{r,v,tp,s} \cdot CA_{r,p} \cdot G\_YRFR_{r,s}\ \ , p \notin PL(p) \quad \text{eq. 12}$$

The main difference in this equation compared to the approach of defining a lower bound on the activity level via the NCAP_AF(LO) parameter of TIMES, is that it does not consider the total installed capacity of the process but only the nominal online capacity. This allows the flexibility the activity to be zero, when the process is offline.

Due to the fact that when endogenous modelling of partial load efficiency losses are considered the concept of the minimum technically achieved activity is also used/estimated in the partial load efficiency losses equations (see also section 3.2.7), to ensure the consistency between the two approaches the above equation is modified in this case as:

$$var\_act_{r,v,t,p,s} \geq var\_pll_{r,v,t,p,s}\ \ , p \in PL(p) \quad \text{eq. 13}$$

[3] Lower bounds for process activities (and availabilities) are supported by TIMES, but imposing such bounds would force the technology to be operating unconditionally.

The activity loss variable $var\_pll_{r,v,t,p,s}$ due to partial load efficiency losses is calibrated to be equal to the activity at the minimum stable operation level. In this context, eq. 13 ensures that the minimum technically achievable activity considered in the capacity-activity constraints and in the partial load efficiency losses equations is always the same.

3.2.2.2. Advanced unit commitment formulation

In the advanced unit commitment formulation a distinct start-up phase is considered with a specified duration. The duration of the start-up phase is based on the chosen start-up type. Hence, in this case an appropriate start-up decision must be taken before the unit starts, which takes into account the non-operational time of the process after a shut-down. The following equation, selects the appropriate start-up type based on the non-operational time:

$$var\_upt_{r,v,t,p,s,upt} \leq \sum_{ts\in C(P(s)),s\neq ts} var\_los_{r,v,t,p,ts} \cdot \left(mod\left(RS\_HR_{r,s} - RS\_HR_{ts} - \frac{DP\_NON_{r,v,p,upt,LO}}{8760} + \frac{G\_YRFR_{r,sl} + 4 \cdot G\_YRFR_{r,s}}{4 \cdot RS\_STGPRD_{r,s}} + \frac{2}{G\_CYCLE_{tsl}}, \frac{1}{G\_CYCLE_{tsl}} \right) < \frac{DP\_NON_{r,v,p,upt,UP}}{8760} + \frac{G\_YRFR_{r,s}}{2 \cdot RS\_STGPRD_{r,s}} \right), \forall\, tsl \in PRC\_TSL(p),\ \forall s \in DPL\_TS(p) \qquad \text{eq. 14}$$

The above equation counts the number of hours passed from the last shut-down of the process and compares it with the length of the time interval corresponding to the start-up type upt. When the number of hours passed from the last shut-down falls into an interval then the corresponding start-up type can be selected for starting the process. Note that although the above equation does not explicitly states that only one start-up type will be chosen in a time slice s, it is expected that due to the different magnitude of costs associated with each start-up type (including both fuel and capacity related costs) the optimisation process will select the least expensive option among the possible start-up types.

After the start-up type decision is made, the load of the process is linearly increased until the process reaches its minimum stable operation level. The linear increase in the power output of a process is enforced via eq. 15, which is a slanting equation, as follows:

$$var\_on_{r,v,t,p,s} = \sum_{ts\in P(s)} \left(var\_mof_{r,v,t,p,ts} - \left(var\_cap_{r,v,t,p} - \sum_{sl\in SUP(s)\cap UPS(p)} var\_off_{r,v,t,p,sl} \right) \right) + \left(var\_cap_{r,v,tp} - \sum_{sl\in SUP(s)\cap UPS(p)} var\_off_{r,v,t,p,sl} \right) - var\_off_{r,v,t,p,s} - \sum_{upt} \left(\sum_{sl\in C(P(s))\cap s\neq sl} \left(\left(mod\left(RS\_HR_{r,sl} - RS\_HR_{r,s} + \frac{G\_YRFR_{r,sl}}{2 \cdot RS\_STGPRD_{r,s,}} + \frac{2}{G\_CYCLE_{tsl}}, \frac{1}{G\_CYCLE_{tsl}} \right) < \frac{ACT\_SDTIME_{r,v,p,upt,UP}}{8760} \right) \cdot \left(var\_upt_{r,v,t,p,sl,upt} \cdot max\left(0,1 - \right.\right.\right.\right. \qquad \text{eq. 15}$$

$$\frac{mod\left(RS\_HR_{r,sl} - RS\_HR_{r,s} + \frac{G\_YRFR_{r,sl} - G\_YRFR_{r,s}}{2 \cdot RS\_STGPRD_{r,sl}} + \frac{2}{G\_CYCLE_{tsl}}, \frac{1}{G\_CYCLE_{tsl}}\right)}{8760 \cdot ACT\_SDTIME_{r,v,tp,UP}}\Bigg)\Bigg)\Bigg) +$$

$$\left(\left(mod\left(RS\_HR_{r,s} - RS\_HR_{r,sl} + \frac{G\_YRFR_{r,sl}}{2 \cdot RS\_STGPRD_{r,s}} + \frac{2}{G\_CYCLE_{tsl}}, \frac{1}{G\_CYCLE_{tsl}}\right) < \frac{ACT\_SDTIME}{8760}\right) \cdot\right.$$

$$\left(var\_los_{r,v,t,p,sl} \cdot\right.$$

$$max\left(0{,}1 - \frac{mod\left(RS\_HR_{r,s} - RS\_HR_{r,sl} + \frac{G\_YRFR_{r,sl} - G\_YRFR_{r,s}}{2 \cdot RS\_STGPRD_{r,sl}} + \frac{2}{G\_CYCLE_{tsl}}, \frac{1}{G\_CYCLE_{tsl}}\right)}{8760 \cdot ACT\_SDTIME_{r,v,tp,LO}}\right)\Bigg)\Bigg)\Bigg)\Bigg) \quad ,$$

$$\forall\, tsl \in PRC\_TSL(p),\ \forall s \in DPL\_TS(p)$$

The slanting equation operates at the level of the process and for the time slices for which the process can be dispatched. The first part of the equation creates the linear trajectory of the increase of the power load of the plant during the start-up phase, while the second part of the equation creates the linear trajectory for the decrease in the power load of the plant during the shut-down phase.

During the start-up phase the equation gradually decreases the offline capacity by the fraction of the started capacity corresponding to each start-up time slice s. The linear increase in the fraction of the started capacity is given by the modulo operation appearing in the formulation of the slanting equation. The same approach is also followed (in reverse) for the shut-down phase, where the offline capacity is linearly increased.

It follows also from the slanting equation that the online capacity variable $var\_on_{r,v,t,p,s}$ is set only at the dispatching phase, and remains zero during the start-up and shut-down phases. It also follows, by taking into account the unit commitment logic equation as well, that the start-up capacity $var\_upt_{r,v,t,p,s}$ is set at the end of the starting phase, while the shut-down capacity $var\_los_{r,v,t,p,s}$ is set at the beginning of the shut-down phase.

The output load of the process during the start-up phase (and during the dispatching and shut-down phases as well) is given by the following equation:

$$var\_act_{r,v,t,p,s} = \left(\left(var\_cap_{r,v,t,p} - \sum_{ts \in SUP(s) \cap UPS(p)} var\_off_{r,v,t,p,s}\right) \cdot ACT\_MINLD_{r,v,p} + var\_udp_{r,v,t,p,s} \cdot \left(AF\_MAX_{r,v,t,p,s} - ACT\_MINLD_{r,v,p}\right)\right) \cdot G\_YRFR_{r,s} \cdot CA_{r,p}\ , \forall s \in PRC\_TS(p) \qquad \text{eq. 16}$$

During the start-up phase, the nominal online capacity (i.e. the difference between the installed capacity and the offline capacity) linearly increases. The minimum stable operation level parameter entered in the first part of the above equation adjust the activity of the process so as not to exceed the minimum technically achievable activity by when the start-up phase completes. The same approach holds also for the shut-down phase (but in reverse).

The second term of the above equation is applicable to the dispatching phase, when the load of the power plant shall be between the minimum stable operation level and the maximum available capacity. In this context, the term $var\_udp_{r,v,t,p,s} \cdot \left(AF\_MAX_{r,v,t,p,s} - ACT\_MINLD_{r,v,p}\right)$ can be considered as the dispatchable capacity of the process above the minimum stable operation level during the dispatching phase. It follows, that eq. 16 also enforces the minimum stable operation constraint, similar to eq. 12. Hence it replaces eq. 12 and eq. 13 when advanced modelling of the unit commitment is considered.

3.2.3. Minimum online capacity constraint

In the advanced unit commitment formulation a link between the dispatchable capacity and the online capacity must be enforced, in order to ensure that the online capacity of a process is greater than or equal to the dispatched capacity in each time slice s, when the process is online. Thus, if the dispatched capacity of a process p is $var\_udp_{r,v,t,p,s}$ in time slice s, then the online capacity $var\_on_{r,v,t,p,s}$ must also be greater than or equal to $var\_udp_{r,v,t,p,s}$ in that time slice.

In addition, an assumption has to be made in the case that the start-up phase of a process requires a non-integer number of time slices for its completion. If we assume that a process completes its start-up phase in the time slices $1 \ldots n = \left\lceil \frac{ACT\_SDTIME_{r,v,p,upt}}{Hours(s)} \right\rceil$ hours, where $Hours(s)$ is the length of the time slice s in hours, then the following three cases are identified and implemented:

i) When the length of the time slices is such that the start-up phase can be completed at the end of the nth time slice, then the minimum online capacity is set to the minimum stable operation level;

ii) when the length of the time slices is such that the start-up phase can be completed before the nth time slice ends and at the same time more than or equal to the half of the nth time slice belongs to the start-up phase, then the minimum online capacity can exceed the minimum stable operation level at the end of the nth time slice, with respect of course to the ramping constraints; and

iii) when the length of the time slices is such that the start-up phase can be completed before the nth time slice ends and at the same time less than half of the nth time slice belongs to the start-up phase, then the nth time slice is ignored from the start-up phase and it is assumed that the start-up phase fully completes in $n-1$ time slices (i.e. the start-up phase is shortened).

The following equation implements the above design features with respect to the minimum online capacity constraint:

$$var\_on_{r,v,t,p,s} + \sum_{ts \in P(s)} var\_udp_{r,v,t,p,ts} \geq var\_udp_{r,v,t,p,s} + var\_ups_{r,v,t,p,s} +$$

$$\sum_{upt}\left(\left(\frac{G\_YRFR_{r,s}}{2 \cdot RS\_STGPRD_{r,s}} \leq \frac{ACT\_SDTIME_{r,v,p,UP}}{8760}\right) \cdot \left(var\_upt_{r,v,t,p,s,upt} - var\_ups_{r,v,t,p,s}\right)\right) \cdot \qquad \text{eq. 17}$$

$$\left(\text{smin}_{upt}\left(\frac{ACT\_SDTIME_{r,v,p,upt}}{8760} < \frac{G\_YRFR_{r,s}}{2 \cdot RS\_STGPRD_{r,s})}\right)\right) \quad ,\forall s \in PRC\_TS(p)$$

In the above equation, the function smin finds the minimum along the upt dimension of the ACT_SDTIME parameter.

3.2.4. Limits on number of start-up cycles

There is the possibility to define a limit for the number of start-up cycles within each full process time slice cycle with the $ACT\_MCC_{r,v,p}$ parameter. The following equation, eq. 18, implements this restriction:

$$\sum_{ts\in C(s)} var\_ups_{r,v,t,p,s} \leq \left(var\_cap_{r,v,t,p} - \sum_{ts\in SUP(s)\cap UPS(p)} var\_off_{r,v,t,p,ts}\right)\cdot ACT\_MCC_{r,v,p} \quad , \quad \forall s \in \{\cup_{sl} P(sl) | sl \in PRC\_TS(p)\} \qquad \text{eq. 18}$$

3.2.5. Dispatching phase and ramping rates

A distinction shall be made between basic and advanced unit commitment formulation as in the previous sections.

3.2.5.1. Basic unit commitment formulation

In the basic formulation of the unit commitment, the power output of the process during the dispatching phase must be above the minimum stable operation level (eq. 12 and eq. 13) and below its nominal available online capacity. The latter is imposed by the following equation:

$$var\_act_{r,v,t,p,s} \leq AF\_MAX_{r,v,p} \cdot var\_oncap_{r,v,tp,s} \cdot CA_{r,p} \cdot G\_YRFR_{r,s} \ , \forall s \in PRC\_TS(s) \qquad \text{eq. 19}$$

In addition, the increase or decrease of the load during the dispatching phase is subject to ramp-up and ramp-down constraints. The ramping constraints enforce a restriction in the speed of activity transients between successive time slices. In the unit commitment extension of TIMES the maximum ramping rates are expressed as fractions of the nominal online capacity per hour and they are formulated according to the following two equations[4]:

$$\left(\frac{var\_act_{r,v,t,p,s}}{G\_YRFR_{r,s}} - \frac{var\_act_{r,v,t,p,s-1}}{G\_YRFR_{r,s-1}} - \left(var\_ups_{r,v,t,p,s} - var\_los_{r,v,t,p,s}\right)\cdot ACT\_MINLD_{r,v,p}\right)\cdot \frac{2\cdot RS\_STGPRD_{r,s}}{8760\cdot\left(G\_YRFR_{r,s}+G\_YRFR_{r,s-1}\right)} \leq var\_oncap_{r,v,t,p,s}\cdot CA_{r,p}\cdot ACT\_UPS_{r,v,p,s,UP} \ , \forall s \in PRC\_TS(p) \qquad \text{eq. 20}$$

$$\left(\frac{var\_act_{r,v,t,p,s-1}}{G\_YRFR_{r,s-1}} - \frac{var\_act_{r,v,t,p,s}}{G\_YRFR_{r,s}} - \left(var\_los_{r,v,t,p,s} - var\_ups_{r,v,t,p,s}\right)\cdot ACT\_MINLD_{r,v,p}\right)\cdot \qquad \text{eq. 21}$$

[4] The time slice dynamic constraint introduced in TIMES v3.6.0 could well be used also for ramping constraints, but that would be convenient only when the DAYNITE time slices are all of equal length. Otherwise the length of the time slice should be taken into account in the coefficients for each individual time slice, which would render defining the constraint rather cumbersome.

$$\frac{2 \cdot RS\_STGPRD_{r,s}}{8760 \cdot (G\_YRFR_{r,s} + G\_YRFR_{r,s-1})} \leq \left(var\_cap_{r,v,t,p} - \sum_{ts \in SUP(s-1) \cap UPS(p)} var\_off f_{r,v,t,p,s}\right) \cdot$$

$$CA_{r,p} \cdot ACT\_UPS_{r,v,p,s,LO} \quad , \forall s \in PRC\_TS(p)$$

In above, eq. 20 implements the maximum ramp up rate constraint and eq. 21 implements the maximum ramp down rate constraint. Note that in order to avoid a potential conflict between the maximum ramp rates and the minimum stable operating level, the ramp between s and $s-1$ time slice is adjusted by the change in online capacity multiplied by the minimum operating level. Given also that in the basic unit commitment modelling a process can reach the minimum stable operation level in the same time slice in which is turned on, some excess ramp rates may occur when start-ups and shut-downs take place at the daily level.

3.2.5.2. Advanced unit commitment formulation

In the advanced unit commitment modelling the enforcement of the restriction that a process should operate below its nominal available online capacity is actually imposed by eq. 16. Hence, the eq. 19 of the basic unit commitment formulation is replaced by eq. 16 in the advanced unit commitment alternative.

On the other hand, the maximum ramp-up and ramp-down rates constraints formulated via eq. 20 and eq. 21 still hold as they are in the advanced unit commitment modelling too. It should be noted that in the advanced unit commitment modelling no excess ramp rates occur during the start-up phase, in contrast to the basic unit commitment modelling, due to the co-existence of the constraints eq. 15, eq. 16 and eq. 17, which control the building up of the started capacity.

3.2.6. Shut-down phase

The shut-down phase is modelled separately only in the advanced unit commitment formulation, where a duration time, $ACT\_SDTIME_{r,v,p,LO}$, is associated with it that corresponds to the desynchronisation time between generator and grid frequency before the unit goes offline. On the other hand, in the basic unit commitment formulation it is assumed that the process goes offline at the moment when this decision is taken.

In the advanced unit commitment formulation, during the shut-down phase the load of the process linearly decreases from the minimum stable operation level to zero according to eq. 15 and eq. 16 in similar way as in the start-up phase.

3.2.7. Partial load efficiency losses

The efficiency of the power plants usually depends on the load level, such that the efficiency is close to the maximum levels only at load levels above for example 60%, or perhaps even only when approaching 100%. These partial load efficiency losses result in increased fuel consumption and emissions and consequently increased operating costs.

As mentioned in section 2.2 there are two ways in the unit commitment extension of TIMES to implement losses due to partial load efficiencies: either as genuinely endogenous efficiencies, or as a penalty cost simulating the additional fuel cost at partial loads, depending on the user's choice. It should be noted that the modelling of endogenous partial load efficiency losses requires that the process has its efficiency modelled by the $ACT\_EFF_{r,v,t,p,s}$ parameter (on the shadow side), while the penalty cost approach can be used for any process, regardless of how the process efficiency has been modelled. However, for processes modelled with the advanced unit commitment formulation the penalty cost approach cannot be used.

3.2.7.1. Endogenous modelling of partial load efficiencies in the basic unit commitment formulation

In the basic unit commitment formulation partial load efficiencies are assumed to occur between a minimum load level and a maximum load level, defined by the parameters $ACT\_LOSPL_{r,v,p,LO}$ and

$ACT\_LOSPL_{r,v,p,UP}$ respectively. It is recommended that $ACT\_LOSPL_{r,v,p,LO} = ACT\_MMINLD_{r,v,p}$ in order to be consistent in the definition of the "minimum load level" in both capacity-activity and partial load efficiency equations. In the basic unit commitment formulation, partial load efficiency losses occur only during the dispatching phase.

As mentioned in section 2.2.1 the partial load efficiency that results in increased fuel consumption is modelled through an additional loss in activity. The activity loss is at its maximum value at the minimum load level $ACT\_LOSPL_{r,v,p,LO}$ and this maximum value is calibrated to be equal to the activity of the process at the minimum load level. Then the activity loss linearly decreases to 0, until the load of the process reaches the level $ACT\_LOSPL_{r,v,p,UP}$, above which no partial load efficiency losses are assumed to occur.

The linearized partial load efficiency losses in the dispatching phase can be formulated using the following equation for defining the non-negative variable $var\_pll_{r,v,t,p,s}$:

$$var\_pll_{r,v,t,p,s} \geq \Big(var\_oncap_{r,v,t,p,s} \cdot CA_p \cdot G\_YRFR_{r,s} \cdot \Big(ACT\_LOSPL_{r,v,p,UP} + ACT\_LOSPL_{r,v,p,LO} \cdot \big(1 - ACT\_LOSPL_{r,v,p,UP}\big)\Big) - var\_act_{r,v,t,p,s}\Big) \cdot \frac{ACT\_LOSPL_{r,v,p,LO}}{ACT\_LOSPL_{r,v,p,UP} - ACT\_LOSPL_{r,v,p,LO} \cdot ACT\_LOSPL_{r,v,p,UP}} \ , \forall s \in PRC\_TS(p) \qquad \text{eq. 22}$$

The equation sets the $var\_pll_{r,v,t,p,s}$ variable to be proportional to the defined efficiency loss, such that at the minimum load level the loss variable is equal to activity. The corresponding increase in the fuel consumption can then be endogenously modelling by adding a loss term in the process-efficiency equation in the same side as the activity term:

$$\sum_{\substack{cg \in AG(p) \\ c \in AGC(p,cg)}} var\_flo_{r,v,t,p,c,s} \cdot CEFF_{r,v,t,p,c,s} = \frac{1}{ACT\_EFF_{r,v,t,p,cg,s}} \big(var\_act_{r,v,t,p,s} + ACT\_LOSPL_{r,v,p,FX} \cdot var\_pll_{r,v,t,p,s}\big) \ , \ \forall (cg, s) \in \{AG(p) \times PRC\_TS(p)\} \qquad \text{eq. 23}$$

Here $AG(p)$ denotes the set of efficiency groups defined for process p, and the set $AGC(p, cg)$ the corresponding input fuels in each group. The loss in activity will thus require additional input fuels, exactly according to the user-defined increase in specific fuel consumption, when operating at the minimum level, because at that level the variable $var\_pll_{r,v,t,p,s}$ is equal to the activity. Hence, the process efficiency will be less when the process is operating at partial loads.

3.2.7.2. Endogenous modelling of partial load efficiency losses in advanced unit commitment formulation

In the advanced unit commitment formulation, the partial load efficiency losses occur in all three operational phases of the power plant: start-up phase, dispatching phase and shut-down phase.

In the dispatching phase, the variable $var\_pll_{r,v,t,p,s}$ corresponding to the linear losses of activity with respect to the defined efficiency loss is defined in the same way as in the basic unit commitment modelling via eq. 22 above.

In the start-up phase the activity losses are defined according to the following equations:

$$var\_pll_{r,v,t,p,s} \geq \sum_{upt} \sum_{ts \in C(P(s))} \left(\left(mod\left(-RS\_HR_{r,s} + RS\_HR_{r,ts} + \frac{G\_YRFR_{r,sl}}{2 \cdot RS\_STGPRD_{r,s}} + \frac{2}{G\_CYCLE_{tsl}}, \frac{1}{G\_CYCLE_{tsl}} \right) < \frac{ACT\_SDTIME_{r,v,p,upt,UP}}{8760} \right) \cdot \left(1 + \min\left(1, \frac{mod\left(-RS\_HR_{r,s} + RS\_HR_{r,sl} + \frac{G\_YRFR_{r,sl} - G\_YRFR_{r,s}}{2 \cdot RS\_STGPRD_{r,s}} + \frac{2}{G\_CYCLE_{tsl}}, \frac{1}{G\_CYCLE_{tsl}} \right)}{\left(\frac{ACT\_SDTIME_{r,v,p,upt,UP}}{8760} \right)} \right) \cdot (DP\_PSUD_{r,v,p,upt,UP} - 1) \right) \cdot var\_upt_{r,v,t,p,ts,UP} \right) \cdot CA_{r,p} \cdot G\_YRFR_{r,s} \cdot ACT\_MINLD_{r,v,p} \quad , \forall\, tsl \in PRC\_TSL(p), \ \ \forall s \in PRC\_TS(p) \qquad \text{eq. 24}$$

In the shut-down phase the activity losses are defined according to the following equations:

$$var\_pll_{r,v,t,p,s} \geq \sum_{upt \in \{\mathrm{HOT}\}} \sum_{ts \in UPS(p)} \left(\left(mod\left(RS\_HR_{r,s} - RS\_HR_{r,ts} + \frac{G\_YRFR_{r,sl}}{2 \cdot RS\_STGPRD_{r,s}} + \frac{2}{G\_CYCLE_{tsl}}, \frac{1}{G\_CYCLE_{tsl}} \right) < \frac{ACT\_SDTIME_{r,v,p,upt,UP}}{8760} \right) \cdot \left(1 + \min\left(1, \frac{mod\left(+RS\_HR_{r,s} - RS\_HR_{r,sl} + \frac{G\_YRFR_{r,sl} - G\_YRFR_{r,s}}{2 \cdot RS\_STGPRD_{r,s}} + \frac{2}{G\_CYCLE_{tsl}}, \frac{1}{G\_CYCLE_{tsl}} \right)}{\left(\frac{ACT\_SDTIME_{r,v,p,upt,UP}}{8760} \right)} \right) \cdot (DP\_PSUD_{r,v,p,upt,LO} - 1) \right) \cdot var\_los_{r,v,t,p,ts,UP} \right) \cdot CA_{r,p} \cdot G\_YRFR_{r,s} \cdot ACT\_MINLD_{r,v,p} \quad , \forall\, tsl \in PRC\_TSL(p), \ \ \forall s \in PRC\_TS(p) \qquad \text{eq. 25}$$

In both equations the parameter $DP\_PSUD_{r,v,p,upt,bd}$ is given by the following assignment:

$$DP\_PSUD_{r,v,p,upt,bd} = \frac{ACT\_MINLD_{r,v,p}}{ACT\_SDTIME_{r,v,p,bd}} \cdot \left(\frac{ACT\_LOSSD_{r,v,p,upt,bd}}{ACT\_LOSSPL_{r,v,p,FX}} - 1 \right) / \left(ACT\_MINLD_{r,v,p,} - \frac{ACT\_MINLD_{r,v,p}}{ACT\_SDTIME_{r,v,p,bd}} \right) \qquad \text{eq. 26}$$

The parameter $DP\_PSUD_{r,v,p,upt,bd}$ is an adjustment of the increased specific fuel consumption due to partial load efficiency losses at the start-up load in order the variable $var\_pll_{r,v,t,p,s}$ calculated by eq. 24 and eq. 25 above to be calibrated so as to simultaneously hold: i) at the start-up and shut-down loads the implied overall efficiency in eq. 23 to be equal to the user defined efficiency

$\frac{ACT\_EFF_{r,v,t,p,c,s}}{1+ACT\_LOSSD_{r,v,p,upt,bd}}$; and ii) the variable $var\_pll_{r,v,p,t,s}$ be equal to the activity when the process reaches the minimum stable operation level at the end of the start-up phase (or at the beginning of the shut-down phase), in order to form a continuous partial load efficiency function in all three operational phases of the process, start-up phase, dispatching phase and shut-down phase.

By endogenously modelling the partial load efficiency losses in all three operating phases of a power plant (i.e. by combining the equations eq. 22 - eq. 26) the resulted activity losses vs load and efficiency vs load curves are similar to the ones presented in section 2.2.1, and replicated below in Figure 8.

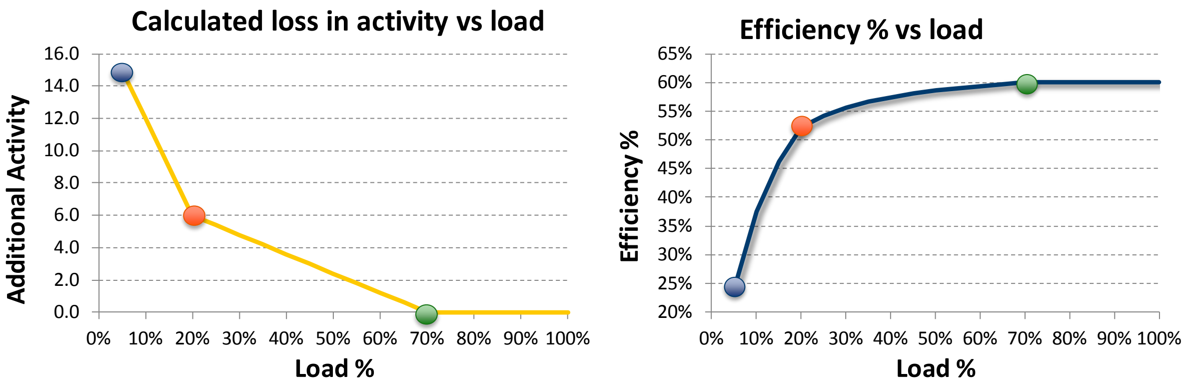


Figure 8: Demonstration of the linearized efficiency losses calculated by the variable var_pll and the resulted overall efficiency vs load curve, when partial load efficiency losses are endogenously modelled in all three operating phases of a unit. The blue point corresponds to the start-up/shut-down load, the red point to the minimum stable operation level and the green point to a load at the dispatching phase above which no partial load efficiency losses occur.

3.2.7.3. *Modelling efficiency losses as a penalty cost*

When modelling efficiency losses a penalty cost there is no increase in fuel consumption or in emissions due to the reduction of the overall efficiency of the process. The costs are directly accounted into the objective function, and this implies that the assumed fuel increase coefficient must be embedded into the parameter $ACT\_CSTPL_{r,v,p,cur}$. Therefore this parameter is defined as cost per unit of lost activity.

It follows from the definition of the parameter that the same $var\_pll_{r,v,t,p,s}$ variables defining the activity loss due to partial load efficiency are also used in this approach. However, the activity-efficiency equation eq. 23 does not include the $var\_pll_{r,v,t,p,s}$ term in order not to account for increased fuel consumption.

To account for the efficiency penalty cost into the objective function, the sum of the $var\_pll_{r,v,t,p,s}$ must be multiplied by the cost attribute $ACT\_CSTPL_{r,v,p,cur}$ and discounted into the base year:

$$obj_{PL} = \sum_{r,t}\left(NPV_{r,t} \cdot \sum_{p,v} ACT\_CSTPL_{r,v,p,cur} \cdot \sum_{s\in PRC\_TSL(p)} var\_pll_{r,v,p,t,s}\right) \qquad \text{eq. 27}$$

The modelling of partial load efficiency losses as a penalty cost can be used for any process, regardless of how the process efficiency has been modelled. However, when the analysis requires completeness of the energy and emission balances then the endogenous efficiency approach should be used. In addition, note that the penalty cost approach cannot be used for processes modelled with the advanced unit commitment formulation.

3.2.8. Minimum online and offline times

Operational performances of power plants can also be characterised by constraints, which will require a minimum offline time before a shut-down and the next start up, and a minimum online time between a start-up and the subsequent shut-down, to sustain production and avoid thermal stress. For example, when a thermal power plant has been turned off, it usually needs a cool down for a while before it can be started up again. We differentiate the modelling of minimum online and offline time requirements between the basic and advanced unit commitment formulations.

3.2.8.1. Basic unit commitment formulation

In the basic unit commitment formulation, the constraint of the minimum online time is imposed by the following equation:

$$\sum_{ts\in C(P(s))} var\_ups_{r,v,t,p,s}\cdot\left(mod\left(RS\_HR_{r,s}-RS\_HR_{r,ts}+\frac{G_{YRFR_{r,s}}}{2\cdot RS\_STGPRS_{r,s,}}+\frac{1}{G\_CYCLE_{tsl}},\frac{1}{G\_CYCLE_{tsl}}\right)<\frac{ACT\_TIME_{r,v,p,UP}}{8760}\right)\le var\_oncap_{r,v,tp,s}\;,\forall\, tsl\in PRC\_TSL(p),\;\;\forall\, s\in PRC\_TS(p) \qquad \text{eq. 28}$$

The above equation imposes the restriction that the nominal online capacity of the process remains above the started capacity as long as the time passed since the start-up of the process is less than the minimum online time requirement.

The minimum offline time constraint is imposed in a similar way by the following equation:

$$\sum_{ts\in C(P(s))} var\_los_{r,v,t,p,s}\cdot\left(mod\left(RS\_HR_{r,s}-RS\_HR_{r,ts}+\frac{G_{YRFR_{r,s}}}{2\cdot RS\_STGPRS_{r,s,}}+\frac{1}{G\_CYCLE_{tsl}},\frac{1}{G\_CYCLE_{tsl}}\right)<\frac{ACT\_TIME_{r,v,p,LO}}{8760}\right)\le var\_off_{r,v,tp,s}\;,\forall\, tsl\in PRC\_TSL(p),\;\;\forall s\in PRC\_TS(p) \qquad \text{eq. 29}$$

According to the above equation, the offline capacity of the process must be above the shut-down capacity as long as the time passed since the last shut-down of the process is less than the required minimum offline time.

The minimum online and offline constraints can be defined only at the process time slice level. If the process level tsl is DAYNITE the minimum times can be at most 24 hours (which would disable any daily start-ups). If the process level is WEEKLY, the online and offline times are calculated module 8760/G_CYCLE(WEEKLY) instead of 24. Normally, G_CYCLE(WEEKLY) is about 52, and thus the times are calculated modulo 24x7.

3.2.8.2. Advanced unit commitment formulation

In the advanced unit commitment formulation, eq. 30 replaces eq. 28 when modelling the minimum online time requirement. The two equations follow the same logic, but eq. 30 adjusts for the start-up and shut-down times:

$$var\_on_{r,v,t,p,s} \geq \sum_{upt} var\_upt_{r,v,t,p,upt,UP} \cdot \sum_{ts \in C(P(s))} \left(mod \left(RS\_HR_{r,s} - RS\_HR_{r,ts} - \frac{1}{G\_CYCLE_{tsl}}, \frac{1}{G\_CYCLE_{tsl}} \right) < \frac{(ACT\_TIME_{r,v,p,UP} - ACT\_SDTIME_{r,v,p,HOT,LO} - ACT\_SDTIME_{r,v,p,upt,UP})}{8760} + \frac{G\_YRFR_{r,ts}}{2 \cdot RS\_STGPRD_{r,s}} \right), \forall\, tsl \in PRC\_TSL(p),\ \ \forall\, s \in PRC\_TS(p) \quad \text{eq. 30}$$

The above equation requires the online capacity to remain at least equal to the started capacity for as long as the time passed from the last start-up is less than the minimum online time requirement by excluding the start-up and shut-down times (because the variable var_on is set at the dispatching phase of the power plant).

The following equation, eq. 31, implements the minimum offline constraint. The equation replaces eq. 29 when the advanced unit commitment formulation is used. The equation states that the offline capacity of the process must remain above the shut-down capacity for as long as the time passed since the last shut-down is less than the minimum offline requirement. The duration of the shut-down phase is excluded from the counting of the hours passed from the time when the shut-down capacity was set, because the variable $var\_los_{r,v,t,p,s}$ is set at the beginning of the shut-down phase.

$$var\_off_{r,v,t,p,s} \geq \sum_{ts \in C(P(s))} \left(var\_los_{r,v,p,t,s} \cdot mod \left(RS\_HR_{r,s} - RS\_HR_{r,ts} - \frac{ACT\_SDTIME_{r,v,p,HOT,LO}}{8760} + \frac{G\_YRFR_{r,s}}{2 \cdot RS\_STGPRD_{r,s}} + \frac{2}{G\_CYCLE_{tsl}}, \frac{1}{G\_CYCLE_{tsl}} \right) < \frac{ACT\_TIME_{r,v,p,LO}}{8760} \right), \forall\, tsl \in PRC\_TSL(p),\ \ \forall\, s \in PRC\_TS(p) \quad \text{eq. 31}$$

As it is in the case of eq. 28 and eq. 29, the minimum online and offline constraints in the advanced unit commitment formulation are only imposed at the process time slice level and the cycling is defined through the C_CYCLE_{tsl} parameter.

3.2.9. Ramping and start-up/shut-down costs

a) The increase or decrease in output load of a process may result in ramping costs per unit of load (i.e. unit of capacity), as mentioned in section 2. The costs are directly applied to the differences in the load level between successive time slices during the dispatching phase and at the process operating level. The following equation calculates the changes in the load $var\_ldc_{r,v,t,p,s,bd}$ during the dispatching phase:

$$\left(\frac{var\_act_{r,v,t,p,s-1}}{G\_YRGR_{r,s-1}} - \frac{var\_act_{r,v,t,p,s}}{G\_YRGR_{r,s}} \right) \cdot \frac{1}{CA_{r,p}} = var\_ldc_{r,v,t,p,s,LO} - var\_ldc_{r,v,t,p,s,UP} - ACT\_MINLD_{r,v,p} \cdot \left(var\_off_{r,v,t,p,s-1} - var\_off_{r,v,t,p,s} \right), \forall s \in PRC\_TS(p) \quad \text{eq. 32}$$

In the above equation the variable $var\_ldc_{r,v,t,p,s,LO}$ holds load decreases, while the variable $var\_ldc_{r,v,t,p,s,UP}$ holds load increases. The two variables appear together in the equation since at each time slice s only one of the two variables can be set (i.e. the load can either increase or decrease).

Having calculated the changes in the dispatchable load, the associated ramping costs are entered into the objective function as the sum of the load changes $var\_ldc_{r,v,t,p,s,UP}$ multiplied by the cost attribute $ACT\_CSTRMP_{r,v,p,UP,cur}$ for the ramping up costs, and the sum of the load changes $var\_ldc_{r,v,t,p,s,LO}$ multiplied by the cost attribute $ACT\_CSTRMP_{r,v,p,LO,cur}$ for the ramping down costs. The costs are discounted to the base year:

$$obj_{RMPC} = \sum_{r,t}\left(NPV_{r,t} \cdot \sum_{p,v,bd\in\{\mathrm{LO,UP}\}} ACT\_CSTRMP_{r,v,p,bd,cur} \cdot \sum_{s\in PRC\_TSL(p)} var\_ldc_{r,v,p,t,s}\right) \qquad \text{eq. 33}$$

b) Start-up and shut-down costs per unit of started capacity:

In the basic unit commitment formulation the start-up and shut-down costs are directly added into the objective function according to the following expression:

$$obj_{UPS} = \sum_{r,t}\left(NPV_{r,t} \cdot \sum_{p,v,tsl} ACT\_CSTUP_{r,v,p,tsl,cur} \cdot Ctc_{r,v,t,p} \cdot \sum_{s\in S(tsl)} var\_ups_{r,v,p,t,s} \cdot RS\_STGPRS_{r,s}\right) \qquad \text{eq. 34}$$

In the advanced unit commitment formulation the start-up costs per unit of started capacity are differentiated according to start-up types. Hence, the above equation is modified as:

$$obj_{UPS} = \sum_{r,t}\left(NPV_{r,t} \cdot \sum_{p,v,tsl,upt,bd\in\{\mathrm{LO,UP}\}} ACT\_CSTSD_{r,v,p,upt,bd,cur} \cdot Ctc_{r,v,t,p} \cdot \sum_{s\in S(tsl)} var\_ups_{r,v,p,t,s} \cdot RS\_STGPRS_{r,s}\right) \qquad \text{eq. 35}$$

3.2.10. Modelling individual process units

In the TIMES unit commitment extension, a discrete variable formulation of the unit commitment problem has been implemented for the modelling of individual process units. In the extension, the discrete formulation has been implemented as a MIP to overcome some drawbacks of approaches using heuristics, dynamic programming or Lagrangian relaxation. There are two ways for modelling individual processes:

- The whole capacity of each process vintage is treated as a single unit, which can be either fully online or fully offline in each individual time slice; in this approach one can optionally make use of the Discrete Capacity Extension of TIMES for prescribing the allowable sizes of the new units.

- The capacity of each process vintage can be internally divided into a number of “virtual units”, the size of which is semi-continuous, with the minimum size defined by the user.

When the discrete unit commitment formulation is enabled, it will be applied to all processes that have been modelled with the advanced unit commitment features. The usage of the discrete unit commitment formulation is otherwise similar to using the linear formulations described so far in the previous sections, and it is thus straightforward to switch between the linear and discrete formulations.

3.2.10.1. Using a single unit for each process vintage

The first option provides an accurate way of unit commitment modelling, but when used for a process without the vintaged specification (*PRC_VINT*) then the whole capacity of the process is treated as a single unit. Nonetheless, when used for a process in which vintages have been specified, existing capacity units can also be treated fully separately by assigning a unique vintage year (past year) for each unit. However, the full amount of new capacity installed in any given period will be treated as a single unit, which remains a drawback of the approach even in the case with vintages. The allowable sizes of such new capacity units can be optionally prescribed by using the input parameter $NCAP\_DISC_{r,v,p,u}$, which then requires that the Discrete Capacity Extension of TIMES is also activated.

3.2.10.2. Using "virtual units" of semi-continuous sizes

The second option gives the additional flexibility of allowing the capacity of each vintage to be internally divided into "virtual units" having a size greater than a used-defined minimum size, which makes the operational constraints more realistic if the total capacity of the process is large. In the case when no vintages have been specified for a process, it is the total capacity that may be divided into these virtual units, and in the case when vintages have been specified it is the capacity of each vintage to be divided. The drawback of this option is that the characteristics of the individual virtual units, i.e. ramping rates, efficiencies, minimum online/offline times, etc., cannot be distinguished by each other. It follows that, within each vintage, the operation of the individual virtual units is not separately modelled, but only their online/offline statutes, thereby making the total online/offline capacity behaving in a discretised way.

This approach does not require activation of the Discrete Capacity Extension of TIMES.

3.2.11. Indicator constraints in advanced unit commitment formulation

In order not to violate the unit commitment logic it is necessary to distinguish the different operating phases of a power plant unit. However, in the basic unit commitment formulation there are only two distinct phases (dispatching phase and offline phase) hence the distinction between them can be well achieved by using the continuous variables for online and offline capacities. However, in the advanced unit commitment formulation there are four distinct phases (offline, start-up, dispatching and shut-down phases) which cannot be always distinguished by only using continuous variables.

Therefore, in the advanced unit commitment modelling formulation, the non-negativity of offline, start-up, dispatchable, and shut-down capacity variables at each time slice is controlled by a set of a binary variables and a corresponding set of indicator constraints[5], i.e. constraints the enforcement of which depends on the value of a binary variable. In this way, the logic of the unit commitment is not violated.

The first set of indicator constraints below is enforced when the corresponding indicator variable $var\_onind_{r,v,t,p,s,bd}$ is 1:

$$var\_onind_{r,v,t,p,s-1,N} = 1 \rightarrow \Big(+var\_on_{r,v,ts,p,s-1} - \textstyle\sum_{sl\in P(s)} \Big(var\_mof_{r,v,t,p,sl} - \big(var\_cap_{r,v,t,p} - \textstyle\sum_{ss\in SUP(s)\cap UPS(p)} var\_off_{r,v,t,p,ss}\big)\Big) - \Big(\big(var\_cap_{r,v,t,p} - \textstyle\sum_{ss\in SUP(s)\cap UPS(p)} var\_off_{r,v,t,p,ss}\big) + var\_los_{r,v,p,t,s-1} + var\_ups_{r,v,t,p,s}\Big)\Big) \cdot \qquad \text{eq. 36}$$

---

[5] An indicator constraint is a way for a user of the Callable Library (C API) to express relationships among variables by identifying a binary variable to control whether or not a specified linear constraint is active [8]. In other solvers, such as Gurobi, the indicator constraints can be implemented by using SOS variables or bigM formulation.

$(NCAP\_SEMI_{r,v,p} = 0) \geq 0$

$$var\_onind_{r,v,t,p,s-1,N} = 1 \rightarrow \left(+var\_on_{r,v,t,p,s-1} - var\_udp_{r,v,t,p,s-1} \cdot \left(tsl \notin PRC\_TSL(p)\right) - NCAP\_SEMI_{r,v,p}\right) \cdot (NCAP\_SEMI_{r,v,p} > 0) \geq 0 \quad \text{eq. 37}$$

$$var\_onind_{r,v,t,p,s-1,FX} = 1 \rightarrow \left(var\_ups_{r,v,t,p,s-1} + var\_los_{r,v,t,p,s-1} - NCAP\_SEMI_{r,v,p}\right) \cdot (NCAP\_SEMI_{r,v,p} > 0) \geq 0 \quad \text{eq. 38}$$

$$var\_onind_{r,v,t,p,s-1,UP} = 1 \rightarrow \left(var\_udp_{r,v,t,p,s-1} - NCAP\_SEMI_{r,v,p}\right) \cdot (NCAP\_SEMI_{r,v,p} > 0) \geq 0 \quad \text{eq. 39}$$

$$var\_onind_{r,v,t,p,s-1,LO} = 1 \rightarrow \left(var\_cap_{r,v,t,p} - var\_on_{r,v,t,p,s-1} - NCAP\_SEMI_{r,v,p}\right) \cdot (NCAP\_SEMI_{r,v,p} > 0) \geq 0 \quad \text{eq. 40}$$

The indicator constraint eq. 36 sets the started-up and shut-down capacity to zero when a process is online, and hence distinguishes the dispatching phase from the start-up and shut-down phase. This constraint holds only when no “virtual units” are defined for process p. Otherwise, the indicator constraints imposed by eq. 37 – eq. 40 replace the indicator constraint eq. 36. In this context, eq. 37 ensures that when a process with “virtual units” is online, then the online capacity is at least the size of one “virtual unit”. The next constraint, eq. 38, enforces that when a process with “virtual units” is online, then at least one “virtual unit” of this process has been started-up and also must be shut-down at the end of the operating phase of the process. Finally, eq. 39 and eq. 40, allow the total online capacity of a process with “virtual units” enabled to behave in discretise way.

The following set of indicator constraints is enforced when the corresponding variable $var\_onind_{r,v,t,p,ts,bd}$ is set to 0:

$$var\_onind_{r,v,t,p,s-1,N} = 0 \rightarrow \sum_{sl \in P(s)} \left(var\_udp_{r,v,t,p,sl} + var\_ups_{r,v,t,p,s-1}\right) \cdot (s \in PRC\_TS(p)) \leq 0 \quad \text{eq. 41}$$

$$var\_onind_{r,v,t,p,s-1,N} = 0 \rightarrow var\_on_{r,v,t,p,s-1} - var\_udp_{r,v,t,p,s-1} \cdot \left(tsl \notin PRC\_TSL(p)\right) + var\_ups_{r,v,t,p,s-1} \leq 0 \quad \text{eq. 42}$$

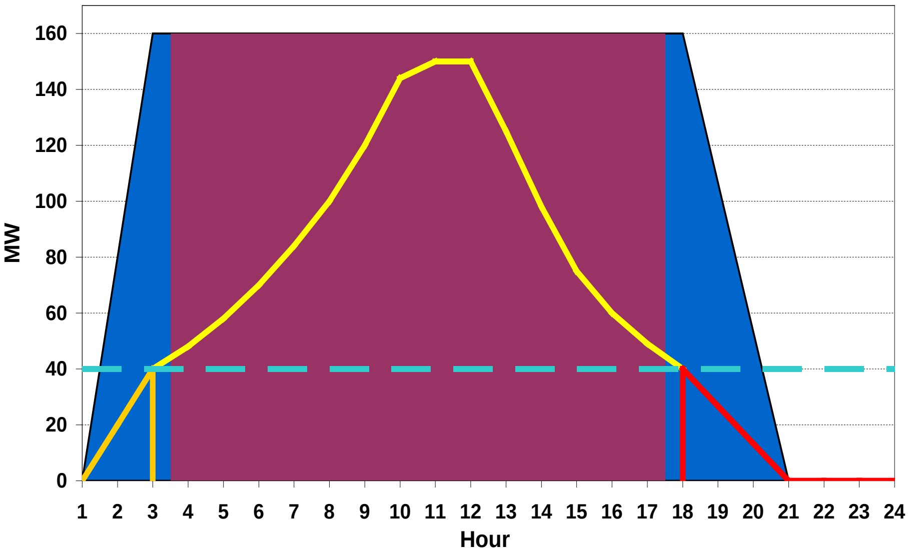
$$var\_onind_{r,v,t,p,s-1,FX} = 0 \rightarrow var\_ups_{r,v,t,p,s-1} + var\_los_{r,v,t,p,s-1} \leq 0 \qquad \text{eq. 43}$$

$$var\_onind_{r,v,t,p,s-1,LO} = 0 \rightarrow$$
$$var\_cap_{r,v,t,p,s-1} - var\_on_{r,v,t,p,s-1} + var\_los_{r,v,t,p,s-1} \leq 0 \qquad \text{eq. 44}$$

$$var\_onind_{r,v,t,p,ts,UP} = 0 \rightarrow var\_udp_{r,v,t,p,ts} \leq 0 \qquad \text{eq. 45}$$

The above indicator constraints, when a process if offline enforce the dispatchable, started and shut-down capacity to be 0 either "virtual units" are modelled or not.

The following figure presents an example of the combined operation of the indicator constraints together with the slanting equation. In this example, the indicator variable remains at 1 as long as the process is in the dispatching phase (no modelling of "virtual units" is assumed in this example).



t	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
On-line	0	0	160	160	160	160	160	160	160	160	160	160	160	160	160	160	160	0	0	0	0	0	0	0
Slanted	0	20	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	27	13	0	0	0	0
On_indic	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0

Figure 9: The blue triangles indicate the slanted on-line capacity, the red rectangle indicate the full online capacity and the table below shows the values of the two capacities together with the values of the online indicator binary variable.

4. Implementation in GAMS

4.1. Overview

As discussed in section 2 special facilities have been implemented into TIMES for modelling the unit commitment features to improve the dispatching of the electricity generation processes. These features can be useful for analysing also the impacts of integrating large amounts of variable renewable generation into the electricity system, as well as for analysing the value of technical flexibility into the system.

4.2. SETS

There is an additional set introduced in the TIMES *upt={HOT, WARM, COLD}* denoting the different start-up types of a unit, depending on its non-operational time after shut-down and before the next start-up.

4.3. PARAMETERS

4.3.1. Input parameters

There is a number of additional input parameters that have been implemented for the dispatching features in TIMES, and should be available for the user input in the user shell.

Table 6: Input parameters for the TIMES dispatching and unit commitment features

Parameter	**Description**
I. Basic input parameters	
G_CYCLE (tsl)	Number of cycles in an average year. Unit: dimensionless
ACT_MINLD (r, v, p)	Defines the minimum stable operating level of online capacity of process p, vintage v in region r. Unit: percentage of the installed capacity
ACT_UPS (r, v, p, s, bd)	Defines the ramping limits for the activity of process p, vintage v in region r and time slice s: • bd=UP: it corresponds to the ramp-up rate • BD=LO: it corresponds to the ramp-down rate. Unit: percentage of online capacity per hour
ACT_CSTUP (r ,v, p, tsl, cur)	Defines the start-up costs of process p, vintage v in region r and time slice level tsl, when different start-up types are not explicitly modelled. Unit: currency units per unit of started-up capacity
ACT_TIME (r, v, p, bd)	For a process p, vintage v in region r the definition of the parameter within the time slice cycles of the process time slice level depends on the bd index as follows: • bd=UP: it corresponds to the minimum operating time of online capacity. Unit: hours • bd=LO: it corresponds to the minimum down time of offline capacity within the time slice cycles of the process time slice level of process p, vintage v in region r. Unit: hours • bd=N: if start-up costs have been defined on the process time slice level it defines the maximum number of start-up cycles of process p, vintage v in region r within the process time slice cycles (usually daily cycles). If start-up costs have not been defined, it just enables start-ups on the WEEKLY level for a DAYNITE process. Unit: dimensionless
ACT_CSTRMP (r, v, p, bd, cur)	For a process p, vintage v, in region r, the parameter defines: • bd=UP: it defines ramp up costs • bd=LO: it defines ramp down costs Unit: currency units per capacity unit
ACT_LOSPL (r, v, p, bd)	For a process p, vintage v in region r, depending on the index bd the parameter defines: • bd=FX: it defines the proportional increase in specific

	fuel consumption at the minimum operating level, when modelling partial load efficiencies endogenously. Unit: dimensionless • bd=LO: it defines the minimum stable operating level used for the partial load efficiency function (regardless if the partial load efficiencies are modelled endogenously or as a penalty cost). Its default value is taken from ACT_MINLD(r,v,p) and this is what it is recommended, but if neither is specified then the default value is set to 0.1. Unit: fraction of installed capacity • bd=UP: it defines the fraction of the feasible load range above the minimum operating level (given by ACT_LOSPL(r,v,p,'LO')), below which the efficiency losses are assumed to occur. Default value is 0.6. Unit: fraction of installed capacity
ACT_CSTPL (r, v, p, cur)	Defines the additional cost per activity at the minimum operating level, corresponding to the efficiency loss at that level, for a process p, vintage v in region r. Note: the ACT_LOSPL(r,v,p,'FX') parameter is not taken into account when modelling these additional costs, and therefore the assumed fuel increase coefficient must be embedded in the ACT_CSTPL value
II. Additional advanced input parameters	
ACT_CSTSD (r, v, p, upt, bd, cur)	For a process p, vintage v, region r and start-up type upt, the definition of the parameter depends on the bd index as follows: • bd=UP: it defines start-up costs • bd=LO: it defines shut-down costs Unit: currency units per unit of started-up capacity Note: When this parameter is used, then the parameter ACT_CSTUP(r,v,p,tsl,cur) should not be used, and is ignored.
ACT_MAXNON (r, v, p, upt)	Maximum non-operational time before transition to next stand-by condition of process p, vintage v in region r and by start-up type upt ∈ {HOT, WARM, COLD}. Unit: hours
ACT_SDTIME (r, v, p, upt, bd)	For a process p, vintage v, in region r and start-up type upt, the definition of the parameter depends on the bd index as follows: • bd=UP: it defines the duration of the start-up phase of the process, by start-up type upt • bd=LO: it defines the duration of the shut-down phase of the process; note that in the shut-down phase only the tuple (bd, upt)=(LO, HOT) is valid. Unit: hours
ACT_LOSSD (r, v, p, upt, bd)	For a process p, vintage v, in region r and start-up type upt, the definition of the parameter depends on the bd index as follows: • bd=UP: it corresponds to the increase in specific fuel consumption due to partial load efficiency at the start-up load ACT_MINLD(r,v,p)/ACT_SDTIME(r,v,p,upt,UP) • bd=LO: it corresponds to the increase in specific fuel consumption due to partial load efficiency at the shut-down load ACT_MINLD(r,v,p)/ACT_SDTIME(r,v,p,HOT,LO) Unit: dimensionless
NCAP_SEMI (r, v, p)	Minimum level of the semi-continuous unit size for process p, vintage y in region r. Unit: capacity unit of the process.

	An inter-extrapolation option IE $\in \{1,\ldots,5\}$ is also required (if IE is not provided or IE $\geq$10, the parameter will be applied only according to the Discrete Capacity extension, if activated). Activating the Discrete Capacity extension is not required. Remark: If the process has existing capacity defined, the minimum unit size will be reduced to the amount of existing capacity remaining in each period, if the value specified for NCAP_SEMI is exceeding it.

4.3.2. Reporting parameters

There are no additional reporting parameters for this extension. However, the existing reporting parameter for activity-related costs (CST_ACTC in TIMES, Cost_Act in VEDA-BE) has been augmented with a new component identified by the UC_N index '+', used for reporting the annualized start-up, shut-down, and ramping costs as well as the penalty costs for partial loads, by region, process vintage, and period. In the objective component reporting, these costs are included in the VAR component.

4.4. Variables

The set of variables introduced in the implementation of the dispatching features extension in TIMES is shown in Table 7 below. For other TIMES variables referred in the equations, the user is directed to Chapter 4 of the TIMES Reference Manual for more details.

Table 7: New variables for the dispatching features and unit commitment extension in TIMES.

Variable	**Definition**
VAR_UPS (r, v, t, p, s bd)	For a process p, vintage v, period t, in region r and time slice s, the definition of the variable depends on the bd index as follows: • bd=UP: it corresponds to the start-up capacity • bd=LO: it corresponds to the shut-down capacity • bd=FX: at the process time slice level it corresponds to activity losses due to partial load efficiency losses • bd=FX: at time slice level above the process operating level, it corresponds to the maximum offline capacity of process over time slice ts directly below time slice s
VAR_UDP (r, v, t, p, s, bd)	For a process p, vintage, period t, in region r and time slice s, the definition of the variable depends on the bd index as follows: • bd=UP/LO: it corresponds to changes in load levels of a process during the dispatching phase • bd=N: it corresponds to the online capacity of process p, which is a genuine endogenous variable used in the advanced unit commitment modelling • bd=FX: it corresponds to the dispatched capacity above the minimum stable operating level and below the maximum installed capacity
VAR_UPT(r, v, t, p, s, upt)	Start-up capacity of process p, vintage v, period t, in region r and time slice s by start-up type upt

4.5. Equations

Given the flexibility in the different modelling approaches of the unit commitment problem, the implementation of the extension involved the introduction of a number of new equations, which are briefly described below in Table 8.

Table 8: Equations for the new dispatching features extension in TIMES

Equation	Definition
I. Basic unit commitment formulation	
EQE_ACTUPS (r, v, t, p, tsl, bd, s)	Equation for the start-up activity. When bd=UP the equation defines the start-up/shut-down activity when no different start-up types are assumed (i.e. the basic formulation is used). When bd=FX the equation defines the dispatchable capacity at a time slice level as the difference between the installed capacity and the maximum offline capacity.
EQL_ACTUPS (r, v, t, p, tsl, bd, s)	Equation for activity offline balance. When bd=N the equation sets the maximum offline capacity at a timeslice ts to be at least the maximum offline capacity in the time slices directly below ts. When bd=FX the equation ensures that the sum of the start-up capacities in each process timeslice cycle is at least equal to the maximum offline capacity in this cycle.
EQ_CAPLOAD (r, v, t, p, s, bd)	Augmented capacity-activity equation; it defines the valid range of the activity level of the online capacity, between the maximum availability (bd=UP) and the minimum stable operating level (bd=LO).
EQ_ACTRAMP (r, v, t, p, s, bd)	Activity ramping equation. Implements maximum ramp-up (bd=UP) and ramp-down (bd=LO) rates as fractions of the nominal online capacity per hour.
EQ_ACTPL (r, v, t, p, s)	Equation for linearized activity partial load efficiency losses during the dispatching phase.
EQL_ACTUPC (r, v, t, p, tsl, bd, s)	Activity cycling constraints. When bd=UP the equation imposes the minimum online time restriction. When bd=LO the equation imposes the minimum offline time restriction. When bd=N the equation imposes a limit on the number of start-up cycles within each full process time slice cycle.
EQ_ACTRMPC (r, v, t, p, s)	Equation implementing activity ramping costs at both directions of load changes between successive time slices.
II. Additional equations considered in the advanced unit commitment formulation	
EQ_SDLOGIC (r, v, t, p, tsl, s, bd, allsow)	Equation implementing the logic of the unit commitment when different start-up types are considered (i.e. advanced linearized formulation and discrete unit commitment formulations). It replaces the EQE_ACTUPS (r, v, t, p, tsl, bd, s) equation of the basic unit commitment formulation.
EQ_SUDUPT (r, v, t, p, tsl, s, upt, allsow)	Equation for selecting the appropriate start-up type according to the non-operational time after shutdown.
EQ_SDSLANT (r, v, t, p, tsl, s, allsow)	Slanting equation for start-up and shutdown phases.
EQ_SUDLOAD (r, v, t, p, s, allsow)	Equation for linearly increasing (in the start-up phase) or decreasing (in the shutdown phase) the load of a process. It also implements the minimum stable operation level restriction during the dispatching phase. It replaces EQ_CAPLOAD when the advanced unit commitment modelling features are used.
EQ_SDMINON (r, v, t, p, s, allsow)	Minimum online capacity constraints; it replaces EQ_CAPLOAD when advanced unit commitment

	modelling features are used.
EQ_SUDPLL (r, v, t, p, tsl, s, allsow)	Equation for defining losses in activity proportional to partial load efficiency losses during the start-up and shut-down phase of the unit.
EQ_SUDTIME (r, v, t, p, tsl, s, bd, allsow)	Equation for the minimum online (bd=UP) and offline (bd=LO) time; it replaces EQL_ACTUPC when advanced unit commitment modelling features are used
EQ_SDIND_1 (r, v, t, p, tsl, s, N/IN, LO/FX/N)	Indicator constraint controlling the capacity related variables in the different operating phases of a power plant; it is enforced when the corresponding indicator variable is set to 1
EQ_SDIND_0 (r, v, t, p, tsl, s, N/IN, LO/FX/N)	Indicator constraint controlling the capacity related variables in the different operating phases of a power plant; it is enforced when the corresponding indicator variable is set to 0

4.6. CHANGES IN THE MODEL GENERATOR CODE

The implementation required small modifications to the existing code and two new components in the model generator source code. The new and modified code components are listed in Table 9 below. The new source file eqactups.vda implements the linearized basic formulation of the unit commitment, which includes the following features: minimum stable operation level, minimum online/offline times, partial load efficiency losses at the dispatching phase, ramping rates and ramping costs, limits on the number of start-up cycles. The new source file eqlducs.vda implements the advanced formulation of the unit commitment, with the following features: start-up and shut-down trajectories and costs, partial load efficiency losses at the start-up and shut-down phases, modelling of individual processes. Both new files are called from the file equ_ext.vda.

Table 9: New and modified files in the TIMES model generator code

Added file	**Description**
eqactups.vda	Declarations, pre-processing and equations of the linearized basic unit commitment formulation
eqlducs.vda	Declarations, prep-processing and equations of the advanced and discrete unit commitment formulations
Modified file	**Description of changes made**
initmty.mod	Declarations of set / parameters referred to in the standard code
preppm.mod	Interpolation/extrapolation of parameters referred to in the standard code
mod_vars.mod	Declaration of new variables
eqobjvar.mod	Expressions for the variable costs related to dispatching and unit commitment
spoint.mod	Initialization of new variables
bndmain.mod	Initialization of new variables
eqobjvar.rpt	Expressions for the variable costs related to dispatching and unit commitment
solve.stp	Fixing of new variables related to dispatching and unit commitment
recurrin.stc	Handling of new variables related to dispatching and unit commitment
clearsol.stc	Handling of new variables related to dispatching and unit commitment
rptmain.stc	Handling of new variables related to dispatching and unit commitment
initmty.vda	Declarations of sets / parameters only referred to in the VDA extension
prep_ext.vda	Interpolation/extrapolation of parameters only referred to in the VDA extension
mod_ext.vda	New equations
equ_ext.vda	Declarations of the new equations and calls for the defining routines
coef_ext.vda	Call for pre-processing routine for advanced unit commitment
initmty.dsc	Cosmetic cleanup
init_ext.dsc	Support for using NCAP_SEMI for discrete unit commitment

5. USER'S REFERENCE

5.1. ACTIVATING THE DISPATCHING FEATURES

5.1.1. Basic unit commitment

The basic unit commitment option is activated automatically, when the user sets one or more of the following input parameters: ACT_MINLD, ACT_UPS, ACT_CSTUP, ACT_TIME, ACT_CSTRMP, ACT_LOSPL, ACT_CSTPL. It is not required all the parameters to be activated by the user, but only the subset that is more appropriate for the user's analysis.

5.1.2. Advanced unit commitment

The advanced unit commitment option is activated automatically when the user sets one or more of the following input parameters: ACT_CSTSD, ACT_MAXNON, ACT_SDTIME, ACT_LOSSD. The main requirement is that when start-up costs are modelled, then in the advanced unit commitment the parameter ACT_CSTSD must be used, instead of the ACT_CSTUP of the basic unit commitment option, in order to be able to account for the different start-up types.

All input parameters of the basic unit commitment, except the ACT_CSTUP, can be used for processes modelled with the advanced approach. Once can also use the basic and advanced modelling options intermixingly for different processes, using the basic option for some processes and the advanced option for other.

5.1.3. Discrete unit commitment

The discrete unit commitment can be activated using the TIMES switch:

$SET DUC YES

Under the discrete unit commitment option, individual processes can be modelled in two ways, as already stated in previous section:

1) By treating the whole capacity of each process vintage as a single unit, which will be either fully on-line or off-line in each individual timeslice; this option does not require any additional specifications from the user, but the parameter NCAP_DISC can be optionally be utilized for specifying the allowable sizes of newly installed units.
2) By allowing the capacity of each process vintage to be internally divided into a number of "virtual units", the size of which is semi-continuous, with the minimum size defined by the user; this option requires that the minimum sizes of the virtual units are defined by the TIMES input parameter NCAP_SEMI.

The first option provides an accurate way of unit commitment modelling, but when used for a non-vintaged process, the whole capacity of the process is treated as a single unit. Nonetheless, when used for a vintaged process, existing capacity units can also be treated fully separately by assigning a unique vintage year (pastyear) for each unit. However, the full amount of new capacity installed in any given period will be treated as a single unit, which remains a drawback of the approach even in the vintaged case. The allowable sizes of such new capacity units can be prescribed by using the following input parameter:

- NCAP_DISC(r,y,p,u): Sizes of new capacity units u that can be added for process p, in region r, by model period y. Unit: capacity unit of the process.

The usage of the NCAP_DISC parameter requires additionally the activation of the Discrete Capacity Extension (DSC). The following TIMES switch can be used for activating Discrete Capacity extension of TIMES:

$SET DSCAUTO YES

The second option gives the additional flexibility of allowing the process capacity to be internally divided into “virtual units” having a size greater than a user-defined minimum size, which makes the operational constraints more realistic if the total capacity of the process is large. In the non-vintaged case, it is the total capacity that may be divided into these virtual units, and in the vintaged case it is the capacity of each vintage to be divided. The drawback of this option is that the operation of the individual virtual units is not separately modelled, but only the on-line / off-line status, thereby making the total on-line / off-line capacity behaving in a discretized way. The characteristics of the individual virtual units cannot be distinguished from each other.

When using the semi-continuous option for modelling individual processes, the following input parameter can be used for specifying the minimum unit sizes:

- NCAP_SEMI(r,y,p): Minimum level of the semi-continuous unit size for process p, vintage y in region r. Unit: capacity unit of the process. An inter-extrapolation option IE $\in \{1,\ldots,5\}$ is also required (if IE is not provided or IE $\geq$10, the parameter will be applied only according to the Discrete Capacity extension, if activated). Activating the Discrete Capacity extension is not required. If the process has existing capacity defined, the minimum unit size will reduced to the amount of existing capacity remaining in each period, if the value specified for NCAP_SEMI is exceeding it.

When the discrete unit commitment formulation is enabled ($SET DUC YES), it will be applied to all processes that have been modelled with the advanced unit commitment features, i.e. those that have start-up costs specified by using the ACT_CSTSD parameter. The usage of the discrete unit commitment formulation is otherwise similar to using the linear formulation, and it is thus straightforward to switch between the linear and discrete formulations.

5.2. Specification of input parameters

The following … lists the available user-input parameters. The following indices are used in the index domain of the parameters

Index	Meaning	Index	Meaning
r	Region	c	Commodity (other than grid node)
datayear	Period / Milestone year	s	Timeslice
p	Process	u	Unit type
v	Vintage	cur	Currency
tsl	Time slice level	bd	Bound
upt	Start-up type	allsow	States of the world (stochastic)

Table 10: Input parameters for TIMES dispatching and unit commitment features

Input parameter (Indexes)[6]	Related parameters[7]	Units / Ranges & Default values & Default inter-/extrapolation[8]	Instances[9] (Required / Omit / Special conditions)	Description	Affected equations or variables[10]
ACT_CSTPL (r,v,p,cur)	ACT_MINLD ACT_LOSPL	• Monetary unit per unit of activity • [0,∞) • default value: none • Default i/e: STD	• Used as an alternative or supplement to using ACT_LOSPL(r,y,p,'FX'). When used as an alter-native, the fuel increase at the minimum operating level that should be in-cluded in the cost penalty must be embedded in the ACT_CSTPL coefficient. • Ignored if ACT_CSTSD is defined for the process	Partial load cost penalty, defined as an additional cost per activity at the minimum operating level, corresponding to the efficiency loss at that load level. Added as an extra term to variable costs in the objective and reporting. Cannot be used for processes modelled with the advanced unit commitment formulation	• EQ_OBJVAR
ACT_CSTRMP (r,v,p,bd,cur)	ACT_UPS	• Currency units per capacity unit • [0,∞) • default value: none • Default i/e: STD	• Can be used in basic, advanced and discrete unit commitment extensions	It defines ramp-up and ramp-down costs for a processes during its dispatching phase • When bd=UP it defines ramp-up costs • When bd=LO it defines ramp-down costs	• EQ_OBJVAR

[6] The first row contains the parameter name, the second row contains in brackets the index domain over which the parameter is defined.
[7] 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.
[8] 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.
[9] 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.
[10] Equations or variables that are directly affected by the parameter

Input parameter (Indexes)[6]	Related parameters[7]	Units / Ranges & Default values & Default inter-/extrapolation[8]	Instances[9] (Required / Omit / Special conditions)	Description	Affected equations or variables[10]
ACT_CSTSD (r,v,p,upt,bd,cur)	ACT_CSTUP	• Currency units per unit of started-up capacity • [0,∞) • default value: none • Default i/e: STD	• Can only be used in the advanced and discrete unit commitment options • Activates the advanced unit commitment option • In the case of the shut-down costs only the tuple (upt, bd) = (HOT, LO) is a valid instance for this parameter • Requires the parameter ACT_MAXNON to be defined as well	Defines start-up / shut-down costs differentiated by start-up type according the standby condition of the power plant. The standby condition of a power plant depends on its non-operational time after shut-down defined via the parameter ACT_MAXNON	• EQ_OBJVAR
ACT_CSTUP (r,v,p,tsl,cur)	ACT_CSTSD	• Currency units per unit of started-up capacity • [0,∞) • default value: none • Default i/e: STD	• Start-ups occur by default at the SEASON level, unless costs on other levels are specified through this parameter. • It can only be used in the basic unit commitment extension	Defines the start-up costs of a process, when the basic unit commitment extension is used. The distinction between different start-up types is based on the timeslice level, the DAYNITE level corresponding to a hot/warm start-up and the SEASON level to a cold start-up.	• EQ_OBJVAR
ACT_LOSPL (r,v,p,bd)	ACT_LOSSD, ACT_MINLD, ACT_EFF	• Dimensionless • [0,∞); default value: ACT_LOSPL(LO)=0.1 ACT_LOSPL(UP)=0.6 • Default i/e: STD	• Can be used in basic, advanced and discrete unit commitment extensions • It is recommended that the minimum operating level above which partial load efficiency losses occur to be defined with	Definition depends on the index **bd**: • When bd=LO it defines the minimum load level above which partial load efficiency losses occur during the dispatching phase as a fraction of the installed capacity. If not provided then the value of the ACT_MINLD parameter is used. If both ACT_LOSPL(LO) and	• EQ_ACTPL • EQE_ACTEFF • EQ_SUDPLL

Input parameter (Indexes)[6]	**Related parameters**[7]	**Units / Ranges & Default values & Default inter-/extrapolation**[8]	**Instances**[9] (Required / Omit / Special conditions)	**Description**	**Affected equations or variables**[10]
			the ACT_MINLD parameter, the value of which will be used by the generator for ACT_LOSPL(LO) • The ACT_LOSPL(FX) instance does not affect the penalty cost modeled via ACT_CSTPL	ACT_MINLD) are not provided then the default value is ACT_LOSPL(LO) = 0.1 • When bd=UP, defines the load level, as fraction of the installed capacity, above which no partial load efficiency losses occur during the dispatching phase. If not provided, the default value is 0.6. • When bd=FX, it defines the proportional increase in specific fuel consumption at the minimum level defined by ACT_LOSPL(LO)	
ACT_LOSSD (r,v,p,upt,bd)	ACT_LOSPL, ACT_MINLD, ACT_SDTIME ACT_EFF	• Dimensionless • [0,∞) • default value: none • Default i/e: STD	• Can be only used in the advanced and discrete unit commitment modelling option, i.e. requires that also ACT_CSTSD has been defined for the process	Used for modeling endogenous partial load efficiency losses during the start-up and shut-down phases. Its definition depends on the **bd** index as follows: • When bd=UP it corresponds to the increase in specific fuel consumption due to partial load efficiency losses at the start up load level defined by the ratio ACT_MINLD/ACT_SDTIME(upt, UP) for each start-up type upt • When bd=LO it corresponds to the increase in specific fuel consump-tion due to partial load efficiency losses at the start up load level defined by the ratio ACT_MINLD / ACT_SDTIME(HOT,LO)	• EQ_ACTPL • EQ_SUDPLL

Input parameter (Indexes)[6]	Related parameters[7]	Units / Ranges & Default values & Default inter-/extrapolation[8]	Instances[9] (Required / Omit / Special conditions)	Description	Affected equations or variables[10]
ACT_MAXNON (r,v,p,upt)	ACT_CSTSD	• Hours • [0,∞) • default value: none • Default i/e: STD	• Can be only used in the advanced and discrete unit commitment modelling option, i.e. requires that ACT_CSTSD has also been defined for the process • By default the instance ACT_MAXNON(COLD) is set to 0 and it can be omitted by the user	Defines the maximum non-operational time after a shut-down before a process changes a standby condition from HOT to WARM and from WARM to COLD • When upt=HOT it defines the maximum non-operational time before the process changes stand-by condition to warm • When upt=WARM it defines the maximum non-operational time before the process changes stand-by condition to cold	• EQ_SUDUPT
ACT_MINLD (r,v,p)	ACT_LOSPL, ACT_LOSSD, ACT_UPS	• Percentage of installed capacity • [0,1] • default value: none • Default i/e: STD	• Can be used in basic, advanced and discrete unit commitment extension	Minimum stable operating level of online capacity.	• EQ_ACTPL • EQ_ACTRMPC • EQ_SUDLOAD • EQ_SUDPLL
ACT_SDTIME (r,v,p,upt,bd)	ACT_CSTSD, ACT_LOSSD	• Hours • [0,∞) • default value: none • Default i/e: STD	• Can only be used in advanced and discrete unit commitment, i.e. requires that ACT_CSTSD has also been defined for the process • When specifying the duration of the shut-down phase, only the tuple (upt,bd)=(HOT,LO) is valid	Defines the duration of the start-up and shut-down phases of a power plant: • When bd=UP it defines the duration of the start-up phase for a start-up type upt • When bd=LO it defines the duration of the shut-down phase	• EQ_ACTPL • EQ_SDSLANT • EQ_SDMINON • EQ_SUDTIME • EQ_SUDPLL

Input parameter (Indexes)[6]	Related parameters[7]	Units / Ranges & Default values & Default inter-/extrapolation[8]	Instances[9] (Required / Omit / Special conditions)	Description	Affected equations or variables[10]
ACT_TIME (r,v,p,bd)	ACT_CSTUP, ACT_CSTSD, ACT_MINLD	• Hours • [0,∞); default value: none • Default i/e: STD	• Can be used in basic, advanced and discrete unit commitment modelling • Requires that ACT_MINLD has been defined for the process	Defines the minimum online and offline time for a process in hours. When bd=UP it corresponds to the minimum operating (online) time. • When bd=LO it corresponds to the minimum offline time • When bd=N and start-up costs have been defined, it defines the maximum number of start-up cycles • When bd=N and no start-up costs have been specified, it just enables zero-cost start-ups on the WEEKLY level	• EQL_ACTUPC • EQ_SUDTIME
ACT_UPS (r,v,p,s,bd)	ACT_CSTRMP	• Percentage of online capacity per hour • [0,1]; default value: none • Default i/e: STD	• Can be used in basic, advanced and discrete unit commitment extension	Defines the ramping limits at the dispatching phase of a process • When bd=UP corresponds to the ramp-up rate • When bd=LO corresponds to the ramp-down rate	• EQ_CAPLOAD • EQ_ACTRAMP • EQL_ACTUPC • EQ_RL_THMIN
G_CYCLE (tsl)	RS_STGPRD	• Dimensionless • Default value: 1 for ANNUAL and SEASONAL level, 52.14 for WEEKLY, 365 for DAYNITE • Default i/e: none	• Optional if the change of the default cycling is desired	Number of cycles in an average year	• EQL_ACTUPC • EQ_ACTPL • EQ_SUDUPT • EQ_SDSLANT • EQ_SUDTIME • EQ_SUDPLL

Input parameter (Indexes)[6]	Related parameters[7]	Units / Ranges & Default values & Default inter-/extrapolation[8]	Instances[9] (Required / Omit / Special conditions)	Description	Affected equations or variables[10]
NCAP_DISC (r,v,p,unit)	NCAP_SEMI	• Capacity unit of the process • [0,∞); default value: none • Default i/e: 1 (interpolation, no extrapolation)	• Can be used for defining block sizes of new capacity in each period • Can be used with any unit commitment option • Requires MIP	Allowed sizes of the new capacity block that can be added in each vintage period. Only a single block size among the allowed sizes can be selected by the model in each period for the amount of new capacity.	• VAR_DNCAP • EQ_DSCNCAP
NCAP_SEMI (r,v,p)	NCAP_DISC	• Capacity unit of the process • [0,∞); default value: none • Default i/e: migration	• Can be used with the discrete unit commitment option • An interpolation option IE $\in$ [1,..,5] is also required; if IE is not provided or IE≥10 the parameter will be applied only according to the Discrete Capacity extension, if activated • Activating the Discrete Capacity extension is not required • If the process has existing capacity defined, the minimum unit size will be reduced to the amount of existing capacity remaining in each period, if the NCAP_SEMI value is exceeding that	Minimum level of the semi-continuous unit size, when the approach of “virtual units” is chosen to model individual units of processes.	• EQ_SDIND_1 • EQ_SDIND_0

5.3. Usage notes for the start-up/shut-downs in the basic unit commitment

As mentioned above, when using ACT_MINLD, start-ups/shut-downs are by default enabled only at the SEASON level, with zero costs. If no start-up costs are defined, start-ups can still be optionally enabled without costs also on the WEEKLY level for DAYNITE processes, by specifying any value for the ACT_TIME(r,y,p,'N') parameter for the process. That is the only impact of this parameter when start-up costs have not been defined. More enhanced dispatchability features can be activated by defining start-up costs. Start-up costs can be optionally defined even on the SEASON level, if desired. Additional start-ups on the WEEKLY or DAYNITE levels (or both) should be enabled by specifying ACT_CSTUP on those levels accordingly. As start-ups and shut-downs will always occur in pairs, any shut-down costs can be directly included in the ACT_CSTUP parameter as well. If start-ups on some level can be assumed without additional costs, it is advisable to leave ACT_CSTUP unspecified at that level. If the start-up costs are assumed zero on some timeslice level, they must be zero also on any higher levels. When enabling start-ups on all three timeslice levels (SEASON, WEEKLY and DAYNITE) the amount of additional equations and the impact on model size may become considerable. However, compared to more accurate discrete formulations, the linearized formulation may still have substantially less impact on solution times. Possible parameter combinations are summarized in the table below.

Table 11: Specification of start-up costs and resulting start-up capability.

	Input parameters specified					**Resulting start-up capability**		
			ACT_CSTUP(TSLVL)			on timeslice levels		
Case	ACT_MINLD	ACT_TIME(N)	SEASON	WEEKLY	DAYNITE	SEASON	WEEKLY	DAYNITE
0	**No**	**NA**	**NA**	**NA**	**NA**	**(S)**	**(S)**	**(S)**
1	Yes	No	–	–	–	S	–	–
2	Yes	Yes	–	–	–	S	S	–
3	Yes	*	Yes	–	–	SC	–	–
4	Yes	*	–	Yes	–	S	SC	–
5	Yes	*	–	–	Yes	S	S	SC
6	Yes	*	Yes	Yes	–	SC	SC	–
7	Yes	*	Yes	–	Yes	S	S	SC
8	Yes	*	–	Yes	Yes	S	SC	SC
9	Yes	*	Yes	Yes	Yes	SC	SC	SC

S = start-ups enabled without cost
SC = start-ups enabled with costs

5.4. Usage notes for basic partial load efficiency modelling

The endogenous partial load efficiencies (using ACT_LOSPL(r,y,p,'FX')) and the additional costs at partial loads (using ACT_CSTPL) represent two alternative ways of modelling the impacts of partial load efficiencies, of which the latter has less impact on model size.

The ACT_LOSPL(r,y,p,'FX') parameter can only be used for processes that have their efficiency modelled by the ACT_EFF parameter (on the shadow side). The process efficiency will then be endogenously modelled according to the actual load level in each timeslice.

It is recommended that the minimum operating level is defined by the ACT_MINLD parameter, which is then used as the default value for ACT_LOSPL(r,y,p,'LO'). However, if desired, the minimum level to be assumed can also be defined by specifying ACT_LOSPL('LO').

The ACT_CSTPL parameter can be used for any process, regardless of how the process efficiency has been modelled. And because of that, both the full load efficiency and the increase in fuel consumption at the minimum operating level must be embedded in the cost parameter when modelling the additional fuel costs caused by the increased fuel consumption at partial loads (see example 2 below).

When using the pure penalty cost approach, energy and emission balances are not affected by the reduced partial load efficiencies, only the operating costs are. Consequently, if completeness of the energy and emission balances is important, one should use the endogenous efficiency approach instead.

Examples:

1. Assume that we want to define endogenous partial load efficiencies, such that the specific fuel consumption increases by 20% when the load is at its minimum level, 30%. Provided that the process efficiency has been defined by ACT_EFF, this can be modelled with the following two parameters:

   ACT_MINLD(r,y,p) = 0.3 – defines the minimum operating level

   ACT_LOSPL(r,y,p,'FX') = 0.2 – defines the increase in fuel consumption at the minimum operating level.

2. Assume that we want to define an additional activity cost corresponding to the additional fuel costs at partial loads, such that the specific fuel consumption increases by 20% when the load is at its minimum level, 30%. Assume that the full load efficiency is 40% and the fuel price is 7 €/GJ. This can be modelled with the following two parameters:

   ACT_MINLD(r,y,p) = 0.3 – defines the minimum operating level

   ACT_CSTPL(r,y,p,'EUR') = 7 × 0.2 / 0.4 = 3.5 – defines the fuel cost for the increased fuel consumption at partial loads (7 €/GJ of additional fuel), by specifying the equivalent additional activity cost at the minimum operating level.

5.5. Usage notes for advanced and discrete unit commitment modelling

As mentioned above, using the advanced unit commitment features for a given process requires that the start-up costs for that process have been specified by using the *ACT_CSTSD* parameter instead of using the basic *ACT_CSTUP* parameter. Defining the *ACT_CSTSD* parameter thus activates the advanced unit commitment formulation for any single process.

Apart from the penalty costs (*ACT_CSTPL*), all other basic attributes can be used also for processes modelled with the advanced approach. One can also use the basic and advanced modelling options intermixingly for different processes, using the basic option for some processes and the advanced option for other. However, one should note that the discrete unit commitment modelling is supported only for processes modelled with the advanced features, i.e. those that have start-up costs specified by using the *ACT_CSTSD* parameter.

When the discrete unit commitment formulation is enabled, it will be applied to all processes that have been modelled with the advanced unit commitment features, i.e. those that have start-up costs specified by using the *ACT_CSTSD* parameter. The usage of the discrete unit commitment formulation is otherwise similar to using the linear formulation, and it is thus straightforward to switch between the linear and discrete formulations.

5.6. Illustrative example

To illustrate the usage of the input parameters we present some illustrative examples, based on a model with 24 DAYNITE timeslices directly under the ANNUAL level for simplicity. We set the duration of each of the DAYNITE time slice ***s*** to be 1 hour, i.e. G_YRFR(r,s)=1/24, and the process capacity to activity conversion factor PRC_CAPACT=8.76 GWh/MW.

5.6.1. Characterisation of a process with unit commitment features

Let us define the following process EGTCC corresponding to a gas turbine combined cycle plant operating at the DAYNITE level with the following (dummy) characteristics:

Table 12: Illustrative example of a process with advanced unit commitment features enabled

Parameter	Indices	Value
NCAP_PASTI	RG. 2010. EGTCC	200
ACT_EFF	RG. 2010 .EGTCC	0.60
NCAP_AF	RG. 2010 .EGTCC. ANNUAL. UP	0.85
ACT_MINLD	RG. 2010. EGTCC	0.20
ACT_UPS	RG. 2010. EGTCC. ANNUAL. LO	0.20
ACT_UPS	RG. 2010. EGTCC. ANNUAL. UP	0.20
ACT_TIME	RG. 2010. EGTCC. LO	2.00
ACT_TIME	RG. 2010. EGTCC. UP	6.00
ACT_SDTIME	RG. 2010. EGTCC. HOT. LO	3.00
ACT_SDTIME	RG. 2010. EGTCC. HOT. UP	2.00
ACT_SDTIME	RG. 2010. EGTCC. WARM. UP	3.00
ACT_SDTIME	RG. 2010. EGTCC. COLD. UP	4.00
ACT_MAXNON	RG. 2010. EGTCC. HOT	8.00
ACT_MAXNON	RG. 2010. EGTCC. WARM	14.00
ACT_LOSPL	RG. 2010. EGTCC. UP	0.68
ACT_LOSPL	RG. 2010. EGTCC. FX	0.15
ACT_LOSSD	RG. 2010. EGTCC. HOT. LO	1.30
ACT_LOSSD	RG. 2010. EGTCC. HOT. UP	1.20
ACT_LOSSD	RG. 2010. EGTCC. WARM. UP	1.40
ACT_LOSSD	RG. 2010. EGTCC. COLD. UP	1.60

According Table 12 above, there are 200 MW installed of this process in region RG in 2010. The (full-load) efficiency of the process is 60% and its annual availability 85%. The minimum stable operation level of the process is 20% and the ramping rates are 20% for both directions.

The process must be offline at least 2 h to cool down before the next start-up. In addition, in order to sustain the electricity the process must be online at least 6 h. The start-up phase lasts 2 h if the process is at the hot state, 3 h if the process is at the warm phase and 4 h if the process is at the cold state. The process can remain at a hot stand-by condition up to 8 h after its shut-down. The process changes stand-by condition to warm from 9 h to 14 h after its shut-down. More than 14 h after its shut-down the process goes to cold state.

In the dispatching phase partial load efficiency losses occur at load levels ranging from the minimum stable operation level of 20% up to the load level of 68%. The incremental fuel consumption due to partial load efficiency is 15% at the minimum stable operation level, which implies an efficiency of 0.60/(1+0.15)=52.2% at this load.

Partial load efficiency losses occur also during the start-up and shut-down phases. In the shut-down phase the incremental fuel consumption due to partial load efficiency is 130% at the load level ACT_MINLD/ACT_SDTIME(HOT,LO) = 6.67%. This implies an efficiency of 26.1% at this load level.

In the hot start-up phase the incremental fuel consumption due to partial load efficiency is 120% at the load level ACT_MINLD/ACT_SDTIME(HOT,UP) = 10%. This implies an efficiency of 27.3% at this load level.

In the warm start-up phase the incremental fuel consumption due to partial load efficiency is 140% at the load level ACT_MINLD/ACT_SDTIME(WARM,UP) = 6.67%. This implies an efficiency of 25% at this load level.

Finally, in the cold-start-up phase, the incremental fuel consumption due to partial load efficiency is 160% at the load level ACT_MINLD/ACT_SDTIME(COLD,UP) = 5%. This implies an efficiency of 23.1% at this load level.

5.6.2. Example of dispatching output of this process

In the illustrative model to which this process belongs, the process starts from a warm state. Figure 10 shows the power output of the process in the typical day of 24h defined in the model. The power output is calculated as VAR_ACT/(G_YRGR*PRC_CAPACT).

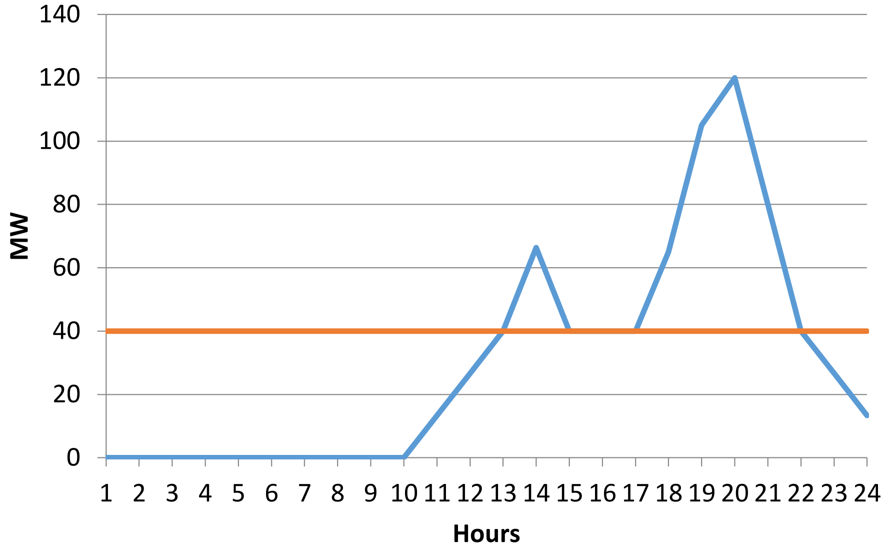


Figure 10: Dispatching profile of the illustrative process. The blue line corresponds to the power output of the process, while the red line denotes the minimum stable operating level.

The process starts from a warm state at time slice H11 and it needs 3h to reach it is minimum stable operating level of 40 MW (=200*20%) at the end of the time slice H13. Then it enters into the dispatching phase, where the power output can increase/decrease by 20% (or 40 MW) between two consecutive time slices. The process enters into the shut-down phase at time slice H22 and it completely shut-downs in time slice H01 of the next typical day. Then it shall remain offline for at least 2 h before the next start-up. This completes a cycle at the DAYNITE level.

Figure 11 presents the efficiency of the illustrative process during is operating cycle. The process starts at a warm start-up type, and at the end of the time slice H11 it reaches a load of 6.67%. As it can be seen from the figure, the efficiency at the end of the time slice H11 is 25%, exactly the same with the value specified by the user. Then the efficiency increases to 52.2% at the end of the time slice H13, by when the process has reached its minimum stable operation level. Then the process enters into the dispatching phase, in which no partial load efficiency losses occur above load levels of 68%. Finally, the efficiency at the shut-down load at one hour before shut-down (time slice H24) it is 26.1%, exactly as the efficiency specified by the user for this load level.

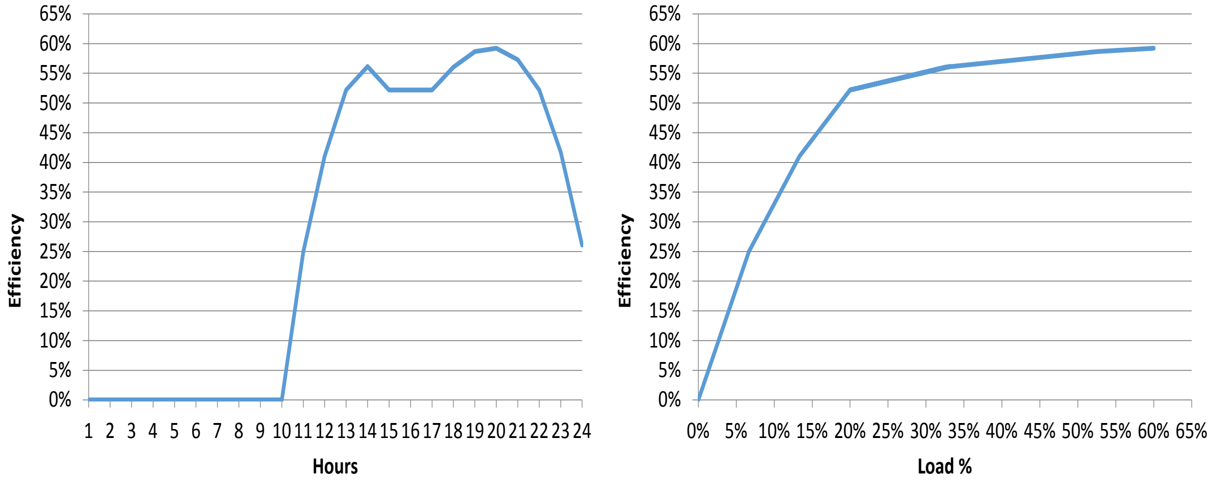


Figure 11: Efficiency of the illustrative process during its operating cycle and efficiency vs load curve.

6. References

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