Energy Technology Systems Analysis Programme
TIMES Version 4.5 User Note

Enhancing the flexibility in TIMES: Introducing Ancillary Services Markets

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December 2019
(Update November 2021)

Foreword

This report contains the full documentation on the design, implementation and use of the Ancillary Services Markets facility of the TIMES model generator.

The report is divided into five chapters. After the general introduction in Chapter 1, Chapter 2 presents the mathematical formulation of the new extension in TIMES. Section 3 presents the implementation of Ancillary Services Markets in TIMES. Chapter 4 demonstrates the use of the Ancillary Services Markets in TIMES with working examples. Finally, Chapter 5 includes a summary of the implementation.

This document is a supplement to the main documentation of the TIMES model generator (Parts I–V), available on the IEA-ETSAP website.

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1. INTRODUCTION

As variable renewable generation increases to achieve energy and climate change strategy goals, so does the need for flexibility and balancing mechanisms. These mechanisms, commonly referred to as *ancillary services*, ensure the reliable operation of the electricity system by compensating for fluctuations in supply and demand. They include a variety of activities, beyond generation and transmission of electricity, which are required to maintain grid stability and security. As the future electricity system will adapt its operation to fluctuating conditions, policymakers need to consider issues such as the effects of intermittent energy sources on the reliability and adequacy of the energy system, the impacts of stored energy or how much dispatchable backup capacity may be required to guarantee that the electricity demand is safely met. As already identified in the energy systems modelling community (see for example the workshop "Addressing flexibility in energy systems models" organized by the European Commission's Joint Research Centre – Institute for Energy and Transport (González et al. 2015)), there is a need to have a clear picture of the costs associated with the integration of renewable sources in the energy system.

The TIMES modelling framework already includes mechanisms that allow for modelling technical options for providing flexibility. For instance, a TIMES user can increase the temporal resolution (via the timeslice tree), introduce several storage options, improve the representation of the variability in electricity generation and demand (via the Residual Load Curve extension), and include detailed technical constraints (via the Unit Commitment extension). However, market-based mechanisms that have particularly designed to provide flexibility to the energy system, such as the ancillary services markets, are currently not endogenously fully supported in the framework. A common approach is to assess ancillary services markets exogenously to TIMES, via (soft-)coupling with detailed power sector models, see for example (Deane et al. 2012).

With the proposed extension, the TIMES framework can assess the true cost of variable in electricity supply and demand to the energy system and the implications on the investments decisions of having sufficient reserve capacity at hand. This is important because the energy only markets and technical approaches do not offer sufficient remuneration for the flexibility actions, the associated cost of which has also to be sought in auxiliary services markets.

1.1 A brief introduction to the Ancillary Services Markets

In general, two constraints are considered in the electricity system. The first constraint, already included in TIMES, is the balance of energy demand and supply. The second constraint, introduced in TIMES with this extension, is the balance between demand for and supply of reserve capacity that enables system operators to cope with short-term system imbalances (SI). Such imbalances are caused by different sources of uncertainty on the network load side (e.g. inaccuracy in load forecast), on the production side (e.g. plant restrictions or stoppages), or on the demand side. Thus, together with the energy markets, the system operators (SO) implement ancillary services markets to balance the demand and supply of operating reserve capacity. The operating reserve can be defined as the generating capacity available to the System Operator (SO) within a short time interval, to meet the demand in case of a disruption in energy supply.

In general, the operating reserve is made up of spinning and non-spinning or replacement reserves. The spinning reserve is the extra generation capacity that is available by increasing or decreasing the power output of generators that are already connected to the power system. The non-spinning reserve is the additional generation capacity that is currently not connected to the system, but it can be brought online after a short delay. ENTSO-E, the European Network of Transmission System Operators for Electricity, categorises the spinning and non-spinning reserves into three major groups (ENTSO-E 2018). While throughout this report we use the naming conventions mainly used to Europe, the ancillary services markets worldwide implement similar products/markets with (slightly) different names:

- The Frequency Containment Reserve (FCR), or primary control reserve: this type of reserve is activated automatically to stabilise the frequency in a matter of seconds.

- The Frequency Restoration Reserve (FRR) restores the system frequency by re-establishing the balance in the control zone. Thereby, it is activated after FCR in order to relieve the units provided FCR. The FRR can be activated automatically (aFRR), i.e. secondary control reserve, or manually (mFRR), i.e. tertiary control reserve.

- The Replacement Reserve (RR) is used to support or relief the activated FRR. Therefore, its activation follows the activation of FRR. The requirements of RR is less stringent, with full activation times up to one hour. Some system operators do not implement at all this type of reserve.

In addition to the time of activation, the control reserve can be classified as positive (upward) or negative (downward). Positive reserve occurs when there is a shortage of supply, and this means that additional units should be brought online, or storage devices should discharge, or demand units should reduce their consumption. Negative reserve occurs when there is an excess of supply, and this means that increased electricity consumption is required either through demand units or by charging batteries and pumping.

Box 1: Example of the dependencies between the different types of the operational reserve

The different types of operational reserves are not independent of each other. An overview of their interrelation is presented in Figure 1. In the example, we consider a power station failure in France. In the entire ENTSO-E region, primary control reserve is activated directly. After 30 seconds (note that the time interval can be even smaller, e.g. 5-15 seconds, depending on the system design), secondary control power is automatically called up in France and replaced after 15 minutes by tertiary control (in this example provided by power plants in France and Spain). The replacement reserve is not activated/implemented in this example.

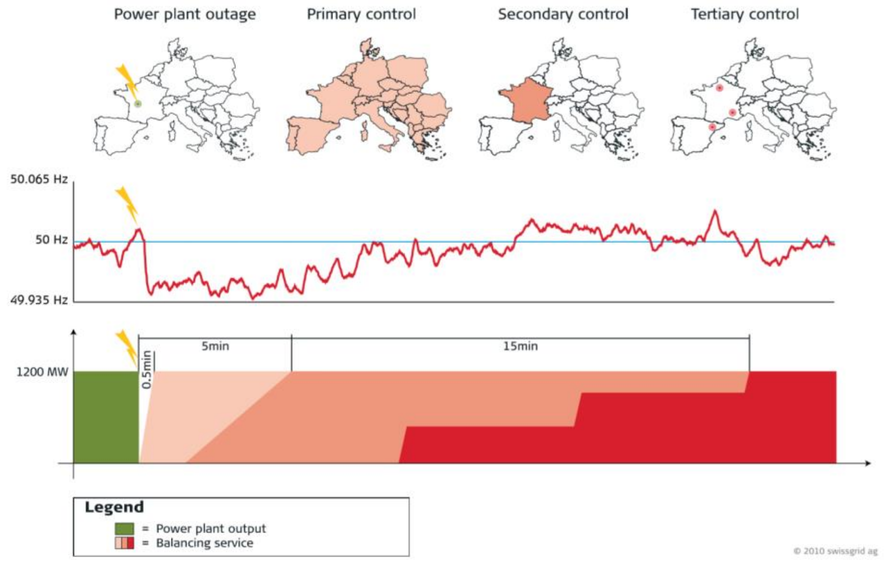

Figure 1: Reserve activation due to a power plant outage in France; the figure and the example is from (Beck and Scherer 2010)

1.2 Principles regarding the sizing of reserve requirements

The sizing, or demand, of the different types of operating reserves is complex and differs from control area to control area. The ancillary services markets often offer six or more products (or types of reserves – see the discussion in section 1.1), with each product having its own market configuration. In this section, a brief overview of the main principles is given. Typically, the sizing of reserves is the responsibility of the system operator (SO), and large countries often have more than one SO. It can be also the case that the demand for reserve is given to the SO by a regional or continental authority[1].

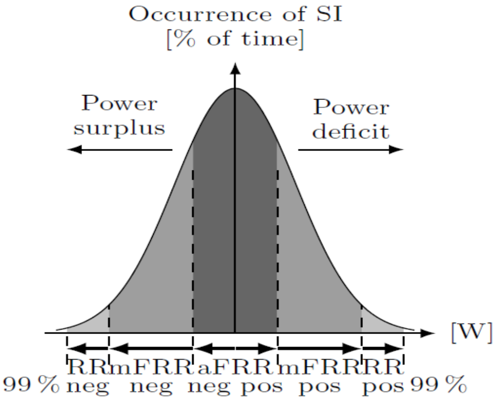

Figure 2: Probabilistic sizing of the total FRR+RR reserve needs, which is also allocated to different types of reserves

When the SO calculates the sizing of the reserve, this can be based on both deterministic and probabilistic assessments (see for example (ENTSO-E 2013a) (ENTSO-E 2013b)), which can be "exogenous", i.e. using historical information, and/or "endogenous", i.e. based on the future or expected capacities, generation or forecast errors.

The deterministic component of the reserve requirements often is equal to a percentage of the loss of the largest possible single grid element or infeed. This large system imbalance can be an existing power plant or interconnector (if the calculation of the deterministic component of reserve is "exogenous") or a future large power plant or interconnector (if the calculation of the deterministic reserve is "endogenous"). Hence, the deterministic component of reserve captures the impact of the largest possible system imbalance (SI) on the security of the system. The contracted reserve has to be sufficient to cover an event caused by this SI in both directions, positive and negative.

The probabilistic component of the reserve is based on recent historical SI time series of at least a full year (if "exogenous") or on the forecast errors (if

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[1] For example, in the ENTSO-E area in Europe the primary control reserve (FCR) is set by ENTSO-E to 3 GW, covering the outage of two of the largest network elements (N-2 criterion). This demand is distributed to the different control zones, according to their share in the European system, by accounting for both consumption and generation. For instance, in Switzerland the FCR is set to around 70 MW, in Belgium 90 – 110 MW, in Germany about 600 MW.

"endogenous"). It uses a probability density function (pdf), representing the occurrence of the SI[2]. The total contracted reserve should be able to cover the 99% of the pdf in both directions, positive and negative. In Figure 2, based on (Brijs et al. 2016), an example of the probabilistic sizing of FRR-type of reserve is presented. The area defined by the 99% quantile in both directions under the pdf corresponds to the total non-FCR reserve requirement, which in turn is split into aFRR, mFRR and RR, by considering different quantiles for the different types of FRR reserves.

Box 2: Example of establishing a dependency between FRR and aFRR using quantiles and normal distributions

To give an example of how to establish a dependency based on the quantiles between the requirements of FRR and aFRR, let's assume that the probabilistic component of FRR follows a normal distribution with a mean μ *and a standard deviation* σ^2*. For a normal distribution with mean* μ *and variance* σ^2 *the quantile function is* $F^{-1}(p) = \mu + \sigma \cdot \Phi^{-1}(p)$ *where* $p \in [0,1]$ *corresponds to the quantile of interest, and* $\Phi^{-1}(p)$ *is the quantile* p *of the standard normal distribution. The function* $\Phi^{-1}(p)$ *can be calculated by using statistical tables of the standard normal distribution, or the NORM.S.INV(p) function of EXCEL, or e.g. the qnorm() function in R. If we assume that the total requirement in FRR is the 99% quantile of the distribution and the requirement in aFRR corresponds to the 90% quantile, then the following relationship holds between the FRR and aFRR:*

$$\frac{aFRR}{FRR} = \frac{\mu + \sigma \cdot \Phi^{-1}(0.9)}{\mu + \sigma \cdot \Phi^{-1}(0.99)} = \frac{\mu + \sigma \cdot 1.282}{\mu + \sigma \cdot 2.326} = \lambda \in (0,1)$$

The ratio λ *defines a relationship between FRR and aFRR. The similar approach can be used to define the relationship between FRR and mFRR (or, alternatively the mFRR can be calculated as the remaining reserve needed to meet the total FRR). The above expression is non-linear, as* μ *and* σ *are endogenous. Therefore, we introduce in this TIMES extension a user-defined exogenous parameter* $\widetilde{\lambda_t}$ *, which is time-dependent so that its evolution over time to approximate the true* λ *(for example,. the user can set the parameter* $\tilde{\lambda}$ *by first looking at already quantified long-term scenarios and calculating the FRR).*

Often, the reserve demands calculated by the deterministic and probabilistic components are compared, and the highest is considered to be the amount of the total reserve that needs to be contracted. The sizing of the reserve can be performed on an annual basis (static method) or over smaller periods, e.g. on a monthly, weekly, daily or hourly basis (dynamic method).

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[2] For example, the pdf of the normalised forecast errors (used in the "endogenous" calculation") can be derived by comparing the day-ahead forecast with the real-time output and describing the error by means of a normal distribution.

Box 3: Example of the sizing of FRR, based on the approach followed by the Belgian TSO Elia

To give a concrete example regarding the sizing of the operational reserves, we present the procedure followed by Elia, the Belgian system operator, which is shown in Figure 3 (ELIA 2017). ENTSO-E provides the sizing of FCR, so it is outside of the scope of Elia. On the other hand, the sizing of the total FRR need (aFRR+mFRR) is performed by Elia, and it is based on the statistical convolution of the probability distribution curve of the forced power plant outages and the probability distribution curve of the expected system imbalance. The 99.9% percentile of the probability distribution curve of the expected upward system imbalances determines the upward total FRR needs. The expected system imbalance for year Y is derived from the historical time series (with a resolution of 15 min) of the system imbalance for one entire year (Y-2) from which all the forced outages are excluded. The expected forecast errors of the incremental renewable generation capacity (photovoltaics, onshore and offshore wind) are then added, based on assumptions concerning to which extent the market can cover part of these forecast errors. Finally, the forced power plant outages are included in the convolution, derived from a Monte Carlo simulation including the outage probability and characteristics of the expected generation fleet, and the outage probability of the offshore wind parks caused by storm events.

Then the need for aFRR is determined based on the probability distribution curve of the absolute variations over each time step of 15 min of the expected system imbalance described above. The 79% percentile of this probability distribution curve determines the symmetric aFRR needs. It follows that the size of mFRR is based on the difference between the total FRR and aFRR.

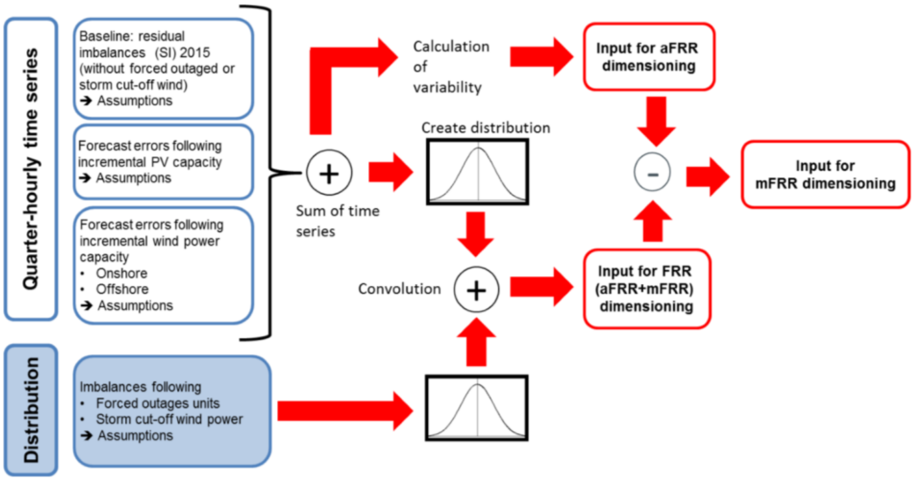


Figure 3: Dimensioning of the total FRR and its split to aFRR and mFRR, based on the approach followed by the Belgian system operator Elia; the picture is from (ELIA 2017)

The above discussion in Box 3 indicates that there is "hierarchy" among the reserves. The FCR-type of reserve comes first, and then the total needs for FRR-type reserves are defined. The needs for FRR-type reserves usually are split into aFRR-type and mFRR-type. The RR-type of reserve is optional for many markets, and can be derived by different ways. Two common approaches is to be part of the total FRR needs or to be the difference between the deterministic and probabilistic assessment of FRR.

1.3 Participation requirements in ancillary services markets

The requirements for a power plant, or other electricity supply or demand unit, in ancillary services markets, are country-specific. A unit that participates in ancillary markets must pass through a certification process to verify specific flexibility criteria, e.g. minimum contracted capacity, online/offline times, ramping rates and minimum stable operating levels. Smaller units, which cannot participate in the market as standalone, can form "virtual power plants". In a "virtual power plant" different types of small units are aggregated into individual feed-in/feed-out nodes in terms of operational planning, control and monitoring. A "virtual power plant" requires specialised software and infrastructure for monitoring and control.

In general, primary reserve may be provided by pumped storage and part-loaded thermal power plants or even by large wind and solar power plants (even though with less requirements than the ones applied to hydro- and thermal power plants). Secondary and tertiary reserves may also draw on plants which can quickly synchronise with the grid, such as hydro-reservoirs, open cycle turbines, diesel generators. Reserve services may as well be provided by demand response measures and other options such as curtailment, enhanced balancing areas, virtual power plants, cross-border trade, storage, heat pumps, electric vehicles, etc. The ancillary markets for the trading of reserve services may ensure that all these options compete against each other to provide reserve at the lower cost.

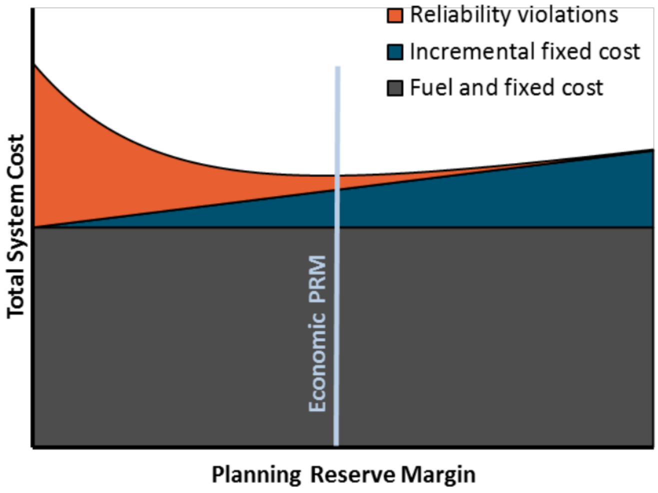
1.4 Bidding for supplying ancillary services

A power plant (or other supply/demand unit) can participate in the reserve auctions. The SO runs auctions for the day-ahead or hour-ahead markets. The configuration of the auctions and the participation requirements depend on market designs and can be different worldwide. For example, suppliers bid to sell reserve capacity, and there is a generally minimum offer size per bid. The bid price for contracted power corresponds to the capacity remuneration. When the unit is activated to provide a reserve, it also produces energy that can be remunerated as well e.g. +20% on the sport price for positive reserve, or -20% for negative reserve (Beck and Scherer 2010),.

1.5 Ancillary Services versus Planning Reserve Margin

The Planning Reserve Margin (PRM), approximated via the peak constraint in energy systems models, applies to the long-term forecast of electricity demand to plan for the generation and distribution of the electricity. It focuses on the peak demand and it is defined as the percentage by which the total capacity of system resources exceeds the median peak load. Surplus capacity is necessary to ensure that the supply of resources is sufficient to meet load under a variety of system conditions such as warmer than average weather (increase in load) or an unexpected generator failure (decrease in system resources).

The PRM is typically determined with one of two common approaches. The first is through benchmarking to a particular engineering metric for customer reliability, e.g. expected number of outage hours per year or expected number of outage events per year. The second approach is through economic analysis to find the point at which the marginal benefits of additional capacity match the marginal cost of a new power plant as shown in Figure 4 (El Paso Electric Co. 2015).



Source: El Paso Electric Co., 2015

Figure 4: The economic approach finds the level of reserves such that the total system cost are minimised. The system cost includes both the cost of installing and maintaining a particular reserve margin as well as the customer outage and reliability costs associated with that planning reserve margin.

Generally, regulatory bodies make it obligatory for generators and transmission companies to enhance their capacity to produce and transmit an additional amount of electricity. For this purpose, it is essential to maintain a reserve margin of 10-20% of the normal capacity. When comes to energy modelling with TIMES, the above figure can be revised upwards depending on the number of timeslices.

In contrast, the ancillary services markets, are the specialty services that help in supporting electric power transmission from the seller to consumer. These services ensure that there is a proper and steady flow of electricity and address the fluctuations that occur due to the variation of demand and supply. Therefore, they ensure a quick fix of the imbalances that may occur between demand and supply of electricity. The ancillary services deal with the operational uncertainty and variations. In systems with significant shares of variable renewable energy there may be need to add more ancillary services to handle the increased imbalances.

The ancillary services are crucial to the successful operation of the electricity grid system. They help in the quick restoration and fixes of power disruptions, and consequently they are paramount to working grid system to avoid blackouts.

The above discussion indicates that the introduction of ancillary services into energy systems planning models does not cancel the need for the reserve margin constraint. The two features are complementary to each other, as the reserve margin deals with the long-term forecasting of supply and demand, while the ancillary services markets deal with the short-term operational imbalances. Both are critical to the planning of a reliable power system. Their combination ensures that the system will have enough capacity to meet the peak load and, at the same time, this capacity will be flexible enough to accommodate increased penetration of variable renewable energy. To this end, the power system costs associated with the integration of renewables can be better approximated and they can be seen by the decision mechanism of the long-term energy planning models.

2. MATHEMATICAL FORMULATION

2.1 Assumptions

Given the complexity of the ancillary services markets, the following assumptions have been made in the design regarding their implementation in TIMES:

- Each process can represent many individual units that are clustered without transmission constraints or other constraints between the units belonging to the same process.
- A "steady state" is modelled, in which the different processes are ready to provide a reserve. The activation of the reserve is not considered, as this would deviate from the "steady state". Moreover, most TIMES-based models do not have the high intra-annual resolution required for modelling the activation of reserve (e.g. hourly or minute-time resolution).
- The extension does not implement a bidding mechanism for participating in the provision of the reserve. Alternatively, a perfect competitive market is assumed with the shadow price (dual) of the reserve market clearing constraint to be a proxy for the accepted bid (clearing price). It is also possible to define an exogenous mark-up cost, if desired.
- Each type of operating reserve is modelled as a commodity, which is produced by the processes participating in ancillary markets. The provision of the reserve is not assumed to consume any input of fuels, or produce energy, as opposed to the actual activation of the reserve, following (Welsch et al. 2015).
- Cross-border trade of reserves is supported via the trade processes of TIMES.
- The user-constraint mechanisms of TIMES are also supported both for the demand for the different types of reserve and the provision of reserve from different processes. This enables additional flexibility in modelling the different configurations of the ancillary services markets.
- Both static and dynamic sizing of the reserve is allowed, depending on the timeslice tree level used for the definition of the reserve demand.
- Not all types of reserve need to be modelled by the user. However, the "hierarchy" of the reserves needs to be respected. For example, the secondary reserve, aFRR, cannot be modelled without the primary reserve, FCR. It is possible for users to define the hierarchy of the tree.

2.2 Nomenclature

The following tables present the nomenclature regarding the indices, parameters and variables used in this section. Indices and parameters are denoting with lowercase letters, while sets and variables with uppercase letters.

Table 1: Basic indices used in the mathematical formulation of ancillary services markets

Index	**Description**
$bd \in \{LO, UP, FX, N\}$	Bound, i.e. lower, upper, fixed, none
$c, c' \in COM$	Commodity (also a type of reserve)
$cur \in CUR$	Currency
$io \in \{in, out\}$	Index denoting consumption (input) or production (output) of a commodity from a process
$k \in \{load, wind, solar, \dots\}$	Source of unpredictable variation in demand and generation
$p \in PRC$	Process
$r \in R$	Region
$t \in T$	Time period
$ts, s, sl, ss \in ALL\_TS$	Timeslice
$tsl \in \begin{Bmatrix} ANNUAL, SEASON, \\ WEEKLY, DAYNITE \end{Bmatrix}$	Timeslice level
$v \in V$	Vintage of a process

Table 2: Basic sets used in the mathematical formulation of ancillary services markets

Sets	**Description**
$A(COM)$	Reserve control type, e.g. FCR^P , FCR^N, $aFRR^P$, $aFRR^N$, $mFRR^P$, $mFRR^N$, RR^P, RR^N; P=positive or upward reserve, N=negative or downward reserve
$A^{FCR}(A)$	Subset of A, including the reserves belonging to the FCR-equivalent category (i.e. primary reserves)
$A^{RR}(A)$	Subset of A, including the reserves belonging to the RR-equivalent category (i.e. replacement reserves)
$A^{aFRR}(A)$	Subset of A, including the reserves belonging to the aFRR-equivalent category (i.e. secondary reserves)
$A^{mFRR}(A)$	Subset of A, including the reserves belonging to the mFRR-equivalent category (i.e. tertiary reserves)

Sets	Description
$A^n(A)$	Subset of A, which only contains commodities representing negative (downward) reserve requirements
$A^p(A)$	Subset of A, which only contains the commodities corresponding to positive (upward) reserve requirements
$AK(A,k)$	Mapping of a reserve with its source of imbalance
$BS(PRC)$	Set of processes allowed to participate in the reserve markets in a region, including supply, demand and storage processes
$C(ALL\_TS)$	Set of child timeslices of timeslice s in the timeslice tree
$P(ALL\_TS)$	Set of parent timeslice of timeslice s in the timeslice tree
$PK(k,PRC)$	Set containing all those processes p related to the imbalance k; for example, if k=wind, then the set will contain all those processes that represent wind turbines in the model
$PRC^{sh}(PRC)$	Set of storage processes that implement load shifts
$S(tsl)$	Set of timeslices s belonging to the timeslice level tsl
$SI(PRC)$	Set of processes included in the calculation of the largest system imbalance (SI) that can occur in the electricity system in a region (used for the reserve requirement calculation)
$SUP(ALL\_TS)$	Set of timeslices above timeslice s in the timeslice tree, but including also s itself
$TOP(R,PRC,COM,io)$	Topology of a process p, in region r: if c is a consuming commodity the $io=\{in\}$, and if c is a producing commodity then $io=\{out\}$
$PRC\_TSL\ (PRC,tsl)$	Timeslice level for a process
$TS\_MAP(ts,s)$	Timeslice hierarchy tree, ts is the node and s are all the nodes below ts

Table 3: Basic parameters used in the mathematical formulation of ancillary services markets

Parameter	Description
$a_{r,t,s,c}^{\text{deter}}$	Weight of the contribution of the largest system element in the calculation of the deterministic component of the demand for reserve $c \in A$ in region r, time period t and timeslice s
$dexog_{r,t,s,c}^{\text{deter}}$	Exogenous deterministic reserve demand provided by the user for a reserve type $c \in A$, in region r, period t and timeslice s (in units of capacity)

Parameter	**Description**
$n_{r,v,p}$	Round-trip efficiency of a storage process p, vintage v in region r
$t_{r,p,c}^{(1)}$	Time required for a storage process to ramp up (bd=UP) in order to provide reserve $c \in A$. The time is expressed in hours.
$t_{r,p,c}^{(2)}$	Duration of the provision of reserve $c \in A$ from a storage process. The time is expressed in hours
$w_{r,t,c}$	Weight of the deterministic component in the formulation of the endogenous reserve requirements of type c, in region r , year t
$\lambda_{r,t,c}$	Dependence factor used in the calculations of the reserve requirements
$\sigma_{r,t,c,s,k}$	Standard deviation of the forecast error regarding the unpredictable variation k, in region r, period t, timeslice s, which is used for the calculation of the demand for reserve type $c \in A$
$\omega_{r,t,s,c}$	Parameter denoting if the demand of a reserve is the maximum of deterministic and probabilistic component ($\omega = 1$), or the weighted sum of the deterministic and probabilistic component ($\omega = 2$), or the difference between the deterministic and probabilistic components ($\omega = 3$)
$af_{r,v,p}^{\text{act}}$	Coefficient bounding stored energy by capacity for storage process p, of vintage v in region r
$af_{r,v,p}^{\text{min}}$	Minimum operating level of online capacity of process p and vintage v
$af_{r,v,t,p,s}^{\text{max}}$	Maximum availability of capacity of a process p, vintage v, in period t, region r and timeslice s
$act\_time_{r,p,v}^{lo}$	Minimum offline time of process p and vintage v
$act\_time_{r,p,v}^{up}$	Minimum online time of process p and vintage v
$act\_ups_{r,v,p,s}^{lo}$	Maximum ramp-down rate of online capacity of process p, vintage v, in timeslice s and region r
$act\_ups_{r,v,p,s}^{up}$	Maximum ramp-up rate of online capacity of process p, vintage v, in timeslices s, in region r
bc_r	Capacity to reserve coefficient in region r
$bsbnd_{r,t,p,c,s,bd}$	Absolute bound $bd = \{lo, up, fx\}$ on reserve provision from process p in region r, in period t and timeslice s
$bsshare_{r,t,c,k,bd}$	Share $bd = \{lo, up\}$ of process group k in provision of reserve c
$ca_{r,p}$	Capacity to activity coefficient
$ctc_{r,v,t,p}$	Capacity transfer coefficient (internally derived by TIMES)
$mnt\_time_{r,p,v,t,s}$	Minimum continuous maintenance duration of process p,

Parameter	Description
	vintage v, in period t, starting at timeslice s (when s=ANNUAL, then TIMES optimally decides when a maintenance should occur)
$ncap\_cost_{r,v,p}$	Investment cost of a process p, vintage v, in region r
$prc\_tlife_{r,v,p}$	Technical life time of a process p, vintage v, in region r
$rmax_{r,v,p,s,c}$	Maximum contribution of process p, vintage v, in timeslice s for the provision of reserve type $c \in A$
$rp\_std_{r,p}$	Flag indicating that a process is a standard TIMES process with VAR_FLO variable
$rp\_stg_{r,p}$	Flag indicating that a process is a TIMES storage process
$rps\_ups_{r,p,s}$	When non-zero: timeslices for which startups are accounting
$rs\_fr_{r,ts,s}$	Fraction of timeslice s in timeslice ts, if s is below ts, otherwise 1
$stg\_cyc_{r,v,p}$	Maximum number of cycles for a storage process p, vintage v
$stg\_eff_{r,v,p}$	Round-trip efficiency of a storage
$tscycles(s)$	Number of cycles under the parent timeslice of s (e.g. the number of days under the parent of a DAYNITE timeslice)

Table 4: Variables used in the mathematical formulation of ancillary services markets

Variable	Description
$VAR\_ACT_{r,p,v,t,s}$	The activity of process p, vintage v, in period t and timeslice s
$VAR\_BSD^{\text{deter}}_{r,t,c,s}$	Demand for reserve requirement of type $c \in A$ in year t in region r and timeslice level s based on the deterministic assessment
$VAR\_BSD^{\text{prob}}_{r,t,s,c}$	Demand for reserve requirement of type $c \in A$ in year t in region r and timeslice s , based on the probabilistic assessment
$VAR\_BSFNSP_{r,v,t,p,c,s}$	Reserve contracted to be provided by non-spinning units of process p, vintage v, period t, and timeslice s, or reserve belonging to units which have been contracted to shut-down in order to provide negative reserve.
$VAR\_BSFSP_{r,v,t,p,c,s}$	Reserve contracted to be provided by spinning units of process p, vintage v, period t, and timeslice s
$VAR\_BSMUP_{r,v,t,p,s}$	Capacity going into maintenance from being offline of process p, vintage v in period t and timeslice s
$VAR\_BSUPSR^{\text{up}}_{r,v,t,p,s}$	Capacity of process p, vintage v, in period t and timeslice s, which is allocated to start-up for the

Variable	Description
	provision of reserve.
$VAR\_BSUPSR^{\mathrm{lo}}{}_{r,v,t,p,s}$	Capacity of process p, vintage v, in period t and timeslice s, which is allocated to shutdown for the provision of reserve.
$VAR\_CAP_{r,t,p}$	Total installed capacity of process p in region r and year t (including past investments)
$VAR\_COMNET_{r,t,c,s}$	Difference between the demand and supply of commodity c, in region r, in year t and timeslice s. For reserve commodities, it represents the total inland demand of reserve c.
$VAR\_COMPRD_{r,t,c,s}$	Production of commodity c, in region r, in year t and timeslice s. For reserve commodities, it represents the total inland supply of reserve c.
$VAR\_FLO_{r,v,t,p,s,c}$	Production of commodity c, in timeslice s and period t, from process p, of vintage v, which is installed in region r
$VAR\_LOS_{r,v,t,p,s}$	The shut-down capacity of process p, vintage v, in period t and timeslice r
$VAR\_NCAP_{r,t,p}$	Installed capacity of process p, in region r and in year t
$VAR\_OFF_{r,p,v,t,s}$	The offline capacity of process p, vintage v, in period t and timeslice s
$VAR\_RLD_{r,t,s,k}$	Load associated with imbalance k and used for the calculation of the operating reserves
$VAR\_STGCC_{r,v,p,t}$	Additional replacement capacity needed for the storage process p, of vintage v, that occurs in period t and region r, when the number of cycles of the storage exceed the maximum cycles defined with the parameter stg_cyc
$VAR\_UPS_{r,v,t,p,s}$	The start-up capacity of process p, vintage v, in period t and timeslice s, committed to provide energy services.

2.3 Endogenous demand for each reserve type

As stated in section 1.2 the demand for each reserve type is based on a probabilistic and a deterministic assessment. Because the exact configuration of the different ancillary markets is complex and country-specific, the current TIMES extension supports three different generic formulations, controlled by the parameter $\omega_{r,t,s,c}$. The objective of this complex formulation of demand is to approximate as close as possible the different worldwide ancillary markets. Table

5 presents some examples of how the parameter $\omega_{r,t,s,c}$ can be used to enable alternative formulations for reserve sizing.

Table 5: Supported formulations for the reserve sizing

Value of $\boldsymbol{\omega_{r,t,s,c}}$	**Description**
1	The demand for reserve $c \in A$ is the maximum of the probabilistic and deterministic components
2	The demand for reserve $c \in A$ is the weighted sum of the probabilistic and deterministic components
3	The demand for reserve $c \in A$ is the absolute difference between the probabilistic and deterministic components

Thus, according to Table 5, the endogenous demand of each reserve type requirement $c \in A$ is given by equations (eq. 1a) and (eq. 1b):

$$\frac{VAR\_COMNET_{r,t,c,s}}{yrfr_{r,s}} = \lambda_{r,t,c} \cdot \begin{pmatrix} \max\left(VAR\_BSD^{\text{prob}}_{r,t,c,s}, VAR\_BSD^{\text{det}}_{r,t,c,s}\right) \cdot \left(\omega_{r,t,c,s} = 1\right) + \\ \left(\left(1 - w_{r,t,s,c}\right) \cdot VAR\_BSD^{\text{prob}}_{r,t,c,s} + w_{r,t,s,c} \cdot VAR\_BSD^{\text{det}}_{r,t,c,s}\right) \cdot \left(\omega_{r,t,c,s} = 2\right) + \\ \left|VAR\_BSD^{\text{prob}}_{r,t,c,s} - VAR\_BSD^{\text{det}}_{r,t,c,s}\right| \cdot \left(\omega_{r,t,c,s} = 3\right) \end{pmatrix} \qquad \text{(eq. 1a)}$$

$$\frac{VAR\_COMPRD_{r,t,c,s}}{yrfr_{r,s}} \leq \sum_{v,p \in BS(p)} \left(ca_{r,p} \cdot \left(VAR\_BSFP_{r,v,t,p,c,s} + VAR\_BSNFP_{r,v,t,p,c,s}\right)\right), \quad \forall r,t,s,c \in A \qquad \text{(eq. 1b)}$$

The VAR_COMNET variables represent the total inland demand, and the VAR_COMPRD variables the total inland supply of reserve c in timeslice s. Both terms appear in the standard commodity balance equation together with any trade flows for that reserve. These variables must be expressed in terms of flows, and not power levels (however, the reporting of the reserves is translated into power levels by using the value of bc_r parameter). The above demand formulation is using the maximum and absolute functions[3]. The factor $\lambda_{r,t,c}$ in equation (eq. 1a) is used to define dependencies between the reserves, e.g. to establish that the aFRR reserve is a fraction of the total FRR reserve or to establish that negative

---

[3] In linear programming the maximum and absolute functions can be approximated. For example, the expression $c \geq \max(a, b)$ is approximated with two constraints $c \geq a$ *and* $c \geq b$. Similarly, the expression $c \geq |a|$ can be formulated with two constraints $c \geq a$ *and* $c \geq -a$.

reserves are fraction of positive reserves (Quoilin, Hidalgo Gonzalez, and Zucker 2017). Examples regarding the application of the control parameters $\lambda_{r,t,c}$ and $\omega_{r,t,c,s}$ are given in Table 6.

Table 6: Examples of reserve sizing using equation (eq. 1a)

Reserve sizing example	**How to apply the demand equation (eq. 1a)**
The FCR reserve is exogenously provided	The weighted-sum formulation of the demand should be selected via the parameter $\omega_{r,t,c,s}$, and the weight $w_{r,t,s,c}$ of the deterministic component to be 1. The parameter $\lambda_{r,t,s,c}$ should be set to 1, as there are no other types of FCR reserves. Hence: • $\omega_{r,t,"FCR",s} = 2$, $w_{r,t,"FCR",s} = 1$, $\lambda_{r,t,s,"FCR"} = 1$
The total FRR reserve is calculated as the maximum of probabilistic and deterministic component; the aFRR is then 80% of the FRR (calculated as e.g. the 90% quantile of the joint pdf – see also Box 2) and the mFRR reserve is the remaining 20% of the FRR (see Figure 2 and Box 2)	The maximum formulation of the demand should be chosen by setting the parameter $\omega_{r,t,c,s}$. The deterministic and probabilistic components should be the same for both aFRR and mFRR reserves, and equal to the ones of the FRR reserve. This implies that the parameters involved in the definition of the probabilistic and deterministic components should be the same for both aFRR and mFRR reserves. The corresponding 80/20 relationships can be established by using the parameter $\lambda_{r,t,s,c}$. Hence: • $\omega_{r,t,"aFRR",s} = \omega_{r,t,"mFRR",s} = 1$ • $VAR\_BSD^{\mathrm{prob}}_{r,t,s,"aFRR"} = VAR\_BSD^{\mathrm{prob}}_{r,t,s,"FRR"}$ • $VAR\_BSD^{\mathrm{prob}}_{r,t,s,"mFRR"} = VAR\_BSD^{\mathrm{prob}}_{r,t,s,"FRR"}$ • $VAR\_BSD^{\mathrm{deter}}_{r,t,s,"aFRR"} = VAR\_BSD^{\mathrm{deter}}_{r,t,s,"FRR"}$ • $VAR\_BSD^{\mathrm{deter}}_{r,t,s,"mFRR"} = VAR\_BSD^{\mathrm{deter}}_{r,t,s,"FRR"}$ • $\lambda_{r,t,s,"aFRR"} = 0.8$, $\lambda_{r,t,s,"mFRR"} = 0.2$
The RR reserve is defined as the difference between the probabilistic and deterministic components of the total FRR reserve	For the RR reserve, the absolute formulation of the demand function should be chosen, by setting the parameter $\omega_{r,t,c,s}$. Then, the calculation of the probabilistic and deterministic component of RR should correspond to the calculation of the total FRR reserve. The parameter $\lambda_{r,t,s,c}$ should be set to 1, as there are no other types of FRR reserves. Hence: • $\omega_{r,t,"RR",s} = 1$ • $VAR\_BSD^{\mathrm{prob}}_{r,t,s,"RR"} = VAR\_BSD^{\mathrm{prob}}_{r,t,s,"FRR"}$ • $VAR\_BSD^{\mathrm{deter}}_{r,t,s,"RR"} = VAR\_BSD^{\mathrm{deter}}_{r,t,s,"FRR"}$ • $\lambda_{r,t,s,"RR"} = 1$

Section 1.2 discusses the factor $\lambda_{r,t,c}$, its meaning and definition in detail. The demand for a reserve can be defined at different levels of the TIMES timeslice tree, e.g. at annual, seasonal, weekly or daily levels. For demands defined on levels above the DAYNITE level, equations (eq. 1b) can be still prescribed to be satisfied at all timeslices below the demand timeslice, by defining the reserve commodity with 'N' limit type in the COM_LIM(r,c,lim) attribute. When using the normal limit types 'LO' or 'FX' in the COM_LIM(r,c,lim) attribute (where 'LO' is the default for NRG commodities), the equations (eq. 1b) are restricted to the demand timeslices and remain unchanged regardless of the limit type being 'LO' or 'FX', because a strict equality in fact cannot be enforced in the formulation.

2.3.1 Probabilistic component of the demand of a reserve

The probabilistic part of the reserve requirements is based on the forecast error of demand and supply. We assume that the forecast error of each unpredictable variation k (e.g. wind or solar electricity production, or end-use electricity load) is normally distributed with mean 0 and standard deviation σ_k equal to the error[4], and that these distributions of the forecast errors are independent (Figure 5).

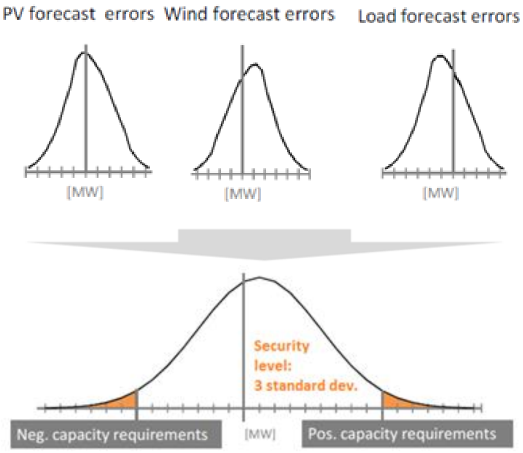


Figure 5: Probabilistic assessment of the positive and negative reserve requirements by assuming independent and normally distributed forecast errors. The resulting distribution is also normal, in which ±3σ would cover 99.7% of all of the possible system states. In this example, symmetric handling of the positive and negative reserve is assumed.

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[4] The probability density function (pdf) of the forecast errors can be obtained by comparing the day-ahead forecast with the real-time output (e.g. from ENTSO-E transparency platform (https://transparency.entsoe.eu/), by describing the error in terms of a standardized normal distribution (i.e. zero mean and standard deviation equal to the error).

The endogenous demand $D^{\text{prob}}_{r,t,s,c}$ for the reserve requirement $c \in A$ is given by equation (eq. 2). The calculation of the probabilistic component of the reserve demand, shown in Figure 5, is based on the convolution method and considers the maximum imbalance that occurs in the timeslices that are below the timeslice used for the definition of the demand:

$$VAR\_BSD^{\text{prob}}_{r,t,s,c} = 3\cdot\sqrt{\sum_{k}\left(\sigma^{2}_{r,t,c,ts,k}\cdot VAR\_RLD^{2}_{r,t,ts,k}\right)} \text{ for each reserve type } c\,.$$

The quantity $VAR\_RLD_{r,t,s,k}$ corresponds to the electricity load associated with the imbalance of the system k. This load can be e.g. electricity produced or consumed by the imbalance. An approximation is given below:

$$VAR\_RLD_{r,t,s,k} = \frac{1}{yrfr_{r,s}}\cdot \sum_{v,\, p\in PK(p,k),\, c\in TOP(r,p,c,io)\,\wedge\, c\in AK(c,k)} VAR\_ACT_{r,v,t,p,s,c} \quad ,\ \forall r,t,s,k \qquad \text{(eq. 2)}$$

The above simplified expression[5] represents the load associated with the imbalance k in timeslice s, for which the sizing of reserve c occurs. The source of imbalance can be related to the production (io=OUT) of commodity c when the process p is a supply process, or to the consumption (io=IN) of commodity c when the process p is a demand process. In the case that the process p is a storage process, then the variable VAR_ACT in the above equation is replaced by the variables VAR_SIN or VAR_SOUT.

Because the equation calculating the probabilistic component of the demand is non-linear, it is linearly approximated[6] in this extension as:

$$VAR\_BSD^{\text{prob}}_{r,t,s,c} \geq \delta_{r,t,c,s}\cdot 3\cdot\sum_{k}\left(\sigma_{r,t,c,k,s}\cdot VAR\_RLD_{r,t,s,k}\right) \ ,\ \forall r,t,s,c\in A \qquad \text{(eq. 3)}$$

In equation (eq. 3), the number 3 is used to account for three standard deviations in the joint probability distribution function approximated with the summation term. Because the non linear expression $\sqrt{\alpha^2+\beta^2}$ is approximated with the linear expression $\alpha+\beta$, the demand calculated by (eq. 3) is higher than the demand

---

[5] The actual implementation in TIMES code to get the load associated with an imbalance k is more complicated, as it can also consider VAR_FLO, VAR_SIN and VAR_SOUT variables depending on the type of the process.

[6] This simplified approach serves well the purpose. Alternative approaches include linearization via the first order Taylor series expansion around the point of interest.

obtained with the non-linear expression of the joint probability distribution function, because $\alpha + \beta \geq \sqrt{\alpha^2 + \beta^2}$. Therefore, the term $\delta_{r,t,s,c}$ acts as a calibration/scaling parameter to bring the demand calculated via (eq. 3) closer to the actual demand.

2.3.2 Deterministic component of the demand

The deterministic component of the demand $D_{r,t,s,c}^{\text{deter}}$ can be defined with three ways:

- It can be exogenously provided via the parameter $dexog_{r,t,s,c}^{\text{deter}}$ as an absolute number
- It can be equal (to a percentage) of the largest grid element, e.g., the capacity of an interconnector or power plant, and in this case, TIMES can also endogenously determine it from a predefined set of processes (SI).
- It can be calculated as the sum of the $dexog_{r,t,s,c}^{\text{deter}}$ and the contribution from the largest grid element, and in this case is a mix of “exogenous” and “endogenous” calculation of reserves.

Hence, the parameter $dexog_{r,t,s,c}^{\text{deter}}$ is actually a lower bound for the variable $D_{r,t,s,c}^{\text{deter}}$. Equation (eq. 4) implements the deterministic component of reserves:

$$VAR\_BSD_{r,t,c,s}^{\text{deter}} \geq dexog_{r,t,s,c}^{\text{deter}} \cdot bc_r \quad \forall r,t,s,c \in A$$

$$\begin{aligned} VAR\_BSD_{r,t,c,s}^{\text{deter}} \geq\ & dexog_{r,t,s,c}^{\text{deter}} \cdot bc_r + \\ & + a_{r,t,s,c}^{\text{deter}} \cdot ctc_{r,v,t,p} \cdot VAR\_NCAP_{r,v,p} \cdot \sum_{\substack{v=t, \\ ts \in PRC\_TS(r,p,ts)}} \left(af_{r,v,t,p,s}^{\max} \cdot rs\_fr_{r,ts,s} \right), \forall r,t,s,c \in A, p \in SI \end{aligned} \qquad \textit{(eq. 4)}$$

The parameter bc_r represents the activity to capacity conversion factor used for converting operating reserves to common flow unit. The different processes providing reserve can have different activity to capacity conversion factors. The user should provide the appropriate conversion factor for expressing the reserves from power to capacity unit; the default value of the parameter bc_r is the maximum activity to capacity conversion factor across all processes p that provide reserve in region r, i.e. $bc_r = \max_p ca_{r,p}$.

Also, in the case that the process timeslice providing the reserve is different than the timeslice for which the demand for reserve is defined, then the average availability factor $af_{r,v,t,p,s}^{\max}$ is used over the process timeslices under the demand timeslice.

2.4 Market clearing equation of ancillary service markets

The reserve demand should be fulfilled at all times by all processes that participate in the reserve market. The commodity balance equations of TIMES for the different reserve types can be used to represent the market clearing equation for each timeslice, and, thus, no additional equations are needed to formulate the market clearing of ancillary services.

Similar to the standard interpretation of the dual the commodity balance constraint, the dual of each reserve type can be considered as the market clearing price, or accepted bid for the reserve provision. Please note that when interpreting the dual of the commodity balance constraint the variables representing the reserve demand and supply, i.e .VAR_COMNET and VAR_COMPRD respectively, are expressed in energy flow units.

2.5 Reserve provision constraints

In the formulation of the reserve provision constraints, we follow the approach of (Brijs et al. 2016; Stiphout, Vos, and Deconinck 2017). The reserve provision constraints implemented below apply to all generating and demand units, as well as to all storage units with capacity bounded by the output commodity, i.e. the TIMES NCAP_AFC parameter has been defined (e.g. pump hydro), and with (optionally) no electricity inputs (e.g. hydro dam power plant storage with "water" as an input).

2.5.1 Minimum online and offline times adjusted for reserve provision

Equation (eq. 5) forces the required online capacity to be at least the sum over started-up capacities for energy provision within the minimum up-time plus the capacity allocated to shut down for negative reserve provision, which should be part of the on-line capacity.

$$\begin{aligned}&\sum_{ts\in C(P(s))}\left\{VAR\_UPS_{r,v,t,p,s}\cdot\left(\mathrm{mod}\left(Hour(s)-Hour(ts),24\right)<act\_time^{\mathrm{up}}_{r,p,v}\right)\right\}+\\&+VAR\_BSUPSR^{\mathrm{lo}}{}_{r,v,t,p,s}\leq VAR\_NCAP_{r,v,p}-\sum_{ts\in SUP(s)}VAR\_OFF_{r,v,t,p,ts}\end{aligned}\qquad\text{(eq. 5)}$$

Equation (eq. 6) forces the offline capacity to be at least the sum over shut-down capacities within the minimum down-time plus the capacity allocated to start-up for positive reserve provision[7].

$$\begin{aligned}&\sum_{ts\in C(P(s))} \left\{VAR\_LOS_{r,v,t,p,ts} \cdot \left(\mathrm{mod}\left(Hour(s)-Hour(ts),24\right) < act\_time^{\mathrm{lo}}_{r,p,v}\right)\right\} + \\ &\quad + VAR\_BSUPSR^{\mathrm{up}}_{r,v,t,p,s} \le VAR\_OFF_{r,v,t,p,s} \quad , \quad \forall r,v,t,p,s\end{aligned} \tag{eq. 6}$$

2.5.2 Ramping constraints, adjusted for reserve provision

Ramping online units up and down for energy provision is limited by the technology's ramping abilities. If, additionally, spinning reserves are contracted for the period when the unit is online, the actual ramp that can take place is further limited since there should be also sufficient margin to provide the contracted reserves. The ramping ability reserved for reserve provision is separately accounted for from the ramping that occurs in the scheduling phase to provide energy services.

Equation (eq. 7) imposes the ramping up ability constraint of a process p. The change in the output of the process in the energy market, represented by the variable VAR_ACT, plus the positive reserve provision represented by the variable VAR_BSFSP is restricted by the maximum ramping up rate act_ups^{up}, expressed as a fraction of the nominal on-line capacity per hour[8].

$$\begin{aligned}&\left(\begin{array}{l}\dfrac{VAR\_ACT_{r,p,v,t,s}}{yrfr_{r,s}} - \dfrac{VAR\_ACT_{r,p,v,t,s-1}}{yrfr_{r,s-1}} - \\ \left(VAR\_UPS_{r,v,t,p,s} - VAR\_LOS_{r,v,t,p,s}\right)\cdot af^{\min}_{r,v,p} + \sum\limits_{c\in A^p} VAR\_BSFSP_{r,v,t,p,c,s}\end{array}\right) \cdot \\ &\cdot \frac{2\cdot tscycles(s)}{8760\cdot\left(yrfr_{r,s}+yrfr_{r,s-1}\right)} \le \\ &\left(VAR\_NCAP_{r,v,p} - \sum_{ts\in SUP(s)} VAR\_OFF_{r,v,t,p,ts}\right)\cdot ctc_{r,v,t,p}\cdot ca_{r,p}\cdot act\_ups^{\mathrm{up}}_{r,v,p,s}\end{aligned} \tag{eq. 7}$$

---

[7] It is a modified version of the existing EQ_ACTUPC equation for minimum offline time to account for capacity contracted to shut down for reserve provision

[8] It is a modified version of the existing EQ_ACTRAMP equation in TIMES, regarding the ramp up limit

In the above equation, the term $\frac{2 \cdot tsCycles(s)}{8760 \cdot (yrfr_{r,s} + yrfr_{r,s-1})}$ calculates the time interval between two timeslices s and $s-1$ as a fraction of one hour. This term relates to the ramping parameter, which is defined on hourly basis

In a similar way, equation (eq. 8) represents the ramping down ability of the process. The change in the output of the process in energy markets plus the contracted negative reserve is restricted by the maximum ramping down rate, expressed as a fraction of the nominal on-line capacity per hour. The online capacity of the process is also adjusted by the capacity contracted to shut down for the reserve provision.

$$\begin{pmatrix} \frac{VAR\_ACT_{r,p,v,t,s-1}}{yrfr_{r,s-1}} - \frac{VAR\_ACT_{r,p,v,t,s}}{yrfr_{r,s}} + \\ \left(VAR\_UPS_{r,v,t,p,s} - VAR\_LOS_{r,v,t,p,s}\right) \cdot af^{\min}_{r,v,p} + \sum_{c \in A^n} VAR\_BFSP_{r,v,t,p,c,s} \end{pmatrix} \cdot$$

$$\cdot \frac{2 \cdot tscycles(s)}{8760 \cdot \left(yrfr_s + yrfr_{s-1}\right)} \le \begin{pmatrix} VAR\_NCAP_{r,v,p} - \sum_{ts \in SUP(s-1)} VAR\_OFF_{r,v,t,p,ts} - \\ -VAR\_BSUPSR^{\mathrm{lo}}{}_{r,v,t,p,s} \end{pmatrix} \cdot \qquad \text{(eq. 8)}$$

$$\cdot\, ctc_{r,v,t,p} \cdot ca_{r,p} \cdot act\_ups^{\mathrm{lo}}_{r,v,p,s} \quad , \forall r, p, v, t, s$$

2.5.3 Capacity margin constraints for reserve provision

In addition to the ramping rate constraints (eq. 7) and (eq. 8), the ramping ability for online capacity is constrained by the capacity margin available to perform spinning ramping (eq. 9) and by the generation level (eq. 10). These two constraints also apply for those storage technologies, which do not have the storage level bounded by capacity as it was the case with the equations described in previous sections.

Equation (eq. 9) restricts the available capacity margin for energy and positive (upward) reserve provision. It requires that the increase in capacity for energy production plus the capacity required to provide the positive reserve should be limited by the online capacity minus the current generation level. The equation also applies for storages, and in this case the discharge level of storage is considered.

$$\begin{aligned}
&\sum_{c\in A^{p}} VAR\_BFSP_{r,v,t,p,c,s}\cdot ca_{r,p} + \\
&\left\{\left(\begin{array}{l} ca_{r,p}\cdot\left(af^{\max}_{r,v,t,p,s}-af^{\min}_{r,v,p}\right)\cdot VAR\_UPS_{r,v,t,p,s}\cdot \\ \min\left(1,\dfrac{\dfrac{act\_sdtime_{r,v,p,"HOT","UP"}}{8760}}{\dfrac{yrfr_{r,s}}{rs\_stgprd_{r,s}}}\right)\end{array}\right)\right\}\cdot rps\_ups(r,p,s)\le \\
&\left(VAR\_NCAP_{r,v,p}-\sum_{ts\in SUP(s)} VAR\_OFF_{r,v,t,p,ts}\right)\cdot ca_{r,p}\cdot af^{\max}_{r,v,t,p,s}- \\
&-\left(\frac{VAR\_ACT_{r,v,t,p,s}}{yrfr_{r,s}}\right)\cdot rp\_std_{r,p}+ \\
&+\sum_{c\in ELC}\left(\frac{VAR\_SOUT_{r,v,t,p,s}}{yrfr_{r,s}}\right)\cdot stg\_eff_{r,v,p}\cdot rp\_stg_{r,p} \qquad ,\forall r,v,t,p,s
\end{aligned} \qquad \textit{(eq. 9)}$$

Equation (eq. 10) limits the available capacity margin for the reduction in energy production and the provision of negative reserve. The reduction in online capacity plus the shutdown of online capacity for reserve provision is limited by the current generation levels, the minimum online stable generation levels, the capacity contracted for the provision of negative reserve and the capacity already allocated to shut down.

$$\begin{aligned}
&\sum_{c\in A^{n}}\left(VAR\_BFSP_{r,v,t,p,c,s}+VAR\_BSFNSP_{r,v,t,p,c,s}\cdot rp\_std_{r,p}\right)\cdot ca_{r,p}\le \\
&\frac{VAR\_ACT_{r,p,v,t,s}}{yrfr_{r,s}}\cdot rp\_std_{r,p}+\sum_{c\in ELC}\frac{VAR\_SOUT_{r,v,t,p,c,s}}{yrfr_{r,s}}\cdot stg\_eff_{r,v,p}\cdot rp\_stg_{r,p}- \\
&-\left(\begin{array}{l}\left(VAR\_NCAP_{r,v,p}-\displaystyle\sum_{ts\in SUP(s)} VAR\_OFF_{r,v,t,p,s}\right)\cdot ctc_{r,v,t,p}- \\ -VAR\_BSUPSR^{\mathrm{lo}}{}_{r,v,t,p,s}\end{array}\right)\cdot ca_{r,p}\cdot af^{\min}_{r,v,p}\quad , \\
&\forall r,v,t,p,s
\end{aligned} \qquad \textit{(eq. 10)}$$

2.5.4 Maximum contribution of a process in reserve provision

Equations (eq. 7) – (eq. 10) ensure that each time that ramping capacity is not double booked for reserve provision and altering the generation level. However, to include the stringent temporal requirements for the provision of spinning reserve products, additional constraints are needed. For example, according to

ENTSO-E, the contracted primary and secondary reserve are expected to be fully available within seconds. This timeframe is significantly shorter than the duration of the timeslices typically used in TIMES. Thus, the maximum ramping rates are adapted to correspond to the time frame required for providing each type of reserve. Hence, two types of ramping rates are provided by the user: the energy-related ramping rates and the reserve-related ramping rates. The reserve-related ramping rate can also be considered as the maximum contribution of each process in the reserve provision[9]. Again, when allocating capacity to the different operating reserves, it is ensured that ramping capacity is not double booked. Furthermore, it is limited by the ramping ability of technology over the time period of the operating reserve category. These ramping rates, relevant for the reserve provision, are exogenously provided. We also assume that FCR-type of reserve and aFRR-type of the reserve can be only provided by online units, while the mFRR- and RR-type of the reserve can be additionally supplied by offline units as well. While the equations presented in this section can be grouped in a single compact formulation, they are presented here individually for clarity.

The equation (eq. 11) limits the provision of spinning FCR-type reserves, positive or negative, depending on the maximum contribution of the process to the reserve provision.

$$
\begin{gathered}
VAR\_BFSP_{r,v,t,p,c,s} \leq \\
\left(VAR\_NCAP_{r,v,p} - \sum_{ts \in SUP(s)} VAR\_OFF_{r,v,t,p,ts} \right) \cdot ctc_{r,v,t,p} \cdot rmax_{r,v,p,s,c} \quad , \\
\forall r,v,t,p,s,c \in A^{FCR}
\end{gathered}
\qquad \textit{(eq. 11)}
$$

The following constraints limit the provision of spinning aFRR-type of reserves, positive (eq. 12) and negative (eq. 13).

$$
\begin{gathered}
\sum_{c' \in A^{FCR} \cap A^{p}} VAR\_BFSP_{r,v,t,p,c,s} + VAR\_BFSP_{r,v,t,p,c,s} \leq \\
\left(VAR\_NCAP_{r,v,p} - \sum_{ts \in SUP(s)} VAR\_OFF_{r,v,t,p,ts} \right) \cdot ctc_{r,v,t,p} \cdot rmax_{r,v,p,s,c} \quad , \\
\forall r,v,t,p,s,c \in A^{aFRR} \cap A^{p}
\end{gathered}
\qquad \textit{(eq. 12)}
$$

---

[9] For example, if the ramping rate of a technology is 4% per minute and the reserve provision requires activation in 30sec then the maximum contribution of this technology to reserve is 2%

$$
\begin{gathered}
\sum_{c' \in A^{FCR} \cap A^{n}} VAR\_BFSP_{r,v,t,p,c',s} + VAR\_BFSP_{r,v,t,p,c,s} \leq \\
\left(\begin{array}{l} \left(VAR\_NCAP_{r,v,p} - \sum_{ts \in SUP(s)} VAR\_OFF_{r,v,t,p,ts} \right) \cdot ctc_{r,v,t,p} - \\ - \, VAR\_BSUPSR^{\mathrm{lo}}{}_{r,v,t,p,s} \end{array} \right) \cdot rmax_{r,v,p,s,c} \quad , \\
\forall r,t,p,s,c \in A^{aFRR} \cap A^{n}
\end{gathered}
\tag{eq. 13}
$$

The following constraints limit the provision of spinning mFRR-type of reserves, positive (eq. 14) and negative (eq. 15).

$$
\begin{gathered}
\sum_{c' \in \left(A^{FCR} \cup A^{aFRR} \right) \cap A^{p}} VAR\_BSFSP_{r,v,t,p,c',s} + VAR\_BSFSP_{r,v,t,p,c,s} \leq \\
\left(VAR\_NCAP_{r,v,p} - \sum_{ts \in SUP(s)} VAR\_OFF_{r,v,t,p,ts} \right) \cdot ctc_{r,v,t,p} \cdot rmax_{r,v,p,s,c} \quad , \\
\forall r,v,t,p,s,c \in A^{mFRR} \cap A^{p}
\end{gathered}
\tag{eq. 14}
$$

$$
\begin{gathered}
\sum_{c' \in \left(A^{FCR} \cup A^{aFRR} \right) \cap A^{n}} VAR\_BSFSP_{r,v,t,p,c',s} + VAR\_BSFSP_{r,v,t,p,c,s} \leq \\
\left(\begin{array}{l} \left(VAR\_NCAP_{r,v,p} - \sum_{ts \in SUP(s)} VAR\_OFF_{r,v,t,p,ts} \right) \cdot ctc_{r,v,t,p} - \\ - \, VAR\_BSUPSR^{\mathrm{lo}}{}_{r,v,t,p} \end{array} \right) \cdot rmax_{r,v,p,s,c} \quad , \\
\forall r,v,t,p,s,c \in A^{mFRR} \cap A^{n}
\end{gathered}
\tag{eq. 15}
$$

The following equations limit the provision of spinning RR-type of reserves, positive (eq. 16) and negative (eq. 17).

$$
\begin{gathered}
\sum_{c' \in \left(A^{FCR} \cup A^{aFRR} \cup A^{mFRR} \right) \cap A^{p}} VAR\_BSFSP_{r,v,t,p,c',s} + VAR\_BSFSP_{r,v,t,p,c,s} \leq \\
\left(VAR\_NCAP_{r,v,p} - \sum_{ts \in SUP(s)} VAR\_OFF_{r,v,t,p,ts} \right) \cdot ctc_{r,v,t,p} \cdot rmax_{r,v,p,s,c} \quad , \\
\forall r,v,t,p,s,c \in A^{RR} \cap A^{p}
\end{gathered}
\tag{eq. 16}
$$

$$\begin{aligned}
&\sum_{c' \in \left(A^{FCR} \cup A^{aFRR} \cup A^{mFRR}\right) \cap A^{n}} VAR\_BSFSP_{r,v,t,p,c',s} + VAR\_BSFSP_{r,v,t,p,c,s} \le \\
&\begin{pmatrix} \left(VAR\_NCAP_{r,v,p} - \sum_{ts \in SUP(s)} VAR\_OFF_{r,v,t,p,ts} \right) \cdot ctc_{r,v,t,p} - \\ - VAR\_BSUPSR^{\mathrm{lo}}_{r,v,t,p,s} \end{pmatrix} \cdot rmax_{r,v,p,s,c} \quad , \\
&\forall r,v,t,p,s,c \in A^{RR} \cap A^{n}
\end{aligned} \tag*{(eq. 17)}$$

The following equations (eq. 18) and (eq. 19) limit the provision of mFRR-type of reserves via non-spinning units if those units can start-up sufficiently quickly and negative reserves via shutting down online units if those units can shut down sufficiently quickly. The processes that can start-up or shut-down sufficiently quickly are defined through the parameter ACT_SDTIME(r,v,p,”HOT”,”UP”) for startup time and ACT_SDTIME(r,v,p,”HOT”,”LO”) for shutdown time.

$$\begin{aligned}
&VAR\_BSUPSR^{\mathrm{up}}_{r,v,t,p,s} \cdot af^{\min}_{r,v,p} \le \sum_{c \in A^{p}} VAR\_BFNSP_{r,v,t,p,c,s} \\
&VAR\_BSFNSP_{r,v,t,p,c,s} \le VAR\_BSUPSR^{\mathrm{up}}_{r,v,t,p,s} \cdot rmax_{r,v,p,c,s} \quad , \\
&\forall r,v,t,p,s,c \in A^{mFRR} \cap A^{p}
\end{aligned} \tag*{(eq. 18)}$$

$$\begin{aligned}
&VAR\_BSUPSR^{\mathrm{lo}}_{r,v,t,p,s} \cdot af^{\min}_{r,v,p} \le \sum_{c \in A^{p}} VAR\_BFNSP_{r,v,t,p,c,s} \\
&VAR\_BSFNSP_{r,v,t,p,c,s} \le VAR\_BSUPSR^{\mathrm{lo}}_{r,v,t,p,s} \cdot rmax_{r,v,p,c,s} \quad , \\
&\forall r,v,t,p,s,c \in A^{mFRR} \cap A^{n}
\end{aligned} \tag*{(eq. 19)}$$

Finally, equations (eq. 20) and (eq. 21) limit the provision of RR-type of the reserve, via non-spinning units.

$$\sum_{c \in A^{p}} VAR\_BFNSP_{r,v,t,p,c,s} \le VAR\_BSUPSR_{r,v,t,p,s,\text{"UP"}} \cdot \max\left\{ c \in A^{p} \mid rmax_{r,v,p,c,s} \right\} \tag*{(eq. 20)}$$

$$\sum_{c \in A^{n}} VAR\_BFNSP_{r,v,t,p,c,s} \le VAR\_BSUPSR_{r,v,t,p,s,\text{"LO"}} \cdot \max\left\{ c \in A^{n} \mid rmax_{r,v,p,c,s} \right\} \tag*{(eq. 21)}$$

It is important that the $rmax_{r,v,p,s,c}$ parameter is higher with the slowest reserve:

$$rmax_{r,v,p,s,\mathrm{FCR}} \le rmax_{r,v,p,s,\mathrm{aFRR}} \le rmax_{r,v,p,s,\mathrm{mFRR}} \le rmax_{r,v,p,s,\mathrm{RR}}$$

If this condition is not met, then the above constraints can lead to infeasibilities. The TIMES generator checks the above condition and takes a remedy action when this condition is violated by considering the maximum value of $rmax$ among the reserves that are prior or equal in the hierarchy of reserves to the reserve under consideration. For example, in the case of the mFRR-type of reserve, the following relationship is considered when setting the $rmax$ parameter for this reserve:

$$rmax_{r,v,p,s,\mathrm{mFRR}} \leftarrow \max(max_{r,v,p,s,\mathrm{FCR}}, rmax_{r,v,p,s,\mathrm{aFRR}}, rmax_{r,v,p,s,\mathrm{mFRR}})$$

When an adjustment of the $rmax$ is made using the above formula, then the user is informed in the QA.log of TIMES (see also the implementation section).

2.5.5 Reserve provision from storages when storage levels are bounded by capacity

When storages are modelled via NCAP_AFC, i.e. the capacity is bounded by the output commodity, or, viewed another way, the capacity of the storage is measured in power units, then the constraints of the previous sections are applicable for these types of storages. However, the previous constraints do not cover the case when the capacity of the storage is in energy units. Hence, this section deals with the reserve provision from storage processes when all the following hold: a) these storage processes have only electricity outputs; b) they also have their storage levels bounded by capacity; c) in addition, they have either electricity inputs or no NCAP_AFC specified; d) and, they have either no $rmax_{r,v,p,c,s}$ specified or no NCAP_AFC specified.

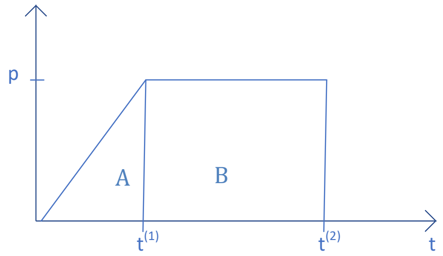

Figure 6: Energy needed to be stored in a storage process to provide a contracted reserve of power p for time $t^{(2)} - t^{(1)}$. The stored energy ramps-up linearly to reach the contracted power, and this ramping phase lasts $t^{(1)}$. Therefore, the total required stored energy to provide reserve is equal to the sum of the areas defined by the triangle A and the rectangle B.

For storages in which the stored energy is bounded by capacity, the available range to provide energy services should be constrained in both directions by the margins that are contracted for reserve provision (Brijs et al. 2016). First, we assume a linear ramping from the current output level to the output after the activation of the reserve in time $t^{(1)}$. The energy reserved for reserve provision is the energy required for the linear ramping plus the energy needed to maintain the reserve provision until time $t^{(2)}$ (see Figure 6).

Equation (eq. 22) states that the energy stored in a storage process, which has been contracted for positive (injection of energy) reserve provision, should be enough to cover the energy needed to ramp up the current output level to the level required for the provision of the reserve at the contracted capacity (first summation term) plus the energy needed to provide the reserve for the contracted period (second summation term).

$$\sum_{ts\in PRC\_TS(r,p,ts)}\left(\frac{VAR\_ACT_{r,v,t,p,ts}\cdot rs\_fr_{r,ts,s}}{rs\_stgprd_{r,ts}}\right)\geq\frac{\dfrac{ca_{r,p}}{\sqrt{stg\_eff_{r,v,p}}}}{8760}\cdot$$

$$\cdot\sum_{c\in A^{p}}\left(VAR\_BSFSP_{r,v,t,p,c,s}\cdot\left(\frac{t^{(1)}_{r,c,p}}{2}+\left(t^{(2)}_{r,c,p}-t^{(1)}_{r,c,p}\right)\cdot\max\left(1,\frac{\dfrac{yrfr_{r,s}}{rs\_stgprd_{r,s}}\cdot 8760}{\left(1+t^{(2)}_{r,c,p}\right)^{0.5}}\right)\right)\right)\quad,\qquad\text{(eq. 22)}$$

$$\forall r,v,t,p,s$$

Equation (eq. 23) states that the energy stored in a storage process, which has been contracted for negative (withdrawal of energy) reserve provision, should be less than the maximum energy that can be stored minus the energy that will enter into the storage through charging required for the negative reserve provision.

$$\sum_{ts\in PRC\_TS(r,p,ts)}\left(\frac{VAR\_ACT_{r,v,t,p,ts}\cdot rs\_fr_{r,ts,s}}{rs\_stgprd_{r,ts}}\right)\leq$$

$$\cdot\, VAR\_NCAP_{r,v,p}\cdot ctc_{r,v,t,p}\cdot af^{\mathrm{act}}_{r,v,p}\cdot ca_{r,p}-\frac{ca_{r,p}\cdot\sqrt{stg\_eff_{r,v,p}}}{8760}\cdot\qquad\text{(eq. 23)}$$

$$\cdot\sum_{c\in A^{n}}\left(VAR\_BFSP_{r,v,t,p,c,s}\cdot\left(\frac{t^{(1)}_{r,c,p}}{2}+\left(t^{(2)}_{r,c,p}-t^{(1)}_{r,c,p}\right)\cdot\max\left(1,\frac{\dfrac{yrfr_{r,s}}{rs\_stgprd_{r,s}}\cdot 8760}{\left(1+t^{(2)}_{r,c,p}\right)^{0.5}}\right)\right)\right)$$

$$\forall r,v,t,p$$

2.5.6 Additional reserve provision constraints for demand units

The demand units, e.g. heat pumps, water heaters , electric vehicles, or large industrial chillers/heaters can also provide a reserve. They can alter their output to serve the ancillary market without compromising the service they provide. When the units are increasing their output, they provide a negative reserve, while when they shut-down, they provide a positive reserve. We assume that the end-use processes can start, ramp-up/down and shut-down fast enough to provide a reserve, and no minimum stable operating level is required for them.

Concerning the contribution of the demand units to reserve provision this is controlled via the $rmax$ parameter and the equations of section 2.5.4. Equation (eq. 24) states that the current operating level plus the power contracted for negative reserve provision should be less than the available capacity of the end-use process. The activity is multiplied by the parameter act_flo since for demand processes the activity may not represent electrical energy at all.

$$\sum_{c\in A^n} VAR\_BFSP_{r,v,t,p,c,s} \le \left(VAR\_NCAP_{r,v,p} \cdot ctc_{r,v,t,p} \cdot af^{\max}_{r,v,t,p,s} - \frac{\dfrac{VAR\_ACT_{r,v,t,p,s}}{ca_{r,p}}}{yrfr_{r,s}} \right) \cdot \sum_{c\in TOPIN(ELC)} act\_flo_{r,v,t,p,c} \qquad \text{(eq. 24)}$$

Equation (eq. 25) states that the operating level of the end-use process should be at least equal to the contracted positive reserve, in the case that the end-use process needs to shut-down when the reserve is activated.

$$\sum_{c\in TOPIN(ELC)} \frac{VAR\_FLO_{r,v,t,p,c,s}}{ca_{r,p} \cdot yrfr_{r,s}} \ge \sum_{c\in A^p} VAR\_BSFSP_{r,v,t,p,c,s} \qquad \text{(eq. 25)}$$

2.5.7 Process-related bounds on reserve provision

In the case that the reserve provision from a process needs to be externally bounded, e.g. due to regulation, the ancillary services markets extension of TIMES offers two options: a) absolute bounds (lower, upper, or fixed) per process; b) share bounds (lower or upper) per process or group of processes.

The following equation implements an absolute bound on the reserve provision per process:

$$\frac{\displaystyle\sum_{ts\in C(s)\cup s} \sum_{v} (VAR\_BSFSP_{r,v,t,p,c,ts} + VAR\_BSNFSP_{r,v,t,p,c,ts}) \cdot yrfr_{ts}}{yrfr_s} \begin{array}{l} \le bsbnd_{r,t,p,c,s,\text{"UP"}} \\ \ge bsbnd_{r,t,p,c,s,\text{"LO"}} \\ = bsbnd_{r,t,p,c,s,\text{"FX"}} \end{array} \qquad \text{(eq. 26)}$$

The bound is given on the capacity unit of the process. The equation can apply the bound to specific timeslices at DAYNITE level, or at higher levels. In the case that the bound is applied at WEEKLY, SEASONAL or ANNUAL level, the reserve provision is first converted to flow units and then back to capacity units to avoid summing capacity units over timeslices. In this way, the bound operates as an ACT_BND at timeslice levels higher than the DAYNITE level.

For a user-defined group of process k (the definition of the group can be achieved via the *gr_genmap* parameter, or implicitly by p=k), the following equation imposes a bound in the share of the total provided reserve:

$$
\begin{aligned}
&\sum_{p\in kp(k,p)}\sum_{v}\begin{pmatrix} VAR\_BSFSP_{r,v,t,p,c,s}+ \\ +\,VAR\_BSFNSP_{r,v,t,p,c,s}\end{pmatrix}\begin{matrix}\le bsshare_{r,t,p,c,s,\text{"UP"}} \\ \ge bsshare_{r,t,p,c,s,\text{"LO"}}\end{matrix}\cdot \\
&\cdot\,\lambda_{r,t,c}\cdot\begin{pmatrix} \max\left(VAR\_BSD^{\text{prob}}_{r,t,s,c}\;,\;VAR\_BSD^{\text{deter}}_{r,t,s,c}\right)\cdot\left(\omega_{r,t,c,s}=1\right)\;+ \\ \left(\left(1-w_{r,t,s,c}\right)\cdot VAR\_BSD^{\text{prob}}_{r,t,s,c}+w_{r,t,s,c}\cdot VAR\_BSD^{\text{deter}}_{r,t,s,c}\right)\cdot\left(\omega_{r,t,c,s}=2\right)\;+ \\ \left|VAR\_BSD^{\text{prob}}_{r,t,s,c}-VAR\_BSD^{\text{deter}}_{r,t,s,c}\right|\cdot\left(\omega_{r,t,c,s}=3\right)\end{pmatrix} \\
&\forall r,t,p,s,c\in A
\end{aligned}
\qquad \textit{(eq. 27)}
$$

2.6 Cross-border or inter-regional trade of ancillary services

The trade of operational reserves, of all types, is supported via the normal unilateral or bilateral trade process of TIMES. The mechanism to enable the trade of reserves is the same as for any other commodity that can be exchanged between regions. The trade in reserves thus must take place in terms of flows.

2.7 Storage degradation due to cycling

The lifetime of storage is limited both by the calendar life and the cycle-life time. The capacity of storage drops as part of the cycling, with the relationship usually being non-linear. We follow (Brijs et al. 2016), and we approximate the impact of the storage degradation on the investment decision, by assuming a targeted number of cycles per year, $stg\_cyc_{r,v,p}/ncap\_tlife_{r,v,p}$, where $stg\_cyc_{r,v,p}$ is the maximum number of cycles (e.g. 3000 or 4500) and $ncap\_tlife_{r,v,p}$ is the technical lifetime of the storage process (e.g. 15 years). If we assume 1kWh of storage process, then the number of cycles occurring in a year is equal to the energy discharged (assuming a discharging is followed by a charging at a later point). If the number of cycles in a year exceeds the annual targeted cycles, then a replacement of the storage has implicitly happened and the replacement capacity that supports this extensive cycling is represented with variable VAR_STGCC. The variable is multiplied in the objective function with the annualised investment cost to account for the replacement cost of the storage[10]. Equation (eq. 28) tracks the amount of the storage replacement capacity needed for extensive cycling.

$$\left(ctc_{r,v,t,p}\cdot VAR\_NCAP_{r,v,p}+VAR\_STGCC_{r,v,t,p}\right)\cdot\max_{s}\left(af_{r,v,p,s}\right)\cdot ca_{r,p}\geq \left(\frac{ncap\_tlife_{r,v,p}}{stg\_cyc_{r,v,p}}\cdot\frac{\sum_{s}VAR\_SOUT_{r,v,p,t,s}}{prc\_actflo_{r,v,p}}\right),\quad \forall\left(r,v,t,p\right)\in RTP\_VINTYR \qquad \text{(eq. 28)}$$

Box 4: STG_MAXCYC versus NCAP_OLIFE functionality

The functionality introduced by the new parameter *stg_cyc* (or STG_MAXCYC in the TIMES implementation) may seem to resemble the functionality of the TIMES NCAP_OLIFE parameter. However, while NCAP_OLIFE simply limits the full-load operating years to the number of year specified (in terms of activity), STG_MAXCYC limits the extrapolated lifetime output from storage in proportion to the storage capacity. Therefore, such storage cycling limits cannot be modelled by using NCAP_OLIFE. Moreover, while NCAP_OLIFE requires the process to be vintaged and with early retirements enabled, STG_MAXCYC does not require either.

2.8 Maintenance and outages of power plants

The demand for the reserve is also influenced by the periods of maintenance and (un)forced outages. In TIMES, there are two approaches to model periods of maintenance and (un)forced outages. The first method considers the derating of the nameplate capacity by using an availability factor of less than 1. The second method limits the yearly generated output, by using, e.g. a bound on the production, which in turns mimics optimal scheduling of the maintenance periods. However, these two methods neglect that the capacity that is shut-down for maintenance cannot be started again until the maintenance period is over. We fill this gap, by approximating the discrete character of maintenance periods. In the proposed design, we modify the approach of (Poncelet et al. 2014).

Equation (eq. 29) enters capacity under maintenance in a timeslice s, which maximum is equal to the $1-af^{\max}_{r,v,t,p.s}$ capacity. When s is above the process timeslice level (e.g. s = *ANNUAL* or s ∊ *SEASON*, while *prc_tsl* = *DAYNITE*), then

---

[10] This feature becomes of importance if the investment in a storage process is related to the investment of another process, e.g. the battery of an electric car. In this example and in the case of excessive cycling, the optimiser will opt to pay the replacement cost of the battery than re-investing in a car, if the car has not reached the end of its lifetime (see also Box 4).

TIMES optimally decides when the maintenance period will occur. When s is at the process timeslice level, then it represent the starting timeslice of the continuous maintenance period. In both cases, the duration of the maintenance period is set with the parameter $mnt\_time_{r,p,v,t,s}$. . The mnt_time is most useful when specified for timeslices above the process timeslice level (defined via prc_tsl), but the implementation supports both cases.

$$\sum_{ts \in PRC\_TS(r,p)} \left(VAR\_BSMUP_{r,v,t,p,ts} \cdot \min\left(1, \frac{\frac{mnt\_time_{r,v,p,s}}{8760} \cdot rs\_stgprd_{r,ts}}{yrfr_{r,s}} \right) \right) \geq \left(1 - af^{\max}_{r,v,t,p,s}\right) \cdot VAR\_NCAP_{r,v,p} \cdot ctc_{r,v,t,p} \qquad \text{(eq. 29)}$$

The equation (eq. 30) when defined at the process timeslice level forces the offline capacity to be sufficient for accommodating the capacity under maintenance during the continuous maintenance period[11].

$$\sum_{ts \in C(P(s))} \left\{ VAR\_BSMUP_{r,v,t,p,s} \cdot \left(\mathrm{mod}\left(Hour(s) - Hour(ts), 24 \right) < mnt\_time_{r,p,v,t,s} \right) \right\} \leq \left(1 - af^{\max}_{r,v,t,p,s}\right) \cdot VAR\_NCAP_{r,v,p} \cdot ctc_{r,v,p,t} + af^{\max}_{r,v,t,p,s} \cdot \sum_{ts \in SUP(s)} VAR\_OFF_{r,v,t,p,ts} \qquad \text{(eq. 30)}$$

---

[11] Of course, by defining some AF<1 for consecutive timeslices one can also force a continuous maintenance outage. The additional feature brought by this extension is that the maintenance period can also be endogenously decided by TIMES.

3. IMPLEMENTATION IN TIMES

3.1 Overview

This section provides the definition of the new input sets and parameters, and the internal model variables required to implement the ancillary markets extension.

3.2 TIMES Input Attributes

3.2.1 Input Sets

No new input sets have been explicitly implemented in the Balancing Services extension. All the positive and negative reserves should be defined as commodities in the model. However, there are two new sets implicitly defined by the input parameters, and two new system sets, as follows:

- b – balancing reserves (implicitly defined by BS_RTYPE, see below)
- k – set of sources for imbalances (implicitly defined by BS_SIGMA)
- dpar – system set of parameters for defining deterministic reserve demands (contains the members 'EXOGEN' and 'WMAXSI')
- dtype – system set of reserve demand types (contains the members 'PRB', 'DET', 'MAX' and 'DIF')

3.2.2 Input Parameters

There are a number of new input parameters that have been implemented for the Balancing Services extension in TIMES, and should be available for the user input in the user shell (see Table 7). Excluding the more general storage cycle parameter (STG_CYCS), all the input parameters are prefixed by BS_ . In addition to the new parameters, the Balancing Services extension specifically makes use of the existing COM_LIM and GR_GENMAP attributes, as also described in Table 7.

Table 7: Input parameters for the TIMES Ancillary Balancing Services extension.

Parameter	**Description**
BS_BNDPRS (r,t,p,b,s,bd)	Absolute bound on the reserve provision **b** from process **p** . It is not levelized (inherited or aggregated), but applied only directly on the timeslice **s** specified. It is by default not inter-/extrapolated, but all interpolation options can be used. Unit: Capacity unit of the process
BS_CAPACT (r)	Conversion factor of reserves from capacity to commodity flow units.
BS_DELTA	Calibration parameter for probabilistic reserve demand for

Parameter	Description
(r, y, b, s)	reserve **b**, in region **r**, year **y** and timeslice **s**. Unit: dimensionless
BS_DEMDET (r, y, dpar, b, s)	Parameters for defining deterministic reserve demands: • dpar='EXOGEN': Exogenous reserve demand provided by the user for reserve **b**, in region **r**, year **y** and timeslice **s.** Unit: capacity unit • dpar='WMAXSI': Weight of the contribution of the largest system element in the calculation of the deterministic component of the demand for reserve **b**, in region **r**, year **y** and timeslice **s.** Unit: dimensionless (fraction of capacity)
BS_DETWT (r, y, b)	Weight of the deterministic component in the formulation of the endogenous requirements of reserve **b** in region **r**, year **y.** Unit: dimensionless
BS_LAMBDA (r, y, b)	Dependence factor (fudge factor) used in the calculations of the reserve requirements for reserve **b** in region **r**, year **y**. If not defined, then the demand for reserve **b** cannot be calculated. Unit: dimensionless
BS_MAINT (r, v, p)	For endogenous maintenance scheduling, defines the minimum continuous maintenance time of process **p**, vintage **v**, timeslice **s**, in hours (where s can be a process timeslice, or more usefully above it, to allow for optimizing the maintenance period). If defined on DAYNITE or WEEKLY level, requires that start-ups are explicitly enabled on that level (using ACT_CSTUP/ACT_CSTSD). Unit: hours (if over 24 hours, continuous over whole season).
BS_OMEGA (r, y, b, s)	Parameter denoting if the demand for reserve **b** is the weighted sum of the deterministic and probabilistic component (ω=2), the maximum of the two (ω=1) or their difference (ω=3). Unit: dimensionless
BS_RMAX (r, v, p, b, s)	Maximum contribution of process **p**, vintage **v**, in timeslice **s** for the provision of reserve **b.** Required for enabling reserve provision from any non-storage processes. Unit: fraction (of capacity)
BS_RTYPE (r, b)	Type of reserve **b** in region **r**. Supported types are: • ±1 : FCR type reserve, +1 = positive, −1 = negative • ±2 : AFRR type reserve, +2 = positive, −2 = negative • ±3 : MFRR type reserve, +3 = positive, −3 = negative • ±4 : RR type reserve, +4 = positive, −4 = negative Unit: dimensionless
BS_SHARE (r, y, b, k, bd)	Maximum (**bd**=UP) or minimum (**bd**=LO) share of process group **k** in the demand for reserve **b**, in region **r** and year **y**, where the demand is measured as defined by BS_OMEGA. The group **k** can be defined by GR_GENMAP, or implicitly for any single process **prc**=**k.**
BS_SIGMA	Standard deviation of the forecast error regarding the

Parameter	**Description**
(r, y, b, k, s)	unpredictable variation **k**, in region **r**, year **y**, timeslice **s**, which is used for the calculation of the demand for reserve **b**. Unit: dimensionless
BS_STIME (r, p, b, bd)	Defines the times (in hours) for reserve provision from storage process **p** for reserve **b** in region **r**: • bd='LO' : Time required for a storage process to ramp up in order to provide reserve **b**, e.g. for FCR-type reserve can be 0.01, for aFRR-type of reserve can be 0.13, etc. • bd='UP' : Duration of the provision of reserve **b** from a storage process, including also the time to ramp up. E.g. the duration of a aFRR-type of reserve can be 7.0 min , and if we assume that the process needs 0.13 min to ramp up, then the parameter BS_STIME (‘UP’) should be set to 7.13/60 hours. Unit: hours
COM_LIM (r, b, lim)	GAMS SET attribute, which defines the limit type for reserve commodity **b** in region **r**. • **lim**='LO' / 'FX' : demand for reserve **b** must be met and may even be exceeded, market balance required at the commodity TS only • **lim**='N' : demand for reserve **b** must be met and may even be exceeded, market balance required at the finest level, such that the demand on the timeslices below the commodity TS are all equal and correspond to the maximum imbalance.
GR_GENMAP (r, p, k)	Mapping of processes **p** to imbalance type **k** (or process group) in region **r**. Value can be any positive or negative number, where a positive value means that output flows should be used for measuring the load level, and a negative value means that input flows should be considered. Unit: dimensionless
STG_MAXCYC (r, y, p)	Maximum number of cycles for a storage process **p**, in region **r**, for process vintage **y**. Unit: dimensionless
UC_COMNET(..) UC_FLO(..)	UC_COMNET may be used for referring to the total inland demand in UC constraints. UC_FLO may be used in timeslice-dynamic UC constraints for referring to reserve provisions.

The parameters BS_OMEGA, BS_SIGMA are of standard inheritance across the timeslice tree, i.e. their value in timeslice *ts* is inherited to all timeslices *s* below *ts*. Moreover, the parameter BS_LAMBDA should be defined in all cases, even in the case of FCR-type and RR-type reserves; when the cardinality of a reserve category is 1, e.g. FCR-type of reserves, then the value of parameter BS_LAMBDA should be set to 1 for this reserve category, i.e. BS_LAMBDA(r, y, “FCR+”)=1.

Finally, the parameter BS_DELTA should be defined for all reserves belonging to the same type, e.g. for both the aFRR and mFRR types of reserve.

3.3 Description of Variables

3.3.1 Virtual Variables

The virtual variables referred to in the documentation and TIMES implementation are described in Table 8. Many of the virtual variables are created from the actual GAMS variables through macros.

Table 8: Virtual variables referred to in the TIMES Ancillary Balancing Services extension.

Variable	**Description**	**New / Old**
VAR_ACT (r,v,t,p,s)	Variable representing activity of process **p** in region **r**, vintage **v**, period **t**, and timeslice **s**.	Old
VAR_BSD (dtype,r,t,b,s)	Variable representing demand of reserve **b** in region **r**, period **t** and timeslice **s**, of type dtype ∊ {'PRB','DET','MAX','DIF'}	New
VAR_BSON (r,v,t,p,s)	Variable representing the online capacity of process **p** in region **r**, vintage **v**, period **t**, and timeslice **s**.	New
VAR_BSFSP (r,v,t,p,b,s)	Variable representing provision of spinning reserve **b** by process **p** in region **r**, vintage **v**, period **t**, and timeslice **s**.	New
VAR_BSFNSP (r,v,t,p,b,s)	Variable representing provision of non-spinning reserve **b** by process **p** in region **r**, vintage **v**, period **t**, and timeslice **s**.	New
VAR_BSUPSR (r,v,t,p,s,bd)	Variable representing the capacity of process **p** in region **r**, vintage **v**, period **t**, and timeslice **s**, allocated to provision of positive/negative reserves via start-up/shut-down (**bd**=UP/LO).	New
VAR_BSMUP (r,v,t,p,s)	Variable representing capacity of process **p** shutting down for maintenance in region **r**, vintage **v**, period **t**, and timeslice **s**.	New
VAR_COMNET (r,t,c,s)	Variable representing the net production of commodity **c** in region **r**, vintage **v**, period **t**, and timeslice **s**.	Old
VAR_COMPRD (r,t,c,s)	Variable representing the gross production of commodity **c** in region **r**, vintage **v**, period **t**, and timeslice **s**; for reserve commodities, however, it represents the total inland supply.	Old
VAR_FLO (r,v,t,p,c,s)	Variable representing flow of commodity **c** for process **p** in region **r**, vintage **v**, period **t**, and timeslice **s**.	Old
VAR_IRE (r,v,t,p,c,s,ie)	Variable representing import/export of commodity **c** by process **p** in region **r**, vintage **v**, period **t**, and timeslice **s**.	Old
VAR_NCAP (r,t,p)	Variable representing new capacity of process **p** in region **r**, period **t**.	Old
VAR_OFF (r,v,t,p,s)	Variable representing off-line status of process **p** in region **r**, vintage **v**, period **t**, and timeslice **s**.	Old
VAR_RLD	Variable representing the reserve-defining loads for the	Old

Variable	Description	New / Old
(r,t,s,k)	source of imbalance **k**, in region **r**, period **t** and timeslice **s**.	
VAR_SIN (r,v,t,p,c,s)	Variable representing inflow of commodity **c** to storage process **p** in region **r**, vintage **v**, period **t**, and timeslice **s**.	Old
VAR_SOUT (r,v,t,p,c,s)	Variable representing outflow of commodity **c** from storage process **p** in region **r**, vintage **v**, period **t**, and timeslice **s**.	Old
VAR_UPS (r,v,t,p,s,lim)	Variable representing start-up / shut-down status of process **p** in region **r**, vintage **v**, period **t**, and timeslice **s**.	Old

3.3.2 New GAMS Variables Implemented

At the low level, the virtual variables described have been implemented through the actual GAMS variables, either indirectly via macros or directly. The new variables implemented are listed in Table 9. As shown by the table, by using GAMS macros the number of new variables implemented has been reduced to only two: VAR_COMLV and VAR_BSPRS.

Table 9: Implemented variables in the TIMES Ancillary Balancing Services extension.

Variable	Description	New / Old
VAR_COMLV (clev,r,y,c,s)	Variable representing the level of commodity **c**, of type **clev,** in region **r**, period **t**, and timeslice **s**.	New
VAR_BSPRS (r,v,t,p,c,s,lim)	Variable representing a level of process **p** in region **r**, vintage **v**, period **t**, commodity **c**, timeslice **s**, and with lim type **lim**.	New

3.4 Reporting Parameters

There are no new reporting parameters implemented in the ABS extension. The existing reporting parameters P_OUT (Var_Pout in VEDA-BE) and CST_ACTC (Cost_Act in VEDA-BE) are utilized for reporting the amount of reserves provided by each process, including imports, and the additional depreciation cost caused by excess storage cycles. In addition, any trade in reserves is reported in the F_IN and F_OUT reporting parameters in the usual way, in terms of flows, as for all other traded commodities. The existing commodity attributes PAR_COMNETL and PAR_COMBALEM (Var_Comnet and EQ_CombalM in VEDA-BE) contain the inland demands and the undiscounted marginals (the dual values) for the reserve commodity balances (both in terms of flows, and not power levels).

The reporting attributes most relevant to the Ancillary Balancing Services are thus the following:

- P_OUT(r,v,t,p,b,s) – level of reserves of type **b** provided by process **p**, or imported by trade process **p** into region **r**
- F_IN(r,v,t,p,b,s) – reserves of type **b** exported by trade process **p** (in terms of flows, not power levels)
- PAR_COMNETL(r,t,b,s) – total inland demand for reserves of type **b** in region **r**, period **t** and timeslice **s** (in terms of flows, not power levels)
- PAR_COMBALEM(r,t,b,s) – undiscounted marginal cost value (dual value) of commodity balance for reserve **b** in period **t** and timeslice **s** (in terms of flows, not power levels)
- CST_ACTC(r,v,t,p,'+') – additional costs from exceeding storage cycle limit (used also for reporting start-up / shut-down costs and ramping costs for normal processes)

The reporting of reserve capacities by processes (P_OUT) is by default enabled whenever the ABS extension is used. The option RPT_OPT('RATE',1)=<value> may be used for defining a conversion factor from the desired capacity unit of the power levels to the unit of energy flows. Hence, if in the model the common energy flow unit is PJ, by defining RPT_OPT('RATE',1)=31.536 the unit of the reported reserve capacities will be GW. When desired, the reporting of reserve provision capacities (P_OUT) can nonetheless be also disabled by using the TIMES reporting option RPT_OPT('RATE',1)=–1 (or any other negative value).

4. WORKING EXAMPLES

In this section, small working examples are presented focusing on each one of the new features. Each example demonstrates how the corresponding feature can be enabled. The description of the examples is extensive and detailed, and we hope they help the user to implement step-by-step the new features.

4.1 Ancillary services

4.2 Reserve sizing (endogenous demand for ancillary services)

The new extension of TIMES supports flexibility in defining the names of the reserves, their hierarchy from faster to slowest and their direction (positive or negative) via the parameter BS_RTYPE(r,b).

Different approaches of reserve sizing can be modelled via the parameters BS_OMEGA(r, y, b, s) , BS_LAMBDA(r, y, b) , BS_DETWT(r, y, b) , BS_DELTA(r, y, b, s) , BS_SIGMA (r, y, b, k, s) , BS_DEMDET (r, y, dpar, b, s) .

In the following example, we provide a hypothetical configuration of a hypothetical ancillary market aiming at demonstrating the features in a comprehensive way.

Example

The demand for FCR-type of reserve in a region RG is exogenously set to 60 MW by ENTSO-E. The demand for aFRR and mFRR types of reserve is based on convolution methods of the forecast errors on wind, solar and electricity loads (probabilistic assessment). The total FRR requirement covers the 99.9% of the probabilistic assessment, with the aFRR being the 90% quantile of it. Let's assume, based on these quantiles, that 80% of the total FRR can be allocated as aFRR type of reserve and the rest of 20% is assigned as mFRR. For the probabilistic assessment, the wind forecast error is calculated to be 1.5%, the solar PV forecast error is 0.8% and the load forecast error is 1.7%. The forecast errors are assumed to follow a normal distribution with mean zero and standard deviations 1.5%, 0.8% and 1.7% respectively for wind, solar and load. The linear approximation of FRR made by TIMES needs to be adjusted by 0.9 to be closer to the observed demand for reserve. For all types of reserve, FCR and FRR, the negative reserve requirements are estimated to be 90% of the positive.

The loss of the largest grid element is accounted with 10% when sizing the reserves (deterministic assessment) and the difference between the deterministic and the probabilistic component is assigned to be RR-type of reserve.

In the parameters that are used in this example, the index **t** denotes a milestone year, the index **r** a region, the index **p** a process, and the index **s** a timeslice.

a. Definition of the reserve commodities

The first step is that the user defines in VEDA_FE commodities of type NRG and that at desired timeslice level that represent the reserves. In this example we define the following commodities representing reserves at the DAYNITE level: FCR+ , AFRR+, MFRR+, RR+, RR- .

The second step is to define the parameter BS_RTYPE(r,b) to establish the hierarchy (smaller number corresponds to faster reserve) and the direction (positive numbers correspond to positive or upward reserve) of the reserves, as follows:

```
BS_RTYPE (‘RG’, ’FCR+’)  = 1
BS_RTYPE (‘RG’, ’FCR-’)  = -1
BS_RTYPE (‘RG’, ’AFRR+’) = 2
BS_RTYPE (‘RG’, ’AFRR-’) = -2
BS_RTYPE (‘RG’, ’MFRR+’) = 3
BS_RTYPE (‘RG’, ’MFRR-’) = -3
BS_RTYPE (‘RG’, ’RR+’)   = 4
BS_RTYPE (‘RG’, ’RR-’)   = -4
```

Then, the BS_CAPACT(r) parameter can be set to introduce the conversion factor from power to activity for the reserve commodities as well:

```
BS_CAPACT (‘RG’)   = 31.536
```

b. Establishing the system imbalances

The next step is to define the system imbalances that are used in the definition of the reserves, namely the forecast errors related to electricity production from solar and wind, the forecast error of the demand, and the loss of the largest grid element. This is accomplished with the parameter GR_GENMAP that maps processes to user-defined imbalances. Any positive value of the parameter indicates that the imbalance is related to the production of electricity (e.g. for the wind and solar imbalances), while any negative value indicates that the imbalance is related to the consumption of electricity (e.g. for the demand imbalance):

```
GR_GENMAP(‘RG’,‘EWND‘,‘WINSI‘)      =1;  // map process EWND to wind imbalance WINSI
```

```
GR_GENMAP(‘RG’,‘ESOL‘,‘SOLSI‘)      =1;  // map process ESOL to solar imbalance SOLSI
GR_GENMAP(‘RG’,‘ESOL1‘,‘SOLSI‘)     =1;  // map process ESOL1 to solar imbalance SOLSI
GR_GENMAP(‘RG’,‘EDEM‘,‘DEMSI‘)       = -1;  // map process ELDEM to demand imbalance
DEMSI
GR_GENMAP(‘RG’,‘ENUC‘,‘SI‘)     = 1;  // ENUC is considered as large grid element
GR_GENMAP(‘RG’,‘EGTCC‘,‘SI‘)   = 1;  // EGTCC is considered as large grid element
```

c. Establishing the demand for FCR-type of reserves

The FCR type of reserve is exogenously given in the example. The weighted sum formulation of the demand function should be selected with the parameter BS_OMEGA, in which the weight of the deterministic component BS_DETWT is 1. Then the exogenous demand can be defined via the parameter BS_DEMDET:

```
BS_OMEGA (‘RG’, ’FCR+’)        = 2 ;      // select the weighted-sum
BS_DETWT(‘RG’, t , ‘FCR+‘)     = 1;       // set the weight of the deterministic component to 1
BS_DEMDET(‘RG’, t , ‘EXOGEN‘ , ‘FCR+‘)  = 0.06;        // set the value of reserve in GW

BS_OMEGA (‘RG’, ’FCR-’)        = 2 ;      // treat negative reserve symmetrically to positive
BS_DETWT(‘RG’, t , ‘FCR-‘)     = 1;
BS_DEMDET(‘RG’, t , ‘EXOGEN ‘, ‘FCR-‘) = 0.054;  // the FCR- is 90% of the positive reserve


BS_LAMBDA(‘RG’, t , ‘FCR+‘) = 1.0;      // lambda is defined as 1 since one type of FCR exists
BS_LAMBDA(‘RG’, t , ‘FCR-‘) = 1.0;      // lambda is defined as 1 since one type of FCR exists
```

d. Establishing the demand for FRR-type of reserves

The FRR type of reserve in our example is based only on probabilistic assessment. The weighted sum formulation should be chosen via the parameter BS_OMEGA. The weight of the deterministic component BS_DETWT should be 0 for all FRR-type of reserves. Then, the probabilistic components of aFRR and mFRR should be equal to each other and equal to FRR. Thus, the BS_SIGMA parameter should be the same for all FRR-type of reserves. The parameter BS_DELTA should be enabled to adjust the approximation of the probabilistic component of reserve and also establish the relationship of the positive to the negative reserve. Finally, the relationship between aFRR and mFRR type of reserves with respect to FRR should be established via the parameter BS_LAMBDA:

```
BS_OMEGA (‘RG’, ’AFRR+’)     = 2;       // set the weighted-sum formulation
BS_OMEGA (‘RG’, ’AFRR-’)     = 2;
BS_OMEGA (‘RG’, ’MFRR+’)     = 2;
BS_OMEGA (‘RG’, ’MFRR-’)     = 2;

BS_DETWT(‘RG’, t , ‘AFRR+‘)  = 0;       // set the weight of the deterministic component to 0
```

```
BS_DETWT(‘RG’, t , ‘AFRR-‘)    = 0;
BS_DETWT(‘RG’, t , ‘MFRR+‘)   = 0;
BS_DETWT(‘RG’, t , ‘MFRR-‘)    = 0;


BS_SIGMA(‘RG’, t , ‘AFRR+‘, ‘DEMSI‘, ‘ANNUAL‘ ) = 0.017;      // std. dev. of demand error
BS_SIGMA(‘RG’, t , ‘AFRR+‘, ‘SOLSI‘, ‘ANNUAL‘ ) = 0.015;      // std. dev. of solar error
BS_SIGMA(‘RG’, t , ‘AFRR+‘, ‘WINSI‘, ‘ANNUAL‘ ) = 0.008;      // std. dev. of wind error
BS_SIGMA(‘RG’, t , ‘AFRR-‘, ‘DEMSI‘, ‘ANNUAL‘ ) = 0.017;      // AFRR- is symmetric to AFRR+
BS_SIGMA(‘RG’, t , ‘AFRR-‘, ‘SOLSI‘, ‘ANNUAL‘ ) = 0.015;
BS_SIGMA(‘RG’, t , ‘AFRR-‘, ‘WINSI‘, ‘ANNUAL‘ ) = 0.008;

BS_SIGMA(‘RG’, t , ‘MFRR+‘, ‘DEMSI‘, ‘ANNUAL‘ ) = 0.017;      // MFRR is symmetric to AFRR
BS_SIGMA(‘RG’, t , ‘MFRR+‘, ‘SOLSI‘, ‘ANNUAL‘ ) = 0.015;
BS_SIGMA(‘RG’, t , ‘MFRR+‘, ‘WINSI‘, ‘ANNUAL‘ ) = 0.008;
BS_SIGMA(‘RG’, t , ‘MFRR-‘, ‘DEMSI‘, ‘ANNUAL‘ ) = 0.017;
BS_SIGMA(‘RG’, t , ‘MFRR-‘, ‘SOLSI‘, ‘ANNUAL‘ ) = 0.015;
BS_SIGMA(‘RG’, t , ‘MFRR-‘, ‘WINSI‘, ‘ANNUAL‘ ) = 0.008;

BS_DELTA(‘RG’, t , ‘AFRR+‘) = 0.9;      // the AFRR+ is adjusted by 10% due to approximation
BS_DELTA(‘RG’, t , ‘AFRR-‘) = 0.9;      // the AFRR- is adjusted by 10% due to approximation

BS_DELTA(‘RG’, t , ‘MFRR+‘) = 0.9;      // the MFRR+ is adjusted by 10% due to approximation
BS_DELTA(‘RG’, t , ‘MFRR-‘) = 0.9;      // the MFRR- is adjusted by 10% due to approximation

BS_LAMBDA(‘RG’, t , ‘AFRR+‘) = 0.8;     // the AFRR+ reserve is 80% of the positive FRR reserve
BS_LAMBDA(‘RG’, t , ‘AFRR-‘) = 0.72;    // the AFRR- reserve is 90% of AFRR+

BS_LAMBDA(‘RG’, t , ‘MFRR+‘) = 0.2;     // the MFRR+ reserve is 20% of the positive FRR reserve
BS_LAMBDA(‘RG’, t , ‘MFRR-‘) = 0.18;    // the MFRR- reserve is 90% of the AFRR+
```

e. Establishing the demand for RR-type of reserves

The RR-type of reserves in the example is calculated as the difference between the deterministic and probabilistic component of FRR. The maximum formulation of the demand should be chosen by setting the parameter BS_OMEGA. Then, the probabilistic component of FRR should be formulated with BS_SIGMA, in the same way with aFRR. Finally, the deterministic component of FRR should be given.

```
BS_OMEGA (‘RG’, ’RR+’)          = 1;      // set the max formulation of demand
BS_OMEGA (‘RG’, ’RR-’)           = 1;
```

```
BS_SIGMA(‘RG’, t , ‘RR+‘, ‘DEMSI‘, ‘ANNUAL‘ ) = 0.017;        // std. dev. of demand error
BS_SIGMA(‘RG’, t , ‘RR+‘, ‘SOLSI‘, ‘ANNUAL‘ ) = 0.015;        // std. dev. of solar error
BS_SIGMA(‘RG’, t , ‘RR+‘, ‘WINSI‘, ‘ANNUAL‘ ) = 0.008;        // std. dev. of wind error
BS_SIGMA(‘RG’, t , ‘RR-‘, ‘DEMSI‘, ‘ANNUAL‘ ) = 0.017;        // std. dev. of demand error
BS_SIGMA(‘RG’, t , ‘RR-‘, ‘SOLSI‘, ‘ANNUAL‘ ) = 0.015;        // std. dev. of solar error
BS_SIGMA(‘RG’, t , ‘RR-‘, ‘WINSI‘, ‘ANNUAL‘ ) = 0.008;        // std. dev. of wind error

BS_DELTA(‘RG’, t , ‘RR+‘) = 0.9;        // the RR+ is adjusted by 10% due to approximation
BS_DELTA(‘RG’, t , ‘RR-‘) = 0.9;        // the RR- is adjusted by 10% due to approximation

BS_LAMBDA(‘RG’, t , ‘RR+‘) = 1;         // the RR+ is equal to the maximum difference
BS_LAMBDA(‘RG’, t , ‘RR-‘) = 0.9;       // the RR- reserve is 90% of the positive RR+ reserve

BS_DEMDET(‘RG’, t , ‘WMAXSI‘ ,‘RR+‘)  = 0.1;  // set the contribution of the largest grid element
BS_DEMDET(‘RG’, t , ‘WMAXSI‘ ,‘RR-‘)  = 0.1;  // set the contribution of the largest grid element
```

4.3 Contribution of supply processes to reserve provision

Let’s consider three dispatchable technologies, i.e. base, mid and peak load, such as a coal power plant (ECOA), a combined cycle gas turbine (ECCGT) and an open cycle oil turbine (EOCT). The operating parameters of these units are reported in the table below[12]:

Technology	Minimum operating level (%)	Ramping rate up/down (%/hour)	Minimum online/offline times (h)
ECOA	50%	30.0%	8 / 8
ECCGT	50%	60.0%	1 / 1
EOCT	20%	100.0%	N/A

We assume that the capacity providing the reserve should be able to perform the promised change in power output in 0.5 min for FCR, 7.5 min for aFRR and 15 min for mFRR. The mid- and peak technologies are allowed to provide non-spinning upward mFRR reserve and downward mFRR through shutting down.

Example

The minimum stable operating levels, the ramping rates, and the minimum online/offline times can be directly entered into the corresponding TIMES

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[12] The data is provisional and only for demonstration

parameters ACT_UPS(r,t,p,s,”FX”) , ACT_UPS(r,t,p,s,”UP”) and ACT_UPS(r,t,p,s,”LO”), ACT_TIME(r,t,p,s,”UP”) and ACT_TIME(r,t,p,s,”LO”). It is assumed that the user is already familiar regarding these variables, which are described in TIMES documentation. For example, for ECOA, the technical constraints of the above table can be entered as:

```
ACT_UPS(‘RG’, t , ‘ECOA‘, ‘ANNUAL‘, ‘FX‘) = 0.5;
ACT_UPS(‘RG’, t , ‘ECOA‘, ‘ANNUAL‘, ‘UP‘) = 0.3;
ACT_UPS(‘RG’, t , ‘ECOA‘, ‘ANNUAL‘, ‘LO‘) = 0.3;
ACT_TIME(‘RG’, t , ‘ECOA‘, ‘ANNUAL‘, ‘UP‘) = 8;
ACT_TIME(‘RG’, t , ‘ECOA‘, ‘ANNUAL‘, ‘LO‘) = 8;
```

The spinning ramping rates BS_RMAX can be derived from the hourly ramping rates, by considering the time limitations of the reserve and the minute-ramp rate of the processes. We assume that the reserve provision requirement is once per hour, and therefore the minute-ramp rate of the process multiplied with the time-limitation of the reserve indicates the percentage of the installed capacity of the process which can participate in the reserve provision. For example, for the ECOA process the hourly ramping rate is 30% or 0.5% per minute. Hence, the maximum capacity of ECOA that can provide aFRR reserve is 0.5*7.5=3.75% . Thus:

```
BS_RMAX(‘RG’, t , ‘ECOA‘, ‘FCR+‘ , ‘ANNUAL‘) = 0.0025;
BS_RMAX(‘RG’, t , ‘ECOA‘, ‘FCR-‘ , ‘ANNUAL‘) = 0.0025;
BS_RMAX(‘RG’, t , ‘ECOA‘, ‘AFRR+‘ , ‘ANNUAL‘) = 0.0375;
BS_RMAX(‘RG’, t , ‘ECOA‘, ‘AFRR-‘ , ‘ANNUAL‘) = 0.0375;
BS_RMAX(‘RG’, t , ‘ECOA‘, ‘MFRR+‘ , ‘ANNUAL‘) = 0.075;
BS_RMAX(‘RG’, t , ‘ECOA‘, ‘MFRR-‘ , ‘ANNUAL‘) = 0.075;

BS_RMAX(‘RG’, t , ‘ECCGT‘, ‘FCR+‘ , ‘ANNUAL‘) = 0.05;
BS_RMAX(‘RG’, t , ‘ECCGT ‘, ‘FCR-‘ , ‘ANNUAL‘) = 0.05;
BS_RMAX(‘RG’, t , ‘ECCGT ‘, ‘AFRR+‘ , ‘ANNUAL‘) = 0.075;
BS_RMAX(‘RG’, t , ‘ECCGT ‘, ‘AFRR-‘ , ‘ANNUAL‘) = 0.075;
BS_RMAX(‘RG’, t , ‘ECCGT ‘, ‘MFRR+‘ , ‘ANNUAL‘) = 0.15;
BS_RMAX(‘RG’, t , ‘ECCGT ‘, ‘MFRR-‘ , ‘ANNUAL‘) = 0.15;

BS_RMAX(‘RG’, t , ‘EOCT‘, ‘FCR+‘ , ‘ANNUAL‘) = 0.05;
BS_RMAX(‘RG’, t , ‘EOCT ‘, ‘FCR-‘ , ‘ANNUAL‘) = 0.05;
BS_RMAX(‘RG’, t , ‘EOCT ‘, ‘AFRR+‘ , ‘ANNUAL‘) = 0.075;
BS_RMAX(‘RG’, t , ‘EOCT ‘, ‘AFRR-‘ , ‘ANNUAL‘) = 0.075;
BS_RMAX(‘RG’, t , ‘EOCT ‘, ‘MFRR+‘ , ‘ANNUAL‘) = 0.15;
BS_RMAX(‘RG’, t , ‘EOCT ‘, ‘MFRR-‘ , ‘ANNUAL‘) = 0.15;
```

4.4 Contribution of storage processes to reserve provision

Storage processes modelled with NCAP_AFC can have the BS_RMAX parameter set to control their contribution in reserve provision. In the case of a storage process for which the stored energy is bounded by capacity, then the BS_STIME parameter should be set to control the energy required for the reserve provision. When the user does not set the BS_STIME parameter, then by default this is set to 24 hours. The BS_STIME is measured in hours. For example, if a BAT process provides, e.g. aFRR reserve, then

```
BS_STIME(r, t, ”BAT”, ”AFRR+”, ”LO”)=2/60;  // 2 minutes for ramping up
BS_STIME(r, t, ”BAT”, ”AFRR+”, ”UP”)=12/60;  // 10 min. reserve provision (10 + 2 to ramp up)
BS_STIME(r, t, ”BAT”, ”AFRR-”, ”LO”)=2/60;  // 2 minutes for ramping up
BS_STIME(r, t, ”BAT”, ”AFRR-”, ”UP”)=12/60;  // 10 min. reserve provision (10 +  2 to ramp up)
```

4.5 Contribution of demand processes to reserve provision

The provision of demand process is controlled with the BS_RMAX parameter, in a similar way as the generation processes. No ramping, minimum stable operating levels, online or offline times are considered for demand processes. For example, to set that the demand technology DMDELC can provide ancillary services, e.g. postivie and negative FRR+, we could write:

```
BS_RMAX(‘RG’, t , ‘DMDELC‘, ‘AFRR+‘ , ‘ANNUAL‘) = 0.01;
BS_RMAX(‘RG’, t , ‘DMDELC‘, ‘AFRR-‘ , ‘ANNUAL‘) = 0.01;
```

The PRC_ACTFLO parameter should be used if the activity does not represent electricity energy at all for a demand process.

4.6 Demand and supply of operating reserves in User Constraints

Since the inland demand for operational reserves is modelled through the VAR_COMNET(r,y,b,s) variable, it can be referred to the user constraint mechanism of TIMES using the standard syntax of UC_COMNET. For instance, to impose a minimum level in the total demand of MFRR+ in region **rg**, period **t** and timeslice **s**, we could write:

```
SET UC_N / UC_MIN_DEMAND /;
SET UC_R_EACH / RG.UC_MIN_DEMAND  /;
UC_COMNET('UC_MIN_DEMAND', 'LHS', 'RG’, t, 'MFRR+', s) = 1;
UC_RHSRTS('RG', 'UC_MIN_DEMAND', t, s, 'LO') = 10;
```

Please note that the operational reserves in TIMES are expressed in flow units, and in terms of a flow, and not a power level. Thus, the value 10 used above is expressed in flow units, and if the timeslice duration is GR_YRFR(s)=1/48 and the power to flow conversion factor is BS_CAPACT(r)=31.536, then the corresponding power is 10*48/31.536=15.22 GW. However, with timeslice-dynamic constraints one can directly refer to VAR_COMNET in terms of power levels instead of flows, due to the automatic conversion in those constraints.

Regarding the supply of reserves, to refer to the process-specific reserve provision of a reserve commodity b, a non-standard use of UC_FLO(ANNUAL) is supported in a timeslice-dynamic UC. Note, that the timeslice-specific terms in a timeslice-dynamic UC are all divided by GR_YRFR(r,s) to make it easy to combine flow and capacity terms in the constraint. Also in this case, the reserve provisions should be referred as power levels in flow units, just like VAR_COMNET is converted into power levels in flow units when using timeslice-dynamic equations. The timeslice-dynamic constraint will be of course activated for the timeslices for which the demand for reserve is calculated.

However, as there is actually no UC component associated with this non-standard UC_FLO(ANNUAL) support for operating reserves, one cannot use any UC modifiers for the reserve provision from a process, and the UC_FLO coefficients for them can only be ANNUAL.

For example, the following parameters will define a fixed share of 15% of the contribution of the EOCT technology in the total provision of MFRR+ reserve in e.g. 2020.

```
SET UC_N / RESUC /;
PARAMETER UC_RHSRTS / RG.RESUC.2020.ANNUAL.FX                EPS /;
PARAMETER UC_FLO / RESUC.LHS.RG.2020.NUCLEAR.MFRR+.ANNUAL  1 /;
PARAMETER UC_COMNET / RESUC.LHS.RG.2020.MFRR+.ANNUAL        -0.15 /;
SET UC_ATTR / RG.RESUC.LHS.UCN.DAYNITE /;
```

It should be noted that when reserve commodities are used in user constraints under the VEDA interface, the topology check of VEDA needs to be disabled. Because the reserve commodities are not in the topology as they are power levels.

4.7 Attaching exogenous costs to the provision of operating reserves

The definition of external costs on the process-specific reserve provisions is supported by using UCs and by tying the reserve provisions to some dummy commodity that has a cost. To give an example, let’s assume that the EOCT process provides aFRR+ type of reserve with an additional cost of 100 EUR/kW (e.g. this can be considered as a mark-up on the bid from the process). Let’s also assume that the power conversion factor for the reserves is BS_CAPACT(r,s)= 31.536.

We define a dummy commodity flow for the EOCT process, e.g. AFRR_COST, with FLO_COST=100/31.536 or FLO_COST = 3.171. The AFRR_COST commodity can then be related to the production of the aFRR+ reserve via a timeslice-dynamic user constraint.

```
PARAMETER FLO_COST / RG.2010.EOCT.AFRR_COST.ANNUAL.CHF 3.171 /;
SET UC_N / UC_AFRRCOST /;
PARAMETER UC_RHSRTS / RG.UC_AFRRCOST.2010.ANNUAL.FX EPS /;
PARAMETER UC_FLO / UC_AFRRCOST.LHS.RG.2010. EOCT.aFRR+.ANNUAL -1/;
PARAMETER UC_FLO / UC_AFRRCOST.LHS.RG.2010. EOCT.AFRR_COST.ANNUAL 1 /;
SET UC_ATTR / RG.UC_AFRRCOST.LHS.UCN.DAYNITE /;
```

An alternative definition of the above can be that the FLO_COST of the dummy commodity is equal to 1, and then we require through the timeslice-dynamic constraint that the dummy flow to be greater than the cost coefficient multiplied with the provision of the reserve:

```
PARAMETER FLO_COST / RG.2010.EOCT.AFRR_COST.ANNUAL.CHF 1 /;
SET UC_N / UC_AFRRCST2 /;
PARAMETER UC_RHSRTS / RG.UC_AFRRCST2.2010.ANNUAL.FX EPS /;
PARAMETER UC_FLO / UC_AFRRCST2.LHS.RG.2010.EOCT.aFRR+.ANNUAL -3.171/;
PARAMETER UC_FLO / UC_AFRRCS2T.LHS.RG.2010.EOCT.AFRR_COST.ANNUAL 1 /;
SET UC_ATTR / RG.UC_AFRRCST2.LHS.UCN.DAYNITE /;
```

In the above examples, when the annual delivery costs of reserves are calculated, the reserve variables are summed at the timeslices below the ANNUAL level in the same way as in equation 26, i.e. first are summed as flows at flows units and then are converted to capacity units to apply the FLO_COST parameter.

The functionality of FLO_FUNC and FLO_EMIS is not supported for the association of the dummy commodity to the reserve commodity because reserves are not in the topology as they are power levsls. This implies that only through user constraints this relationship can be established.

As in section 4.7, when using the VEDA interface to import constraints involving reserve commodities, the topology check needs to be disabled.

It should be noted that a similar approach can be followed if a subsidy needs to be defined for the provision of a reserve. In this case, instead of FLO_COST the attribute FLO_SUB needs to be used.

4.8 Bounds on reserve provision by process and process groups

Although the bounds on absolute levels of productions and on production shares regarding the reserve provision from a process or group of processes can be modelled with timeslice-dynamic constraints, the implementation also supports specific parameters to easily set a bound.

For example, to establish an absolute bound on the provision of reserve AFRR+ from the process EOCT, the parameter BS_BNDPRS could be set:

BS_BNDPRS(‘RG’, t , ‘EOCT‘, ‘AFRR+‘ , s, ‘LO‘) = 1.5; //Upper bound on the provision of reserve AFRR+ in all timeslices is set to 1.5 GW for process EOCT

As another example, if a specific group of processes is required to provide, e.g. a minimum share of the total reserve provision, then the parameter BS_SHARE could be defined. The group of processes for which a bound in their share to total reserve provision is required, can be defined via the parameter GR_GENMAP. It follows that if the share bound applies to a single process, then the same approach is applied and in this case the group of processes contains a single member.

For example, to impose the regulatory constraint that at least 10% of the total reserve AFRR+ should be provided from EOCT and ECCGT units:

GR_GENMAP(‘RG’,‘EOCT‘,‘LOSHRAFR+‘)=1; // map process EOCT to user defined group LOSHRAFR+

GR_GENMAP(‘RG’,‘ECCGT‘,‘LOSHRAFR+‘)=1; // map process ECCGT to user defined group LOSHRAFR+

BS_SHARE(‘RG’, t , ‘AFRR+‘ , ‘LOSHRAFR +‘, ‘LO‘) = 0.1; // impose minimum 10% contribution

4.9 Storage degradation due to cycling

With the new extension of TIMES, the calendar lifetime of a storage process can be distinguished from the cycling lifetime. To enable the cost of replacement due to extensive cycling the parameter STG_MAXCYC(r,y,p) must be set. Then, the capacity that it is additionally needed due to the extensive cycling is reported in the variable VAR_UPS(r,v,t,p,”ANNUAL”,”UP”), and the “penalty cost of replacement”, i.e. the product of VAR_UPS with the capital recovery factor, enters into the objective function. The “penalty costs” are then reported in VEDA_BE in the parameter Cost_Act(r,v,t,p,'+')

Example

A battery technology BAT has a maximum number of 3000 cycles, a calendar lifetime of 10 years and investment cost of 400 EUR per kWh. The output of the battery is tracked in PJ, while the capacity is tracked in GWh.

```
PRC_CAPACT(r,”BAT”) = 0.0036;
NCAP_COST(r,t,”BAT”,cur)=400;
NCAP_TLIFE(r,t,”BAT)=10;
STG_MAXCYC(r,t,”BAT”)=3000;
```

4.10 Maintenance and outages of power plants

Three options are given regarding the endogenous scheduling of maintenance of power plants:

- To specify the duration of the maintenance at a timeslice level above the process level; this option will allow TIMES to cost-optimally define the scheduling of the maintenance at the process timeslices
- To specify a starting timeslice for the maintenance period at the process timeslice level; this option will force continuous maintenance of capacity starting from the specified timeslice and for the duration specified by the user
- To specify the percentage of capacity that will be under maintenance at a timeslice level above the process timeslice; this option will force the capacity to enter into maintenance across all timeslices at the process timeslice level

The capacity that is shutdown to enter into maintenance is then reported in the variable VAR_BSPRS(r,v,t,p,’ACT’,s,’N’), while the offline capacity in the variable VAR_UPS(r,v,t,p,s, ’N’). It could be worthy these variables to be also reported via the VEDA_BE interface.

a. Enable endogenous scheduling of a continuous maintenance period

To specify the duration of the maintenance period and let TIMES endogenously schedule the maintenance, the user should first enable startups at the process timeslices with the parameter ACT_CSTUP and then an availability factor for the parent timeslice via NCAP_AFC. Second, the user should define the duration of the maintenance period via the parameter BS_MAINT. The following example enables maintenance of the ENUC power plant for 12 consecutive hours in summer:

```
ACT_CSTUP(‘RG’, t , ‘ENUC‘, ‘DAYNITE‘, cur) = 0.05; // the value can also be zero
NCAP_AFS(‘RG’, t , ‘ENUC‘, ‘SU‘, ‘UP‘) = 0.7; // controls max avail capacity
BS_MAINT(‘RG’, t , ‘ENUC‘, ‘SU‘) = 12; // 12 hours consecutive maintenance for ENUC
```

The above will force up to 30% of the nuclear capacity to shutdown for maintenance during the season SU, so that to meet the upper availability of 70% during this season.

b. Specify the starting timeslice of a continuous maintenance period

If it is desirable to specify a staring timeslice for maintenance period, the user has two options: a) either to use NCAP_AF(S) for a consecutive number of timeslices; or b) using the maintenance feature of this extension. To enable the second option, the steps are the same with the option (a), with the difference that the NCAP_AFS and BS_MAINT parameters are defined for the timeslice from which the maintenance will start. For example, to force a consecutive maintenance of 12 hours of the ENUC power plant in summer, starting in timeslice H05 of the SU season:

ACT_CSTUP(‘RG’, t , ‘ENUC‘, ‘DAYNITE‘, cur) = 0.05; // the value can also be zero
NCAP_AFS(‘RG’, t , ‘ENUC‘, ‘SU-H05‘, ‘UP‘) = 0.7; // controls max avail capacity
BS_MAINT(‘RG’, t , ‘ENUC‘, ‘SU-H05‘) = 12; // 12 hours consecutive maintenance for ENUC

The above will force up to 30% of the nuclear capacity to shutdown for maintenance in timeslice H05 and stays offline for maintenance until 12 timeslices later.

c. Specify the percentage of capacity entering into maintenance

The third option allows to define the fraction of capacity to be under maintenance with BS_MAINT parameter, without using NCAP_AFS for that. For example, to force 30% of the capacity under continuous maintenance in the SU summer season:

ACT_CSTUP(‘RG’, t , ‘ENUC‘, ‘DAYNITE‘, cur) = 0.05; // the value can also be zero
BS_MAINT(‘RG’, t , ‘ENUC‘, ‘SU‘) = 0.3; // 30% of ENUC capacity under consecutive maintenance

4.11 Applying the extension to coarse timeslices

The implementation of the extension takes care that the number of timeslices in TIMES-based models can vary from only a few timeslices per year to hundreds of timeslices. However, the coarser the intra-annual resolution is, the less are the gained insights from the use of the extension as the variability of the supply and demand will be smoothened. To this end, the calibration parameters provided with the extension (forecast errors and the delta parameter) as well as the use of the deterministic component of the demand may help to mitigate the underestimation of the need for flexibility when the intra-annual resolution is coarse. For example, when only a few timeslices are used then the demand resulted from the probabilistic component might be less than the demand observed in the statistics. The delta parameter can be used here to scale up the calculated demand.

5. IMPLEMENTATION NOTES

5.1 Modifications into the TIMES Code

The extension has been implemented as a separate extension module (ABS), striving to minimize any modifications to the standard code. The ABS extension consists of the following GAMS code files:

Table 10: GAMS code files for the TIMES Ancillary Balancing Services extension.

File	**Description**
initmty.abs	Declaration of sets and parameters for the ABS extension
init_ext.abs	Initial processing for the ABS extension
prep_ext.abs	Interpolation / extrapolation of parameters
coef_ext.abs	Further pre-processing for model coefficients
mod_vars.abs	Declaration of variables and equations in the ABS extension
equ_ext.abs	Final pre-processing and formulation of the ABS equations
mod_ext.abs	Equations added into the TIMES MODEL statement

Small modifications have been made to the following GAMS code files:

- eqactups.vda – added optional capacity-defining equations, as well as the implementation of the storage cycling constraint (in order to make that available also without using the ABS extension)
- eqlducs.vda – added reserve provision term into eq_sudload
- powerflo.vda – added the restriction of power flow equations to ELC type commodities only (in case reserves might be traded trough power lines)
- uc_cap.mod – added support for non-standard use of UC_FLO for referring to the process-specific reserve provisions in UC constraints
- rptlite.rpt – added reporting of reserve provision levels

5.2 Running the Ancillary Balancing Services (ABS) Extension

Using the ABS extension package requires TIMES v4.4.0 or above. The ABS mode can be activated by the following settings in the run file:

```
$ SET ABS YES
```

The ABS extension can be used with all major features of ETSAP-TIMES (and in general also with any minor extensions).

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