# Security of supply and flexibility of backup documentation

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# Introduction

The security of supply and the flexibility of backup are two calculations that were implemented in the ETM in Q3 2011 and Q1 2012. Both projects were carried out for GasTerra.

The security of supply phase resulted in a dashboard item showing the loss of load probability of a scenario (see definitions in next section). This dashboard item communicates the importance of combining reliable electricity generation capacity with volatile electricity production.

As a follow up to the security of supply project, the flexibility of backup calculation offers users more information about how different technologies compare when used as backup for volatile electricity production. The comparison is made in terms of cost and $CO_2$ emissions exclusive to providing backup for volatile electricity production.

In this document the two calculations are explained. In this introduction chapter the visualization in the ETM for the two calculations is shown and some import terms that are used throughout the document are defined. In the following sections the details of the two calculations are given.

## Visualization in the ETM

In this section the frontend implementation of the two projects is shown.

### Security of supply

The security of supply calculation has a dashboard item, which can be accessed via the flexible dashboard; this item is called the “loss of load probability” (see definitions).

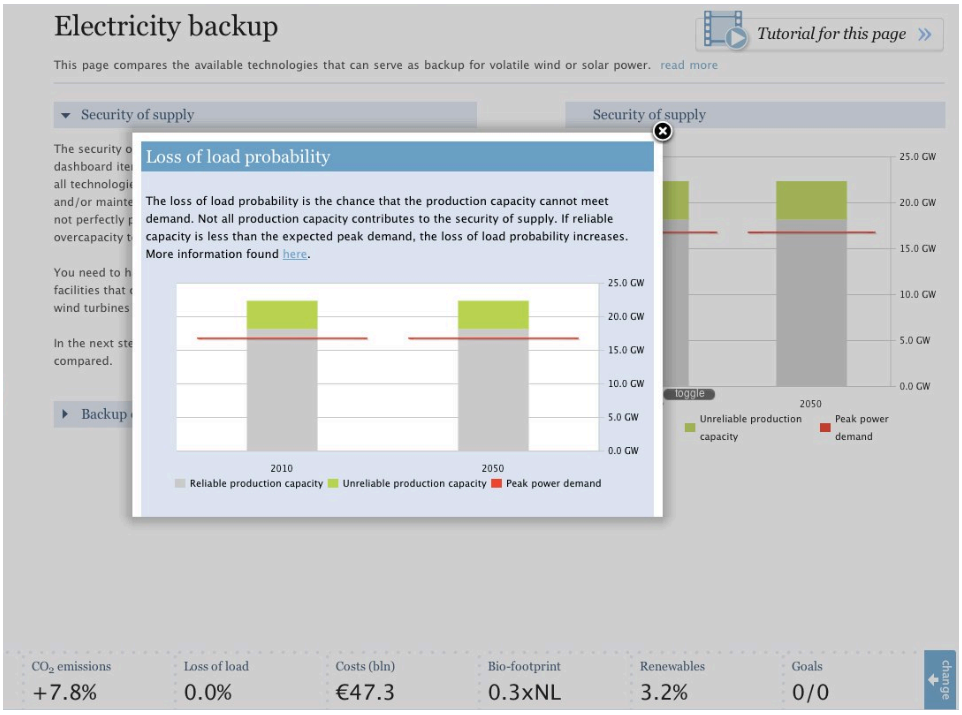


**Figure 1: Information about the flexibility of electricity production is found both in the dashboard item as well as on its own page under the tab "Supply"**

Clicking the dashboard item reveals a popup showing a chart with three values for both the present and the future year. In the chart the three things shown are:

**Peak electricity demand –**
This is the largest power demand expected to occur in a year. In this figure the maximum positive variability of demand is also included, giving an absolute peak.
**Reliable capacity –**
The reliable capacity is electricity production capacity that can be counted on at all times and/or periods of the year. Volatile energy technologies such as solar PV and wind turbines have a limited, to zero, contribution to the reliable capacity (often referred to as capacity credit. See below).
**Unreliable capacity –**
Unreliable capacity is electricity production capacity that cannot be guaranteed at all times and/or periods of the year. Production by solar PV and wind turbines fall into this category.

## Backup for volatile electricity production

The backup for volatile electricity production module is found under the sidebar item "electricity backup" under the tab "supply" (found here). It consists of a scatter plot comparing different electricity backup options based on the additional costs and emissions that would be incurred *on top of the* costs and emissions of volatile electricity production. Figure 2 shows a screenshot of the scatter plot.

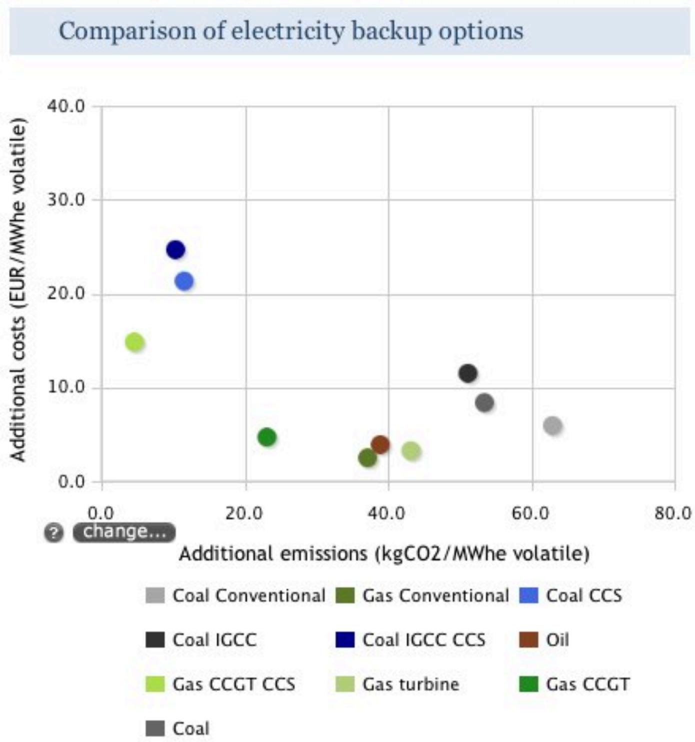


Figure 2: Screenshot of scatter plot showing comparison of electricity backup options

## Definitions

The following terms are used throughout the document that might not be self explanatory:

**Loss of load probability –**
The chance that a power generation park is unable to meet the expected demand. In most power systems this value should be very close to 0%. A non-zero value however does not imply that a blackout will occur, since often it is the case that electricity can be imported if it cannot be locally produced.

**Unreliable electricity production capacity –**
Capacity that cannot always be counted on due to unpredictability and (unexpected) maintenance requirements. Unreliable capacity includes most volatile electricity production (solar PV and wind) as well as the average expected unavailability of fossil fuel power plants.

**Reliable electricity production capacity –**
As opposed to unreliable capacity, reliable capacity is the fraction of the total production capacity that can be deemed reliable. This includes the majority of the fossil fuel production capacity (with exclusion for the unavailability) and some volatile electricity production capacity (depending on the capacity credit).

**Capacity credit –**
This is a term used to express a technologies 'contribution to capacity'. The capacity credit is expressed as a percentage and is the fraction of the capacity that can be relied on. For example: Solar PV panels have no capacity credit since there is not always sun. Fossil fuel power plants on the other hand have a very high capacity credit because these are controlled and are available to produce electricity when needed. Finally, for the Netherlands, wind turbines have a capacity credit of approximately 14-20%. This implies that approximately one-fifth of wind turbine capacity is reliable, which depends on the assumption that the wind turbines are sufficiently dispersed over a large geographic area.

**Additional capacity –**
Backup capacity for long periods of no wind/sun.

**Reserve capacity –**
Capacity dedicated to dealing with fluctuations due to forecasting errors on short time scales (<1 hour).

## Security of supply

In this section the security of supply calculation is explained that is used to determine the loss of load probability. First the calculation methodology is explained followed by the details of how it is modeled and contained in the ETM.

### Calculation theory

The loss of load probability is determined by comparing the expected peak electricity demand with the available electricity production capacity. Figure 3 illustrates the concept used for the calculation.

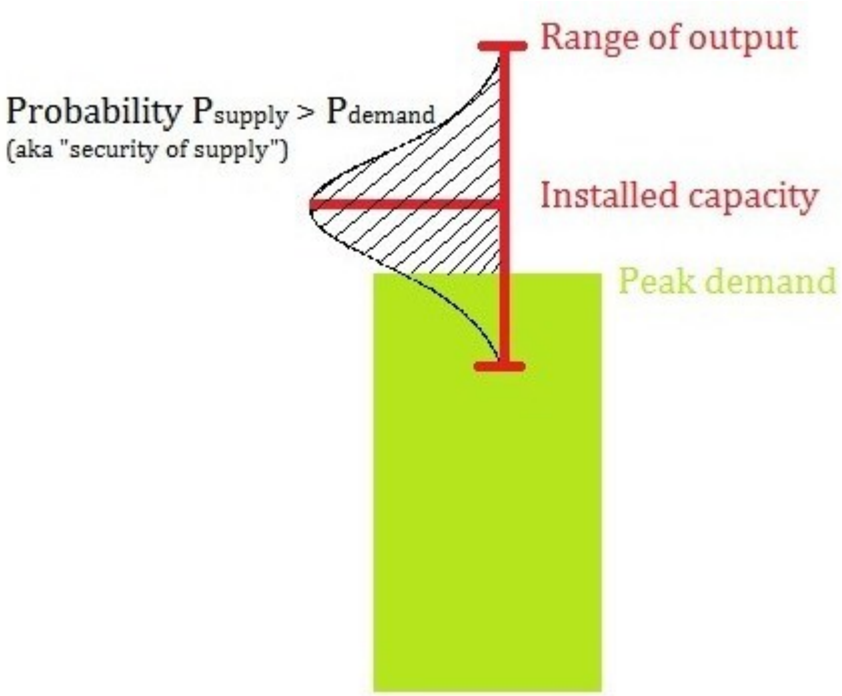


**Figure 3: Illustrative sketch of security of supply calculation**

The security of supply is given as the probability that the peak supply is greater than the peak demand. The loss of load probability is the compliment of the security of supply. As can be seen in the figure, consideration is given for the variations that can occur in the output.

The loss of load probability (LOLP) is calculated as the probability that electricity power supply is less than peak demand assuming a normal distribution due to the variability of demand. This is expressed in the following equations:

$$LOLP = P\left(P_{supply} < P_{demand}\right)$$

The available electricity production capacity, $P_{supply}$, is given by:

$$P_{supply} = \sum P_i * A_i * (1 - V_i)$$

With:

P – Installed production capacity of a power plant [MW]

A – Availability of the power plant [%]

V – Variability, compliment of the capacity credit [%] (see definitions)

The peak electricity demand is calculated from the total yearly demand by using a load factor (cf, capacity factor). The load factor is the ratio between the average demand and the peak demand over a period of time.

$$P_{demand} = \sum \frac{E_i}{cf * 8760}$$

With:
E – Electricity demand of the sectors [MWh]
Cf – Load factor of the demand [%]

Finally, the variability is determined by summing the squares of the individual variabilities.

$$\sigma = \sum V_i^2$$

## Calculation in the ETM

The calculations described above are contained in the gqueries listed in Table 1. These gqueries are found in the folder:
etsource/gqueries/modules/security_of_supply

**Table 1: Gqueries used for the loss of load probability dashboard item**

| Gquery name | Description |
|---|---|
| Security_of_supply_loss_of_load_probability | Calculates the loss of load probability assuming a normal distribution |
| Available_electricity_production_capacity | Calculates the electricity production capacity with consideration for availability and variability |
| Peak_electricity_demand | Calculates the peak electricity demand based on the yearly electricity demand |
| Total_supply_and_demand_variability | Calculates the total variability by summing the individual variabilities |

The queries in the table above are used to calculate the loss of load probability for the dashboard item. In addition to these gqueries are also used for the chart that accompanies the dashboard item. The gqueries in Table 2 are used for the security of supply chart. These gqueries are found in the folder:
etsource/gqueries/output_elements/output_series/vertical stacked bar_111_security of supply

**Table 2: Gqueries used for security of supply chart**

| Gquery name | Description |
|---|---|
| Minimum_available_capacity_in_security_of_supply | The reliable electricity production capacity |
| Unreliable_electricity_production_capacity | Unreliable electricity production capacity |
| Present_peak_electricity_demand | Present value of the peak electricity demand |
| Future_peak_electricity_demand | Future value of the peak electricity demand |

## Input for the calculation

To be able to carry out the calculations described in the previous section certain parameters are required for electricity production and electricity demand converters. The following table lists the required inputs and where these are found:

**Table 3: Input for the security of supply calculation**

| Parameter | Description | Location |
|---|---|---|
| Variability | Attribute. The compliment of the capacity credit. For dispatchable capacity this is 100%. For wind turbines values of 80-86% are used, and for solar panels values of 0% are used. | InputExcel, Cost sheets |
| Availability | Attribute. Availability of power plants due to planned and unplanned maintenance. Values range between 80% and 97% | InputExcel, Cost sheets |
| Peak power demand of start scenario | Attribute. The peak power demand of a country for the start scenario. Used to calculate the full load hours of demand so that the model can calculate the peak power demand for future scenarios<br>*** See section Security of supply for other areas** | Research dataset Excel, Conversions Sheet, cell G144 |
| mw_input_capacity | Method. Uses demand calculated by recursive factor along with parameters in InputExcel Cost sheets (full load hours and typical input capacity) | InputExcel, Cost sheets |

## Security of supply for other areas

The security of supply calculation also works for other areas in the ETM, however since the required research data has not been gathered a "workaround" calculation has been implemented in the InputExcel to ensure that the loss of load probability of the start scenario is always 0%. In this section it will be explained why a workaround has been implemented, what the underlying assumption is, and how and where it has been implemented.

### Reason for a workaround: why loss of load can be non-zero without one

The security of supply calculation requires knowing the peak electricity demand (GW) of a scenario. Because the ETM works with energy instead of capacities, this information is not readily available and hence the peak electricity demand needs to be calculated from the total electricity demand (TWh).
To calculate the peak demand from the total demand a value for the "load factor" of the demand is required. Load factor can be seen as the equivalent of full load hours of production technologies.
For the Netherlands, a value for the load factor has been obtained from various sources (TenneT and Nora Meray). For other countries however this has not been done, and using the Netherlands value results sometimes in incorrect values of the peak electricity demand, possibly leading to non-zero loss of load probability values in the start scenario.

### Assumption: all countries have extra production capacity in start scenario

To prevent countries having a non-zero loss of load probability in the start scenario an assumption is made that this is simply impossible. It is assumed that all countries in the present scenario have sufficient electricity production capacity to meet the their own peak electricity demand.
In other words, every country has a certain amount of extra production capacity, or "over capacity." The over capacity is defined as the excess reliable electricity production capacity compared to the peak electricity demand.
By assigning a greater than zero value for the over capacity and using this to calculate the load factor of a country, it is assured that the loss of load probability of the start scenario will always be non-zero.
The value for the over capacity is calculated for countries for which the data is available; otherwise a default value is used.

### Calculations: over capacity and full load hours of demand

If the data is available, the over capacity is calculated as follows:

$$over\ capacity\ [\%] = \frac{reliable\ production\ capacity\ [GW]}{peak\ electricity\ demand\ [GW]} - 1$$

The reliable production capacity is the sum of the capacities of all electricity power plants excluding wind turbines and solar panels. This information should be available for all areas and therefore no assumptions are used here.

The peak electricity demand of a country is data that is not standardly used in the ETM, and has only been implemented for the security of supply calculation. Therefore if this value is not known, an assumption is made for the value of the over capacity. In the next section information is provided about where the calculation is found in the ETM.

Knowing the over capacity, the full load hours of the electricity demand (aka load factor) is calculated as follows:

$$FLH\ of\ demand = \frac{Electricity\ demand\ [GWh]}{Reliable\ production\ capacity\ [GW]/(1 + over\ capacity\ [\%])}$$

This is simply equal to the electricity demand divided by the peak power demand. However since the absolute value of the peak power demand varies from country to country it is more convenient to assume a value for over capacity.

### Location of input data and calculations

The input data for this workaround is included in the Research Dataset Excel in the sheet Conversions. The only input required for this part of the calculation is the peak power demand of a country. The tables below list the input data and the calculations.

**Table 4: Required input data for security of supply over capacity**

| Parameter | Description | Location |
| --- | --- | --- |
| Peak power demand [GW] | If known, used to calculate the over capacity. Otherwise a value for over capacity is assumed | Research Dataset Excel, Conversions sheet, cell G144 |

**Table 5: Calculations**

| | | |
| --- | --- | --- |
| Overcapacity [%] | Calculated in the Research dataset using reliable production capacity and peak power demand (if known), otherwise assumed to be 30% | Research Dataset Excel, Conversions sheet, cell G146 |
| Full load hours of demand [hrs] | Calculated in the InputExcel using electricity demand (from CBS data) and overcapacity factor.<br>Links to the Cost Other sheet and subsequent sheets where it enters the model as a converter attribute | InputExcel, Dataset calculations, cell M1152 |

## Improvement to the security of supply – Ramp rates

A shortcoming of the security of supply calculation is that it does not take into account the ramp rate of electricity production technologies. This shortcoming was pointed out by KEMA, and it is there opinion that this essential for the ETM and similar energy models. This opinion is not shared with everyone however, and therefore the ramp rate has considered out of scope of the project. In this section considerations are given for this calculation.

### Background

The security of supply module calculates the loss of load probability of a scenario. To do this a comparison is made between the expected peak electricity demand and the reliable electricity production capacity.
KEMA's concern with this however is that it is too simplistic and does not take into account very short-term variations (on the <1m scale). It is their opinion that in scenarios with very high variabilities (due to, for example, large market penetrations of solar pv and/or wind turbines) not all reliable electricity production are capable of changing their output capacity sufficiently fast to guarantee security of supply. This, according to KEMA, should be taken into account by incorporating a "ramp rate" calculation.

Ramp rate is a parameter describing how quickly a power plant can change its power output. Common units for ramp rate are [%/min] or [MW/min]. Every electricity production park should have a good mix of different types of power plants, including a few with high ramping capabilities. This is required to deal with the unexpected fluctuations in demand that occur on an hourly and daily basis. It is expected that these fluctuations will increase in magnitude due to increasing shares of volatile electricity production, making ramp rate requirements all the more important in future energy scenarios (according to KEMA).

Adding such a calculation to the ETM would make it possible to calculate whether the scenario has sufficient flexibility for the very short-term fluctuations in supply and demand. The calculation would in particular work to show that scenarios will only nuclear and wind turbines will not work in the future because of the high ramp rate requirements of wind and the low flexibility of nuclear.

### Calculating ramp rate requirements

To determine if a scenario has sufficient ramping capabilities a comparison needs to be made between two things: The required ramp rate based on the characteristics of the electricity demand and the total available ramp rate.

**Required ramp rate –**

The minimum required ramp rate is based on the "residual" electricity demand profile[1]. The maximum value of the derivative of this profile determines the ramping requirements of a scenario.  Since ramping is usually defined on a

[1] Residual implies that the production of some technologies (such as solar panels, wind turbines,

minute scale, the profile would also be required in this resolution. This however is likely not an option in the ETM and simplifications would be necessary, a suggestion for how this could be done is documented below.

**Total available ramp rate –**
The available ramp rate depends on the characteristics of the electricity production park and the chosen power plants. For each power plant the ramp rate needs to be determined. The total ramp rate is simply the sum of the individual ramp rates.

### Ramp rate calculation in the ETM

Adding minute profiles to the ETM is not an option since this would slow down the calculation to unreasonable levels. To avoid this, rules of thumb can be used. The following gives an indication of what could be done to avoid this:

- **Required ramp rate**
  - Quantify the ramp rate of the start scenario based on information provided KEMA or TenneT
  - Define rules of thumb for how the ramp rate changes as a function of installed volatile production and other ETM sliders
  - The required ramp rate for the present scenario can be added ad AREA data or as attributes to the electricity demand converters
  - Calculations can be done in the GQL and/or input statements
- **Total available ramp rate**
  - For each power plant type in the ETM a value for the ramp rate is needed. KEMA has said they can provide this data.
  - The total available ramp needs to be calculated. This might be as simple as calculating the sum of the individual ramp rates of each power plant, although this calculation will need to be verified. This calculation would be done with a query.

As can be seen the calculation would require only adding 1 new attribute to approximately 20-30 converters. This therefore should have a low impact on the ETM and can be implemented easily.
The only thing that needs to be worked out is how the ramp rate calculation is added to the current security of supply calculation. The loss of load probability is expressed as a percentage, therefore it would need to be determined how the ramp rate considerations equate to a loss of load probability.

## Flexibility of electricity backup

In this section the second calculation in the project is described, the flexibility of electricity backup. This calculation results in a scatter plot showing a comparison between dispatchable electricity production technologies in terms of their ability to serve as backup capacity.
In this section the calculation is explained along with how it is modeled in the ETM. The calculation is rather technical, therefore the outcome of the calculation are first described in more detail. Following this calculation details are explained along with the input required for the calculation.
To complement this document an Excel document is available that reproduces the calculation. This document is available on the reference manager: "Flexibility of electricity backup – Example calculation.xlsx"

### Flexibility of electricity backup outcome

As was shown in the introduction the flexibility of electricity backup is expressed in a scatter plot, the figure shown in the introduction is shown once more below.

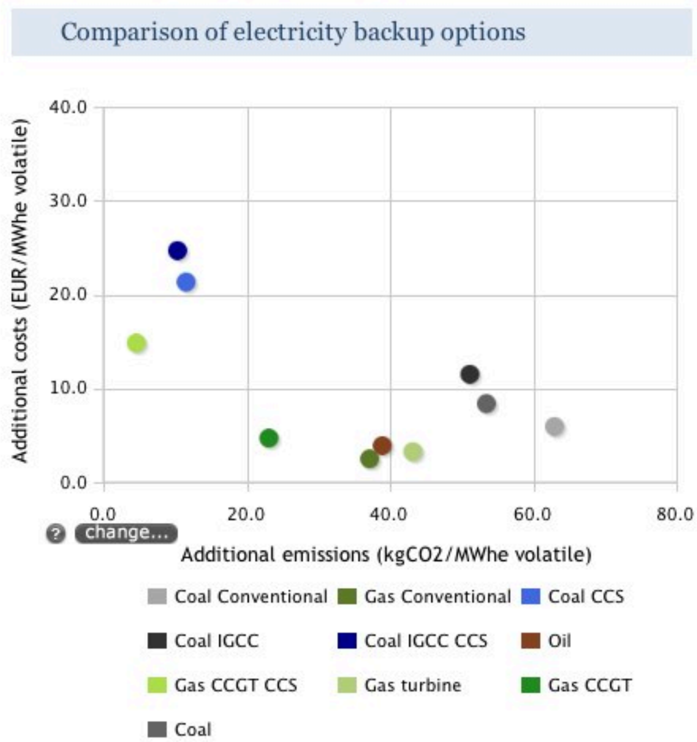


**Figure 4: Scatter plot for flexibility of electricity production**

In the figure different dispatchable electricity production technologies are plotted along two axes, showing the additional emissions and additional costs both expressed per $MWh_e$ volatile.

For example, based on the figure it is seen that a Gas CCGT plant had additional costs of approximately 5 EUR/$MWh_e$ and emissions of 23 kgCO2/$MWh_e$. Some important things to understand about the values expressed in the scatter plot:

- Everything is expressed per MWhe of the **volatile electricity production**. For example: an offshore wind turbine costs has levelised electricity costs of approximately 165 EUR/MWhe, on top of this an additional 5 EUR are required for the costs of the backup when using as Gas CCGT.
- The additional costs and emissions values are only those costs and emissions associated with the backup. For example: backup reserve capacity does more than only provide reserves, it also provides useful electricity. The costs associated with this useful electricity are disregarded. A Gas CCGT working at optimal efficiency produces electricity at costs of approximately 50 EUR/MWhe. When working to provide backup capacity, the Gas CCGT does not operate optimally and the electricity generation costs increase to 55 EUR/MWhe. Only the difference, 5 EUR/MWhe, is taken into account for the additional costs of backup capacity. This also applies for the $CO_2$ emissions. (note: this 5 EUR/MWhe difference is not the same as the 5 EUR/MWhe that is seen in the chart as more than only reserve costs are taken into account. The first value is in MWhe of the Gas CCGT power plant itself and the value in the chart is in MWhe of the volatile electricity production, that these two are the same is therefore only a coincidence.)

## Calculation details

As can be understood from the previous section, the calculation has two parts: Costs and emissions. The following things are taken into account:

- Investment costs of additional backup capacity. In other words, for every MW of volatile electricity production capacity a certain amount of MW of backup capacity is required. The investment costs for this backup are included.
- *Extra* operating costs of the backup due to needing to operate at a less than optimal efficiency to provide reserve capacity for shorter timer periods (<1 hr). As mentioned above, only the additional costs are taken into account by comparing the costs of electricity at optimal operation and at part load operation.
- Emissions of the additional capacity, which is required during longer periods of no wind or sun.
- *Extra* emissions of the backup due to needing to operate at a less than optimal efficiency to provide reserve capacity.

## Costs calculation

The costs calculation is as follows:

$$Costs = \frac{P_{ac}*IC+P_{sr}*OP*H*OC*\left(\frac{1}{\eta_{OP}}-\frac{1}{\eta_{FL}}\right)}{E_{vol}} \quad (1)$$

With:

$P_{ac}$ – Required additional backup capacity [MW], (equation given below)
IC – Cost of capital and depreciation costs of backup capacity [EUR/MW/yr]
$P_{sr}$ – Required capacity for spinning reserves [MW], (equation given below)
OP – Operating point of reserve capacity [%]
H – Number of hours per year, 8760
OC – Operating costs of backup plant (i.e. fuel, CO2, and variable costs) [EUR/MWh]
$\eta_{OP}$ – Efficiency at operating point [%]
$\eta_{FL}$ – Efficiency at full load [%]
$E_{vol}$ – Yearly volatile electricity production [MWh]

The required additional backup capacity is calculated as the difference between the capacity credit and capacity factor of the volatile electricity production:

$$P_{ac} = \sum P_{vol} * (c.f. - c.c.) \quad (2)$$

With:

$P_{vol}$ – Installed volatile electricity production capacity [MW]
c.f. – Capacity factor of volatile electricity production [%]
c.c. – Capacity credit of volatile electricity production [%]

The required spinning reserve capacity is given by three standard deviations of the expected variability. The total variability is determined by taking the root of the sum of squares of the individual variabilities, including that of the demand as well as of the volatile electricity production. The demand variability is subtracted to determine only the portion related to the volatile electricity production.

$$P_{sr} = 3 * \left(\sqrt{(P_d\sigma_d)^2 + \sum(P_{vol}\sigma_{vol})^2} - \sqrt{(P_d\sigma_d)^2}\right) \quad (3)$$

With:

$P_d$ – Peak electricity demand [MW]
$\sigma_d$ – Variability of electricity demand [%]
$\sigma_d$ – Variability of volatile electricity production capacity [%]

## Emissions calculation

The emissions calculation is similar to the costs calculation:

$$Emissions = \frac{P_{ac}*FLH*SE+P_{sr}*OP*H*SE*\left(\frac{1}{\eta_{OP}}-\frac{1}{\eta_{FL}}\right)}{E_{vol}} \quad (4)$$

With:

FLH – The full load hours of the additional capacity [hr]
SE – The specific emissions of the backup capacity [kgCO2/MWh]

The full load hours of the backup capacity is calculated as the weighted average difference between the capacity factors and capacity credits:

$$FLH = \frac{\sum P_{vol} * (c.f. - c.c.)}{P_{vol}} * H \qquad (5)$$

## Calculation in the ETM

In the ETM the calculations are carried out through gqueries. The gqueries for this project can be found in the folder:
etsource/gqueries/modules/security_of_supply/

The following queries are used:

**Table 6: Gqueries used in flexibility of electricity production scatter plot**

| **Gquery** | **Description** |
|---|---|
| <*converter*>_in_overview_backup_capacity_options_costs | equation (1). 1 query per converter shown in the scatter plot |
| <*converter*>_in_overview_backup_capacity_options_emissions | equation (4). 1 query per converter shown in the scatter plot |
| additional_backup_capacity_required_in_mw | Equation (2) |
| additional_spinning_reserve_required_in_mw | Equation (3) |
| full_load_hours_of_backup_capacity | Equation (5) |
| volatile_electricity_production | Calculates yearly electricity production by volatile technologies |

## Calculation input

The flexibility of electricity backup and security of supply calculations use both calculation specific and non-calculation specific parameters. The non-calculation specific parameters used are methods used in other parts of the ETM to determine things such as electricity production and costs. The following two tables contain a list of the parameters used by the calculations.

**Table 7: Non-calculation specific input for flexibility of backup and security of supply calculations**

| Parameter | Description | Location |
|---|---|---|
| electricity_output_conversion | Attribute | InputExcel, Cost sheets |
| typical_input_capacity | Attribute | InputExcel, Cost sheets |
| full_load_hours | Attribute | InputExcel, Cost sheets |
| co2_free | Attribute | InputExcel, ConvertersInput |
| initial_investment_costs_per_mw_electricity | Method, based on parameters in InputExcel Cost sheets | InputExcel, Cost sheets |
| variable_costs_per_mwh_input | Method, based on parameters in InputExcel Cost sheets and carrier properties | InputExcel, Cost sheets ETSource carrier properties |
| weighted_carrier_co2_per_mj | Method, based on parameters in InputExcel Cost sheets and carrier properties | InputExcel, Cost sheets ETSource carrier properties |

Table 8: Calculation specific attributes

| **Parameter** | **Description** | Location |
|---|---|---|
| Forecasting_error | Attribute. Prediction error of volatile electricity production on short time scales (~15 min) | InputExcel, Cost sheets |
| Variability | Attribute. Variation of volatile electricity production technologies and electricity demand on time scales of 1-4 hours | InputExcel, Cost sheets |
| Part_load_operating_point | Attribute. The operating point of dispatchable capacity when providing reserves. Assumed to be half way between 100% and minimal stable generation (in most cases 40%) | InputExcel, Cost sheets |
| Part_load_efficiency_penalty | Attribute. The decrease in efficiency when running at the part load operating point | InputExcel, Cost sheets |
| Availability | Attribute. Maximum capacity factor of electricity production technologies due to planned and unplanned maintenance (also used in a few other calculations, but was originally implemented for the security of supply) | InputExcel, Cost sheets |

## Literature


- Meray, N., 2011. Wind and Gas: Back-up or Back-out, "That is the Question".
- UK Energy Research Center (UKERC), 2006. The Costs and Impacts of Intermittency.
- Vourinen, A., 2009. Planning of Optimal Power Systems.
- Strbac, G., et al., 2006. Impact of wind generation on the operation and development of the UK electricity systems
- TenneT, 2011. Security of supply monitoring report 2010-2026. Available at: http://www.tennet.org/english/images/099%20Rapport_Monitoring_2010-2026_UK_tcm43-20212.pdf

## Appendix A – Flexibility of electricity production example calculation

The flexibility of electricity production is a rather complicated calculation. An Excel document therefore has been created that reproduces the calculation as it has been implemented in the ETM. This can be consulted for more information. This document is available on the reference manager: “Flexibility of electricity backup - Example calculation.xlsx”