TenneT Storage Tool

User Guide

V1.0

By: Niels Verkaik

Date: July 9th 2018

© Ecofys 2018, commissioned by TenneT
Contact

Ecofys - A Navigant Company
Ecofys Netherlands B.V.
Kanaalweg 15G, 3526 KL Utrecht
Tel: +31 (0) 30 662-3300
Fax: +31 (0) 30 662-3301
info@ecofys.com
ecofys.com
Table of contents

1 Introduction                                      1
  1.1 Background                                   1
  1.2 Purpose of the tool                          1
  1.3 How to use the tool                          2

2 Description of inputs                             4
  2.1 Technical characteristics                    4
  2.2 Costs                                        5
    2.2.1 Cost scope                               5
    2.2.2 CAPEX                                    5
    2.2.3 OPEX                                     6
    2.2.4 Other                                    6
  2.3 Revenues                                     7
    2.3.1 FCR                                      7
    2.3.2 aFRR                                     7
    2.3.3 Day ahead market                         7
  2.4 Business case cashflow modelling              8

3 Description of outputs                            9
  3.1 Results summary                               9
  3.2 Result details                                10

4 Description of interface                          14
  4.1 Calculating, creating, saving, loading, renaming and deleting projects 14
    4.1.1 Creating a new project                   14
    4.1.2 Saving a project                         14
    4.1.3 Open a project                           15
    4.1.4 Renaming a project                       15
    4.1.5 Deleting a project                       16
    4.1.6 Calculating a project                    16
    4.2 Entering project information               16
    4.2.1 Project parameters                       17
    4.2.2 Technical parameters                     19
    4.2.3 Financial parameters                     19
    4.2.4 Revenue                                  20
    4.3 Adding additional timeseries                21

5 Sample projects                                   22
  5.1 Source data                                   22
  5.2 Li-Ion NMC (2018) & (2026)                    23
5.3 Vanadium Flow Battery (2018) & (2026) 24
5.4 Pumped hydro (2018) & (2030) 25
5.5 CAES (2018) & (2030) 26
5.6 PEM Electrolysis with compressed hydrogen storage (2018) 27

6 Model assumptions and limitations 28
1 Introduction

1.1 Background

In December 2015, at the Paris Climate Change Conference (COP21), 195 countries adopted the first-ever legally binding global climate agreement to put the world on track to limit climate change by keeping global warming well below 2°C, and pursue efforts to limit the increase to 1.5°C. To reach this target the energy sector undergoes a sweeping transition in production, demand behaviour and market/system operation. With solar and wind rapidly positioning themselves among the least expensive options for low-carbon energy, their share in the future energy supply is expected to grow considerably.

1.2 Purpose of the tool

Both wind and solar energy are variable energy sources, which requires specific considerations from market parties and system operators. Energy storage technologies can become crucial building blocks in the future energy system, as it allows to grasp opportunities in future wholesale and reserve markets, and/or it allows production and demand actors to better manage their energy portfolio.

In order to facilitate the market, and support stakeholders in their understanding of the business case of an energy storage project, TenneT has created an interactive Storage Tool. This tool is meant to give companies and other stakeholders interested in the energy storage business a way to evaluate and compare different technologies, financings and market revenue options.

Users can define key parameters of a storage project, or make adaptations of a set of pre-defined cases. The tool controls about 45 parameters ranging from technology performance, to project design, financing options, and market price series.

The model assesses the maximum revenue by means of a dispatch optimization (on 15min or hour level). It provides the user with a detailed breakdown of net present value components and cashflow over the project lifetime (Figure 1).
1.3 How to use the tool

The user interface is a spreadsheet. This allows to select and adapt all parameters to fully specify a project case. The optimization of the dispatch on 15-min or hourly basis is done via a remote web server. The end results are again visualized in the spreadsheet.

Figure 2 gives a simple visual on how to use the tool. All parameters and calculation methods are further detailed in this guidance note.
IMPORTANT NOTE

The tool interface is a spreadsheet (xlsx-file) supported by Macros. To use the tool the user needs to download this file from the TenneT website and be able to run such file. Use of a recent MS OFFICE version is advised, with permission settings that allow to run macros.

The optimization is run on a remote webserver. Therefore, the user needs to be connected online, and have IT permissions allowing connection to the webserver. In case of connectivity issues, follow the guidance in the pop-up note or contact info@ecofys.com

By using the tool, the user understands and accepts that the project parameters that are defined, are passed on to a remote web server. Due to constraints in excel and VBA this information is not send via a secured connection, so the user should understand that no confidential data should be entered in the tool.

In order to prevent abuse of the webserver, the IP of the users is logged. Additionally, the project parameters send to the webserver are logged in order to speed up the optimization process. The project parameters and IP address are stored separately and are not corelated to each other, they are also not visible for other users. The data stored will not be used for any other purposes than the ones mentioned above.
2 Description of inputs

The TenneT storage tool models the business case of a grid-connected energy storage project. It takes into account technical characteristics (chapter 2.1), costs (chapter 2.2) and revenues (chapter 2.3) of a project, and combines them into a business cashflow model (chapter 2.4).

2.1 Technical characteristics

Project size

The size of the project is defined by its charge and discharge capacity (MW), as well as its storage volume (MWh). The charge and discharge capacity indicate the maximum power that can flow in and out of the storage (before the application of conversion losses). The storage volume indicates how much energy can be stored in total.

Energy losses

Not all energy stored by the project can be released again, and some will be lost. Two types of (in)efficiencies are considered in the model: roundtrip efficiency, indicating the how efficient the conversion is, and self-discharge, indicating how energy is lost regardless of charge/discharge operations.

Ramp rate

The full charge and discharge capacity are not met instantaneously. Time is needed to either ramp up or down. The ramp rate indicates the speed at which capacity can be ramped up or down (MW/min.).

Availability

The storage system will not always be available to operate due to planned and unplanned maintenance. The time the system is available is indicated by availability. Each of the revenues streams is corrected for the availability of the project (%). Note that no optimized scheduling is included for planned unavailability (maintenance).

Aging and degradation

Some energy storage technologies will wear as a result of operation. This affects the technical lifespan of the system (the number of years that a storage system can operate before it has to be refurbished or replaced). One key parameter is the maximum amount of full charge/discharge equivalent cycles. A second parameter is the degradation which is a correction of the usable storage volume.

The amount of energy that is stored by the system in a year, is divided by its total volume which gives the number of full charge/discharge cycle equivalents the project is handling every year. The number of cycles is assumed to be constant every year in this model, causing the aging and degradation to be constant too.
Repowering

If the technical lifespan of the project is shorter than the economic lifetime (the maximum number of years a project is expected to operate, from business/economic perspective), the project can be repowered. If the repower option is selected in the tool, the project will be repowered at the end of its technical lifespan, resetting its aging and degradation for a given cost (CAPEX). The already calculated yearly revenue, degradation and aging are also applicable to the repowered project. The project will only be repowered when the remaining economic lifetime of the project at the time of repowering is more than 50% of technical lifetime of the repowered system. The project can be repowered multiple times.

2.2 Costs

2.2.1 Cost scope

Different kind of expenses will occur during the lifetime of an energy storage project, categorized in capital expenditures (CAPEX), operational expenditures (OPEX) and other expenditures.

The cost parameters aim to cover all relevant substantial costs for storage projects. Also for the selected examples in the tool, attention is paid that the entire infrastructure investment and operational costs are included. The user should take into account that various public sources provide cost projections for only part of the infrastructure (e.g. a battery cell or storage tank).

On the other hand some cost components can vary over time (e.g. taxation) or are for some financial analyses not taken into account. Therefore the tool provides simple tick-boxes to either include such costs or leave them out of scope.

2.2.2 CAPEX

Initial investment

The initial investment covers all capital expenditures for the project before start of operation. CAPEX can be considered as two parts. A first capacity related cost includes power electronics, balancing system, part of the structural design. The second volume-based cost covers the storage system and part of the structural design. For both parts CAPEX costs parameters can be supplied. The total initial investment cost will be the sum of those parts. Note that external literature sometimes scales CAPEX to either capacity or volume costs. It is possible to use only one parameter in the tool if the reference is robust. Care needs to be taken when combining references to avoid double-counting, or to avoid only part of the cost is included.

Repowering

Costs for repowering can be lower than the initial CAPEX. For example, in a battery storage project the battery cells may have to be replaced, while the power electronics and structural design are still intact. The costs for repowering occur in the last year of the technical life.
Grid connection

Investment costs for the grid connections can be defined separately.

2.2.3 OPEX

Project related

Similar to the CAPEX, the OPEX can also be split up into a capacity based and a volume based part.

Network tariffs

Network tariffs can be included as well. Standard rates in the Netherlands for distribution and transmission are included in the model. The tariffs are split into a consumption dependent part and a capacity dependent (kWMax monthly and kWcontract yearly) part.

Taxes

Taxes related to the consumption of energy can be included as well. Costs for the sustainable energy tax ('ODE') and energy tax ('Energiebelasting') are already included in the model.

2.2.4 Other

Corporate tax

Corporate tax, tax which is a percentage of the operating profit, is included in the model

Decommissioning

At the end of life, the energy storage system might have to be decommissioned, leading to costs at the end of its operating life.

Repayment

Often energy storage projects will be partly financed by debt. The debt will be repaid during the operation of the project.

Debt interest

If debt financing is used, an interest rate over the debt amount will be paid during the debt term.
2.3 Revenues

Energy storage projects can generate revenue by operating on different markets. In this model three market segments can be selected: FCR, aFRR and day-ahead market. Multiple markets can be selected at the same time, each using a dedicated part of the projects charge/discharge power and energy storage volume. The model excludes dynamic co-optimization over time. The revenue of each market is calculated with price series, which can be either supplied manually, or selected from a list that is already included in the tool.

Revenue calculation

The revenue for a single year for each of the selected markets will be optimized (see chapter 2.3.1 through 2.3.3). The prices are assumed to be constant over the operational lifetime of the project. However, multiple factors can reduce the revenue and those factors can differ per year.

The total revenue is reduced by the technical unavailability of the project.

The revenue of both the aFRR (the non-capacity compensation part) and the day-ahead market after the first year will be linearly scaled with the total storage volume degradation of each year. Additionally, the combined revenue of the last year of the technical lifetime will be adjusted for lifetime left in that year (e.g. if the technical lifetime is 6.8 years, the last (7th) year of the technical lifetime the revenue will only be 80% of complete 7th year).

2.3.1 FCR

The FCR is based on capacity prices. First a basic check is done in the tool whether the project pre-qualifies for this market based on response time and ramp rate. The revenue of the project is determined by the average of bids of a given price series. The required storage volume is determined by the chosen capacity since 30 minutes of full capacity should be available.

2.3.2 aFRR

The activation price per PTU (ISP) in both upward and downward reserves in 2017 is used to optimize the buy and sell strategy. This is determined based on project design parameters and the assumption that the price can be perfectly predicted (perfect foresight). A maximum capacity and volume is set in the tool to reflect the fact that a single user can only occupy a certain share of the market.

Additionally, a fixed yearly compensation for contracted capacity can be included.

2.3.3 Day ahead market

Using a historical or user-uploaded price series, an optimum buy and sell strategy is set. This assumes that the price can be perfectly forecasted for the whole year.
Price series scaling

The price series of the day ahead market can be statistically altered by the user. The tool can analyse a given price series and split it into a daily pattern and the remaining noise. Both parts can be scaled individually, as a percentage of the original parts.

2.4 Business case cashflow modelling

The viability of the business case is evaluated by taking into account the defined costs, financing parameters, and the calculated revenue. This is done by a business cashflow model, which evaluates these parameters over time. The main methodology of this model is not discussed in this manual. Some specific details are explained below.

Developer or project perspective – The results of the cashflow calculations can be viewed in the model from two perspectives, those of the developer and those of the project. The main difference that the project cash flow is discounted by the WACC, while for the equity (developer) cashflow, the equity return rate is used, as if it were an equity investor’s perspective.

Debt term and depreciation term – If the technical lifetime of a system is shorter than user given debt and depreciation term, these terms will be adjusted to reflect the technical lifetime.
3 Description of outputs

After the results are calculated a brief results overview can be found on the Project tab, and the complete results overview on the Results tab.

3.1 Results summary

In the Results summary section on the Project tab the results of the current project are shown in the left column, the results of two other projects (which already have been calculated and saved) are shown in the other two columns. The projects can be selected in the drop-down menu, which appears when project name is clicked on.

The summary results are divided in key results and net present values:

Key results

Revenue per year – Total revenue per year

Revenue FCR market per year – Total revenue from the FCR market per year

Revenue aFRR market per year – Total revenue from the aFRR market per year

Revenue day ahead market per year – Total revenue from the day ahead market per year

IRR – The internal rate of return of a project, based on the net cashflow, will show a high negative value when the net cashflow is always negative.

NPV project – Net present value of the project from a developer perspective

Energy stored per year – The total amount of stored energy per year

Full cycles eq.t per year – The amount of full charge/discharge equivalent cycles per year

Operational lifetime – The total operational lifetime of the project
**Number of repowerings** – Number of times the projects is repowered

**Net present values**

The net present values of the different cashflow components can be shown from either the developer or the project perspective. The perspective can be selected in the drop-down menu, which appears when perspective cell is clicked on.

<table>
<thead>
<tr>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developer</td>
<td></td>
</tr>
<tr>
<td>Developer</td>
<td></td>
</tr>
<tr>
<td>Project</td>
<td></td>
</tr>
</tbody>
</table>

In case of the developer perspective the equity cashflow component is discounted with the equity return rate. In case of the project perspective, the WACC is used for discounting the project cash flow.

### 3.2 Result details

On the *Results* sheet an overview of the results is shown. This overview consists of the trading overview on the aFRR market, the trading overview on the day ahead market and project cashflow. The trading overview on the aFRR and day ahead market will be hidden if those market were not used to trade energy on.

**aFRR market**

The up-regulation price, the down regulation price and the stored energy volume are shown in the *aFRR trading* graph.
With the slider bar you can scroll through the data of the whole year.

**Day ahead market**

The trading price and the stored energy volume are shown in the *day ahead trading graph*.

With the slider bar you can scroll through the data of the whole year.

The distribution of the day ahead price series is shown in a histogram, both the values for the original and altered times series (when the *day pattern scaling* and *noisiness scaling* are set to value other than 100%) are shown.
Cashflow

The business cashflow results are shown both in the Cashflow table and the Project cashflow graph. In addition, the real and discounted (to the return on equity) investor net cashflow are shown in the Investor net cashflow graph.
4 Description of interface

In this chapter the various parts of the interface are explained.

4.1 Calculating, creating, saving, loading, renaming and deleting projects

The top part of Project sheet is used to control the project database. In this project database all project inputs and results are stored. The user can define their own cases, or start with one of the sample projects, which they can edit themselves. In Chapter 5 some background information on these cases is given. In this chapter provides an explanation on how to open, save, delete and rename projects.

4.1.1 Creating a new project

With the New Project button a new project can be created.

First, the user will be asked to enter a new project name, this name must be different from existing project names.

A new project will have no default values for all input parameters, the user can supply them.

4.1.2 Saving a project

A project, and its results, can be saved by clicking on either the Save project & results or Save project & results as button.
The **Save project & results** button will save the project under the current name, the **Save project & results as** button will save the current project and results under a new name, which is supplied by the user.

*Note: To save the project and the results, the project as well as the tool itself must be saved. If you do not save the tool after using it, all changes will be lost!*  

### 4.1.3 Open a project

An existing project and its results can be opened by clicking on the name of the current project, which will open a drop-down menu, from which another project can be selected.

*Note: If you open a new project, without saving the current one, all changes in the current project will be lost.*

### 4.1.4 Renaming a project

A project can be renamed clicking on the **Rename** button.

The user will be asked to enter a new project name; this name must be different from existing project names.
4.1.5 Deleting a project

A project and its results can be deleted by clicking on the *Delete project* button.

*Note: a deleted project cannot be restored, consider keeping backup files of the tool.*

4.1.6 Calculating a project

When all the parameters of the project are defined, and the markets are selected (see Chapter 4.2) you can calculate the business case by pressing the *Calculate* button.

All the provided information will be used to calculate the business.

*Note: The entered information is sent to a web server, which handles calculation and evaluation of the business case. The process of sending and calculating the input, and receiving the results can take up to a couple of minutes!*

*Note: the results will only be saved when the business case (see paragraph 4.1.2) and the tool itself is saved!*

4.2 Entering project information

The parameters which define a storage case can be entered and modified in the *Project parameters, Technical parameters, Financial parameters and Revenue parameters* sections, these parameters are explained in paragraphs 4.2.1 through 4.2.4.
Values can be manually adjusted by entering them in the Value column, in the yellow cells.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge capacity</td>
<td>[MW]</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Alternatively, the values can be adjusted by using the slider next to the input cell.

The value will be set to a certain percentage of the base values. These base values are already defined in the sample cases. In new cases these base values can be set to the current input by pressing the *Set as 100%* button.

This can also be done with the sample projects, if you want to set different base values.

### 4.2.1 Project parameters

In the project parameters section, the basic parameters describing your project can be set.

**Project**

- **Charge capacity** – The maximum power at which the system can be charged from the grid, before conversion losses.
- **Discharge capacity** – The maximum power at which the system can be discharged into the grid, after conversion losses.
- **Storage volume** – The maximum amount of energy stored that can be stored in the system.

**Project costs**

- **CAPEX – Capacity based** – Part of upfront investment costs which scales with the charge capacity of the project.
- **CAPEX – Volume based** – Part of upfront investment costs which scales with the storage volume of the project.

*Note: Both CAPEX parameters can be used simultaneously, the total CAPEX cost is the sum of these values.*

- **CAPEX - grid connection** – The upfront investment cost for connecting the project to grid, it scales with the charging or discharging capacity of the project (whichever is the largest).
**Annual OPEX – Capacity Based** – Part of the fixed annual operation costs which scales with the charge capacity of the project.

**Annual OPEX – Volume Based** – Part of the fixed annual operation costs which scales with the storage volume of the project.

**OPEX – Utilisation based** – Operational costs associated with every unit of stored energy.

*Note: Similar to the CAPEX parameters, multiple OPEX parameters can be used. The total OPEX cost is the sum of these values.*

**Include network tariffs**

[Checkbox] – Determines whether network tariffs costs are included.

**Grid connection point** – Either the distribution grid or the transmission grid, based on the storage facility’s connection point. When either of these options is selected, the values in the three input parameters below are automatically completed, reflecting often seen values for the Netherlands. The user can still change these values manually.

**Grid tariffs – Capacity based annual** – Fixed annual grid costs for the grid connection, based on the charging or discharging capacity of the project (whichever one is the largest).

**Grid tariffs – Capacity based monthly** – Fixed monthly grid costs for the grid connection, based on the charging or discharging capacity of the project (whichever one is the largest).

**Grid tariffs – Utilisation based** – Grid costs associated with every unit of charged and discharged energy.

*Note: when a grid connection point is selected, all parameters will be added automatically. These values can still be manually adjusted.*

**Repower assets after technical lifetime if remaining economical lifetime is at least 50% of technical lifetime**

[Checkbox] – Determines whether the project is repowered if the technical lifetime is shorter than the economic lifetime.

**CAPEX – Capacity based** – Part of the re-investment costs which scales with the charge capacity of the project.

**CAPEX – Volume based** – Part of the re-investment costs which scales with the storage volume of the project.

*Decommissioning costs / end of life resale value*
[Checkbox] – Determines whether the decommissioning costs or resale value at the end of project life is taken into account.

Decommissioning costs / EOL resale value– The cost for decommissioning the project and the end of life (when a negative value is entered), or the net capital gained from dismantling and selling the project assets at the end of project life (when a positive value is entered).

4.2.2 Technical parameters

In the technical parameters section the parameters describing the used technology can be set.

Ramp rate – The maximum rate at which the storage facility can be (dis)charged.

Availability – The average operational availability of the project. This covers both planned (maintenance) and non-planned (incidents).

Roundtrip efficiency – The total efficiency of charging and discharging the system. The efficiency is assumed identical in charging and discharging.

Self-discharge – The amount of energy that is lost in the storage per day.

Degradation – The percentage of usable storage volume which is lost for every full charge/discharge equivalent cycle.

Response time – The time needed by the system’s controls and inherent technical constraints to execute a requested change of the charging power.

Max full cycles – The maximum amount of full charge/discharge equivalent cycles before a project reaches the end of its technical lifetime.

4.2.3 Financial parameters

In the financial parameters section all the parameters describing the financing and economics can be set.

Debt share – Share of the CAPEX which is financed with debt.

Debt interest rate – The interest rate of the debt used for the CAPEX.

Debt term – Duration of the debt payback period

Depreciation term – Depreciation duration of the project.

Cost of equity – Cost of equity used for the equity share of the investment (CAPEX)
Max. economic life. – The maximum economic lifetime of the project.

Corporate tax – Corporate tax rate

Construction period – The length of the construction period

4.2.4 Revenue

In the revenue parameters section the different market and their properties can be set.

FCR Market

[Checkbox FCR] – Determines whether revenue from the FCR market is calculated.

Timeseries – Timeseries to be used for the FCR revenue.

Capacity – The charging and discharging capacity which is used for the FCR market.

(Volume) – The storage volume used for the FCR market, is calculated automatically based on the capacity.

aFRR Market

[Checkbox aFRR] – Determines whether revenue from the aFRR market dispatch is calculated.

Contracted capacity compensation – Additional fixed revenue for contracted bidding on the aFRR market.

Timeseries – Timeseries to be used in aFRR revenue calculation.

Capacity – The charging and discharging capacity which is used for the aFRR market.

Volume – The storage volume used for the aFRR market, is calculated automatically based on the capacity.

Day Ahead Market

[Checkbox Day ahead market] – Determines whether revenue from the Day ahead market is calculated.

Timeseries – Timeseries to be used in the Day ahead market dispatch optimization.

(Charge capacity) – The charging and discharging capacity used in the Day ahead market, is calculated automatically based on the remaining capacity not used in other markets.

(Discharge capacity) – The charging and discharging capacity used in the Day ahead market, is calculated automatically based on the remaining capacity not used in other markets.
(Volume) – The storage volume used for the aFRR market, is calculated automatically based on the remaining volume not used in other markets.

Day pattern scaling – The scaling of the daily pattern in the selected prices series, i.e. a % adaptation of peak vs off-peak differences.

Noisiness scaling – The scaling of the noise in the selected price series, i.e a % adaptation of all volatility which is not attributed to recurring peak vs off-peak swings.

4.3 Adding additional timeseries

In the tool several timeseries for each market are already included, these cover the Netherland and Germany, in both 2016 and 2017. Additional timeseries can be added manually in the Timeseries tab.

For each timeseries a unique name has to be defined in the Name row. The timescale, defining the size of the timestep of the prices series, can be selected in the next row, this can either be 15 minutes, an hour, a day or a week.

**Price series - aFRR up**

<table>
<thead>
<tr>
<th>Name</th>
<th>aFRR 21</th>
<th>aFRR NL 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timescale</td>
<td>Unit</td>
<td>15 m</td>
</tr>
<tr>
<td>1</td>
<td>[€/MWh]</td>
<td>250</td>
</tr>
<tr>
<td>2</td>
<td>[€/MWh]</td>
<td>250</td>
</tr>
<tr>
<td>3</td>
<td>[€/MWh]</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>[€/MWh]</td>
<td>42.89</td>
</tr>
<tr>
<td>5</td>
<td>[€/MWh]</td>
<td>65.56</td>
</tr>
<tr>
<td>6</td>
<td>[€/MWh]</td>
<td>250</td>
</tr>
<tr>
<td>7</td>
<td>[€/MWh]</td>
<td>39.13</td>
</tr>
<tr>
<td>8</td>
<td>[€/MWh]</td>
<td>46.60</td>
</tr>
<tr>
<td>9</td>
<td>[€/MWh]</td>
<td>250</td>
</tr>
<tr>
<td>10</td>
<td>[€/MWh]</td>
<td>250</td>
</tr>
<tr>
<td>11</td>
<td>[€/MWh]</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>[€/MWh]</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>[€/MWh]</td>
<td>250</td>
</tr>
</tbody>
</table>

Note: for the aFRR there always are two price series required, one for up and one for down regulation. The name and timescale entered for the up regulation is also used for the down regulation, this is done automatically.

Note2: A good reference for including other historic price series is [https://transparency.entsoe.eu/](https://transparency.entsoe.eu/)
5 Sample projects

In the tool a number of diverse sample projects are already included. These projects are examples of what current and future storage projects could look like. Each of those projects is described in this chapter.

5.1 Source data

The sample projects are composed from various sources, covering both present performance/cost characteristics as well as projections (or ambitions) for the next decade.

- Navigant Research
- DNV GL / Pacificorp, Battery Energy Storage Study (2017)
- Lazard, Levelized cost of storage 3.0 (2017)
- IRENA, Electricity storage and renewables: costs and markets to 2030 (2017)
- Fraunhofer Umsicht, Speicher für die Energiewende (2013)
- ENTSO-E, TYNDP2016
- European Commission SET-plan (2016)
- DOE, Hydrogen storage targets
5.2 Li-Ion NMC (2018) & (2026)

Present day large-scale Li-Ion project with a 0.5-h energy content focusing on FCR or energy arbitrage. Includes energy storage equipment cost, power conversion system equipment cost, power control system cost, balance of system and installation.

The costs of the future large-scale Li-Ion project are based on industry projections. Note that present political targets aim for even lower CAPEX by 2030 (<150Euro/kWh), mainly drive by a projected rise in e-mobility applications.

More aggressive financial parameters have been assumed for 2026, showing the reduced risk in technology and increased confidence a stable revenue.

Table 1 Technical parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>2018</th>
<th>2026</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge capacity</td>
<td>[MW]</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Discharge capacity</td>
<td>[MW]</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Storage volume</td>
<td>[MWh]</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Ramp rate</td>
<td>[Max cap/min.]</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Roundtrip efficiency</td>
<td>[%]</td>
<td>81%</td>
<td>86%</td>
</tr>
<tr>
<td>Degradation</td>
<td>[%/cycle]</td>
<td>0.01%</td>
<td>0.002%</td>
</tr>
<tr>
<td>Max 100% DOD cycles</td>
<td>[100% DOD cycles]</td>
<td>3500</td>
<td>10000</td>
</tr>
<tr>
<td>Availability</td>
<td>[%]</td>
<td>97%</td>
<td>97%</td>
</tr>
</tbody>
</table>

Table 2 Financial parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>2018</th>
<th>2026</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPEX</td>
<td>[M€/MW]</td>
<td>0.492</td>
<td>0.408</td>
</tr>
<tr>
<td>CAPEX</td>
<td>[M€/MWh]</td>
<td>0.430</td>
<td>0.208</td>
</tr>
<tr>
<td>Yearly OPEX</td>
<td>[M€/MW/year]</td>
<td>0.007</td>
<td>0.007</td>
</tr>
<tr>
<td>Yearly OPEX</td>
<td>[M€/MWh/year]</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Max. economic life.</td>
<td>[years]</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Debt share</td>
<td>[%]</td>
<td>50%</td>
<td>80%</td>
</tr>
<tr>
<td>Debt interest rate</td>
<td>[%]</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>Debt term</td>
<td>[years]</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Cost of equity</td>
<td>[%]</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Corporate tax</td>
<td>[%]</td>
<td>25%</td>
<td>25%</td>
</tr>
</tbody>
</table>
5.3 Vanadium Flow Battery (2018) & (2026)

Present day large-scale Vanadium Redux Flow (VRB) project with high-end industry estimates on the number of cycles. This is often used in situations where high power and energy density are needed; design also allows for easier scaling of power or energy. In the capacity dependent CAPEX costs the power conversion system equipment, power control system, balance of system is included. In the volume dependent CAPEX costs the energy storage equipment cost and installation are included.

The costs of the future large-scale VRB project are showing limited cost reduction based on present industry projections.

More aggressive financial parameters have been assumed for 2026, showing the reduced risk in technology and increased confidence in a stable revenue.

Table 3 Technical parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>2018</th>
<th>2026</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge capacity</td>
<td>[MW]</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Discharge capacity</td>
<td>[MW]</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Storage volume</td>
<td>[MWh]</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Ramp rate</td>
<td>[Max cap/min.]</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Roundtrip efficiency</td>
<td>[%]</td>
<td>72%</td>
<td>77%</td>
</tr>
<tr>
<td>Degradation</td>
<td>[%/cycle]</td>
<td>0.0002%</td>
<td>0.0002%</td>
</tr>
<tr>
<td>Max 100% DOD cycles</td>
<td>[100% DOD cycles]</td>
<td>100000</td>
<td>100000</td>
</tr>
<tr>
<td>Availability</td>
<td>[%]</td>
<td>95%</td>
<td>95%</td>
</tr>
</tbody>
</table>

Table 4 Financial parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>2018</th>
<th>2026</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPEX</td>
<td>[M€/MW]</td>
<td>0.686</td>
<td>0.460</td>
</tr>
<tr>
<td>CAPEX</td>
<td>[M€/MWh]</td>
<td>0.616</td>
<td>0.464</td>
</tr>
<tr>
<td>Yearly OPEX</td>
<td>[M€/MW/year]</td>
<td>0.008</td>
<td>0.008</td>
</tr>
<tr>
<td>Yearly OPEX</td>
<td>[M€/MWh/year]</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Max. economic life.</td>
<td>[years]</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Debt share</td>
<td>[%]</td>
<td>50%</td>
<td>80%</td>
</tr>
<tr>
<td>Debt interest rate</td>
<td>[%]</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>Debt term</td>
<td>[years]</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Cost of equity</td>
<td>[%]</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Corporate tax</td>
<td>[%]</td>
<td>25%</td>
<td>25%</td>
</tr>
</tbody>
</table>
5.4 Pumped hydro (2018) & (2030)

A pumped hydro storage (PHS) project based on an energy storage island in the North Sea area close to shore. Relatively small-size storage plant in terms of max. power and hours energy stored. Price is higher than for under-development projects in mountain areas due to the extended offshore civil works required for the storage volume. The cost is based on actual considered projects both off- and onshore. It does not include grid integration costs. Note the cost carries a high uncertainty due to limited public info, and will for PHS be very much case specific depending on spatial/environmental conditions. The capacity based CAPEX is based on the costs for pumps in a regular (i.e. in a mountainous area) hydrodam.

The costs do not account for possible synergies in using the island for other other purposes, eg as an offshore maintenance hub or as part of an offshore electricity network.

Due to the maturity of the used technologies only modest further cost reduction is assumed, based on industry projections. However multiple uses for such an island could substantially improve the business case for an island.

More aggressive financial parameters have been assumed for 2030, showing the increased confidence in a stable revenue.

Table 5 Technical parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>2018</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge capacity</td>
<td>[MW]</td>
<td>550</td>
<td>550</td>
</tr>
<tr>
<td>Discharge capacity</td>
<td>[MW]</td>
<td>550</td>
<td>550</td>
</tr>
<tr>
<td>Storage volume</td>
<td>[MWh]</td>
<td>2200</td>
<td>2200</td>
</tr>
<tr>
<td>Ramp rate</td>
<td>[Max cap/min.]</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Roundtrip efficiency</td>
<td>[%]</td>
<td>70%</td>
<td>81%</td>
</tr>
<tr>
<td>Degradation</td>
<td>[%/cycle]</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Max 100% DOD cycles</td>
<td>[100% DOD cycles]</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Availability</td>
<td>[%]</td>
<td>97%</td>
<td>97%</td>
</tr>
</tbody>
</table>

Table 6 Financial parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>2018</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPEX</td>
<td>[M€/MW]</td>
<td>0.600</td>
<td>0.531</td>
</tr>
<tr>
<td>CAPEX</td>
<td>[M€/MWh]</td>
<td>0.453</td>
<td>0.401</td>
</tr>
<tr>
<td>Yearly OPEX</td>
<td>[M€/MW/year]</td>
<td>0.012</td>
<td>0.011</td>
</tr>
<tr>
<td>Yearly OPEX</td>
<td>[M€/MWh/year]</td>
<td>0.009</td>
<td>0.008</td>
</tr>
<tr>
<td>Max. economic life.</td>
<td>[years]</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Debt share</td>
<td>[%]</td>
<td>50%</td>
<td>80%</td>
</tr>
<tr>
<td>Debt interest rate</td>
<td>[%]</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>Debt term</td>
<td>[years]</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Cost of equity</td>
<td>[%]</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Corporate tax</td>
<td>[%]</td>
<td>25%</td>
<td>25%</td>
</tr>
</tbody>
</table>
5.5 CAES (2018) & (2030)

Large-scale CAES plant, example of one planned in the North Sea region. Note that given the limited experience, this takes into account cost estimates of historic facilities, which are higher than projections for under-development projects. This project is based on storage in a salt cavern. In this example only the capacity dependent CAPEX is given, which reflects the costs for the power conversion plant. Note that this is a significant simplification as in reality the storage volume and its cost is highly dependent on the size of the caverns at the specific locations. At http://www.estmap.eu more information can be found on the different types of CAES storage and their geologic potential across Europe.

Due to the maturity of the used technologies only modest cost reduction is assumed for the future project, based on industry projections.

More aggressive financial parameters have been assumed for 2030, showing the increased confidence in a stable revenue.

Table 7 Technical parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>2018</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge capacity</td>
<td>[MW]</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Discharge capacity</td>
<td>[MW]</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Storage volume</td>
<td>[MWh]</td>
<td>2500</td>
<td>2500</td>
</tr>
<tr>
<td>Ramp rate</td>
<td>[Max cap/min.]</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Roundtrip efficiency</td>
<td>[%]</td>
<td>70%</td>
<td>77%</td>
</tr>
<tr>
<td>Degradation</td>
<td>[%/cycle]</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Max 100% DOD cycles</td>
<td>[100% DOD cycles]</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Availability</td>
<td>[%]</td>
<td>97%</td>
<td>97%</td>
</tr>
</tbody>
</table>

Table 8 Financial parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>2018</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPEX</td>
<td>[M€/MW]</td>
<td>1.120</td>
<td>0.990</td>
</tr>
<tr>
<td>CAPEX</td>
<td>[M€/MWh]</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Yearly OPEX</td>
<td>[M€/MW/year]</td>
<td>0.022</td>
<td>0.020</td>
</tr>
<tr>
<td>Yearly OPEX</td>
<td>[M€/MWh/year]</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Max. economic life.</td>
<td>[years]</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Debt share</td>
<td>[%]</td>
<td>50%</td>
<td>80%</td>
</tr>
<tr>
<td>Debt interest rate</td>
<td>[%]</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>Debt term</td>
<td>[years]</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Cost of equity</td>
<td>[%]</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Corporate tax</td>
<td>[%]</td>
<td>25%</td>
<td>25%</td>
</tr>
</tbody>
</table>
5.6 PEM Electrolysis with compressed hydrogen storage (2018)

A large-scale hydrogen storage system using combined PEM electrolysers/fuel cells and compressed hydrogen storage. Based on above ground storage of the hydrogen. In the capacity price the power electronics are included as well as the membranes. Extra losses for hydrogen compression are taken into account.

Table 9 Technical parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge capacity</td>
<td>[MW]</td>
<td>10</td>
</tr>
<tr>
<td>Discharge capacity</td>
<td>[MW]</td>
<td>10</td>
</tr>
<tr>
<td>Storage volume</td>
<td>[MWh]</td>
<td>80</td>
</tr>
<tr>
<td>Ramp rate [Max cap/min.]</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>Roundtrip efficency [%]</td>
<td></td>
<td>29%</td>
</tr>
<tr>
<td>Degradation [%/cycle]</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Max 100% DOD cycles [100% DOD cycles]</td>
<td>6000</td>
<td></td>
</tr>
<tr>
<td>Availability [%]</td>
<td></td>
<td>98%</td>
</tr>
</tbody>
</table>

Table 10 Financial parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPEX [Mc/MW]</td>
<td></td>
<td>1.120</td>
</tr>
<tr>
<td>CAPEX [Mc/MWh]</td>
<td></td>
<td>0.025</td>
</tr>
<tr>
<td>Yearly OPEX [Mc/MW/year]</td>
<td></td>
<td>0.022</td>
</tr>
<tr>
<td>Yearly OPEX [Mc/MWh/year]</td>
<td></td>
<td>0.000</td>
</tr>
<tr>
<td>Max. economic life. [years]</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Debt share [%]</td>
<td></td>
<td>50%</td>
</tr>
<tr>
<td>Debt interest rate [%]</td>
<td></td>
<td>4%</td>
</tr>
<tr>
<td>Debt term [years]</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Cost of equity [%]</td>
<td></td>
<td>10%</td>
</tr>
<tr>
<td>Corporate tax [%]</td>
<td></td>
<td>25%</td>
</tr>
</tbody>
</table>
6 Model assumptions and limitations

The main objective of this tool is to provide interested parties a detailed and understandable platform to analyze the impact of technology/project/finance/market parameters on the economic viability of a storage project.

While the tool considers an extensive set of 45 parameters and a detailed optimization engine, the user should take into account the following assumptions and limitations of the tool:

Data uncertainty

Cost and performance of technologies can vary based on vendor, location, financial means, usage and many other aspects. The default cases in the tool are based on public sources, and should be considered by the user as a starting point for own sensitivities and analyses.

Market revenues

The optimization of storage dispatch assumes perfect foresight of price curves which allows the unit to take maximum revenue. In reality the success rate may be lower. A simple way to introduce this assumption by the user is to adapt the unit’s availability.

Market impact

The tool assumes the storage unit is a price-taker. Large units should consider the impact they have in price-setting, as well as the total volume requested, especially in limited size reserve markets.

Price curves

The tool provides a set of historic price curves. While cost projections are included based in public references, the tool gives no suggestion for future market prices. The tool can be used to identify thresholds of daily/weekly/seasonal price swings which could make a case profitable.

Multiple revenue streams

The tool allows to allocate capacity blocks to different market segments, but not to co-optimize across segments. The focus is also on FCR, aFRR, day-ahead markets. Other revenue streams such as portfolio balancing, peak reduction, etc. are not included.
Disclaimer

Under no circumstances shall TenneT Holding BV nor its subsidiaries, in particular TenneT TSO B.V. and/or TenneT TSO GmbH, hereinafter “TenneT”, be liable for any claims, penalties, losses or damages resulting from, or connected to the use of (the information in) this tool or the user guide. Please read the user guide to know more about this tool and how to use it.

The Storage Tool built by an external party for TenneT, uses available public information that can be found on open sources. All information is provided to facilitate those who would like to understand more about energy storage technologies and to offer a way to evaluate and compare different technologies, financings and market revenue options. All information is presented “as is”. TenneT makes no warranties or representations, whether express or implied, about the information contained in this publication. In particular, TenneT is not liable for information that is not accurate, up-to-date, comprehensive, verified or complete. TenneT expressly disclaims all liability for claims, penalties, losses or damages (whether arising in contract, tort or otherwise), that arise after the use of, or reliance upon, any information and material provided by the tool or published in the user guide.