EUCALC

Explore sustainable European futures

Storage requirements module

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Short Description

This report introduces the storage requirement module of EUCalc with describing the trends and evolution of electricity balancing, setting the scene and providing the basis for the methodology of the calculation. Having reviewed the background, the report then goes on describing the ambitions and goals of this specific module. After this, it describes the overall calculation logic of the storage module, detailing the input, outputs, the module's relation to other modules and the detailed calculation tree. The calculation methods are thoroughly explained, by detailing the scope, the choice of the lever levels, and the influence of a multitude of external factors.

Quality check

Name of reviewer	Date
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Statement of originality:

This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both.

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List of abbreviations

CAES – compressed air energy storage

CAPEX - capital expenditure

CEG - centralised energy generation

CF - capacity factor

COE -cost of electricity

DEG - decentralised energy generation

DESSTinEE – Demand for Energy Services, Supply and Transmission in EuropE

DSM - demand-side measures

ENTSO-E - the European Network of Transmission System Operators for Electricity

EU - European Union

EV - electric vehicle

GHG - greenhouse gas

GTAP – Global Trade Analysis Project

JRC IDEES - Integrated Database of the European Energy Sector

NREL – National Renewable Energy Laboratory

OPEX - operating expenses

PHS - pumped hydroelectric storage

TSO - transmission system operator

VRE - variable renewable energy

WACC – weighted average cost of capital

1 Introduction

Despite the apparent stability of electricity systems from a consumer point of view, there is indeed significant effort exerted by the network managers to guarantee the stability of the electricity supply. Although, from a technical point of view, electricity demand and supply always need to be equal, both supply and demand of electricity are indeed rather variable, even on a short time, thereby requiring significant efforts from Transmission System Operators (TSOs).

It is likely that due to expected structural changes in the European electricity grid, balancing activities and capacities will advance in the future. Growing share of intermittent renewable electricity generation, as well as changing patterns in electricity demand create challenges for grid balancing. On the demand side, this is due to the electrification of sectors, as well as empowering consumers with the options to wisely influence consumption and even produce electricity on their own, thus finally becoming prosumers. Thus, new technologies and investments, as well as grid management strategies are needed for seamless integration. Currently, balancing of the grid is mostly solved by natural gas-based power generation, a widely spread and applied technology, and also by pumped hydro storage (PHS). Nowadays, these technologies provide the required flexibility for the grid. Using natural gas, however, is not climate neutral and is mostly imported to Europe, while PHS is geographically limited to certain countries. In the continental Europe the largest potential of PHS is in the Alps, and the existing units of PHS here already play a role in balancing the intermittency of renewables in European level (Gurung et al., 2016). Combining wind and PHS can be a viable option for Ireland, too (Coburn et al., 2014).

Therefore, the storage requirement module investigates how new technologies can help the electricity system of the EU to operate stable in light of increasing renewables penetration, demand side measures and decarbonisation paths. The objective of this report is to introduce the operation of this module with the calculation steps, assumptions and levels. The module uses the outputs of the electricity supply module and the ones defining the electricity demand in order to find an appropriate mix of storage and balancing technologies that allows the demand for electricity is met given the conditions set by the user in the geographical scope of EU-28 and Switzerland up to the year of 2050.

The structure of the report is as follows. In chapter 2, the report describes the trends and evolution of electricity balancing, thereby setting the scene and providing the basis for the methodology of the calculation. Having reviewed the background, in chapter 3 we introduce the ambitions and goals of this specific module. After this, chapter 4 describes the overall calculation logic of the storage module, detailing the input, outputs, the module's relation to other modules and the detailed calculation tree. Section 5 details the levers for the technology portfolio required for the balancing of the European grid. For the levers of the module, extensive documentation is provided to describe the various ambition levels ranging from a low ambition to disruptive. Ambition levels are proposed based on the most up to date research, historic trends and other relevant studies that are highlighted and gathered in the bibliography.

2 Trends and evolution of electricity balancing

The goal of this section is to give a short overview of the context and current trends in electricity storage and system balancing.

2.1 Electricity supply side

In the last years, tremendous changes have started both on the supply and demand sides of the electricity sector which are expected to accelerate in the future. On the supply side, renewable based power generation technologies, mostly wind power and PV are becoming dominant parts of the electricity system, as show on Figures 1 and 2. From a balancing perspective, the intermittent nature of these renewable energy sources – which are also expected to be subject to the effects of climate change – are creating challenges in the electricity sector that previously were not of concern. In the short term, renewable based power generation needs to be properly integrated with non-intermittent traditional baseload power plants, which puts significant strains on network operators and the operators of the existing power plant portfolio. In the long term, however, it has to be resolved that excess renewable power that is generated in favourable conditions needs to be stored for later, when the conditions are not ideal for weather-dependent renewable generation.

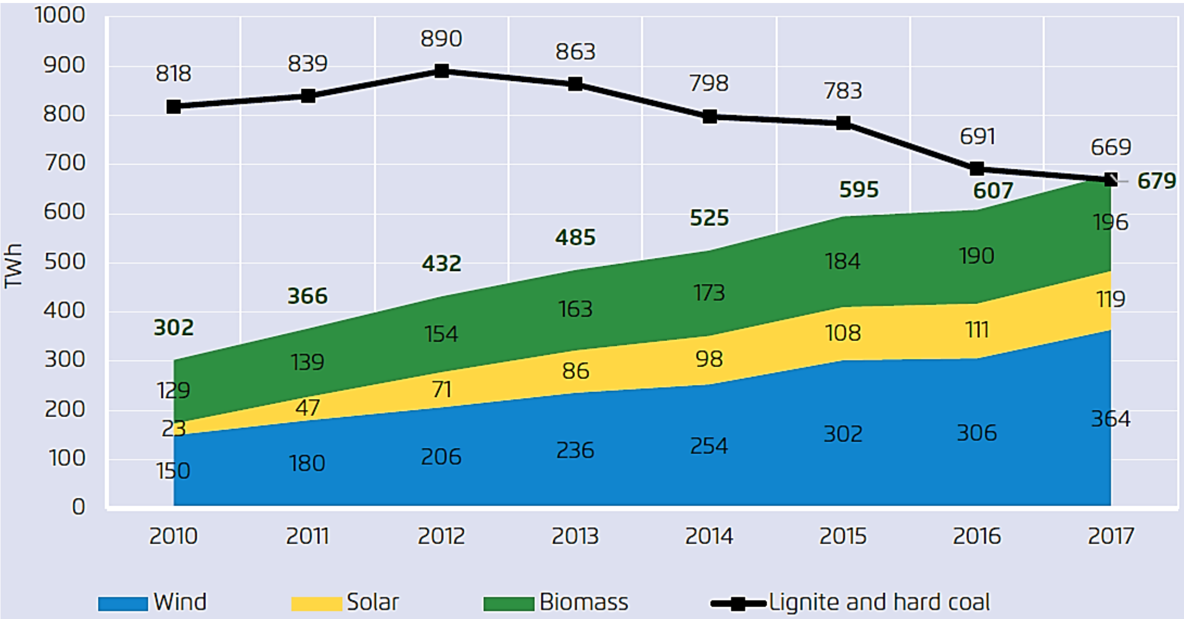

Figure 1 - Renewables versus coal electricity generation in the EU, source: Agora Energiewende and Sandbag, 2018

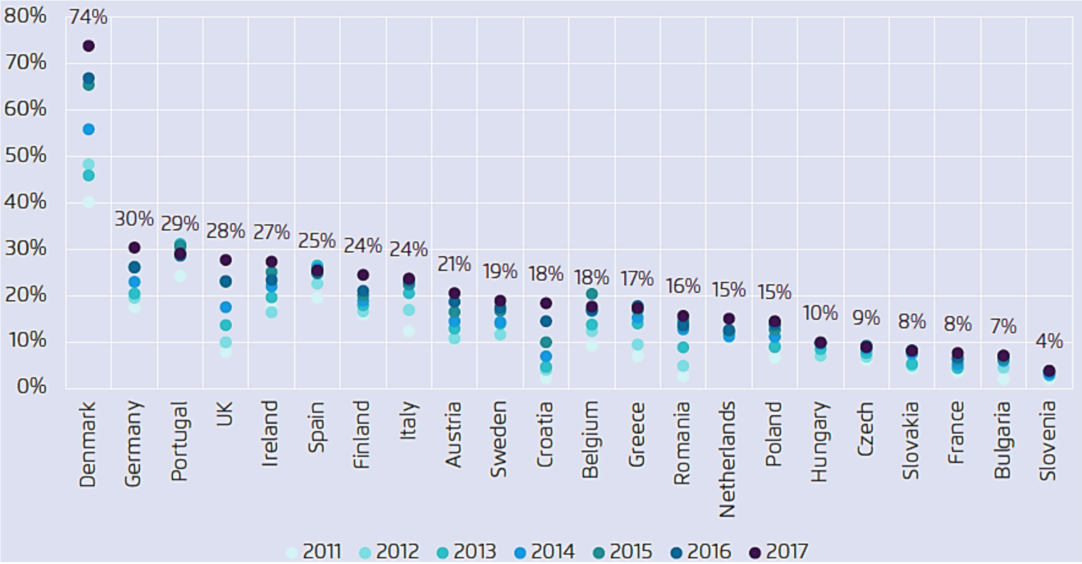

Figure 2 - Wind, solar and biomass as percentage of national electricity production in the EU, source: Agora Energiewende and Sandbag, 2018

Yet, it is not only the increased overall level of renewables that is creating challenges in terms of balancing, but the location where these renewable power generation capacities are connecting to the existing electricity grid. As a result, the electricity system is becoming more and more decentralized, as for instance household scale PV installations are connecting to the low voltage network. This phenomenon, as shown on Figure 3, was not experienced by centralised power systems before. Thus, a potential metric for decarbonization is the generation of household size PV in relation to the overall demand. From a balancing perspective, this is important, as storages will be increasingly required in cases where the generation capacities are connecting to the distribution instead of the transmission network. These storage devices that are integrated into the distribution network along with the renewable power capacities are essential to prevent bi-directional flows that would otherwise decrease the supply qualities of the electricity system, while also increasing the costs associated with operating these systems.

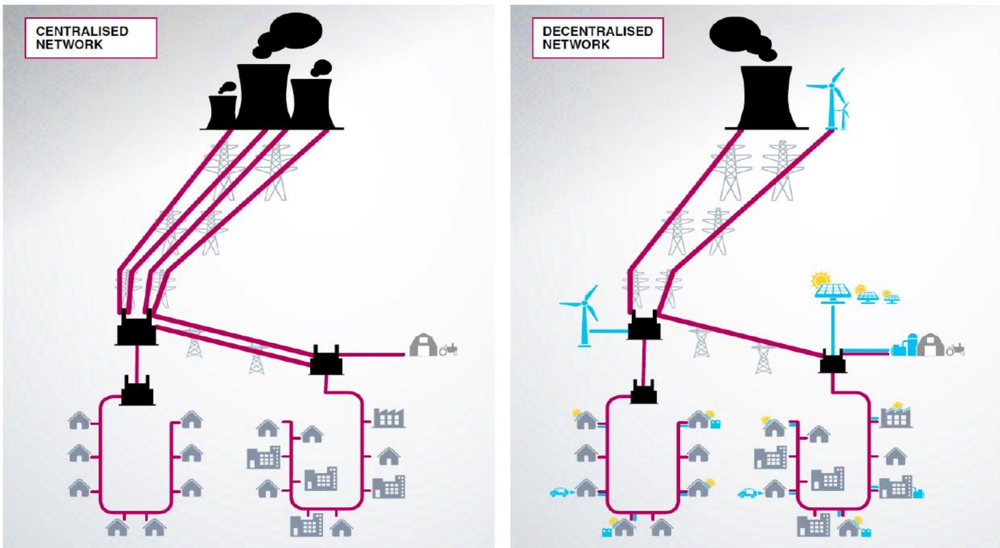

Figure 3 - Schematic illustration of a centralised and decentralised network, source Rutovitz et al., 2014

Decentralisation also creates the possibilities for micro-grids to evolve that are basically self-sustainable electricity production communities that at times may function completely separately from the nation-wide electricity grids. The application of decentralised energy generation in micro-grids – especially in those that operate on PV and wind power – cannot be reliable on its own. The intermittency of renewables is perhaps an even greater issue in micro-grids and therefore requiring balancing technologies. Yet despite these apparent shortcomings, complementing the centralised grid with decentralised power and storage systems improves energy independence and reliability for the overall system (Liu et al., 2017, Kursun et al., 2015, Ogunjuyigbe et al., 2016).

2.2 Electricity demand side

Turning to the consumer (demand) side, one finds that consumers are starting to have the tools that allow them to become prosumers of electricity from simple users. This entails that not only do they produce electricity, but they are also demanding information and flexibility with regards to their power consumption patterns. Demand Side Management (DSM) coupled with the appropriate tariff structure that incentivises consumers to act can provide the right signals for the consumers to change their consumption patterns. An example on the impact of DSM on consumption patterns and how those measures can help smoothing out the load profile are presented in Figure 4 from the study by Liu et al. These features make DSM an effective method for network operators to reduce demand from the grid in critical hours of the day (Jabir et al., 2018).

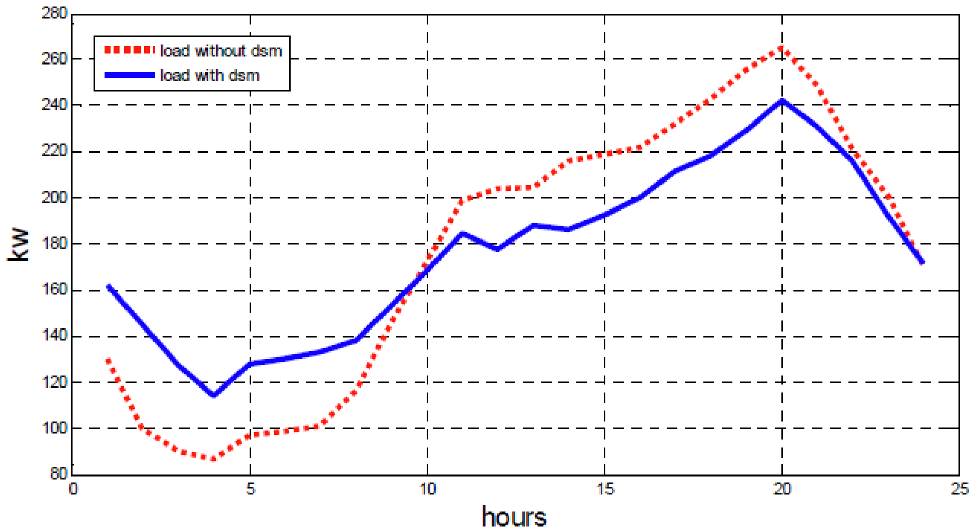

Figure 4 – Load profile with and without demand side management, from Liu et al., 2015

As shown above, DSM is embedded in the load profiles as the main influence of DSM is captured via changes in how the actual consumption is scheduled.

In addition to this, it also has to be mentioned that on the demand side, as a result of changing patterns of lifestyle and technology, load profiles are changing and new areas of electricity demand are appearing such as road transport and heating (Bossmann and Staffell, 2015). The changes in load profiles, however, have an effect on how peak loads are covered – let them be daily or seasonal – and therefore have an effect on electricity balancing as well.

2.3 Balancing and storage in context of the module

The previous chapter summarised why storage and balancing will be more prevalent in future electricity systems, while this subchapter defines what the storage module considers to be electricity balancing and storage, and also showcases how balancing activities are carried out nowadays.

2.3.1 The definition of balancing and storage

There are various definitions of balancing depending on the level of complexity and target audience, which is also reflected in various EU policy documents defining the act of balancing. According to the Commission Regulation (EU) 2017/2195, balancing means "*all actions and processes, on all timelines, through which TSOs ensure, in a continuous way, the maintenance of system frequency within a predefined stability range*" (European Commission, 2017a). From this definition it emerges that from one point of view balancing is strictly focused on maintaining the frequency of the electricity system, which has to be maintained at 50 Hz Europe-wide in order to maintain the stability of the grid.

A European Commission working document that accompanied the Winter Energy Package also adopts a similarly narrow definition of balancing "*the situation after markets have closed in which a TSO acts to ensure that demand is equal to supply, in and near real time*" (European Commission, 2017b). This definition highlights that although securing the required balancing capacities is based on market-based auctions and therefore actors are selected competitively, however, the act of balancing itself is the sole responsibility of the TSOs, ordering the required capacities to be dispatched on demand. The common part of these definitions is that the TSO is responsible for balancing, therefore balancing activities are aggregated at the TSO level, which also resembles the national level in Europe, with a few exceptions[1].

The fact that demand and supply should be equal "*in and near real time*" highlights that this definition also mostly focuses on frequency control, thereby guaranteeing the stability of the system. From the reviewed definitions it is also clear that balancing, at whichever time scale, will always have to focus on frequency control, the matching of supply and demand. This is because if demand is systematically higher than the supply that is delivered by machines driving the generators, then the rotational speed of the generators themselves will drop, which will lower the frequency. In the absence of intervention, this process would be self-generating and ultimately resulting in blackouts within seconds. Balancing mechanisms are required therefore, as the electricity system itself is unable to store electricity, thereby requiring instant intervention possibilities to maintain grid frequency. This instant intervention possibility can be delivered by different technologies at different time scales. In the context of growing renewable energies with seasonally diverging outputs though, the importance of electricity storage will grow, in order to deliver the required power at the right time to sustain supply and demand matching, thereby keeping frequency within the predefined band requirement.

Table 1 details the European categorisation of balancing activities (Glowacki Law Firm, 2019a) that contains three categories also with reference to time considerations.

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[1] In most countries in the EU, there is a single TSO in each country. Only Germany and the United Kingdom have multiple TSOs in their territories.

Table 1 – Types of balancing activities with activation times and relation to the storage module

Balancing activity	Activation time	Time scale in the storage module
Frequency containment reserve	< 30 seconds	Short-term balancing
Frequency restoration reserve		
with automatic activation	30 seconds - 2 minutes	Short-term balancing
with manual activation	2 minutes - 15 minutes	Short-term balancing
Replacement reserve	> 15 minutes	Long-term balancing

Of these three categories, the first two concern the containment and upholding of the frequency of the grid by running generators, thereby requiring almost instant reactions and intervention by power plants that are either dedicated to do this or have reserve rolling capacities set aside. It is interesting that replacement reserves themselves are defined as a means that are capable of "*restoring or supporting the required level of frequency restoration reserves to be prepared for additional system imbalances, including generation reserves*" (Glowacki Law Firm, 2019b), but this category of balancing functions as replacement in the case of unavailability of other supply sources, with generators that are not already running as highlighted by the activation time as well.

2.4 The link between balancing and storage

In order to justify the methodological approach of the calculation, the module is categorising the above three categories of balancing activities into short-term and long-term balancing. We consider frequency containment reserves and frequency restoration reserves as short-term balancing, while replacement reserves as long-term balancing.

The storage module is working with an hourly granularity; thus, it is unable to capture short-term balancing needs based on the definition above. It is therefore solely focusing on long-term balancing activities on country and EU level. This approach is justified by Brown et al. (2018) stating that at large spatial scales the variations in aggregated load, wind and solar time series are statistically smoothed out, none of the large-scale model results change significantly when going from hourly resolution down to 5-min simulations. Hourly modelling will capture the biggest variations and is therefore adequate to dimension flexibility requirements. Sub-hourly modelling may be necessary for smaller areas with older, inflexible thermal power plants, but since flexible peaking plant and storage are economically favoured in highly renewable systems, sub-hourly modelling is less important in the long-term (Brown et al., 2018).

Describing a year by hourly data, i.e. 8760 values also includes the variations in lower time granularity, thus the curves obtained by the 8760 data points show also weekly and seasonal patterns, thus though weekly and seasonal patterns of supply and demand are captured in the modelling.

On the other hand, the supply module uses capacity factors[2] to calculate annual production of power plants. The historical capacity factors inform us about the

[2] Capacity factor is the ratio of the net electricity generated, for the time considered, to the energy that could have been generated at continuous full-power operation during the same period [48].

historical observed generation compared to the maximal generation through a period of time including all the time the unit was running. Therefore, capacity factors include also the generation that was provided for flexibility purposes. For example, when observing historical capacity factors of natural gas power plants in a country, the capacity factor of the gas power plants already includes the times when the power plants were used for balancing purposes and not for general power production. Typically, though, balancing power plants have relatively low annual utilisation rates, rarely exceeding 1% of the time of the year (see MAVIR & MEKH, 2017 for the example of Hungary). Therefore, the capacity factors of power plants used in the supply module already encompass the kind of short term balancing that was needed before. As these balancing needs and outages are already factored into the capacity factors, therefore any additional balancing needs afterwards calculated in the storage module focuses on the most important source of future balancing need, the ratio of intermittent renewables projected to grow further.

The storage module considers storage as an operational tool of the electricity system that can help to achieve electricity balancing with the ability of shifting the (over)supply of electricity to a later time point, when demand exceeds supply, thus the stored electricity will be needed in order to maintain frequency and sustain the stability of the system. Storage can be realized on different time scales, though, by different technologies. Therefore, in the context of the module, storage and balancing can be interchangeable terms, as storage is a technical toolset within balancing.

It is important to mention that electricity storage technologies have various functions that they can fulfil. Based on the International Renewable Energy Agency (IRENA), categorisation of the services is on Figure 5, due to the characteristics of EUCalc and the assumptions of the supply module, this module focuses on the bulk energy services that are needed for a well operating electricity system.

On Figure 5, pink fields are the services directly supporting the integration of variable renewable energy which is the key component of decarbonisation of which process EUCalc is investigating the impact of. On the other hand, as the module works in close relation with modules defining the electricity demand, the pink fields under other services on the right-hand of the model are considered with interaction from there. For example, the transport sector is considered in the form of input received from the transport module about the demand response potential of the batteries used in transportation. Exceptions are off-grid energy storage applications, as the main aim of the module along with the supply module, to model the grid in view of increasing renewable energy penetration and how different storage technology can influence it.

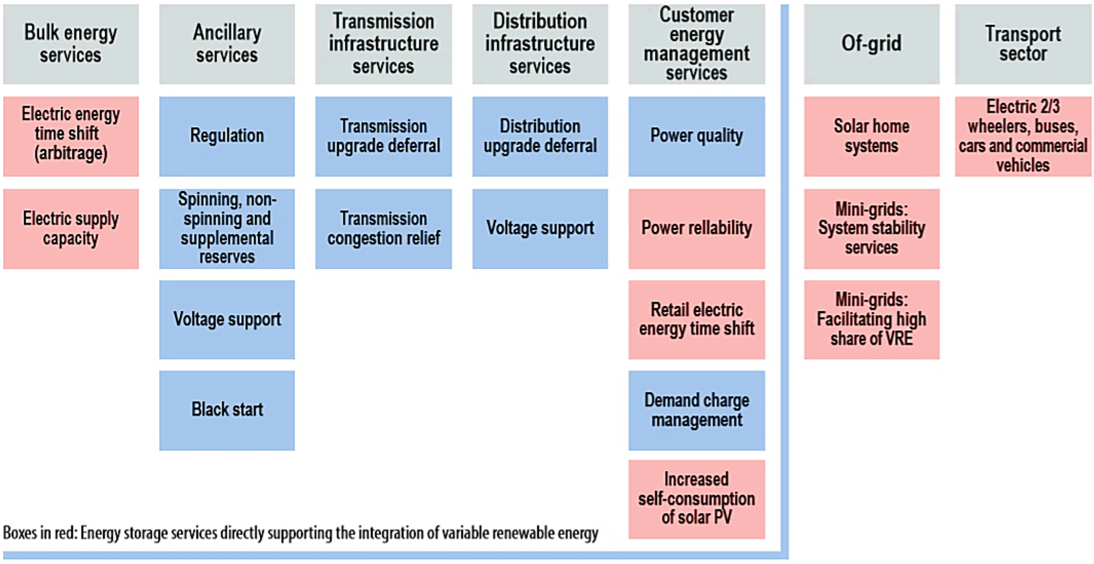

Figure 5 - The range of services that can be provided by electricity storage, source: IRENA, 2017

In general, blue fields are outside of the scope of current modelling. For ancillary services of storage, the module functions do not take into consideration electricity system specifics, such as voltage or frequency level, which indeed can be influenced by various factors, such as temperature itself. Transmission infrastructure services cannot be evaluated either in the module, as the whole EUCalc is based on countries, thereby unable to differentiate between different transmission characteristics within a country. The same kind of reasoning can also be applied to the distribution infrastructure services.

Balancing can also be achieved through cross-border trade, importing or exporting electricity based on the required balancing need. Cross-border electricity trade between any given countries is happening through organised markets, but the definition of balancing as used before ("*after markets have closed*") prohibits the cross-border trade to be used for balancing, because cross border trade is carried out in markets. As a result of this, the module will consider trade as an alternative to store electricity in a country locally.

2.4.1 Summary of balancing and storage as used by the module

The module defines balancing as actions taken towards equalising electricity supply and demand within a year in hourly time granularity. When differentiating between short-term balancing (frequency control with running generation equipment) and long-term balancing (replacement reserves), the module focuses on replacement reserves. The module considers electricity storage as a means to achieve the balance of the electricity system, especially over the long term. Also related to balancing, the module considers cross-border trade as an alternative to electricity storage, while also considering DSM solutions to limit demand rather than extending supply from the grid directly.

3 Questions addressed by the module

The main purposes of the storage module are:

- to match electricity demand and supply with making the necessary adjustments;
- to determine and meet the flexibility needs for a given scenario of demand and VRE penetration
- to determine how much CO_2 emissions are caused by the flexibility needs;
- to give estimations of costs linked to high renewables scenarios.

The strength and aim of this module are of creating a realistic electricity production mix, security of power supply and take into account impacts created by large share of renewables (with considering also the impact of climate change on the renewables production) and changing load profiles. So, the module itself has no specific output, it is rather supportive to the supply module to complement the electricity generation mix by necessary additional capacities and assisting the user to see the implications on the grid. This analysis can only happen at increased time granularity of 8760 datapoints (hourly resolution) describing the demand and also the supply of intermittent electricity by PV and wind power.

The storage module considers the impacts of the lever setting in the supply module on the electricity system and grid. It calculates the needed flexible capacities to complement supply and thereby balancing the intermittency of renewables and variability of load profiles, thus meeting demand. The overall annual electricity demand is coming from the supply module that aggregates the sector level values, however, the way the annual demand is distributed throughout the year in an hourly resolution is computed directly in the module, based on hourly data generated by load profiles of typical periods coming as direct input of demand modules. Direct GHG emissions of the additional balancing technologies are also calculated.

In terms of ambition levels, the module investigates the composition and scale of a storage and flexible generation portfolio of electricity storage technologies. In order to exploit those opportunities, in some cases breakthroughs are needed – not only in technology but policy ambitions, too.

Table 2 summarizes the topics the storage module is addressing.

Table 2 – ambitions of the storage module

Theme	Questions		Ambition
What are the types of impacts we want to take into account in the model?	Energy	• Power generation: What is the amount of needed flexible power generation and storage capacity to balance the intermittency of renewables and changing patterns of electricity consumption?	Yes
	Emissions	• Direct emissions: What are the direct emissions of the installed flexible power generation and storage capacities?	Yes
	Products, materials & resources	• Material use: what is the resource usage of the investments in flexible power generation and storage capacities?	Partially through other modules
	Economy	• Economy: What is the cost and economic impact of the different scenarios (e.g. jobs)?	Partially through links with other modules
		• Trade: electricity and natural gas?	Through GTAP model integration
	Other	• Other: Biodiversity? Health?	Partially through other modules
What are the existing solutions to decarbonize the sector?	Improve	• Impact of large share of renewables	Yes
		• Impact of storage technology choice	Yes
Can we identify some potential breakthrough (technologies or societal) that could have an impact?	Improve	• What would be the impact of improved technologies on the intermittency and balancing of large share renewables?	Yes
What are the impacts of balancing/storage on the other sectors?	Manufacturing	• What are the material requirements of investments into power generation technologies?	Partially through other modules
What are the impacts of other sectors on energy supply?	Lifestyle	• Meeting the demand for electricity	Partially through other modules
	Buildings	• Meeting the demand for electricity, considering changing patterns of electricity consumption due to electrification of heating and other DSMs	Partially through other modules
	Transport	• Meeting the demand for electricity, considering changing patterns of electricity consumption due to electrification of transport, and the potential for battery storage	Partially through other modules
	Agriculture	• Meeting the demand for electricity	Partially through other modules
	Industry	• Meeting the demand for electricity, considering changing patterns of electricity consumption due to electrification of the industry processes	Partially through other modules

4 Calculation logic and scope of module

The objective of the storage module is to match supply and demand, and account for the flexibility needs of the system due to the increased share of VRE. This module functions in close connection to the supply module and the ones defining the demand; thus, the calculation is based on inputs gathered from those modules. The user has the option to influence the volume of storage capacities via the levers of the module, as detailed in Chapter 5.

The added value of the storage module compared to the supply module and the modules defining the demand for electricity is that this module works on an hourly resolution for a single year, which therefore adds up to the yearly resolution of the complementing modules. The module does this by applying increased granularity through the downscaling of the annual electricity demand and production figures to load curves with hourly resolution, and applying hourly capacity factors for PV and wind power generation on the supply side.

Considering the aims of EUCalc, the module complements the outputs of the supply module with the below listed characteristics:

- The module predicts renewable power generation from variable sources (PV and wind) for each country at the hourly level, thereby capturing the need for electricity storage as a function of variable renewable electricity production.
- The module breaks down annual demand of each country into load curves with hourly granularity for each country, thereby capturing balancing electricity need at the hourly level.
- The module includes trade flows of electricity between the countries, thus correcting the supply-demand match with trade.
- The module integrates specific storage technologies into the calculation to match flexibility needs on three timescales of balancing.
- Direct CO_2 emissions from additional, flexible power generation capacities that are needed to balance electricity demand with supply.

The module however, does not consider indirect emissions as they are addressed by other WPs (e.g. manufacturing assesses the emissions related to the manufacturing of the power plants)[3].

The details of the overall calculation logic of the module are presented in the following sections.

[3] WP3: Production and Manufacturing http://www.european-calculator.eu/research-approach-wps/

4.1 Overall logic

The high-level calculation logic of the storage module, as shown on Figure 6, consists of the next steps.

Generating the hourly level information in three parallel steps on country then aggregated to trading zone level:

- Step 0: the module matches annual electricity demand with supply, and in case of excess in a trading zone accounts for electricity trade.
- Step 1: the module determines hourly load curves for electricity demand based on load profiles and inputs from electricity consuming sectors.
- Step 2: the module creates the hourly granularity residual supply curves based on hourly capacity factors for PV, on- and off-shore wind power.

Securing the flexibility needs for the system on trading zone level:

- Step 3: the module calculates the residual load curve from the hourly granularity values and generates flexibility needs on three different timescales.
- Step 4: the module assigns different technologies to the different flexibility needs.

Disaggregating parameters to country level and adjusting flows between modules:

- Step 5: the module calculates disaggregates the physical storage and generation capacities to individual countries.
- Step 6: the calculation may adjust the primary electricity production due to adjustment of capacity factors on hourly level, this module will finalise the values of the flows from the supply module and forward the final data to the Transition Pathway Explorer – these changes are associated to the changes in the capacity factor values influencing not only the produced electricity but the used fuel input and produced emissions.
- Step 7: the module determines the cost of electricity production.

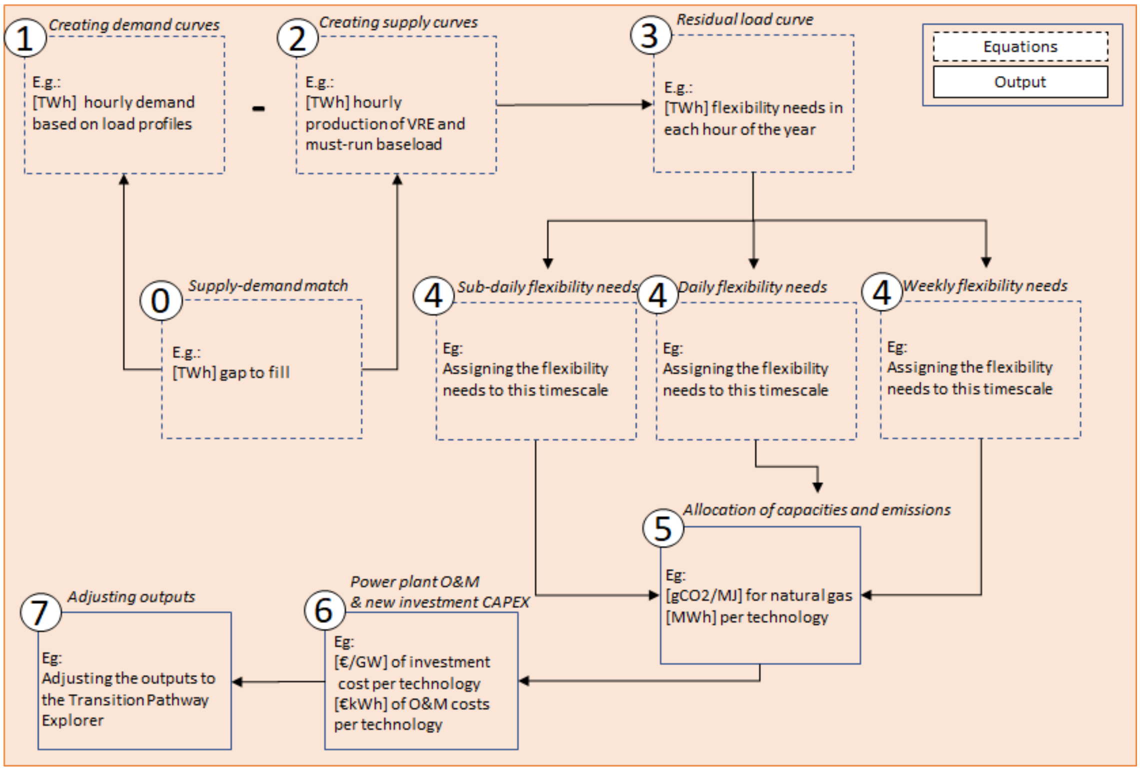

Figure 6 - Calculation logic of storage requirements module

4.2 Scope definition

Figure 7 defines the scope of the module in terms of:

- The technologies included in the model;
- The types of vectors of energy considered.

Technologies:

- Electro-chemical, battery, stationary
- Pumped hydroelectric storage
- Electro-mechanical, compressed air storage
- Electro-mechanical, flywheel
- Natural gas turbine
- Power to gas

Energy vectors:

- Electricity
- Natural gas
- E-fuel

Figure 7– Scope definition of the storage requirements module: technologies and vectors of energy

Due to the special characteristics of the module, i.e. considering impact of electricity transmission and balancing between countries and working with enhanced time granularity, not only technical scopes but geographical and time granularities need to be defined, too.

4.2.1 Geographical scope

The lowest level of geographical granularity in the module is the country level. From a methodology perspective this means that the module cannot assess the geographical location of any of the technologies and variables used in the module within a country, thus uses country level stock values or averages. From a practical point of view, this means that the module treats countries perfectly homologous from an electricity transmission and distribution point of view.

Above that we consider the electricity trading zones containing several countries. This geographical resolution is used to calculated hourly balances and needed flexibility capacities. A total of 9 regions were created, which represent the trading zones in electricity (Table 3).

Table 3 – Trading zones to be utilised in the module

	Trading zone	Countries included
1	Central Western Europe	France, the Netherlands, Belgium, Luxembourg, Germany, Austria, Switzerland
2	Central Eastern Europe	Poland, Czech Republic, Hungary, Slovakia, Slovenia, Croatia
3	South Eastern Europe	Romania, Bulgaria, Greece
4	Apennine Peninsula	Italy, Malta
5	Iberian Peninsula	Spain, Portugal
6	British Isles	United Kingdom, Ireland
7	Northern Europe	Denmark, Sweden, Finland
8	Baltic countries	Estonia, Latvia, Lithuania
9	Cyprus	Cyprus

The reason why the module is using these regions is that considering the current electricity transmission infrastructures and capacities, the countries within one region are well connected with each other, but less so with countries that are outside of their regions, even if they are neighbouring countries. This categorisation of regions also resembles that of the reporting structure of ENTSO-E and the European Commission. This has two consequences from the perspective of the modelling. First, as a result of intra-region connectivity, wholesale electricity market prices very often converge within one region (for example see Figure 8), and as a result of the electricity market coupling procedures, cross-border capacities are also traded implicitly within these regions, as opposed to being explicitly traded as in the case of inter-region trade. As a result of these already existing market trends, it is safe to assume that bottlenecks only exist between regions, but not within regions.

Secondly, due to this perfect competition-like market nature, balancing also happens at the trading zones level considering also the geographical limitations of PHS (currently, for example, concentrated in the Alps) which storage capacity is frequently used to fulfil flexibility needs of other countries. This regional balancing approach is aligned with European energy policies, too. The "Clean energy for all Europeans" package encourages Member States to establish a modern design for the EU electricity market where "*electricity to move freely to where it is most needed and when it is most needed via undistorted price signals, consumers will also benefit from cross-border competition*"[4].

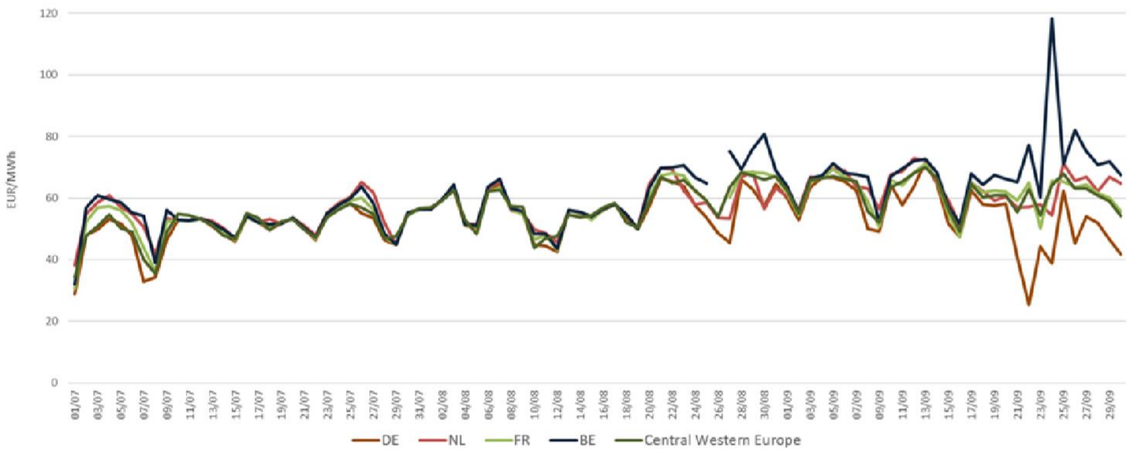

Figure 8 – Daily average wholesale prices in the Central Western Europe region in Q3 2018, source: European Commission, 2019

The next level of geographical resolution is the EU plus Switzerland aggregated level with interaction with the rest of the world.

4.2.2 Time granularity

When considering the lowest level of observation from a time perspective, the hourly level has been chosen (Table 4). Hourly granularity means that there are 8760 data points describing the demand patterns, as well as PV and wind power fluctuations. While we work with actual 8760 capacity factors for those technologies to describe fluctuations within a year, for the demand pattern we apply a different approach. We use typical load profiles (the repetitive 24-hour distribution of load from a given sector) of a sector to generate the load curve for the whole economy, i.e. the annual 8760-hour time-series of demand.

As working with 8760 hourly data per year describing the changes of those parameters through the whole year, this dataset and calculation method for both supply and demand sides include hourly, daily, weekly and seasonal levels of balancing, but sub hourly measures (frequency controls) are excluded. The hourly values are used both on the supply and demand sides, to create annual load curves to create discrete values for the 5 year interval period that the module is considering for 2015-2050.

[4] https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/clean-energy-all-europeans

Table 4 – Details of the enhanced granularity methodology applied by the module, details are given on country level per year

	Annual values			Enhanced granularity values		
	Raw values	**Origin**	**Details**	**Raw values**	**Origin**	**Method**
Supply	1 per technology and country	Supply module	Annual electricity production by technology and country	3x8760 values, hourly capacity factors for PV, on- and off-shore wind power	input excel table	averaged and adjusted to climate impacts based on renewables.ninja[5]
Demand	1 per demand sector	Supply module	Supply module collects sectorial annual electricity demand values	Load profiles	directly from demand side modules	all the load profiles are used to synthetize the load curve with 8760 value describing a year

4.3 Inputs and outputs of the module

The module aims to complement the supply module by calculating details of necessary balancing and storage capacities for a realistic electricity production mix and secure operation.

In this sense, the main inputs are used to describe the electricity production and demand in more detail allowing higher time granularity modelling, whereas the outputs are complementary to the supply module by adjusting existing capacities and adding new flexible storage and generation ones.

Inputs include annual values of electricity supply and demand, as well as load profiles from demand side modules and capacity factors of VRE in hourly resolution – both used to enhance the time granularity. Other import elements of the system flexibility are the e-fuel demand and the DSM potential, both also coming from the demand side modules. Apart from that, technology module provides input necessary for cost calculation, whereas trading electricity with the rest of the world is included to account for electricity export-import outside the EU.

Outputs mainly the complementary capacities of flexible generation and storage for the full electricity generation mix with their associated outputs (emissions, energy use, costs and material use). Thus, outputs are CO_2 emissions from energy mix, estimation of the electricity stored and used at the different timescales, as well as estimation of the storage capacity needs.

[5] https://www.renewables.ninja/

4.4 Interactions with other modules

Figure 9 shows the modules that the storage module interacts with. The kinds of data exchanges are explained in the subchapters to be followed.

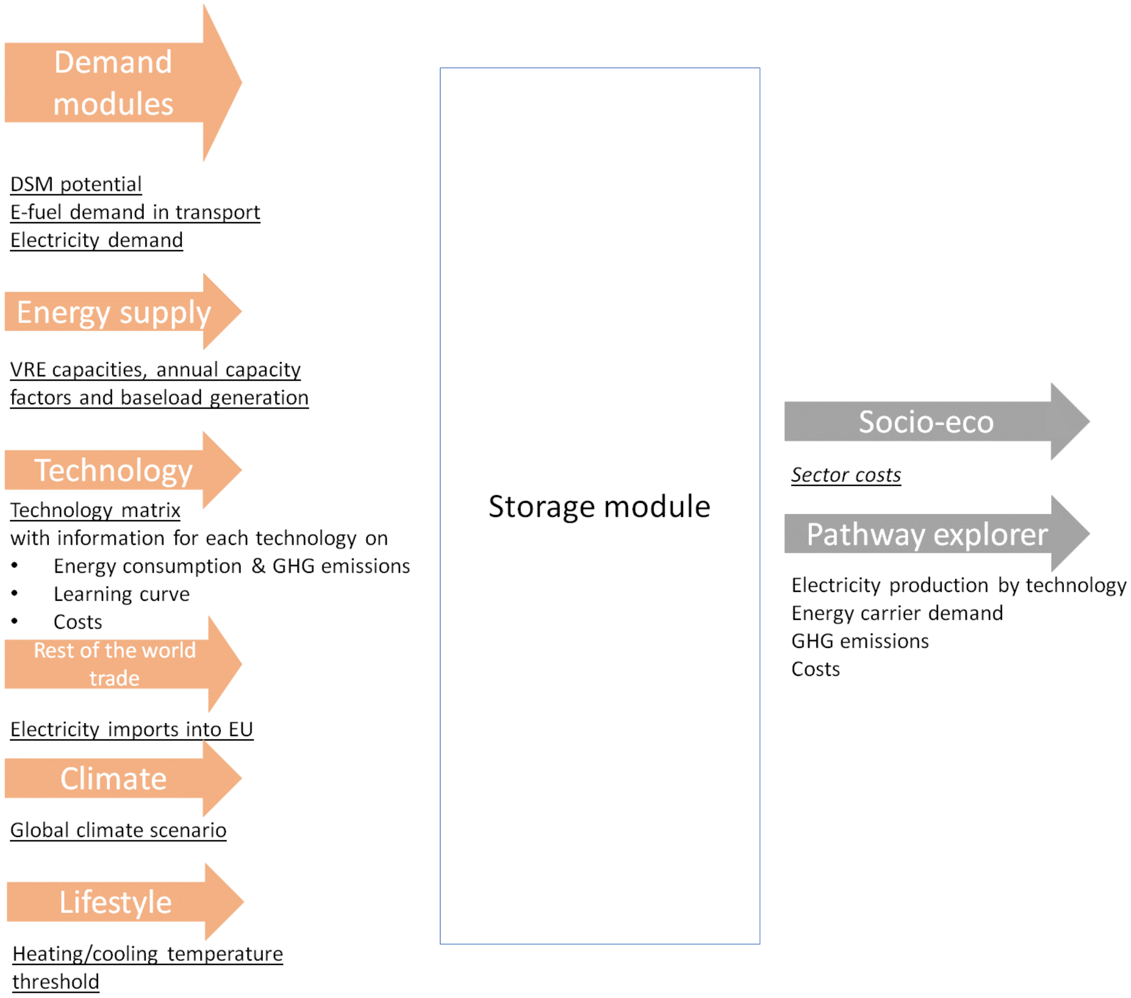

Figure 9 – Interactions of other modules with the storage module

4.4.1 Inputs

4.4.1.1 Energy supply

The module receives the VRE (wind and PV) capacities in the generation mix, annual capacity factors, as well as electricity production from the other capacities considered as baseload production as complementary to the residual load curves generation in later steps.

4.4.1.2 Demand side modules

Demand side modules provide the annual sectorial aggregated electricity demand, however, which in case of two sectors, buildings and transport, is broken down further to sub-sectors in order to capture the daily, weekly and seasonal patterns of electricity consumption when generating residual load curves. The daily and weekly routine of society leads to typical load profiles in the residential and commercial sectors that are considered in creating yearly load curves. In addition to these load curves, as indicated by Bossmann and Staffell (2015) the main measures on the demand side that cause changes in electricity use patterns are electric vehicles and heat pumps. In order to capture those effects, the electricity demand from buildings and transport is received as follows:

- electricity demand from road transportation,
- electricity demand from rail transportation,
- electricity demand in non-residential buildings,
- electricity demand from residential appliances, cooking and lighting,
- electricity demand from residential cooling,
- electricity demand from residential hot water and heating.

Those electricity demands are used to shape the hourly electricity demand curves as described in the calculation chapter. The demand from other sectors are considered in even distribution through the year.

Additionally, each demand side module provides the potential for DSM on the three timescales (weekly, daily, sub-daily) in order to integrate that potential into the flexibility needs. The main objective of DSM actions to shift and smooth the demand profiles. DSM describes the amount of power that can be actively managed on the demand side and not needed action from a power plants perspective to balance demand side fluctuation. The DSM value includes various demand side management tools, such as coordinated charging electric of vehicles where the DSM potential value is the amount of power that the batteries of cars can provide to the grid, or smart home solutions, for example when a home itself can shift loads (i.e. turning on schedulable devices, such as washing machines). Therefore, DSM potential ideally should be embedded and linked into demand side lever choices, as actions leading towards decarbonization on the demand side significantly influence load profiles.

Noteworthy, that household scale batteries are not recognized as DSM, as they are assumed to be available for the gird, and thus included in the battery capacity values used in the lever of this module.

4.4.1.3 Transport

Additionally to DSM (expressed as storage capacities of electric vehicles), e-fuel demand from transport is also provided as input.

4.4.1.4 Technology

The technology module provides the following parameters for the technologies considered within the module:

- investment cost (CAPEX) as €/kW,
- operation and maintenance cost (O&M) without fuel cost as €/kWh,
- lifespan of technologies,
- emission factors for the fossil fuel-based technologies expressed as the amount CO_2 emitted per input calorific value.

4.4.1.5 CCUS

Annual electricity demand from carbon capture and storage and utilisation is coming directly to the storage module to prevent feedback loop with the supply module (source of captured CO_2). This electricity demand is not due to the increased self-consumption caused by carbon capture (which is considered in the supply module) but the energy needs for carbon storage and utilization as implemented in the CCUS module.

4.4.1.6 Lifestyle

Lifestyle provides the temperature threshold when heating/cooling is switched on. This is needed for the hourly electricity profiles of heating and cooling in buildings.

4.4.1.7 Climate

The actual chosen global climate scenarios is obtained from the climate module in order to consider the impact of climate change on VRE. Based on this input, the hourly capacity factors are adjusted by parameters estimated by Tobin et al. (2018).

4.4.1.8 EU Rest of the World Trade Module

The module receives data about net electricity imports between EU and the rest of the world on yearly granularity.

4.4.2 Outputs

4.4.2.1 Economic sector costs

The module provides sector-based economic variables to the relevant module.

4.4.2.2 Pathway explorer

The pathway explorer receives the balancing adjusted electricity production data per technology, energy demand per carrier, GHG emissions and overall costs from the storage requirement module.

4.5 Detailed calculation tree

The calculation tree presented hereafter represents steps one to eight of Figure 6. In the subsections of this chapter, each calculation step is detailed throughout the process. As table 5 shows, steps are carried out on country or trading zone levels.

Table 5 – Geographical resolution of calculations within the module and their justification

Step*	Calculation	Resolution	Justification
0	Supply-demand matching	trading zone	
1	Creating demand curves from load profiles	calculated on country level, then aggregated on trading zone level	to account for differences in demands (i.e., for example, due to climatic conditions in case of heating/cooling)
2	Creating electricity production curves	calculated on country level, then aggregated on trading zone level	to account for the climatic differences influencing PV and wind power generation, as expressed through the capacity factors
3	Calculating flexibility needs based on residual load curves	trading zone level	long term EU energy policy encourages cross-border measures and balancing
4	Assigning flexibility technologies	trading zone level	
5	Allocation of capacities	country level	to complement the country level electricity generation mix
6	Final electricity, emissions and fuel use outputs	country level	important to project emission trajectories for each country
7	Cost calculation	country level	

*with reference to Figure 6

4.5.1 Step 0 – Supply-demand matching on annul level

The aim of this step is to compute and fill up the annual electricity supply-demand gaps on trading zone level. First, the annual electricity supply-demand gap is calculated and adjusted with the EU – rest of the World trading balance. For the gap calculation, to keep it consistent with the flexibility needs calculation, production is subtracted from demand.

The relation of EU28 plus Switzerland is analysed to the rest of the world and annual net import balances are calculated for multiple commodities including electricity. In order to consider the trade between EU and rest of the world, the annual net import electricity value is allocated to interconnector capacities to non-EU countries. Historical values and future projections are for the net import value are provided through the EUCalc – GTAP model integration.

4.5.1.1 Electricity trade within EU

After that, having aggregated the annual demand and supply values at the trading zone level, and adjusted with rest of the world trade balance, the module determines whether a region is in a net exporter or in a net importer position. This is the starting point to allocate excess electricity from exporting regions to regions where demand is higher than production.

In the model the exporter regions export electricity with their neighbouring trading zones. The model starts the exporting with the region which has the lowest number of transmission connection and moving toward the most complex regions. If an exporter region is connected to two importing regions, exports are oriented to the region where the demand and supply gap is the largest, thereby mimicking how the pricing mechanism would work in practice. If there are two regions with the same number of connections and they have the same neighbour too, that region will trade first with common neighbour who has a larger interconnection capacity with it. At the end of the process all exporter region gives excess electricity to the importers. In the calculation the maximum cross-zone capacity factors are taken in consideration. In order to avoid endless loops in the algorithm, an originally exporter region is not allowed to import in a later stage of a run.

The interconnection capacities for the 2015 base year were collected from ACER's 2016 publication (ACER, 2016), reflecting the aggregated net transfer capacities (NTC) between regions as of 2015 shown on Figure 10. Net transfer capacities are defined as the difference between the Total Transferable Capacities and the Transmission Reliability Margin, thereby truly capturing the usable capacity of a transmission line.

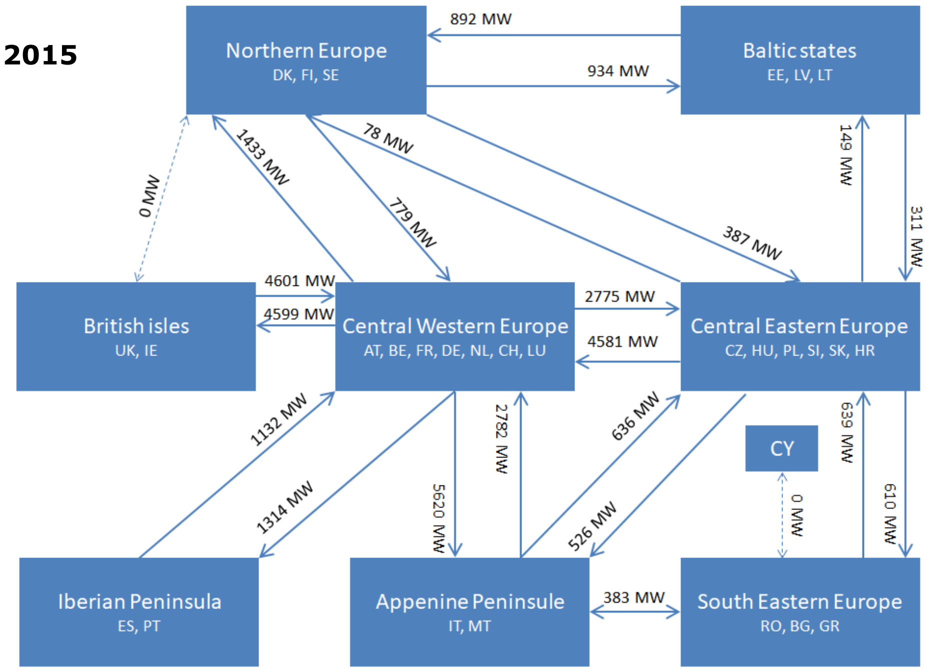

Figure 10 – Schematic model of country aggregates in the storage module to allocate exports from an oversupplying region to a region in need of imports in 2015

In order to include the existing plans for the expansion and intensification of cross-border electricity trade, the Regional Investment Plans (ENTSO-E, 2017a-f) for the regions were used. These investment plans detail near term expansion projects that are already included in the Ten-Year Network Development plans, however, also taking into account longer term investments up to 2040. The Regional Investment Plans give a summary about cross-border net transfer capacities in relation to every country within a region, from which it was easy to conclude the cross-border NTC values for the regional aggregation of the module. Although the Regional Investment Plans only list projects that are planned until 2040, the module argues that it is a good approximation to consider 2040 values as 2050 values in the module, as transmission network developments are increasingly contested investments and therefore are difficult to execute, likely will be subject to delays.

For the cross-border capacities development, the Global Climate Action scenario of ENTSO-E was considered, as that is the one where it is envisaged that the EU reaches its 2050 climate goals. Based on this, the module includes the changes of the available transfer capacities between regions from 2015 to 2050. Interim values are determined by interpolation, with changes in the capacity occurring in steps of up to 700-1000 MW, which is the average range for transmission network capacity increases. Figure 11 summarises the expected 2050 state of the European electricity transmission network. Note the large capacity increases along basically all exchange corridors, and the new connection from Northern Europe to the British Isles, and the connection of Cyprus to South Eastern Europe. Finally, the module considers that cross-border interconnectors have a maximum capacity factor of 85%, which is the value that the most used interconnectors are approaching in Europe.

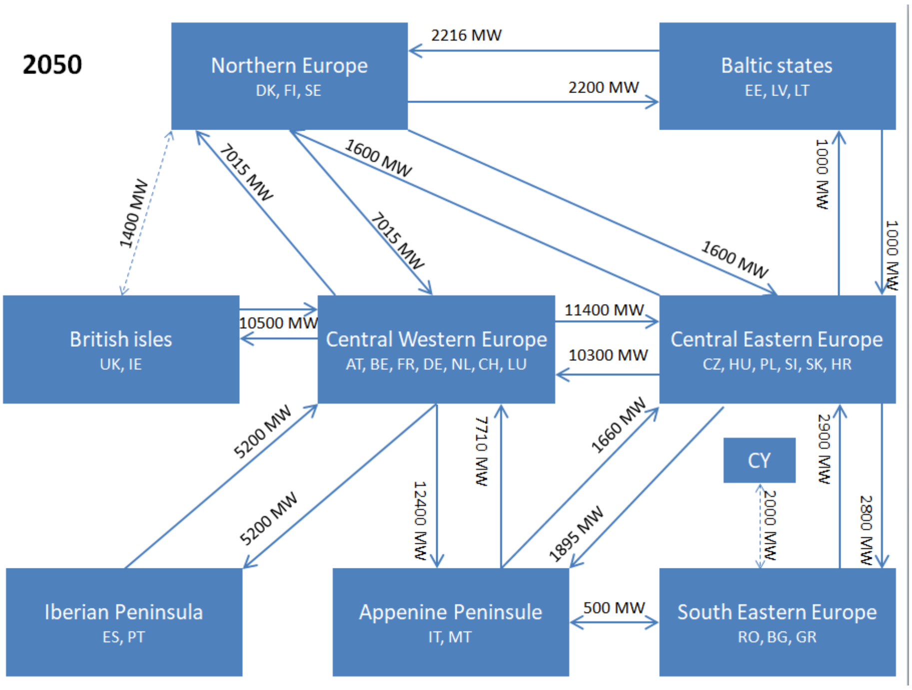

Figure 11 – Schematic model of country aggregates in the storage module to allocate exports from an oversupplying region to a region in need of imports in 2050

Aligned with the time scale of the whole EUCalc model, for each fifth year the cross-border transmission NTC values are included in the modelling using the above interpolation.

4.5.1.2 Supply-demand matching

After considering trade, the trade adjusted supply-demand gap is closed on trading zone level. If there is deficit then the capacity factor of the existing natural gas based capacities is increased to the maximum of 85% (IEA, 2015), and additional new natural gas based capacities are proposed if there is still deficit remaining.

In case of excess, first – aligned with decarbonisation objectives – the capacity factor of coal based power plants is decreased even down to zero. This managed on trading zone level but equally in the included countries. If there is still excess the lever dependent PtX capacities are considered for hydrogen production to meet e-fuel demand. The produced hydrogen is the basis for the further synthesis of e-fuels. E-fuels are defined as gaseous and liquid fuels such as hydrogen, methane, synthetic petrol, and diesel fuels generated from renewable electricity (Siegmund et al., 2017). Their most important feature, however, is that hydrogen is the basis for their production.

In the module, the maximum available PtX capacity for the flexibility uses is determined by lever setting. This applied capacity is shared between two different uses of PtX. First the available capacity produces as power-to-fuel to respond the hydrogen and associated e-fuel demand coming from the transport module. In Step 0, it is assumed that the PtX capacities are operating in open cycle mode, which means that the output of PtX is directed immediately to e-fuel production, the produced hydrogen is not stored. This also means that in Step 0, the installed capacities of PtX are capable of operating continuously throughout the year. If the excess or PtX capacity is not sufficient to meet e-fuel demand a warning will be issued.

If there is still idle PtX capacity after this, it is used in the flexibility needs calculation later in Step 4. It can happen that excess is still remaining on annual level, which is mainly due to the VRE contribution. This excess is not managed here, as VRE has high fluctuation that can be captured and managed by flexibility solutions only in higher time granularity.

Nevertheless, there could be lever settings in the whole EUCalc model leading to such oversupply where electricity supply and demand matching is not possible or not giving plausible outcomes due to high risk of unnecessary investments and stranded assets. Therefore, regardless the automatic adjustment of supply, flag is issued in the pathway explorer that there are unnecessary overcapacities, thus, prompting the user to adjust levers to avoid stranded assets.

The calculations in step 0 are shown in figure 12.

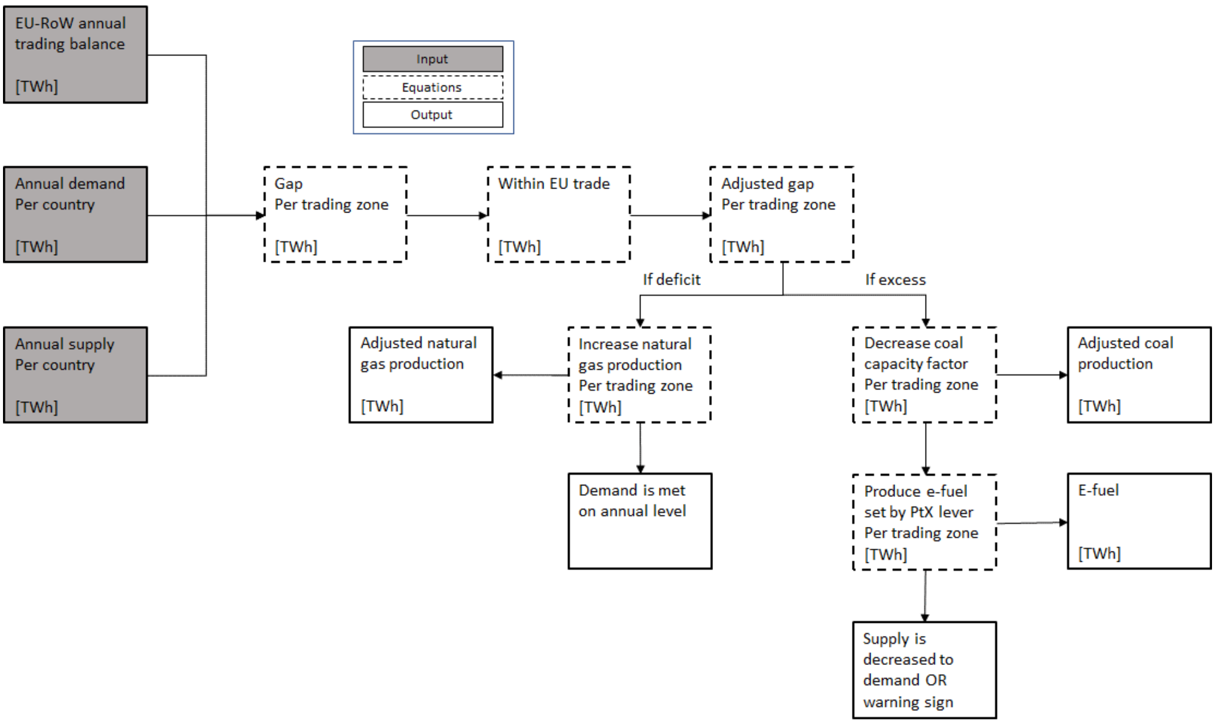

Figure 12 – Detailed calculations of step 0

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4.5.2 Step 1 – Creating load curves from load profiles

Hourly electricity demand curve is calculated from the sectoral annual electricity demands by the method used in the DESSTINEE model[6] using few typical daily load profiles of 24 values to generate load curves of 8760 values, as shown on figure 13.

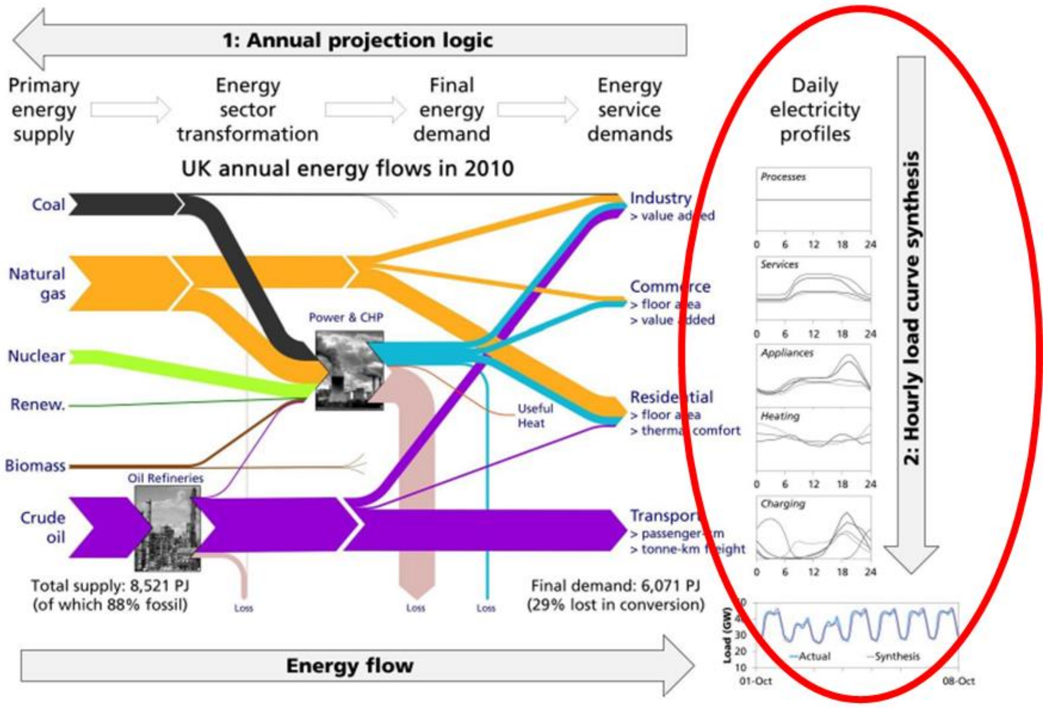


Figure 13 – Logic of the DESTINEE model noting the synthesis of load curve from load profiles

Building and transport sectors are described by 8 typical load profiles in the DESSTINEE environment and we use those profiles in this module. Electricity demand in sectors without typical load patterns is also considered by using flat load profiles (i.e. even distribution of demand through the year).

For the building sector the following typical load profiles (equal to 24 data points as hourly need for electricity) are used from the DESSTINEE and applied on the annual respective sub-sectoral demand:

- commercial sector, summer weekday,
- commercial sector, summer weekend,
- commercial sector, winter weekday,
- commercial sector, winter weekend,
- residential sector, summer weekday,

---

[6] The DESSTINEE model, similar to EUCalc, uses a predictive simulation technique, rather than solving a partial or general equilibrium. Data is therefore specified by the user (exogenously), and the model calculates a set of answers for the given set of assumptions. The DESSTINEE model written in Excel and VBA is available (at https://sites.google.com/site/2050desstinee/getting-the-model) as a set of standalone Excel spreadsheets which perform three tasks:

- Project annual energy demands at country-level to 2050;
- Synthesise hourly profiles for electricity demand in 2010 and 2050;
- Simulate the least-cost generation and the transmission of electricity around the continent.

- residential sector, summer weekend
- residential sector, winter weekday,
- residential sector, winter weekend,

For the transport sector the following typical load profiles (equal to 24 data points as hourly need for electricity) are used from the DESSTINEE and applied on the annual respective sub-sectoral demand:

- road transport, summer weekday,
- road transport, summer weekend,
- road transport, winter weekday,
- road transport, winter weekend,
- rail transport, summer weekday,
- rail transport, summer weekend,
- rail transport, winter weekday,
- rail transport, winter weekend,

Moreover, the load profiles of road transport are influenced by the 'Charging patterns of EVs' lever setting that defines how the electric vehicle stock is charged, as explained in more detail in chapter 5.

It is important to mention that the sum demand from the above load profiles matches the annual electricity demand from the building module in order to keep the modelling consistent.

From the above profiles country level demand curves are generated by considering country specific factors (considering time zones, different daily routines and public holidays), heating and cooling threshold values, as well as hourly temperature profile for the base year (from NASA MERRA 2 database) adjusted with climate change impacts.

As output, the annual, 8760 values of the load curve are synthetized per country, which is then aggregated on trading zone level. The 8760 datapoints representing the load curve are equal to the hourly electricity demand of a given hour. The calculation in step 1 is summarized in Figure 14.

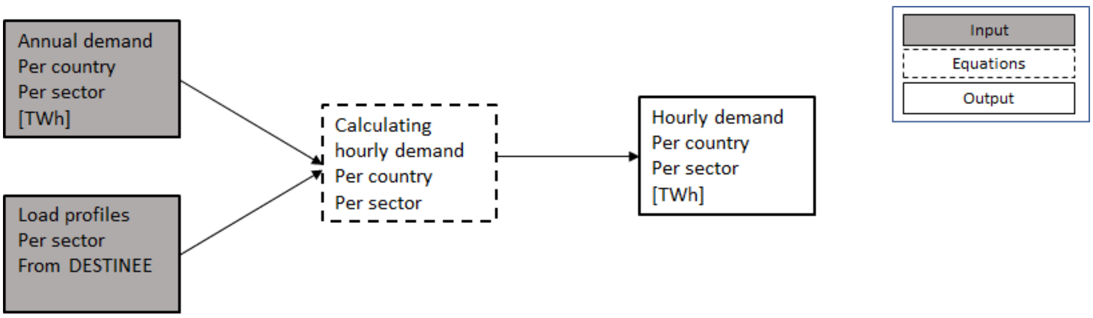


Figure 14 – Detailed calculation logic of step 1

4.5.3 Step 2 – Creating electricity production curves

Similarly to the demand curve, production curve is also prepared by applying two approaches depending on the nature of the production technology.

For PV and wind (separately on- and off-shore), in order to consider their intermittency, the hourly production is obtained by using hourly capacity factor (CF) values as described in equation 1; all obtained from renewables.ninja (of which data and details are in Pfenninger and Staffell, 2016 and Staffell and Pfenninger, 2016) multiplied by the capacities for that year to calculate hourly production.

Equation 1 – obtaining intermittent VRE production

$$VRE_{hour\ n}^{country}[GWh] = \left(CF_{hour\ n}^{on\ wind} \cdot GW_{year}^{on\ wind} + CF_{hour\ n}^{off\ wind} \cdot GW_{year}^{off\ wind} + CF_{hour\ n}^{PV} \cdot GW_{year}^{PV}\right) \cdot 1hour$$

The renewables capacity factors for the base year (2015) are corrected by the future impact of climate change based on the input lever choice from the climate module. Tobin et al. (2018) assessed the impacts of climate change on wind and solar photovoltaic (among others) power generation in Europe resulting in changes of power generation at different global warming scenarios: +1.5 °C, +2 °C and +3 °C. Based on the climate change scenario selection, i.e. when +1.5 °C and +2 °C are reached globally, we adjust the capacity factor with the changes (for exact values see chapter 6) found by Tobin et al.

VRE is complemented by the hourly production of the base load power plants of which productions are distributed evenly to the hours. In the next steps we are using the production curve to calculate the residual load curve, which is by definition (Andrey et al., 2017) is the load that has to be served by dispatchable technologies. It is computed by subtracting the wind, solar and must-run generation from the demand. Thus, the production technologies we are adjusting (either up or down regulation) to meet the flexibility needs are not included in the production curve.

Given the example of Germany, with randomly chosen summer and winter months production curves from 2015 as shown in Figure 15, we are considering hydro, biomass and nuclear as baseload and thus distributed evenly for the production curve, whereas as production of coal and natural gas are changing, we exclude them from this calculation as subject for further adjustment to meet flexibility needs.

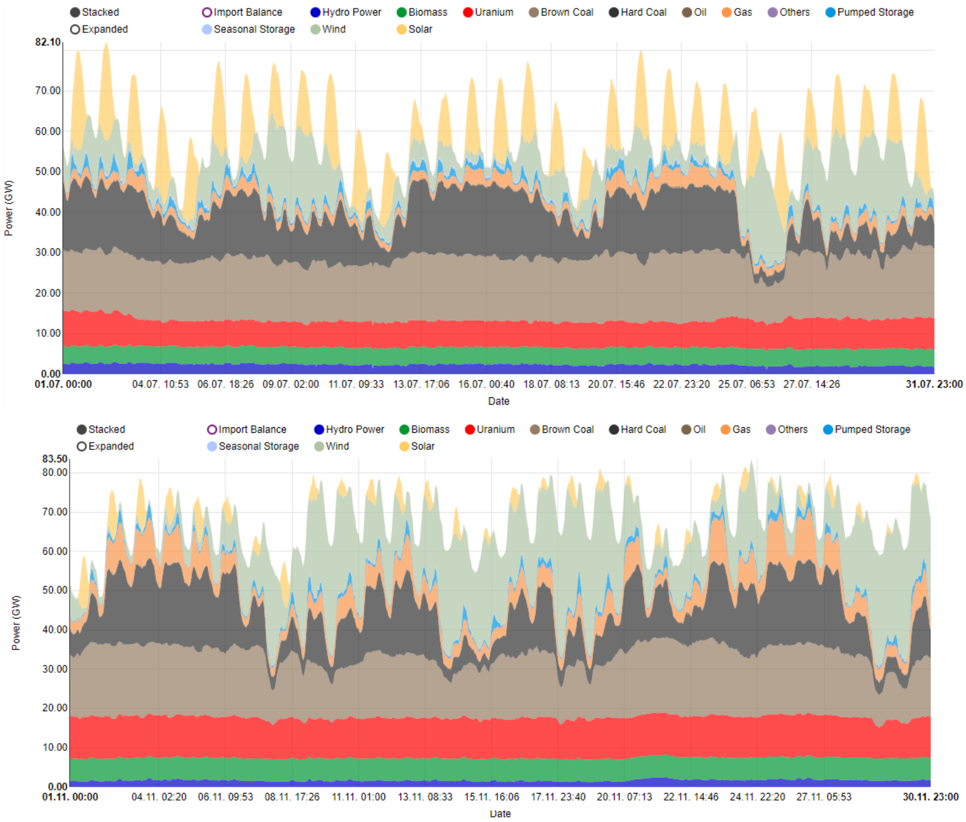


Figure 15 - Electricity production in Germany in July and November of 2015, source: https://www.energy-charts.de/power.htm

Figure 16 summarizes the calculations within this step. VRE is calculated on country level using country level hourly capacity factors and then aggregated to trading zone level. Regional sum of baseload supply is disaggregated directly on trading zone level to hourly resolution.

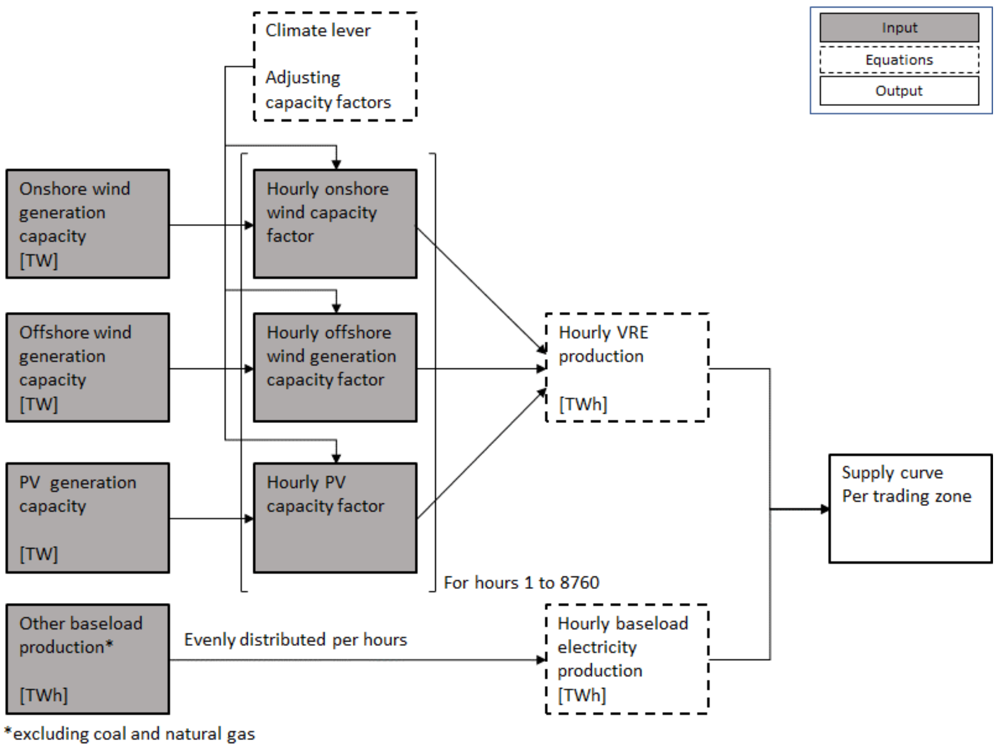


Figure 16 – Detailed calculation logic of step 2

4.5.4 Step 3 – Calculating flexibility needs based on residual load curve

Due to perfect competition within the trading zones, as well as cross-border use of PHS units, the residual load curve and the flexibility needs are calculated on trading zones level. Applying the definition of Andrey et al., 2017 the hourly production of wind, solar and non-adjusted baseload (output of step 2) is subtracted from the hourly demand curve (output of step 1). As result, shown on Figure 17, these new 8760 datapoints create the hourly resolution residual load curve per trading zone. If the sign of the curve is positive then extra electricity is needed to meet demand, if negative there is excess electricity.

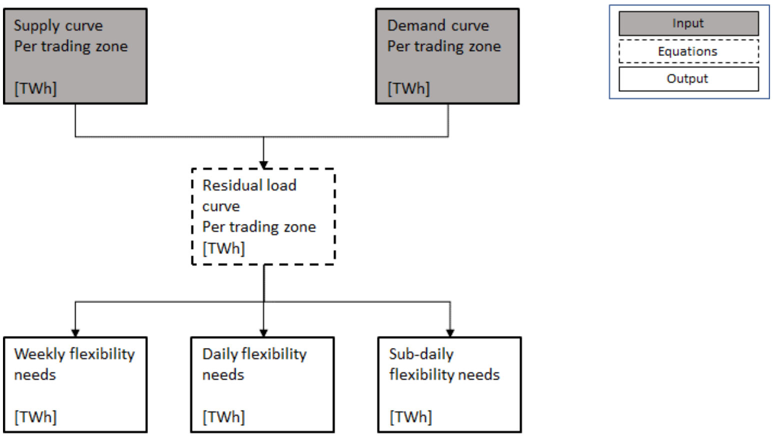


Figure 17 – Detailed calculation logic of step 3

From these hourly residual load values, we assessed flexibility needs based on the metrics by the French transmission system operator RTE (RTE, 2017). This methodology was also applied in several studies ordered by the European Commission applying the METIS framework[7] (see Andrey et al., 2017 and Bossmann et al., 2018). These metrics are calculated on the basis of the residual load and facilitate the understanding of the extent to which rising VRE shares increase these needs.

In this context, flexibility is defined as the ability of the power system to cope with the variability of the residual load curve at all times. Responding to these needs would lead to a fully smoothened net load that could be fully satisfied by baseload capacities. A large number of technical solutions exist to respond to flexibility needs at different time scales. Hence, flexibility needs are likewise distinguished regarding the time horizon. Aligned with the RTE methodology and the above studies, we distinguish flexibility needs on different timescales (Bossmann et al., 2018).

Each timescale is derived from the hourly residual load curve as described herein. As in the next step, when assigning flexibility solutions to the needs, we manage timescales separately and do not carry on flexibility needs between timescales, we adjusted the original calculations in order to prevent double counting, as follows:

[7] METIS is a mathematical model providing analysis of the European energy system for electricity, gas and heat. It simulates the operation of energy systems and markets on an hourly basis over a year, while also factoring in uncertainties like weather variations. METIS is used by the European Commission to further support its evidence-based policy making, for electricity and gas

1. Weekly flexibility need is based on the difference between annual average and respective weekly averages. The positive differences are summed up over the year and defined as the weekly flexibility need.
2. Daily flexibility needs are based on the difference between the daily average of (the hourly residual load curve minus the weekly flexibility need for each hour) and the respective weekly average. The positive differences are summed up per week and then over the year and defined as the daily flexibility need.
3. Sub-daily flexibility needs are based on the difference between the hourly residual load curve minus weekly flexibility need for each hour minus daily flexibility need for each hour. The positive differences are summed up per day and then over the year and defined as the sub-daily flexibility need.

Once we defined the flexibility needs per period the aim is to flatten out the residual load curve around averages of different timescales in order to consider the different features of storage technologies. If the residual load were to be flat (i.e. the average over a period), no flexibility would be required from the dispatchable units. Indeed, in such a situation, the residual demand could be met by baseload units with a constant power output during the whole period. In other words, a flat residual load does not require any flexibility to be provided by dispatchable technologies (Ardeley et al., 2017).

Note that due to the fact that natural gas and coal are not included in the residual curve calculation, the sum of the different periodic averages are not zero (there is no supply-demand balance) but value of the annual average. The annual average of the residual load curve over the year is equal to the gap from step 0. In case it was deficit, the adjusted natural gas and coal based productions need to be considered as minimum values to keep the balance.

4.5.5 Step 4 – Assigning flexibility solutions to the needs

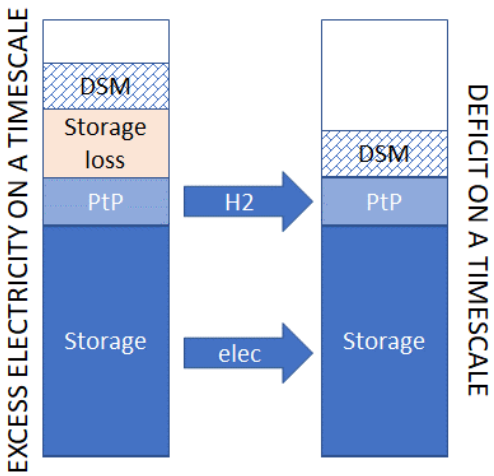
This chapter introduces the approach of allocating the annual total flexibility needs to a set of certain technologies. The following principles are applied in this calculation step:

1. We tackle each timescale sequentially, until the deficit (positive differences) is not filled.
2. This means also that there is no carry on of flexibility needs between timescales, each timescale is calculated separately following each other.
3. For each timescale, we consider that the stored energy and DSM are available at any moment.

In order to find the equilibrium a portfolio of flexibility solutions is included in the analysis with the basic calculation approach introduced here. Basically, there are two ways to reach supply-demand balance: either by up or down regulation of the flexible production units (natural gas or coal in this calculation) or by shifting the sign of the difference by using storage (with accounting for process losses) or DSM. However, due to the definition of the residual load curve, the excess only includes production that cannot be down regulated (i.e. VRE or must-run). Thus, practically there is no option to decrease the excess by down regulation only to shift the production.

The key question of the calculation process if there is enough capacity that would allow shifting the excess to periods with deficit within the given timescale. If shifting the excess is completely possible that would mean zero carbon solution, otherwise the system still needs to rely on the ramp up of emitting natural gas based power plants.

This basic approach is shown on Figure 18 and applied at each of the three timescales with different sets of technologies, as explained after. Given the mathematical calculations yielding the flexibility needs, the positive and negative areas are equal. The priority is filling up the deficit in order to make supply-demand match in all minutes.

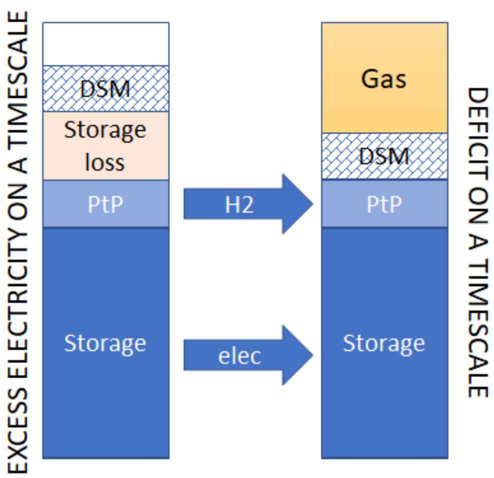


Influenced by lever settings the excess area or only a part of it is stored down allowing shifting the excess (left bar) to when there is deficit (right bar). The portfolio of storage technologies differs by timescale. Here, the part of PtX is used as power-to-gas-to-power that remained after meeting the e-fuel demand or using all the excess in step 0.

The amount of electricity the storage technologies used from the excess is limited by the next conditions:

1. application order of the technologies (different per timescale)
2. cap of the maximum available storage capacity of each technology influenced by lever setting

Or until all the excess is stored including losses.



The remaining deficit filled up by increasing the natural gas based production, first by existing capacities, then if not enough by adding new ones.

Figure 18 – General calculation sequence, performed on each timescale starting with the weekly timescale

This above sequence is performed for all the three timescales with considering the next technologies, as well as their limitations and contribution to the flexibility needs. This minimum and maximum values are defined by external conditions and could be understood as availability. As described above, the actual contribution to meeting the flexibility needs of a timescale can be between of these limits.

In meeting the needs, the order reflects the intention for decarbonisation as natural gas based flexibility is considered last, after all the low carbon technologies (i.e. storage for shifting the excess VRE production to other time periods) have been considered, i.e. locking out fossil fuels from the balancing.

While timescales are managed separately, figure 19 shows how the available production or storage capacities of the flexibility solutions are carried on. For solutions that are defined by lever (storage, PtX), the exploitation of the available capacities starts from the first timescale and the leftover carried on the next ones. For natural gas, the installed capacities and the production by them are limited by the maximal annual capacity factor, thus the available increase the natural gas power plants is set by the free available capacity factor up to the limit. Over the limit, new capacities are added in order to meet demand.

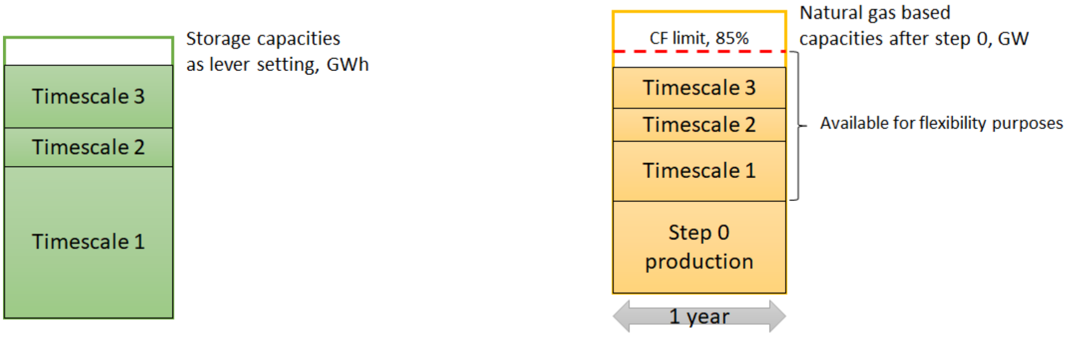
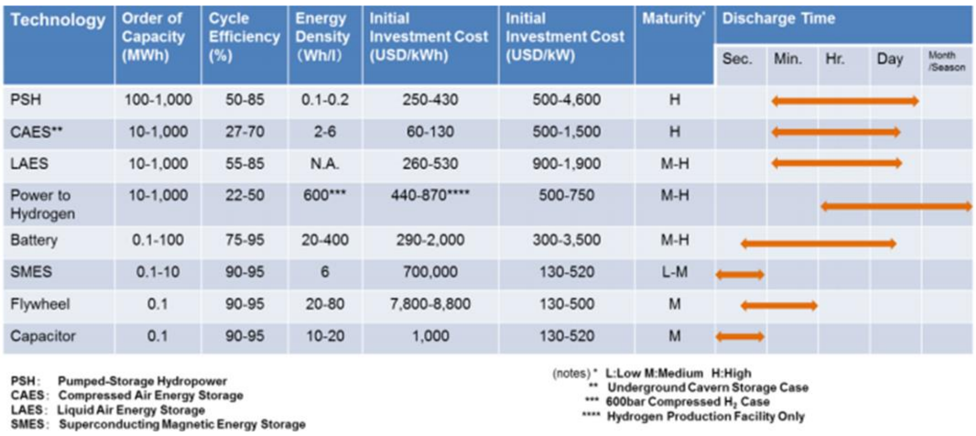


Figure 19 – Total potential for storage (left) and natural gas (right) and its carry-on between timescales, sizes are only illustrative

The exception from this is DSM for which the potential is defined separately for each timescale considering the differences from uses of electricity.

Given the characteristics of the EUCalc modelling (non-equilibrium and non-optimization modelling, allowing free choice to the user), the application of flexibility solutions per time zones based on their basic discharge time parameter, as shown on Figure 20 and Table 6. Policy measures, market conditions and economic factors, in reality, can influence more the application fields than solely the technical parameters. However, as general the EUCalc model, the user can experiment freely with different storage conditions influenced by lever setting.



Technology	Order of Capacity (MWh)	Cycle Efficiency (%)	Energy Density (Wh/l)	Initial Investment Cost (USD/kWh)	Initial Investment Cost (USD/kW)	Maturity*	Discharge Time				
							Sec.	Min.	Hr.	Day	Month /Season
PSH	100-1,000	50-85	0.1-0.2	250-430	500-4,600	H					
CAES**	10-1,000	27-70	2-6	60-130	500-1,500	H					
LAES	10-1,000	55-85	N.A.	260-530	900-1,900	M-H					
Power to Hydrogen	10-1,000	22-50	600***	440-870****	500-750	M-H					
Battery	0.1-100	75-95	20-400	290-2,000	300-3,500	M-H					
SMES	0.1-10	90-95	6	700,000	130-520	L-M					
Flywheel	0.1	90-95	20-80	7,800-8,800	130-500	M					
Capacitor	0.1	90-95	10-20	1,000	130-520	M					

PSH: Pumped-Storage Hydropower
CAES: Compressed Air Energy Storage
LAES: Liquid Air Energy Storage
SMES: Superconducting Magnetic Energy Storage

(notes) * L:Low M:Medium H:High
** Underground Cavern Storage Case
*** 600bar Compressed H_2 Case
**** Hydrogen Production Facility Only

Figure 20 – Basic characteristics of storage technologies,
LAES, SMES and capacitors are not considered in EUCalc. Source: ICEF, 2017

Table 6 – Application of flexibility solutions per timescales in the EUCalc model

	Natural gas	PtX	PHS	CAES	Battery	Fly-wheel	DSM
Sub-daily	x				x	x	x
Daily	x		x	x			x
Weekly	x	x	x				x

4.5.5.1 Demand side management (DSM)

Demand-side management, is a category of technologies that allow the demand-side to intentionally modify its consumption in response to price signals or other incentives from grid operators. Demand-response can be deployed in a number of sectors, among which the industrial, residential and transport sectors are probably the ones with the largest potentials. The potential role that demand-response can play at the Member State level mostly depends on the structure of the local industry, on the foreseen deployment of electric vehicles, and on the deployment of smart meters, which are required in order to provide price signals to the residential and commercial sectors (dynamic pricing) and to validate flexible demand-response transactions (Andrey et al, 2017).

In the module, we consider DSM as load shifting when the demand is shifted or delayed to another period depending on the supply situation. The potential is DSM is defined by the demand side modules for each of the timescales and is an input for the module. Similarly to the other load shifting technologies, it depends on the actual residual load curve if the potential is fully utilized or not. We do not assume losses in the DSM process, meaning that the same amount that is removed from the excess can be switched to fill deficit.

As DSM potential defined separately per timescales, this has the first priority to shift between excess and deficit in order to secure fullest exploitation and leave better share among timescales for the other solutions.

4.5.5.2 Power-to-X (PtX)

PtX is the process of converting the surplus power to different types of hydrogen based energy carriers for use across multiple sectors, or to be reconverted back into power. It has the potential to greatly increase the flexibility of the power grid. It represents an optional place to put the temporary surplus of power from VRE and reduces carbon by displacing fossil fuel energy sources in other sectors (IRENA, 2019).

In the module, the maximum available PtX capacity for the flexibility uses is determined by lever setting. First, in step 0 this is used to meet hydrogen based e-fuel demand or up to the amount of excess, and the remaining PtX capacity is used in power-to-gas-to-power mode, where the generated energy carrier is converted back to power to reduce deficit. Practically this means that while in Step 0 PtX units are operating in open cycle mode, in Step 4 the units are operating in closed cycle. Therefore, in Step 4, a discharge and charge time is taken into consideration for PtX, which resembles the storage capacity of the hydrogen tanks of PtX units. The detailed calculation methodology for PtX is found in section 5.6.2.

In filling the flexibility needs PtX is second in the order, as its application (and thus exploitation of the capacity by lever) is only limited for one timescale.

4.5.5.3 Storage

Storage is a very versatile technology that can provide a wide range of applications. As a flexibility solution, it can store excess energy for later use. Depending on the discharge time of the considered storage technology (energy to capacity ratio), a given unit can provide sub-hourly regulation services and/or arbitrage services (e.g. by storing the excess PV and feeding it back into the grid during evening peak demand episodes). Next to regulation and arbitrage services, storage flexibility solutions can also provide voltage regulation services, black start services, avoid or delay network reinforcements by managing congestions, and capacity value by lowering the need for investments in conventional generation units (Ardeley et al., 2017). The scope of modelling includes the regulation services of the storage solutions.

Storage technologies in the EUCalc model include PHS (for weekly and daily flexibility needs), CAES (for daily needs) as well as flywheels and batteries (both for sub-daily flexibility purposes). While the potential of flywheels, batteries and CAES are not limited by geographical conditions, the deployment of storage with longer discharge times is mainly limited by the Member State level potential to host PHS (Ardeley et al., 2017). These potentials are considered in the level definitions.

Annual storage capacities for all the four technologies are defined through one lever, as setting the storage portfolio that defines the total year storage capacity calculated based on cycle times as described in a later chapter. That means the storage technologies for the same timescale are considered together and by equal proportion compared to the maximum available value (i.e. if there are two storage technologies for a timescale, then both use their maximum amount to the same percentages).

4.5.5.4 Flexible generation

Natural gas can serve as backup for situations when VRE production is low. Given their continuous availability throughout the year, they may reply to flexibility needs from hourly to annual scales (Bossmann et al., 2018).

As electricity production by natural gas is not included in the residual load curve, the starting point for their inclusion into meeting the flexibility needs is its production after step 0. With considering a maximum capacity factor (85% by IEA, 2015) the available production from those existing units can be calculated and carried on through the timescales, or if exploited new units are added. These new capacities are in the system for their lifetime, thus in the next time steps (i.e. after five years), they are considered in step 0. As addition of new natural gas based capacities is not bound by system limitations or other boundaries, it will fill up the deficit.

4.5.6 Step 5 – Disaggregation of capacities to individual countries

The previous steps define the total annual storage capacity used by each technology. In Step 6, the module first determines how much of the storage capacity set by the lever is located in each trading zone. In the case of PHS, the topographical characteristics and country-level analysis determines how much of the technology in each region can develop, if any. Table 15 lists the annual storage capacities of PHS in each trading zone.

Disaggregating all other storage technologies to the trading zone level is based on input from the supply module. The storage module uses the residual load concept to assess annual needs for storage at different timescales, therefore the disaggregation of the non-PHS technologies is based on the share of VRE generation capacity in the trading zone compared to the overall (EU-28 plus Switzerland) VRE generation capacities. This approach is underpinned by the fact that storage capacities are needed in regions where the VRE penetration is the highest. Furthermore, with this approach, the storage capacities in each trading zone can follow the lever setting in the supply module (low wind with high PV and various combinations), thereby truly responding to needs. On the other hand, it is also good to focus on generation capacities (GW) as opposed to the output of RES-E technologies (GWh) as balancing markets are exclusively focusing on available capacities to replace missing ones. To give an example, the disaggregation would work as follows: in 2020 the Baltic region has 8% of wind and PV generation capacity (GW) among all regions, thus 8% of the EU28+CH level non-PHS storage capacity (Table 14) would be located in the region.

In order to get the necessary physical (investments) units (defined as rated power, P) for storage technologies as an output of the model and as basis for cost calculation, equation 2 is used.

Equation 2 – Obtaining rated power from annual stored volume

$$P_{technology\,[GW]} = annual\ storage\ volume_{technology}\ [GWh] \cdot \frac{8760}{2 \cdot cycletime_{technology}[hour]}$$

The cycle times are considered as constants and detailed in chapter 6.

Having determined the needed electricity storage units to be installed, the module allocates these capacities and the new natural gas based ones to the countries included in EUCalc.

Allocation of the capacities to the country level from trading zone levels happens two ways, also shown on figure 21:

- in case of technologies where the geographical conditions define the potential per country (PHS), the units are shared accordingly as defined in the lever – for PHS which already exists in large scale new units are only added of exceeding the annual storage volume in the given trading zone;
- in case of technologies not dependent on geographical conditions (natural gas power plants, batteries, flywheels and CAES), the capacities are allocated based on the ratio of annual supply-demand gap of the country to the total trading zone level annual supply-demand gap.

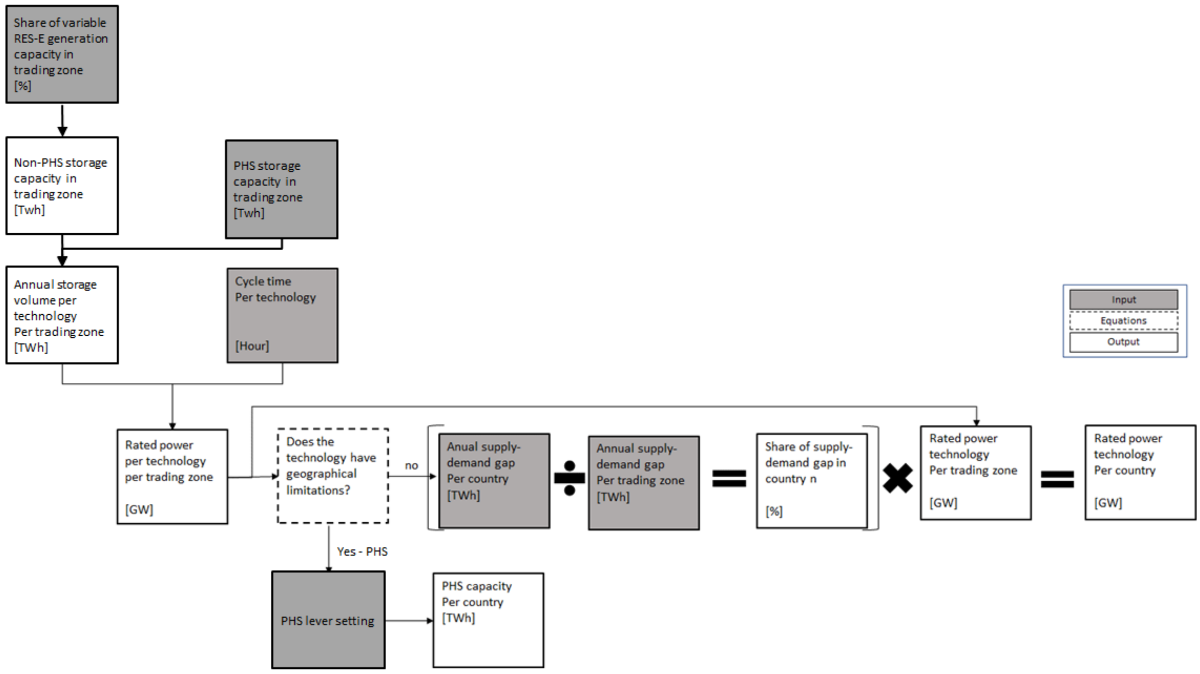


Figure 21 – Detailed calculation logic of step 6

4.5.7 Step 6 – Finalising variable flows between modules

As the above calculation may change the annual electricity production per technology per country as calculated in the supply module, and in order to prevent feedback loop, the supply module will forward all the annual electricity production values and associated emissions and fuel inputs per technology per country solely to the storage module which – after adjusting it for balancing and supply-demand matching – will forward the final data to the Transition Pathway Explorer, shown on figure 22. These changes are associated to the changes in the capacity factor values influencing not only the produced electricity but the used fuel input and produced emissions.

Eventual curtailment and/or adjustments of capacity factors do not influence lever settings in the supply module as the chosen capacities are there in the system and functional but for certain hours of the year only working with reduced or increased power output.

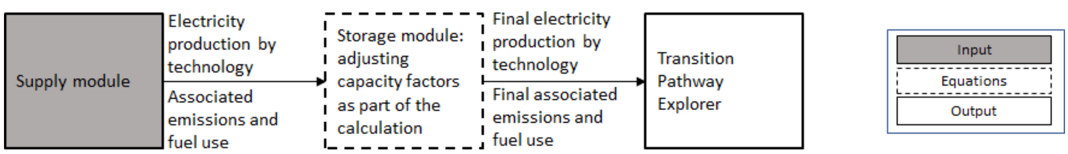


Figure 22 – Detailed calculation logic of step 6

4.5.8 Step 7 – Determining cost of electricity

As the storage module alters electricity production and adds additional capacities and technologies, the cost of electricity is calculated here but also considering the other technologies from supply module of which production is not affected by the storage calculation mechanism.

Similar to other modules, costs are calculation is linked to the technology module. The cost calculation uses unit costs for technology CAPEX and OPEX from the technology database. The evolution of those unit costs is expressed by applying a learning rate, i.e. the reduction of the cost as the installed capacity doubles. For fossil fuel based electricity production technologies and nuclear power plant, no learning rate was assumed but a trajectory between fixed CAPEX and OPEX cost in 2015 and 2050. The unit costs then are multiplied by the actual capacities or production. Same is applied for the fuel costs where the unit costs of fuels are imported to the model. All unit costs are expressed in 2015 EUR.

From those values the cost of electricity production (COE) is defined based on the next components. The components of the costs for a given year are the total CAPEX, total OPEX and total fuel costs which are summed up and divided by the sum of electricity produced. This calculation is performed by equation 3 for each country and time period.

Equation 3 – Cost of electricity production calculation

$$COE\left[\frac{EUR}{kWh}\right]=\frac{\sum_{i=1}^{tech\,n} O\&M_{tech}+\sum_{i=1}^{fuel\,n} fuel\ cost_{fuel}+\sum_{i=1}^{tech\,n} CAPEX_{tech}}{total\ electricity\ produced}$$

However, while OPEX and fuel costs are actual costs for the year, the total CAPEX in a given year is not reflected fully in the costs as it is distributed through the whole lifetime. Therefore, from the CAPEX values calculated from the unit costs, yearly CAPEX values are formed by applying equation 4. As for a technology, the capacities in a given year consist of units with different ages, we differentiate them by applying the WACC factor which is considered constant (7.5%, from IRENA, 2018). As the EUCalc uses 5 year periods, we assume 2.5 year average age for the capacities entered in one period.

Equation 4 – Calculation of CAPEX for a given year

$$CAPEX_{year\,N}^{technology\,M}=\frac{1}{lifespan}\cdot\sum_{i=2020}^{N}\left(\frac{CAPEX_i}{(1+WACC)^{N-i+2,5}}\right)$$

CAPEX component is only considered for the units that are commissioned on the 2015-2050 period, as for the capacities from the base year we assume full deprecation of the initial costs.

5 Description of levers and ambition levels

5.1 Lever description and justification

There are three levers defined in this module, see Table 7. The first describes a portfolio of balancing and storage technologies. The user can select the composition of the technology portfolio defined as ambition level. The lever works on EU28 plus Switzerland level and disaggregation to Member State level is applied directly in the calculation. With this lever, the user can influence the technology portfolio delivering (at least partially) the flexibility needs.

The other lever describes the future development of PtX technology capacities. The reason for differentiating PtX is that it can transfer the excess electricity into other forms of energy and thus connect it to other sectors (the other storage technologies considered in the first lever can only shift the electricity).

In case of both levers, the trajectories for storage capacities express a maximum value that could be exploited depending on the residual load curve as described in previous chapters. Thus, the user may not experience full exploitation of the available capacities. Rationale behind is that further installations will reflect the actual flexibility need and its changes.

With the third lever the user can influence the charging patterns of electric vehicles, thus influencing when charging happens and able to shift demand. Therefore, this lever functions as a tool for DSM.

Table 7 – List of levers for the storage module

	Lever	Brief description
1.	Balancing and storage strategies portfolio	Needed amount of balancing power is shared to the next set of technologies: ▪ pumped hydroelectric storage; ▪ electro-chemical, battery, stationary; ▪ electro-mechanical, flywheel; ▪ electro-mechanical, compressed air storage. For each technology, the ratios per level are based on analysing the potential the changes in production, as described in details in the next section. In general, the next factors were considered: • past and current features; • future development; • future performance and scale; future importance in other models and policies.
2.	PtX capacity additions	Based on literature review, this lever defines the PtX capacities added to the system.
3.	Charging patterns of EVs	Based on the charging patterns identified by NREL and what percentage of the EV stock is charging according to a given pattern.

5.2 Definition of ambition levels

The levers about the storage portfolio and EV charging patterns are ABCD type, as the levels describe scenarios for further development of the storage technologies depending which technology gets more focus, as explained in Table 8, and similarly for charging patterns of EVs in Table 9.

Table 8 – Definition of ambition levels of storage portfolio

Level A	**Level B**
This scenario considers that the storage electricity volumes will grow according to the least ambitious trajectories found in literature across each technology.	This scenario considers that there is a rapid breakthrough in battery technologies, therefore this technology is growing according to the most ambitious trajectory. As a result, all other technologies are only growing at the least ambitious levels.
Level C	**Level D**
This scenario considers that the currently less attractive technologies of CAES and flywheels will gain wide-spread acceptance and hence will grow at their most ambitious trajectories. In this case, however, the growth trajectories of PHS and batteries will be an intermediate growth trajectory between their least and most ambitious trajectories.	This scenario considers that all storage technologies grow according to their most ambitious trajectories. This level is considered as transformational and requires some additional breakthrough or efforts such as important costs reduction for some technologies, very fast and extended deployment of infrastructures, major technological advances, strong societal changes, etc.

Table 9 – Definition of ambition levels of charging patterns of EVs

Level A	**Level B**
This scenario considers that most of the EVs will be charged in uncontrolled manner not using fully the storage potential of electric vehicles for flexibility purposes.	This scenario considers that uncontrolled charging patterns are still dominating the scene but intelligent charging solutions are gaining more opportunity, thus some of the storage potential can be used for flexibility purposes.
Level C	**Level D**
This scenario considers that intelligent charging options and patterns are penetrating more, thus the storage potential of electric vehicles is better exploited for flexibility purposes.	This scenario considers that most of the EVs will be charged in an intelligent manner and thus making the storage potential of EVs available for flexibility purposes. This requires some additional breakthrough or efforts such as important costs reduction for some technologies, very fast and extended deployment of infrastructures, major technological advances, strong societal changes, etc.

The PtX level is defined on levels 1-4, as shown in Table 10.

Table 10 – Definition of ambition levels

Level 1	**Level 2**
The projections are aligned and coherent with the historical trends.	This level is an intermediate scenario, more ambitious than level 1 but not reaching the full potential of available solutions.
Level 3	**Level 4**
This level is considered as very ambitious but realistic scenario, given the current technology evolutions and the best practices observed in some geographical areas.	Strong commitment and exploitation of the potential which requires some additional breakthrough or efforts such as important costs reduction for some technologies, very fast and extended deployment of infrastructures, major technological advances, strong societal changes, etc

5.3 Policy description

Policies influencing the market and technologies of storage are the energy policies and development of balancing and storage are embedded into the context of energy policy. The general energy policy of the EU is introduced in the documentation of the supply module.

The topic of storage in the context of energy policy is closely linked to decarbonization objectives and its main tool, large share of intermittent renewables. By 2050, the European Union aims to reduce greenhouse gases by more than 80%. A decarbonised power system will depend on a large share of non-dispatchable, weather dependent sources, primarily solar and wind power. The key to addressing the variability and uncertainty of variable renewable electricity integration is the increasing of the overall flexibility in the power system. Energy storage can provide a variety of flexibility services, including provision of operating reserves and shifting energy over time to better match generation and load. Storage can provide both downward and upward flexibility, storing energy either when there is generation surplus or lower demand and discharging in the opposite case.

In line with the above, the European Commission recognizes that energy storage can support the EU's plans for the Energy Union by helping to ensure energy security and a well-functioning internal market, and helping to bring more carbon-cutting renewables online[8]. Considering the need for further development of storage technologies, apart from energy policy, promoting innovation in key technologies is also important, thus technological innovation in storage is part of the Horizon 2020 programme and the Strategic Energy Technology Plan. In line with this approach, the ambition levels reflect the need for breakthrough for scaling up certain storage solutions.

[8] https://ec.europa.eu/energy/en/topics/technology-and-innovation/energy-storage

5.4 Current situation of electricity storage technologies

The global stationary and grid-connected energy storage capacity was 156.4 GW in 2016 of which only the pumped storage hydropower technology was 150 GW (IHA, 2016). Other technologies only constitute a small slice of the pie but growing continuously: around 0.8 GW of new energy storage capacity was built in 2016, bringing the year-end capacity total to an estimated 6.4 GW (DOE, 2019). Most of the growth was in electrochemical (battery) storage technologies, which increased by 0.6 GW for a total of 1.7 GW energy storage capacity (Figure 21). Lithium-ion technologies constituted the majority of new capacity installed and nowadays the rechargeable battery is one of the most widely used electrical energy storage technologies in many areas (Figure 22). Battery storage is attractive because it is already economical, easy to deploy, compact, and provides virtually instant response both when being charged and discharged (Zsiborács et al., 2018, Luo et al., 2015, May et al., 2018).

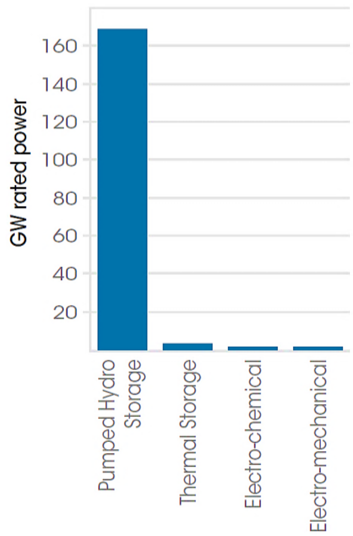


Figure 23 – Global operational electricity storage power capacity by technology, mid-2017, source: IRENA, 2017

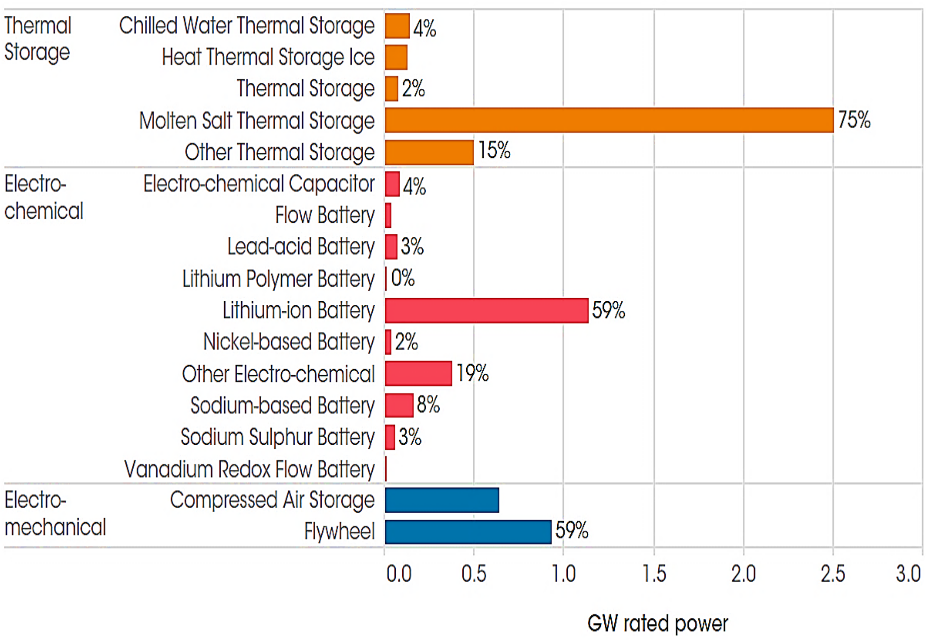


Figure 24 – Global operational electricity storage power capacity by technology without PHS, mid-2017, source: IRENA, 2017

PHS also dominates in Europe, figure 20 shows the sum of installed storage units in Europe as of 2016.

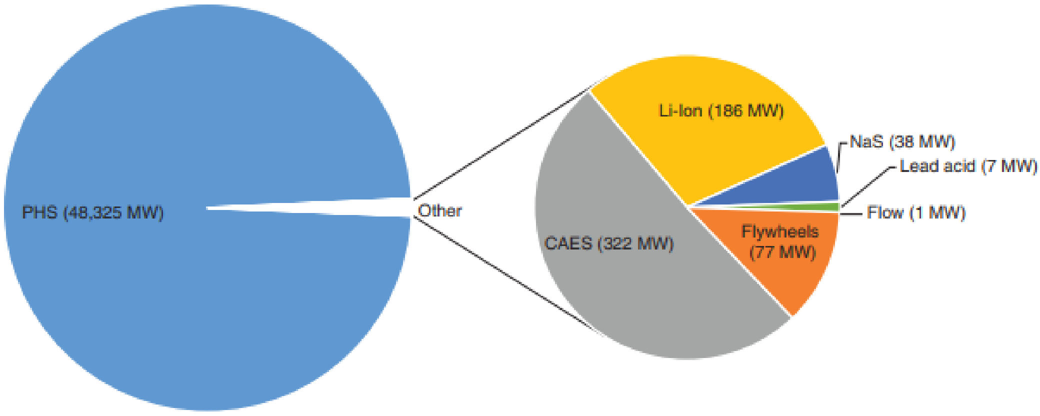


Figure 25 – Operational grid-connected electricity storage capacity in the 28 Member States of the EU (EU28) plus Norway and Switzerland[9].
source: EASAC, 2017

5.5 Various scenarios for electricity storage in 2050

IRENA scenarios show that the total electricity storage volumes are projected to grow from an estimated 4.67 TWh of 2017 to 6.62-15.89 TWh by 2030 (Figure 23), if the share of PV and wind energy in the energy system is to double by 2030. Based on the reference forecasts to 2030, the global PHS capacity will increase at least by 1,2 TWh compared to 2017. However, it should be noted that the TWh forecasts have significant uncertainty till 2030 (IRENA, 2017).

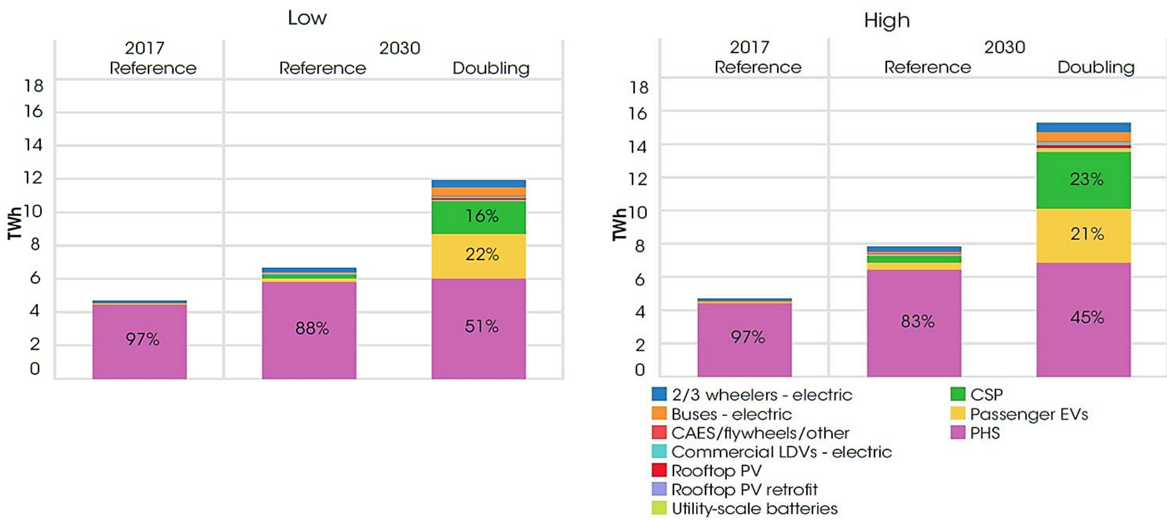


Figure 26 – Electricity storage energy capacity growth by source, 2017-2030, source IRENA (2017)

The large increase in storage technologies as forecasted by IRENA (2017) will be driven by the rapid growth of utility-scale and behind-the-meter applications. It means that the total electrochemical storage volumes in stationary applications

[9] Note: the figure title is copied from the original source, however, in the calculation scheme of the storage requirement module we use capacity as storage capacity (i.e. the amount of electricity the storage units can store simultaneously, TWh), in the terminology of the module the data on the figure can be understand as rated power and for PHS as electricity generation capacity of the water turbine.

will grow from an estimated 11 GWh in 2017 to 100-421 GWh by 2030 (Figures 24). High residential and commercial electricity rates, the competitive cost structures for PV, and the low levels of remuneration for grid feed-in constitute important aspects that are helping the spread of stationary battery technologies (IRENA, 2017). It is expected that regulatory reforms will open up other opportunities for electro-chemical storage deployment, given that battery storages will be increasingly offering competitive and flexible services (such as time shift services, frequency regulation, voltage support or renewable capacity firming) to markets (Garrett et al., 2015).

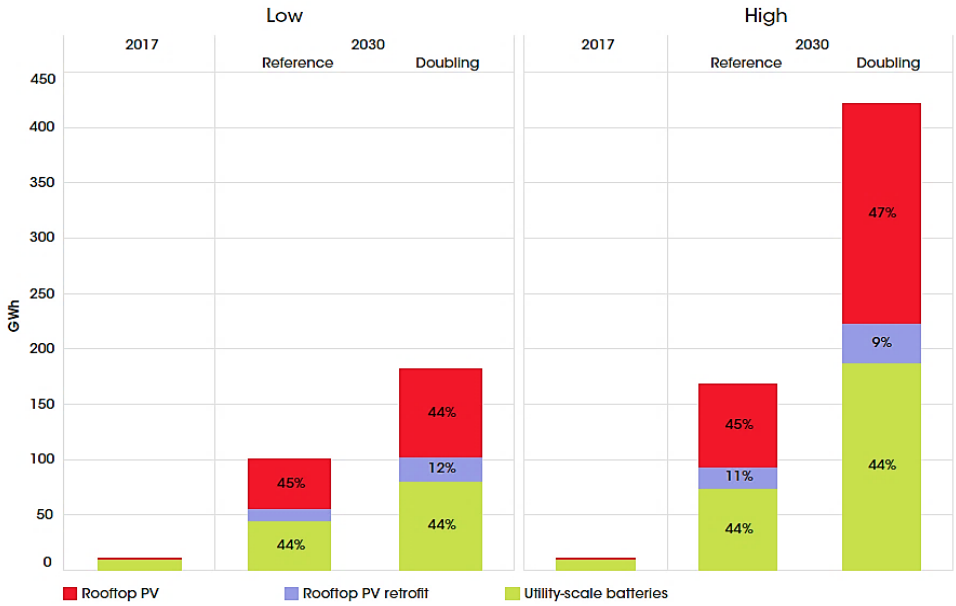


Figure 27 - Electro-chemical electricity storage capacity growth in stationary applications by sector in the case of low and high scenarios, 2017-2030, source: IRENA, 2017

In 2030 the estimated role of PHS will be still significant but smaller because the cost reduction of battery technologies will open up new economic opportunities for storage technologies (Figure 25). In the future, it is likely that the total installed cost for stationary Li-ion battery applications will be in the range of 145-480 USD/kWh, depending on battery chemistry, which is a 50-60% reduction compared to current costs. The cost of Li-ion batteries used in electric vehicles already decreased by 73% from 2010 to 2016 (IRENA, 2017). But it is not just Li-ion based batteries that have great prospects. The cost reduction potential for emerging technologies (like zinc bromine or vanadium redox flow batteries) are also significant. Other than these two technologies, the IRENA reference scenario does not count with significant advancements.

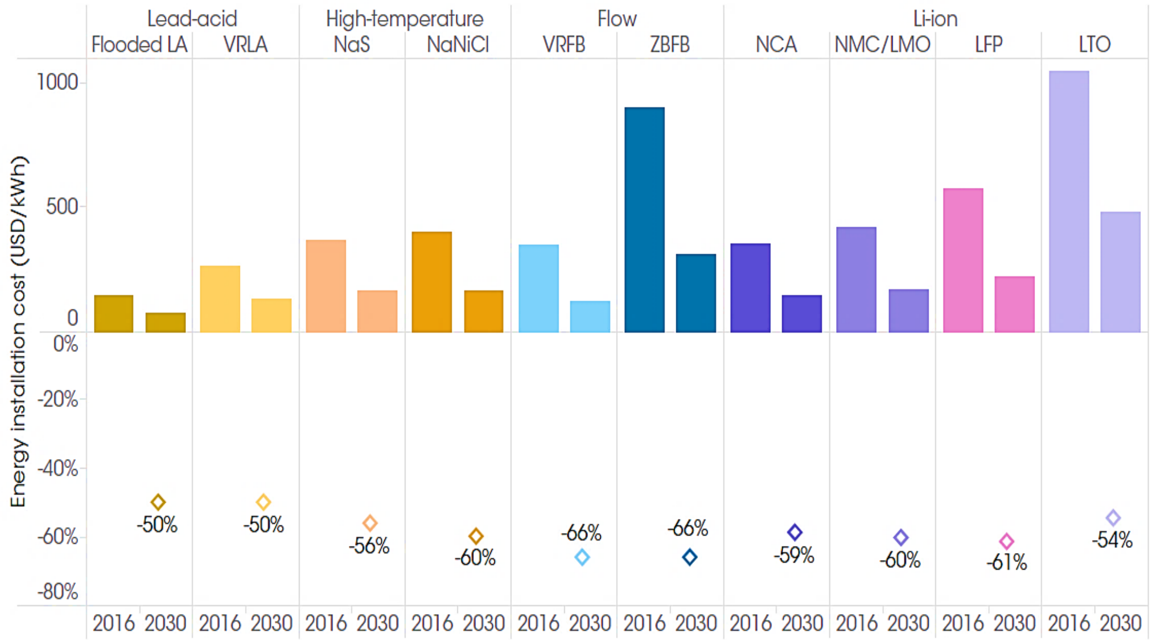


Figure 28 – Battery electricity storage system installed energy cost reduction potential, 2016-2030, source: IRENA, 2017
**LA = lead-acid; VRLA = valve-regulated lead-acid; NaS = sodium sulphur; NaNiCl = sodium nickel chloride; VRFB = vanadium redox flow battery; ZBFB = zinc bromine flow battery; NCA = nickel cobalt aluminium; NMC/LMO = nickel manganese cobalt oxide/lithium manganese oxide; LFP = lithium iron phosphate; LTO = lithium titanate.*

5.6 Lever specification

5.6.1 Storage portfolio

With this lever, the user can set the available yearly storage capacities for a portfolio of storage technologies. Under this lever, the next technologies are considered, namely:

- pumped hydro storage;
- electro-chemical, battery, stationary;
- electro-mechanical, flywheel;
- electro-mechanical, compressed air storage.

5.6.1.1 Rationale for lever and level choices

The different levels in this lever reflect a diverging composition of storage technologies in the overall storage portfolio. The composition of the storage portfolio at each level is detailed below:

<u>Level A – current trends:</u> all storage technologies develop according to their least ambitious projections.

<u>Level B – battery breakthrough:</u> only batteries develop according to their most ambitious trajectory, all other storage technologies develop according to their least ambitious trajectories. The rationale and main impact of this lever setting is to test the ratio and spread of battery storage for which ambitions and even breakthroughs are needed. Applicability of battery storage and its potential to substitute flexible power generation are key topics for full decarbonisation of the power sector relying on high share of renewables.

Level C – breakthrough in alternatives: flywheels and CAES develop according to their most ambitious trajectory, while PHS and batteries develop according to their intermediate trajectory. The rationale behind this lever choice is that flywheel and storage technologies are not as advanced as battery technologies yet, therefore the intermediate development of batteries and PHS can be thought of as a prerequisite for most ambitious developments in the flywheel and storage technologies. Intermediate advancement in PHS and batteries mean that these technologies develop according to a trajectory that is the arithmetic mean of the most and least ambitious trajectories.

Level D – strong commitment to storage: all storage technologies develop according to their most ambitious trajectories. The lever also contains the possibility of further expanding PHS, as current only large-scale storage solution is limited due to geographical potential. Already in many countries the potential has been already exploited, while in other countries – mainly in the Alps – there is still significant untapped potential. This will be available for the other countries in the same trading zone due to the approach applied to calculate storage.

5.6.1.2 Determining storage capacity (volumes) for each technology

This section elaborates the annual storage capacities each technology may be able to offer in the different level settings as explained above. The module focuses on the annual storage capacities (expressed in Wh) of the storage technologies due to the calculation logic as opposed to the rated power (expressed in W). In this step we describe how the EU28 plus Switzerland level trajectories for the different storage capacities were obtained, after which the disaggregation is elaborated to the trading zone and country level.

2015 data for installed PHS units were extracted from the JRC IDEES database (Mantzos et al., 2018), which is used as a starting point. The reported capacities express the electricity production capacity of the water turbine (i.e. installed generation capacity). As reported by Gimeno-Gutierrez and Lacal-Arántegui (2015), there are no official figures in Europe for the storage capacity of PHS units. The only source, is a 2011 survey by Eurelectric (2011) that includes the storage capacity of PHS for certain countries in Europe of which results are shown on figure 26.

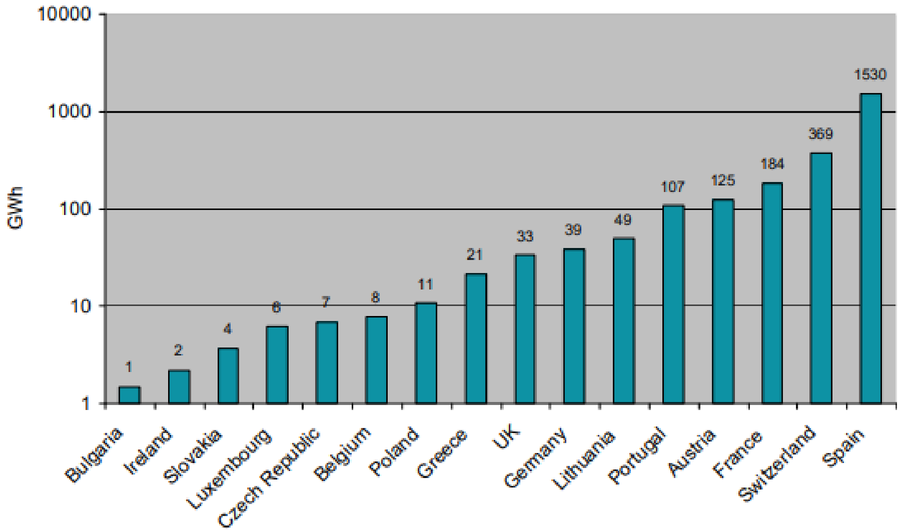


Figure 29 – Total amount of electricity (logarithmic scale) that can currently be stored in one ideal pumping cycle, source: Eurelectric, 2011

Generation capacities for 2011 were also taken from the JRC IDEES database (Mantzos et al., 2018) in order to calculate the 2011 country specific ration of the generation and storage capacities. This ratio was used to deliver the 2015 storage capacities in TWh. In case of a country has PHS units but the survey did not provide storage capacity values, the ratio of a similar country was used: for Italy the ratio of France, and for Romania, Croatia, Slovenia and Sweden the ratio of Ireland.

In case of the least ambitious trajectory for PHS, we only assume additional PHS capacities that are part of the ENTSO-E Ten Years Network Development Plan 2018 Storage project database[10], see Table 11. These capacities will start operation in the schedule as indicated below.

Table 11 – New pumped hydroelectric storage projects in Europe

ENTSO-E project number	Country	New storage capacity (GWh)	Expected commission date	Current status
1000	Austria	1,8	2022	Under Construction
1001	Austria	152	2034	In Permitting
1026	Austria	3,5	2025	In Permitting
1002	Belgium	2	2022	Planned But Not Yet Permitting
1003	Bulgaria	5,2	2025	In Permitting
1004	Estonia	5,45	2028	In Permitting
1006	Greece	3,974	2023	In Permitting
1025	Ireland	1,8	2026	Under Consideration
1030	Ireland	6,1	2024	Planned But Not Yet Permitting
1009	Lithuania	8,2	2024	Under Consideration
1029	Slovenia	8,56	2027	In Permitting
1011	Spain	75,11	2020	In Permitting
1012	Spain	3,6	2023	In Permitting
1019	Spain	34,9	2027	In Permitting
1027	Spain	1,62	none	In Permitting
1014	UK	30	2027	In Permitting
1015	UK	6,9	2025	Under Consideration

In case of the most ambitious trajectory for PHS in 2050, the full exploitation of PHS potential is considered as defined by Gimeno-Gutierrez and Lacal-Arántegui (2015). Table 12 summarizes the figures obtained as described above. Linear interpolation was used for calculating the intermediate ambition level which is not shown in the table below.

[10] available here: https://tyndp.entsoe.eu/tyndp2018/projects/storage_projects

Table 12 – Pumped hydroelectric storage capacity ambition levels

Country	Annual storage capacity, GWh		
	2015	**2050 least ambitious**	**2050 most ambitious**
Austria	22 776	50 335	77 614
Belgium	1 402	1 752	2 102
Bulgaria	175	1 086	20 849
Croatia	350	350	350
Cyprus	-	-	5 431
Czech Republic	1 332	1 332	6 833
Denmark	-	-	-
Estonia	-	955	955
Finland	-	-	2 102
France	32 237	32 237	207 437
Germany	6 640	9 566	15 593
Greece	3 679	4 380	29 434
Hungary	-	-	701
Ireland	350	1 734	16 469
Italy	35 460	35 460	327 098
Latvia	-	-	-
Lithuania	8 585	10 021	10 740
Luxembourg	1 244	1 244	1 244
Malta	-	-	-
Netherlands	-	-	-
Poland	1 927	1 927	12 790
Portugal	30 678	30 678	94 958
Romania	473	473	7 709
Slovakia	701	701	6 833
Slovenia	228	1 734	7 884
Spain	298 401	318 584	1 014 058
Sweden	123	123	8 935
Switzerland	64 649	64 649	290 131
UK	5 782	12 246	174 149

For non-PHS storage technologies, there is no country, not even Europe level projections for installed capacities of these other storage technologies, therefore we disaggregated the scenarios from IRENA (2017) to obtain storage capacity values.

In order to estimate electricity storage volumes for electro-chemical batteries, the 'ES5: Battery electricity storage energy capacity growth in stationary applications by main-use case, 2017-2030' figure was used from (IRENA, 2017) (Figure 27). From the scenarios presented in the source, the lowest 100 GWh and the highest ambition 421 GWh global battery storage power outputs were considered. 35% of this new, global electro-chemical energy storage power was estimated to be realised in the EU-28 plus Switzerland. It is important to note that there are not any suitable scenarios for battery storage after 2030. First, linear interpolation was used for calculating 2020 and 2025 values from the 2030 values (in order to match the 5-years EUCalc resolution). After 2030, the excel forecast function (least square method) was used to determine the values for 2035-2050. For each analysed year, the entire previous period was taken into account. This means that for instance in the case of 2035, the 2015-2030 period was taken into account, while in 2040 the period 2015-2035 was considered. It is also important to mention that the module considers that battery storages can be installed in any country; the technology does not have any geographical of topographical constraints.

As a result of the calculations, we determined the annual electricity storage volumes for the least and most ambitious cases for 2050 in battery storages. Intermediate storage volumes have been calculated using linear interpolation, which are not shown in the table below. The below table shows the theoretical maximum energy storage capacity of batteries in the respective years at the EU-28 plus Switzerland level. Disaggregation of these capacities to trading zone and country levels are carried out as detailed in Step 6 of the calculation process.

Table 13 – Annual electricity storage volumes for batteries, TWh

Technology	Ambition level	2015	2020	2025	2030	2035	2040	2045	2050
Electro-chemical, battery, stationary	Least	0,3	17,2	34,2	51,1	68,0	84,9	101,9	118,8
	Most	0,3	71,9	143,5	215,2	286,8	358,4	430,1	501,8

For the 2015 values of power output of electro-mechanical storage technologies, the DOE Global Energy Storage Database (DOE) was used. For future values of these technologies, the IRENA (2017) study was used, in which projections for many technology-specific storage scenarios are described until 2030 (IRENA, 2017). For electro-mechanical storage 'ES3: Electricity storage energy capacity growth by source, 2017-2030' figure was used. From the scenarios the 20 GWh lowest and the highest ambition 84 GWh global electro-mechanical storage energy capacity were estimated. 30% of this new, global electro-mechanical energy storage power was estimated for EU plus Switzerland. Furthermore, based on IRENA and DOE data, a share of 63% flywheel and 37% CAES has been assumed for electromechanical storage technologies. The below table shows the theoretical maximum energy storage capacity of CAES and flywheels in the respective years for the least and most ambitious trajectories at the EU-28 plus Switzerland level. Intermediate ambition levels that have been calculated with linear interpolation are not shown in the table below. Disaggregation of these capacities to trading zone and country levels are carried out as detailed in Step 6 of the calculation process.

Table 14 – Annual electricity storage volumes for other technologies, TWh

Technology	Ambition level	2015	2020	2025	2030	2035	2040	2045	2050
Electro-mechanical, CAES	Least	0,5	2,1	3,8	5,4	7,0	8,7	10,3	11,9
	Most	0,5	7,9	15,2	22,6	29,9	37,2	44,6	52,0
Electro-mechanical, flywheel	Least	21,0	87,6	154,2	220,8	287,3	353,9	420,5	487,1
	Most	21,0	324,1	625,5	928,6	1 231,7	1 533,0	1 836,1	2 139,2

After combining the data in Tables 12, 13 and 14, the following table (Table 15) emerges that represents the annual storage volumes of each technology at the EU-28 plus Switzerland level, given the lever setting.

Table 15 – Ambition levels of the module

Level	Technology	Ambition level	Unit	2015	2020	2025	2030	2035	2040	2045	2050
Level 1 - Current trends	Electro-chemical, battery, stationary	Least	TWh	0,29	17,23	34,16	51,10	68,04	84,97	101,91	118,84
	Pumped hydroelectric storage	Least	TWh	517,19	526,39	535,58	544,78	553,98	563,17	572,37	581,57
	Electro-mechanical, compressed air	Least	TWh	0,51	2,12	3,80	5,40	7,01	8,69	10,29	11,90
	Electro-mechanical, flywheel	Least	TWh	21,02	87,60	154,18	220,75	287,33	353,90	420,48	487,06
	Total		TWh	539,02	633,33	727,72	822,03	916,35	1010,74	1105,05	1199,37
Level 2 - Battery breakthrough	Electro-chemical, battery, stationary	Most	TWh	0,29	71,98	143,52	215,20	286,89	358,43	430,12	501,80
	Pumped hydroelectric storage	Least	TWh	517,19	526,39	535,58	544,78	553,98	563,17	572,37	581,57
	Electro-mechanical, compressed air	Least	TWh	0,51	2,12	3,80	5,40	7,01	8,69	10,29	11,90
	Electro-mechanical, flywheel	Least	TWh	21,02	87,60	154,18	220,75	287,33	353,90	420,48	487,06
	Total		TWh	539,02	688,08	837,07	986,14	1135,20	1284,20	1433,26	1582,32
Level 3 - Breakthrough in altern	Electro-chemical, battery, stationary	Intermediate	TWh	0,29	44,60	88,84	133,15	177,46	221,70	266,01	310,32
	Pumped hydroelectric storage	Intermediate	TWh	517,19	652,16	787,13	922,10	1057,07	1192,04	1327,01	1461,98
	Electro-mechanical, compressed air	Most	TWh	0,51	7,88	15,18	22,56	29,93	37,23	44,60	51,98
	Electro-mechanical, flywheel	Most	TWh	21,02	324,12	625,46	928,56	1231,66	1533,00	1836,10	2139,19
	Total		TWh	539,02	1028,77	1516,62	2006,37	2496,12	2983,97	3473,72	3963,47
Level 4 - Strong commitment	Electro-chemical, battery, stationary	Most	TWh	0,29	71,98	143,52	215,20	286,89	358,43	430,12	501,80
	Pumped hydroelectric storage	Most	TWh	517,19	777,93	1038,68	1299,42	1560,17	1820,91	2081,65	2342,40
	Electro-mechanical, compressed air	Most	TWh	0,51	7,88	15,18	22,56	29,93	37,23	44,60	51,98
	Electro-mechanical, flywheel	Most	TWh	21,02	324,12	625,46	928,56	1231,66	1533,00	1836,10	2139,19
	Total		TWh	539,02	1181,92	1822,84	2465,74	3108,64	3749,57	4392,47	5035,37

Having determined the overall storage capacities at the EU-28 plus Switzerland level for each respective year, it is then necessary to translate these values to trading zone and then country-level values, as written at Step 5 of the calculation process. The below table gives a summary about the PHS storage capacities in each trading zone in the least and most ambitious scenarios that the lever setting is using.

Table 16 – annual PHS storage capacities in each region according to ambition level [TWh]

Technology	Ambition level	2015	2020	2025	2030	2035	2040	2045	2050
Central Western Europe	Least	128,9	133,4	137,8	142,2	146,6	151,0	155,4	159,8
	Most	128,9	195,4	261,9	328,3	394,8	461,2	527,7	594,1
Central Eastern Europe	Least	4,5	4,8	5,0	5,2	5,4	5,6	5,8	6,0
	Most	4,5	8,9	13,4	17,8	22,2	26,6	31,0	35,4
South Eastern Europe	Least	4,3	4,6	4,8	5,0	5,2	5,5	5,7	5,9
	Most	4,3	12,0	19,7	27,3	35,0	42,7	50,3	58,0
Apennine Peninsula	Least	35,5	35,5	35,5	35,5	35,5	35,5	35,5	35,5
	Most	35,5	77,1	118,8	160,4	202,1	243,8	285,4	327,1
Iberian Peninsula	Least	329,1	332,0	334,8	337,7	340,6	343,5	346,4	349,3
	Most	329,1	440,5	551,9	663,3	774,8	886,2	997,6	1 109,0
British Isles	Least	6,1	7,3	8,4	9,5	10,6	11,7	12,9	14,0
	Most	6,1	32,5	58,8	85,2	111,6	137,9	164,3	190,6
Northern Europe	Least	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
	Most	0,1	1,7	3,2	4,8	6,4	7,9	9,5	11,0
Baltic countries	Least	8,6	8,9	9,3	9,6	10,0	10,3	10,6	11,0
	Most	8,6	9,0	9,5	9,9	10,4	10,8	11,3	11,7
Cyprus	Least	-	-	-	-	-	-	-	-
	Most	-	0,8	1,6	2,3	3,1	3,9	4,7	5,4

As PHS storage potential is determined by topographical conditions, the above region specific disaggregation is necessary. Other, non-PHS technologies, however, are not dependent on topographical conditions and hence are shared between regions depending on the share of VRE generation capacity located in the region, as explained more in detail in Step 6 of the calculation process.

5.6.2 PtX capacities

With this lever, the user can set the available yearly capacities for power-to-x technologies. In the module, we consider two applications: power-to-fuels when the excess electricity is turned into hydrogen as the basis for transport e-fuel generation, as well as power-to-gas-to-power when the excess electricity is stored in the form of H_2 gas and used again to produce electricity in times of deficit.

5.6.2.1 Rationale for lever and level choices

At the hydrogen energy storage systems, the H_2 is produced by electricity through an electrolyser during the charging process. This hydrogen can be either used for e-fuel production, in Step 0, or stored down to produce electricity at later times. In case of discharging process, the hydrogen can be used to drive fuel cells or combustion turbines and the gas can be directly used in hydrogen cars or special internal combustion engines or for heat generation. The specific costs of the storage itself are low, however, the round-trip efficiency is very low, i.e. below 40% for one charge-discharge cycle. There are no large-scale hydrogen energy storage systems in operation today because at the current level of variable renewable energy penetration the long distance transmission plus instant consumption and the conventional backup generation capacity are cheaper. This storage technology is expected to become more important for power systems with very high fractions of variable renewable energy penetration (e.g. 80-100%). The maximum possible share of hydrogen in the necessary adjustments to the infrastructure and the gas grid are currently a matter of debate among experts. However, even if limited to a few percent of volume this technology option constitutes a very large energy reservoir. An alternative to the storage of H_2 is the storage of synthetic natural gas. The end product is methane, which is the main constituent of natural gas and therefore fully compatible with the existing infrastructure and the H_2 can be injected into the natural gas grid without restriction. Nevertheless, this technology provides the possibility to interconnect the electricity system with the heat and fuel market (Fuchs et al., 2012).

5.6.2.2 Ambition levels & disaggregation method

For power-to-X, the EU Reference Scenario 2016 and the 'Technical report on Member State results of the EUCO policy scenarios' sources were used to create Level 1 and Level 4 trajectories, between which linear interpolation was applied. Table 17 shows the maximum amount of electricity PtX technologies may withdraw from the electricity grid, which is equal to the volume of electricity that electrolysers draw from the electricity system over an entire year.

Table 17 – Annual electricity storage capacities for PtX, TWh

Technology	Ambition level	2015	2020	2025	2030	2035	2040	2045	2050
Power-to-X	1	0,04	0,15	0,26	0,40	0,51	0,62	0,73	0,84
	2	0,04	0,29	0,54	0,79	1,04	1,29	1,54	1,79
	3	0,04	0,42	0,81	1,19	1,58	1,97	2,35	2,74
	4	0,04	0,55	1,10	1,61	2,12	2,66	3,18	3,69

According to the detailed calculation tree presented in Section 4, PtX has two main usages in the electricity system. The module assumes that in Step 0, the electricity volumes presented in Table 17 are used for hydrogen production, which is the basis for further e-fuel production. The module assumes that electrolysers work with 80% efficiency, which is the higher range of the currently most viable alkaline electrolysers and polymer electrolyte electrolysers (Schmidt et al., 2017). Depending on the lever setting, that means that on calorific value 80% of the above figures can be obtained as hydrogen.

Following Step 0, if there are unused storage capacities of PtX, in Step 4 these capacities are used on a power-to-gas-to-power basis to store down electricity. In this case, the PtX units are assumed to operate on a closed cycle basis, i.e. storing the produced hydrogen in a tank, and releasing it at times of electricity supply shortage. In order to do this, the remaining PtX units are assumed to have a 24-hour discharge time as per Fuchs et al. (2012). Thus, the maximum possible volume to be withdrawn is limited by the 24-hour discharge time of the units, therefore it takes 48 hours in Step 4 to completely charge and discharge PtX units. As Table 17 does not consider discharge time, the leftover after open cycle PtX mode needs to be halved in order to consider the time for discharge.

In order to estimate how much of the stored electricity in PtX can be put back into the electricity grid at a later time, it is required to factor in the efficiency of the whole process. As per Table 19, the round trip efficiency of PtX used as in Step 4 is only 35%, therefore the values in Table 17 have to be adjusted accordingly.

The disaggregation of the PtX units to trading zone and country levels is performed similarly as in the case of non-PHS storage technologies. The share of VRE generation capacity each trading zone has compared to the EU-28 plus Switzerland level VRE generation capacity determines the share of PtX in each trading zone.

5.6.3 Charging patterns of EVs

With this lever the user can set the percentage of the EV stock following a distinct charging pattern. The lever is a mix of three fixed pattern adopted from an NREL study while the fourth options is a controlled or intelligent charging when charging can adapt to the flexibility needs of the electricity system. Thus, this part of charging demand can be moved freely in the sub-daily timescale depending on the flexibility needs.

5.6.3.1 Rationale for lever and level choices

Number of electric vehicles on the road is forecasted to grow significantly, and thus their impact on the grid and demand profiles is also increasing. Nevertheless, charging of EVs can adopt to the daily routine of the users and can be adjusted based on the situation on the electricity system, thus with proper incentives EVs can realize significant DSM potential. This is needed as the widespread adoption of electric vehicles could increase the risk of overloading the power grid by inflating peak demand. It is estimated that for every new 1 000 EVs charging on the grid, the load drawn is approximately an additional 2.5-2.75 MW. Due to this, there is particular interest for integrating DSM into EV charging using economic incentives such as dynamic pricing (Kielthy et al., 2013).

5.6.3.2 Ambition levels & disaggregation method

The levels are different mixes of charging scenarios. The least ambitious level contains only uncontrolled charging while the ratio of intelligent (i.e. flexible) charging patterns is growing with the ambition level.

The three uncontrolled charging scenarios are adopted from an NREL study (Parks et al., 2007). In each of those scenarios, the authors developed an aggregated hourly charging profile for a fleet of vehicles. This hourly load is then applied to a part of the EV stock, thus electricity demand from road transport and considered in creating the hourly demand side curves as described in the calculation part, step 1. The aggregated hourly charging profile of the three uncontrolled scenarios are explained in hereafter, as adopted from Parks et al. (2007), while the fourth scenario means that that part of the electricity demand from charging can be placed freely, responding the sub-daily (and daily) flexibility needs.

The home charging scenario is an uncontrolled charging case that considers a simple scenario where vehicle owners charge their vehicles exclusively at home in an uncontrolled manner. The EV begins charging as soon as it is plugged in, and stops when the battery is fully charged. This can be considered a reference or "do nothing" case, because it assumes a business-as-usual infrastructure requirement (no charging stations at work or other public locations). In addition, it requires no intelligent control of how or when charging occurs, or incentives (such as time-of-use rates) to influence individual consumer behaviour. It can also be considered a boundary (worst-case) scenario, given the high coincidence of normal electric system loads and likely consumer vehicle-charging patterns. The aggregated hourly profile of this scenario is on figure 30

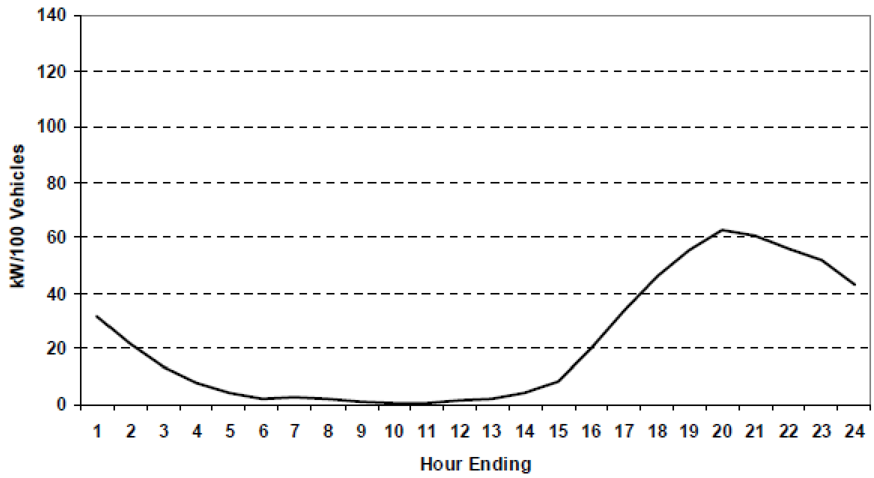


Figure 30 – Hourly aggregated curve of home charging scenario, source: Parks et al., 2007

The second scenario is the delayed home charging as on figure 31. The delayed charging case is similar to case 1, in that all charging occurs at home. However, it attempts to better optimize the utilization of low-cost off-peak energy by delaying initiation of household charging until 10:00 PM. This requires only a modest increase in infrastructure, i.e., a timer in either the vehicle or in the household charging station.

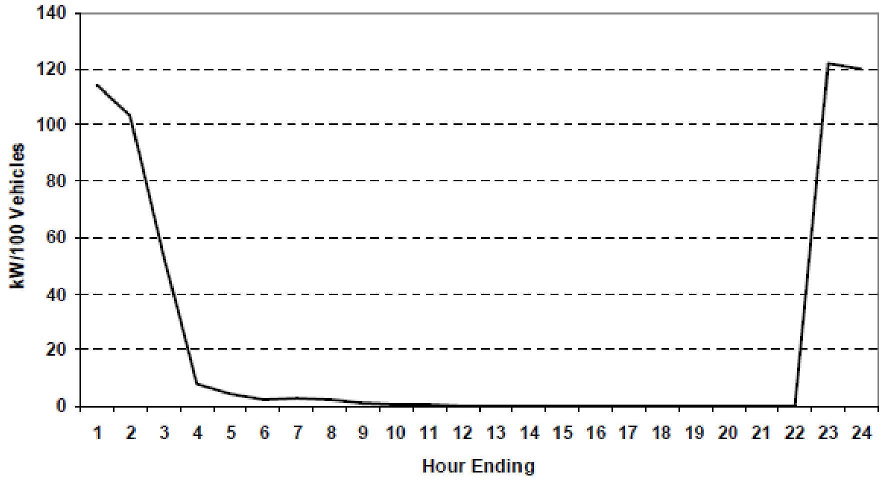


Figure 31 – Hourly aggregated curve of delayed home charging scenario, source: Parks et al., 2007

The home and work scenario, as on figure 32, is a continuous charging scenario is similar to Case 1, in that it assumes that charging occurs in an uncontrolled fashion whenever the vehicle is plugged in. However, it also assumes that public charging stations are available wherever the vehicle is parked. As a result, the vehicle is continuously charged whenever it is not in motion, (limited by the battery capacity).

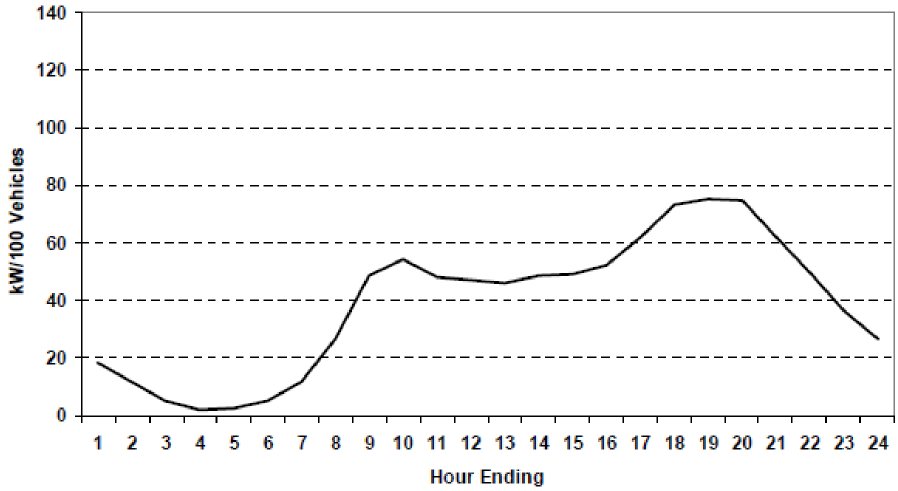


Figure 32 – Hourly aggregated curve of home and work charging scenario, source: Parks et al., 2007

The levels are a combination of the above scenarios considered as the same for all the countries, as shown in Table 18. The level expresses the ratio of the EV stock charged in a given pattern. We assume that each EV in the stock has the same electricity consumption and this way, the sum electricity consumption allocated to each charging scenarios make the total of the road transport electricity consumption.

Table 18 – Ambition level trajectories for charging patterns of EVs

Ambition level	Charging scenario	2020	2025	2030	2035	2040	2045	2050
A	Home charging	50	45	40	35	30	25	20
	Delayed home charging	5	11	17	23	29	35	41
	Home and work charging	45	41	37	33	29	25	21
	Intelligent (flexible) charging	0	3	6	9	12	15	18
B	Home charging	50	45	40	35	30	25	20
	Delayed home charging	5	9,5	14	18,5	23	27,5	32
	Home and work charging	45	39,5	34	28,5	23	17,5	12
	Intelligent (flexible) charging	0	6	12	18	24	30	36
C	Home charging	50	43	36	29	22	15	8
	Delayed home charging	5	8	11	14	17	20	23
	Home and work charging	45	40	35	30	25	20	15
	Intelligent (flexible) charging	0	9	18	27	36	45	54
D	Home charging	50	43	36	29	22	15	8
	Delayed home charging	5	6,5	8	9,5	11	12,5	14
	Home and work charging	45	38,5	32	25,5	19	12,5	6
	Intelligent (flexible) charging	0	12	24	36	48	60	72

6 Description of constant or static parameters

6.1 Constants list

6.1.1 Round-trip efficiency

Due to losses of any storage technologies, output is lower than stored energy as input. Therefore, in order to account for the losses and calculate the amount of energy needed as input to provide 1 unit of output, the parameters in Table 19. are used to calculate the necessary input power.

Table 19 – Round-trip efficiency of the included electricity storage technologies

Technology	Output electricity (kWh)	Input electricity (kWh)	Round-trip efficiency (%)	Reference
Electro-chemical, battery, stationary	1	1.25	80	IRENA, 2017
Pumped hydroelectric storage	1	1.25	80	IRENA, 2017
Electro-mechanical, compressed air storage	1	1.67	60	IRENA, 2017
Electro-mechanical, flywheel	1	1.18	85	IRENA, 2017
Power-to-gas-to-power	1	2.86	35	Schill, 2014, Fuchs et al., 2012
Power-to-hydrogen	1	2.5	80	Schmidt et al., 2017

6.1.2 Cycle time

In order to calculate the necessary physical (installation) units from the annually stored electricity we used the cycles times as in Table 20 for the calculation described earlier.

Table 20 – Time constant of the included electricity storage technologies

Technology	Discharge time for 1 cycle (hours)	Reference
Electro-chemical, battery, stationary	3	ENTSO-E, 2018
Electro-mechanical, compressed air storage	6	ENTSO-E, 2018
Electro-mechanical, flywheel	0.25	Stornetic, 2018
Power-to-gas-to-power	24	DOE

Unlike the other technologies, PHS already operates in large scale, thus we have data to calculate real discharge cycles which varies significantly over trading zones, as shown in Table 21. These values are based on weighted averages of the existing discharge times of PHS units operating in the countries that make up the regions, hence the widely diverging discharge times. Discharge times for each country have been calculated as detailed in section 5.6.1.2. For modelling reasons, the module assumes that discharge times do not change over time.

Table 21 – Discharge cycle for duration for PHS in each trading zone

Region	Countries included	Existing rated power (GW)	Discharge time for 1 cycle (hours)
Central Western Europe	FR, NL, BE, LX, DE, AT, CH	23,4	114,17
Central Eastern Europe	PL, CZ, HU, SK, SL, CR	4,4	5,98
South Eastern Europe	RO, BG, GR	2,1	26,28
Apennine Peninsula	IT, MT	7,7	26,3
Iberian Peninsula	ES, PT	7,7	270,83
British Isles	UK, IE	3	11,9
Northern Europe	DK, SE, FI	0,1	7
Baltic countries	EE, LV, LT	0,8	61,3
Cyprus	CY	0	40*

*Cyprus currently does not have PHS capacities, however, intermediate and most ambitious trajectories identified PHS potential, which would be harvested using the 40 hour discharge time as shown in the table above

6.1.3 Climate change impact on EU power generation

Adopted from the work of Tobin et al. (2018), the following values, as presented in Table 22, are used to adjust capacity factors. The climate module provides the year when the temperature change is happening and between the years, we apply linear interpolation to obtain change values for capacity factors. If the source did not include values for countries, we assume no changes.

Table 22 – Future changes in national solar PV and wind power productions under +1.5 °C and +2°CC global warming, source: Tobin et al., 2018

Country	Mean change for PV (%) for 1.5°C warming	Mean change for PV (%) for 2°C warming	Mean change for wind (%) for 1.5°C warming	Mean change for wind (%) for 2°C warming
Austria	-1,253	-2,040	-1,369	-0,696
Belgium	-1,708	-2,242	-0,909	-1,836
Bulgaria	-0,226	-0,405	-0,851	-1,436
Croatia	NA	NA	-2,369	-1,429
Cyprus	-0,345	-0,410	-3,974	-4,368
Czech-Rep	-1,568	-2,371	-2,456	-2,015
Denmark	-1,856	-2,500	0,004	-0,848
Estonia	-3,296	-4,620	-0,243	-0,223
Finland	-4,132	-5,875	-1,149	-0,827
France	-1,228	-1,305	-1,864	-3,223
Germany	-1,727	-2,368	-1,368	-2,289
Greece	-0,123	-0,169	1,639	1,947
Hungary	-0,712	-1,237	-2,177	-1,622
Ireland	-1,474	-2,376	-1,168	-2,156
Italy	-0,636	-0,836	-1,210	-2,071
Latvia	-2,645	-4,064	-0,183	0,127
Lithuania	-2,456	-3,839	0,309	0,418
Luxemburg	-1,740	-2,037	-2,759	-3,617
Malta	NA	NA	NA	NA
Netherlands	-1,862	-2,547	-1,216	-2,396
Poland	-1,775	-2,955	-1,419	-1,770
Portugal	0,213	0,444	-0,914	-2,831
Romania	-0,494	-0,953	-0,888	-0,589
Slovakia	-1,110	-1,903	NA	NA
Slovenia	NA	NA	-1,214	0,038
Spain	-0,067	-0,072	-0,038	-1,691
Sweden	-3,498	-5,038	-0,732	-1,205
Switzerland	-1,566	-2,239	-1,962	-2,177
UK	-1,345	-2,033	-0,670	-1,569

7 Historical database

7.1 Database for storage technologies production

Table 23 – Database for storage technologies

Dataset	Description	Main sources	Data quality check	Hypotheses
Pumped hydroelectric storage technology (GW)	Historical capacities by country	• Integrated Database of the European Energy Sector (JRC IDEES), Manzos et al., 2018	• Good quality data from reliable, coherent and credible sources	-

8 Conclusion

Electricity systems in the future will need to show ever increasing flexibility in order to cope with variable renewable energy production on the supply side, and shifting patterns of electricity consumption on the demand side. Balancing will thus be an integral part of future electricity systems, and hence is an important module of EUCalc complementing the modelling on electricity supply.

Based on the widely adopted definition of balancing, electricity balancing actions are carried out by TSOs after markets have closed to ensure that electricity demand always equals supply. Given the current practices of balancing services, one may categorise these into short term (frequency containment reserves, and frequency restoration reserves) and long-term balancing actions (replacement reserves). Given the characteristics of the closely linked supply module that is working with annual capacity factors of various electricity generation technologies, the short-term balancing actions are on the one hand are already included in the supply module (including their electricity consumption), and on the other hand are influenced by factors that are out of the scope of the entire EUCalc.

As a result, the storage module focuses on long term balancing actions, the issues of replacement reserves that are used at times when generation capacity is not adequate to meet demand in the system. These replacement reserves will be increasingly important in the future with the ever-increasing levels of renewable electricity generation, which the module considered as the most important driver for electricity balancing. This balancing though can also be referred to as storage, which the module considers a means to achieve balancing. Further to storage, the module considered cross-border electricity trade and demand side management as additional sources of flexibility to the power systems under consideration in the calculator.

The calculation logic implemented in the module determines the hourly flexibility needs based on load and supply curves, as well as annual electricity trade balance between EU and rest of the world. This flexibility need with matching the hourly supply with demand is answered by a series of logical tests including measures such as within EU electricity trade, storage technologies, capacity factor adjustment and curtailment of VRE. These all are required for balancing activities, as output the electricity production mix is complemented by flexibility measures securing matching the supply with demand in each hour of the year, associated costs of building up the required balancing capacities and GHG emissions are also calculated. In addition to these outputs, the user may influence how and with what technologies the balancing actions are carried out in the calculator. Currently it appears that the unresolved issue of electricity storage stands in the way of decarbonisation of the electricity sector. As a result, the module drafted up four distinct scenarios that enable users to test potential developments in electricity storage technologies. With the help of the storage module therefore, electricity demand and supply that have been treated separately before in the overall logic of the calculator are brought into interactions with each other, spelling out additional effects and requirements of EU-wide energy and climate policies.

9 References

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