Modelling Assumptions

This document describes the modelling assumptions used in the case study of the paper entitled "Societal Effects of Large-Scale Energy Storage in the Current and Future Day-Ahead Market: A Belgian Case Study". The paper is part of the 18th International Conference on the European Energy Market (EEM22). A description of the case study is provided in the mentioned paper while the used data is included as part of this supplementary material package. The modelling assumption for each scenario are as follow:

Basecase Scenario

The Baseline scenarios were based on the Belgian power system in 2019. The hourly simulations assumed that all the energy is sold and bought in the day-ahead (DA) market, therefore no long-term, intraday (ID), or real-time (RT) markets are included in the model.

Supply was modelled according to the Belgian Production Park in 2019, as registered by Elia, the Belgian TSO [2]. For simplification purposes, a perfectly competitive market was considered, where the supplier (generator) bid is equal to the short run marginal cost (SRMC) for producing electricity. The SRMC for each thermal generator (i) was calculated as shown in Equation 1.

$$SRMC_i = h_i(C_{fuel} + e_{CO_2} \cdot C_e) \tag{1}$$

Where h_i is average heat rate in GJ/MWh, C_{fuel} the cost of fuel in $€/GJ$, e_{CO_2} the fuel's emissions factor in $tCO_2\ /GJ$, and C_e is the tax on emissions in $€/tCO_2$. The heat rate was calculated as the inverse of the efficiency η_i, as shown in Equation 2, and it was assumed to be constant and independent of the load.

$$h_i = \frac{1 \cdot 3.6}{\eta_i} \tag{2}$$

Efficiencies of each plant were obtained from the Joint Research Centre (JRC) Open Power Plants Database [3]. If no efficiency was found for a plant, the efficiency of another plant with a similar generation technology was used. The CO_2 emissions factors were taken from the IPCC Guidelines for National Greenhouse Gas Inventories [4] and the CO_2 tax from the average price of the European Emission Allowances (EEA) in 2019. Detailed considered information can be found in Appendix B.

The SRMC of variable renewable energy source (VRES) generation and hydropower was assumed to be zero due to null or neglectable fuel price and the lack of carbon taxes. Each generator is assumed to place a bid for the maximum generation capacity for each hour. For VRES generation, the bid quantity is equivalent to the installed capacity times the daily average capacity factor according to wind or radiation conditions of the modelled day [5], [6].

Due to maintenance, reparation, or unexpected issues, generation facilities are not always fully available. To take the previous into consideration, expected available generation capacity and planned and forced outages from Elia's historical data [2] were used to determine which generators were not operating or had limited capacity on the modelled days.

The total load data from Elia was used for the demand bids modelling. The energy traded in the day ahead market in Belgium represents around 26% of the total hourly load [7]. Therefore, 74% of the historical load data was modelled as an inelastic bid with a price bid of 3000 €/MWh, the price cap. The remaining 26% was divided in different demand bids, as shown in Figure 1.

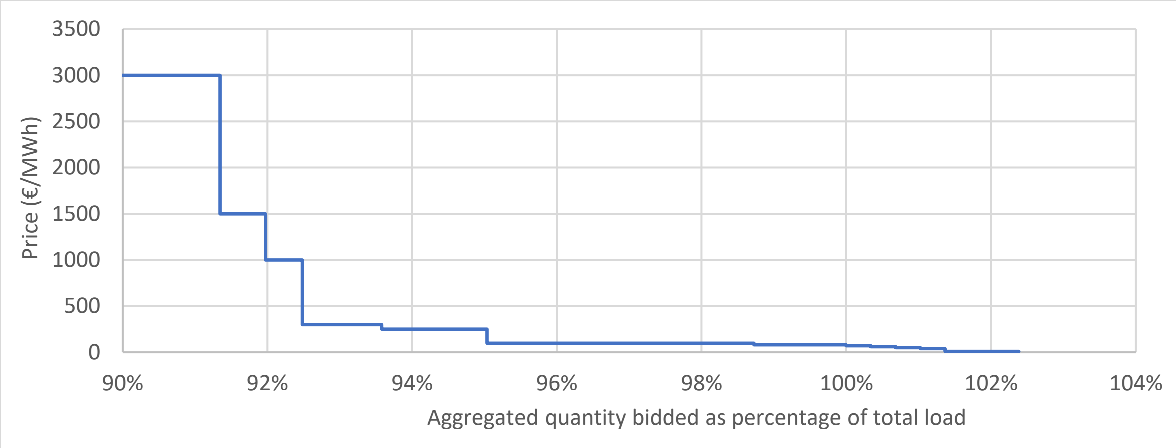

Figure 1. Modelling of aggregated demand curve based on percentage of Elia's total load.

In 2019, Belgium was directly interconnected to five bidding zones: The Netherlands (NL), France (FR), Germany/Luxembourg (DE-LU), and the United Kingdom (UK). The actual cross-border power flows of the modelled day [8] were used to model the imports and exports to or from these zones to Belgium. Each interconnected bidding zone was added to the market clearing model either as a generator or a load (depending on the direction of the flow) with a price bid of 0 or 3000 €/MWh, respectively to ensure that the bids are accepted by the market. These flows were used for all the scenarios.

Regarding the historical prices needed as input for the price-taker storage operation, the DA market clearing prices in Belgium for the modelled days in 2019 were used [8]. Given that the Baseline market modelling tried to replicate the supply and demand conditions of the representative days (including the operation of the existing PHES), the actual DA market clearing prices should approximate the resulting modelling prices. However, due to the impossibility to get exact market information and the presence of some assumptions (made regarding the demand elasticity, imports, exports, and marginal costs) the obtained MCPs are slightly different. The previous results in a ESS operation modelling with imperfect price foresight.

<u>LVRES</u>

The new generation mix was based in the "Large Scale RES" scenario proposed by Elia for 2030 [10]. The previous considered reaching the 2030 European climate targets and added additional renewable energy generation via large-scale projects, which are mainly onshore and offshore wind power. It is also assumed that there is no nuclear capacity due to the nuclear phase-out planned for 2025. Additionally, some old natural gas-based thermal plants are decommissioned. New thermal plants are used to ensure adequacy. The used Elia study proposed the installed capacity per technology for 2030 based on the assumption that demand will increase from the 2019 levels. However, the demand from 2019 was held constant for the purpose of this study. Therefore, the installed capacity was scaled to fit the 2019 demand, maintaining the share per technology in the generation mix proposed by Elia. This was done by calculating the percentage increase in demand foreseen from the present to the 2030 scenario and subtracting it to the percentage increase in installed capacity. The result represents the necessary capacity to cover the Baseline demand given the decommissioning of most of the base generation capacity and the lower capacity factors of VRES in comparison to the thermal plants. Table 1, summarizes the assumptions regarding the generation mix and compares it with the Baselines scenarios.

Table 1 Generation capacity in Baseline and LVRES scenarios

	Baseline		LVRES	
Total Generation (MW)[a]	17,476		23,608	
Capacity by Type (MW)	**Installed Capacity**	**Percentage**	**Installed Capacity**	**Percentage**
Nuclear	5,919	34%	0	0.0%
Biomass	363	2%	833	3.5%
Waste and CHP	1,034	6%	1,815	7.7%
Geothermal	0	0%	95	0.4%
OCGT/CCGT	4,715	27%	5,490	23.3%
Other thermal	553	3%	61	0.3%
Run-of-River Hydro	86	0%	86	0.4%
Wind Offshore and Onshore	1,410	8%	8,770	37.1%
Solar	3,396	19%	6,459	27.4%

[a] Excludes PHES as this is considered as ESS in modelling.

The fuel costs, emission costs, and demand were maintained constant from the Baseline scenario in order to ensure comparability between the scenarios. Although a different generation mix is likely to impact the imports and exports, these were also kept constant to simplify the analysis. To include the effects of generation outages, the 2019 historical outage rate of each generation technology for each modelled day was calculated and assumed to remain constant in the LVRES scenarios.

The historical prices for the ESS operation optimization model of the LVRES scenarios could not be obtained from real data like in the Baseline case. Therefore, the resulting MCPs of the price-maker operation of the biggest existing PHES (Coo 1&2) with the LVRES generation mix was used as input for the model. Said MCPs can be comparable to the historical prices used for the Baseline scenarios because they both consider the generation mix of the scenario and the operation of the existing price-maker PHES capacity.

<u>Storage Levels</u>

Belgium currently has a 1.3 GW capacity of PHES divided in two storage plants, Coo 1&2 and Plate Taille. To assess the inclusion of large-scale ESS, the Baseline and LVRES scenarios described above were ran with no storage, the existing PHES, and three different ESS capacities, which were added considering three separately operated ESS. For the no-storage scenario, all storage, including the existing PHES capacity, was removed from the system. For the Low, Medium, and High storage scenarios, the existing PHES capacity was modelled next to 100, 500, and 1000 MW of new storage capacity in the form of Lithium-ion BESS with a four-hour duration, respectively. The duration represents a common upper limit for the chosen technology, and it was chosen based on literature's suggestion that the discharge duration should be between three and ten hours to better capture the benefits of energy arbitrage [1].

Given the 24-hour modelling timeframe, all ESS were assumed to have daily cycles, starting the day at their recommended DoD, which represents an empty storage. Table 2 shows which of these plants were considered to be active in each storage level scenario.

Table 2. Active ESS and total capacity for each storage level scenario

Storage Level	Coo1 & 2	Plate Taille	ESS 1	ESS 2	ESS 3	Total Storage Capacity (MW)
No Storage	✕	✕	✕	✕	✕	0
Existing PHES	✓	✓	✕	✕	✕	1300
Low	✓	✓	✓	✕	✕	1300 + 100
Medium	✓	✓	✓	✓	✕	1300 + 500
High	✓	✓	✓	✓	✓	1300 +1000

Key Performance Indicators

The Key Performance Indicators (KPIs) shown in Table 3 were calculated for each scenario.

Table 3. Key performance indicators

KPI	Explanation
SEW	The overall benefit that arises from trading, equals the sum of consumer and producer surplus.
Consumer surplus (CS)	Benefit resulting from the difference between the amount that consumers are willing and able to pay for electricity (demand curve) and the market-clearing price.
Producer Surplus (PS)	Benefit resulting from the difference between the minimum price for which suppliers are willing to sell (assumed to be production costs) and the market-clearing price.
ESS Net Revenue (ESS R)	Net revenue resulting from the storage operation, considering charging and discharging costs.
Market-clearing prices (MCP)	Price in €/MWh at which demand equals supply.

For the purpose of this analysis, the SEW was calculated following the formulation used by Sioshansi [11] where the SEW is separated in consumer surplus, producer surplus, and ESS net revenue as shown in Equation 3a. The calculation of each of the mentioned elements composing the SEW is shown in Equations 3b to 3d. Separating the ESS net revenue from the consumer and producer surplus allows to better analyse the effect of storage in non-ESS market players.

$$SEW = PS + CS + ESS\ R \tag{3a}$$

$$PS = \sum_{t\in T}\left(\sum_{s\in S}\left(\lambda_t * Qs_{s,t}\right) - \left(Ps_{s,t} * Qs_{s,t}\right)\right) \tag{3b}$$

$$CS = \sum_{t\in T}\left(\sum_{d\in D}\left(Pd_{d,t} * Qd_{d,t}\right) - \left(\lambda_t * Qd_{d,t}\right)\right) \tag{3c}$$

$$ESS\ R = \sum_{t\in T}\left(\sum_{n\in N} \lambda_t\left(Qdis_{n,t} - Qch_{n,t}\right)\right) \tag{3d}$$

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