Supplementary Materials for the construction of the Belgian System in 2030

Aurélia Hernandez

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1 Different database used

1. [1]: **20181231-grid-statc-data-.xslx** The grid topology can be found on Elia website. Th excel file gives information about lines, interconnections with neighboring countries, and transformers. Hereunder are listed the parameters given in this excel file:

    - Lines parameters: Voltage U [kV], length [km], nominal current Inom [A], line resistance R [ohm], line reactance X [ohm], shunt admittance wC [µC].
    - Interconnections parameters: Voltage U [kV], length [km], nominal current Inom [A], line resistance R [ohm], line reactance X [ohm], shunt admittance wC [µC].
    - Transformers parameters: Voltage U [kV], primary voltage V1 [kV], secondary voltage V2 [kV], tertiary voltage V3 [kV] (optionnal), primary nominal power P1 [MVA], secondary nominal power P2 [MVA], tertiary nominal power P3 [MVA] (optional), primary short-circuit impedance Zcc1 [%], secondary short-circuit impedance Zcc2 [%], tertiary short-circuit impedance Zcc3 [%] (optional), minimum tap [#], nominal tap [#], max tap [#].

    This database enumerates 93 lines, 12 interconnections, and 67 transformers.

2. [2]: **20221028_AssumptionsWorkbook_AdFlex_2023_PublicConsult.xlsx** The generators data can be found on Elia website. This excel file gives informations about the owner, the type of unit, the fuel type, the net generation capacity [MW], and the existence (nor not) of the unit for the next ten years.

3. [3]: **The Elia High Voltage Grid Map 2022** This map allows to visualize the existing lines, substations, and generators.

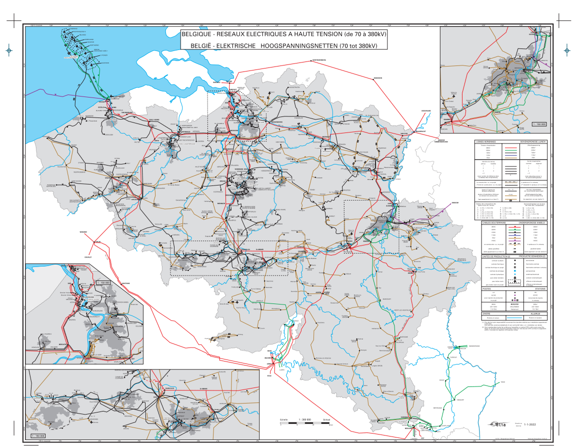


Figure 1: The Elia High Voltage Grid Map 2022

4. [4]: **Adequacy and Flexibility Study for Belgium 2024-2034** This report gives a lot of data concerning installed capacities for the 2030 horizon.

2 Electrical System

2.1 Construction of the grid topology

The Belgian high voltage transmission grid is composed of 380 and 220 kV lines.

Historically, the high voltage network was composed of 150 kV lines, except for lines connecting the south of the country and covering long distances. These latter were 220 kV lines. When nuclear power plants were built, the 380 kV network begun to be deployed. This is why, in Belgium two level of high voltage lines coexist.

– checker age des lignes pour avoir les dates

From the databases listed above, a realistic Belgian transmission network was built:

2.1.1 Buses of the network

The buses have been defined from the lines data [1]: *from* buses and *to* buses. Moreover, the following modifications have been brought:

- Duplicate the nodes that are at the 220/380 kV networks interface :
  - *Aubange (AUBAN)* has been split into *Aubange 220 kV (AUBAN220)*, and *Aubange 380 kV (AUBAN380)*.
  - *Lixhe (LIXHE)* has been split in *Lixhe 220 kV (LIXHE220)*, and *Lixhe 380 kV (LIXHE380)*.
  - *Rimière (RIMIE)* has been split in *Rimière 220 kV (RIMIE220)*, and *Rimière 380 kV (RIMIE380)*.
- Merge nodes
  - All Tihange substations (*TIBIS, TIHA1, TIHA2, TIHA3*) have been merged into one bus: *TIHA1*
  - *Achene SNCB (ACHES)* has been aggregated to *Achène (ACHEN)*
  - *André Dumont* has been aggregated to the *Zutendaal (ZUTE+)* station.
  - *Drogenbos (DROGE)* has been aggregated to *Mekingen (MEKI+)*.
  - *RODEN* substation has been merged with to *RODE+*
  - *Tergnée (TERGN)* has been aggregated to *St-Amand STAM+*
  - *Heinsh (HEINS)* aggregated to *Aubange (AUBAN220)*
  - *Houffalize (HOUFF, and HOUF+)* substations to *Brume (BRUME)*.
  - *Latour (LATOU, LATO+)* to *Aubange 220 (AUBAN220)*.
  - *Marcourt (MARCO, and MARC+)* to *Aubange 220 (AUBAN220)*
  - *Romssée SNCB (ROMSS)* to *Romsée (ROMSE)*
  - *Rouvroy (ROUVR)* to *Aubange 220 (AUBAN220)*
  - *St mard (SMARD, SMARS)* to *Aubange 220 (AUBAN220)*.
  - *La Troque (ATRO)* to *Seraing (SERAI)*
  - *Le Val (LEVAL)* to *Seraing (SERAI)*.
- Add nodes:
  - The 220 kV node *BERNEAU (BERN)* is not in the database [1] but is present on the grid if we look at the Elia Grid Map [3]. It has thus been added.

The resulting buses are listed in Table 12 and 13.

2.1.2 Branches of the network

Branches are defined as assets linking two busbars, i.e. transformers and transmission lines. The lines listed in [1] are set as branches. However, the following modifications have been brought.

- Add lines:
  - The 220 kV line connecting *Jupille* to *Berneau* is not in the database [1] but is present on the grid if we look at the Elia Grid Map [3]. Supposing, the line is 30 km long, and has the same per length characteristics than lin ... , The following characteristics have been set:
- Remove lines:
  - When merging nodes together, some lines have to be removed as well.
- Add transformers:
  - all 380/220 step-down transformers are extracted: as they connect 380 and 220 kV lines at one node: with the corresponding characteristics: X (ohm) = Zcc (ohm).

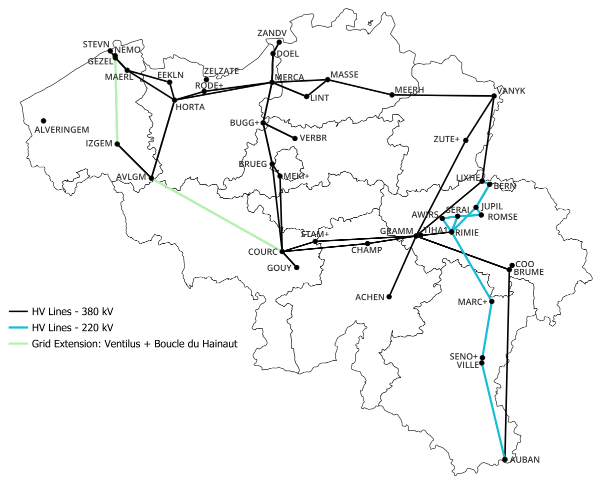


Figure 2: Belgian High Voltage Grid (220 & 380 kV)

The topology (buses, and lines) of the built model illustrated in Fig. 2.

2.1.3 HVAC and HVDC interconnections other countries

The HVAC lines crossing the border are listed in [1]. Additionally, two HVDC lines exist: NemoLink (Belgium - UK: 1GW), and ALEGrO (Belgium-Germany: 1GW).

2.1.4 Outages

The outages of branches (transformers and internal lines) and interconnections (tielines) are considered in this study. Their MTTR and MTTF are defined thanks to data from Elia [5] and are summarized in Table 1. The transformers MTTR/MTTF are based on only 3 components that have failed with a very large spread of outage durations (2 outages of $\sim$ 3 months): the fact that few data is available and that some seem extreme, the MTTR/MTTF of the transformers will be based on internal lines instead.

Table 1: Outages of 220/380 kV components from Elia database [5] that studies a period of $\sim$ 9 years (77344 hours).

[a]**220/380 kV components**	[a]**Existing comp.** [1]	[a]**Failed comp.**	**Total outages**	**MTTR** [hours]	[b]**MTTF$_{\text{failed}}$** [hours]	[c]**MTTF$_{\text{no failed}}$** [hours]	[d]**MTTF** [hours]
Internal lines	90	18	27	26	57606	77344	73397
Transformers	67	3	9	547	27838	77344	75128
Tielines (HVAC)	12	6	9	84	44807	77344	61076
Tielines (HVDC)	2	2	18	24	3287	77344	3287

[a] excludes the lines going from Stévin towards the offshore wind farms.
[b] the mean duration between two failures of an asset (concerns the assets that have failed on the studied period). If an asset fails only once, the MTTF = studied period.
[c] it is assumed that the assets that haven't failed have a MTTF = studied period.
[d] The MTTF is a weighted sum of both MTTF$_{\text{failed}}$, and MTTF$_{\text{no failed}}$.

2.2 Conventional Production Units

2.2.1 Large-scale Conventional Generators

The units that are taken into account in this study are the units that will be operational in 2030 and listed by Elia in [2]. For each generator, the following data is available: unit type (TJ: Turbo-Jet, CCGT: Combined Cycle Gas Turbine, GT: Gas Turbine, T: Steam Turbine, CHP: Combined Heat and Power, IS: incinerator, NU: nuclear) - fuel type (Oil, Gas, Biomass, Waste, Uranium) - generation capacity [MW] - efficiency [%] - VOM (variable operations and maintenance) costs [€/MWh].

- The distribution of the generation units among the different nodes of the system has been done manually thanks to the Elia Grid Map [3].

- The variable operational costs of the large-scale conventional generators modeled individually is the sum of the fuel cost, the cost of emissions, and the VOM.

$$\begin{aligned}
\text{Variable cost } [€/\text{MWh}_{\text{elec}}] &= \frac{\text{fuel cost } [€/\text{MWh}_{\text{fuel}}]}{\text{efficiency } [\text{MWh}_{\text{elec}}/\text{MWh}_{\text{fuel}}]} \\
&+ \frac{\text{carbon price } [€/\text{t}_{\text{CO}_2}] \times \text{CO}_2\text{emission factor } [\text{t}_{\text{CO}_2}/\text{MWh}_{\text{fuel}}]}{\text{efficiency } [\text{MWh}_{\text{elec}}/\text{MWh}_{\text{fuel}}]} \\
&+ \text{VOM } [€/\text{MWh}_{\text{elec}}]
\end{aligned} \tag{1}$$

- The fuel costs are defined in Table 2 and the carbon price in Table 3. In both tables, several sources are given. The chosen numbers are the

Fuel	Corresponding Name	Source	Cost in 2030 [ref 2021]	[€/MWh]	Cost in 2030* [ref 2022]* [€/MWh]
Gas	Natural Gas in EU	WEO 2022 - AP	7.9 USD2021/MBtu	25.67	28.14
	Natural Gas - NT*	TYNDP 2022	6.23 €/GJ	22.43	24.58
	Natural Gas - DE&GA**	TYNDP 2022	4.02 €/GJ	14.47	15.86
Oil	IEA Crude Oil	WEO 2022 - AP	64 USD2021/barrel	35.85	39.30
	Light Oil	TYNDP 2022**	81.92 USD2021/barrel	45.89	50.30
Waste	-	-	-	-	-
Biomass	-	-	-	-	-
Uranium	Nuclear	TYNDP 2022	0.47 €/GJ	1.69	1.85
H2*	Renewable H2 - NT	TYNDP 2022	20.25 €/GJ	72.90	79.90
	Renewable H2 - DE&GA	TYNDP 2022	20.63 €/GJ	74.27	81.40
	Decarbonised H2 - NT	TYNDP 2022	20.25 €/GJ	72.90	79.90
	Decarbonised H2 - DE&GA	TYNDP 2022	17.11 €/GJ	61.60	67.51

Table 2: Prediction of fuel costs for 2030.

Fuel	Corresponding Name	Source	Cost in 2030 [ref 2021]	[€/t_{CO_2}]	Cost in 2030* [ref 2022]* [€/t_{CO_2}]
CO2	CO2	WEO2022	135 [USD_{2021}/t_{CO_2}]	114.40	125.38
	CO2 - NT	TYNDP 2022	70 [€/t_{CO_2}]	70.00	76.72
	CO2 - DE&GA	TYNDP 2022	78 [€/t_{CO_2}]	78.00	85.49

Table 3: Prediction of CO_2prices for 2030.

- The carbon price for 2030 is taken from the Announced Pledges Scenario in the 2022 World Energy Outlook (WEO) report [6], as 135 [$\text{USD}_{2021}/\text{t}_{\text{CO}_2}$] = 114.4 [€/$\text{t}_{\text{CO}_2}$] if we consider a USD/€exchange rate of 1.18 in 2021. The CO_2 emission factor fo each fuel type from originating from two different sources is detailed in Table 4.

Fuel	IPCC 2006 [7] Corresponding Name	kg CO2/kWh	UBA 2022 [8] Corresponding Name	kg CO2/kWh
Gas	Natural Gas	2.03E-01	Natural Gas Germany	2.01E-01
Oil	Kerosène	2.59E-01	Kerosène	2.64E-01
Waste	Municipal Waste (non-biomass)	3.50E-01	Household waste, municipal waste	3.29E-01
Biomass	Wood / Wood waste	4.09E-01	Wood waste, residual wood (industry)	3.88E-01
Uranium	-	-	-	-

Table 4: Emission factors

- From the average forced outage rates (FOR) and the average repair time (MTTR) of the different units defined by Elia in [4] and detailed in Table 5, the mean-time-to-failure (MTTF) can be derived with the following relation: $\text{FOR} = \frac{\text{MTTR}}{\text{MTTR}+\text{MTTF}}$.

Unit Type	Average FOR [4] [%]	MTTR [4] [hours]	MTTF [hours]
Nuclear	4*-20.5**	199	4776-771.73
CCGT	5.5	110	1890
OCGT	8.2	221	2474.12
TJ	9.8	130	1196.53
CHP, waste, biomass	6.4	111	1623.37

Table 5: Forced outage rate (FOR), mean-time-to-repair (MTTR) and mean-time-to-failure (MTTF) of different units. *Only considering technical forced outages. **Also considering long-lasting forced outages

The data is summarized and listed in Table 26 and 27.

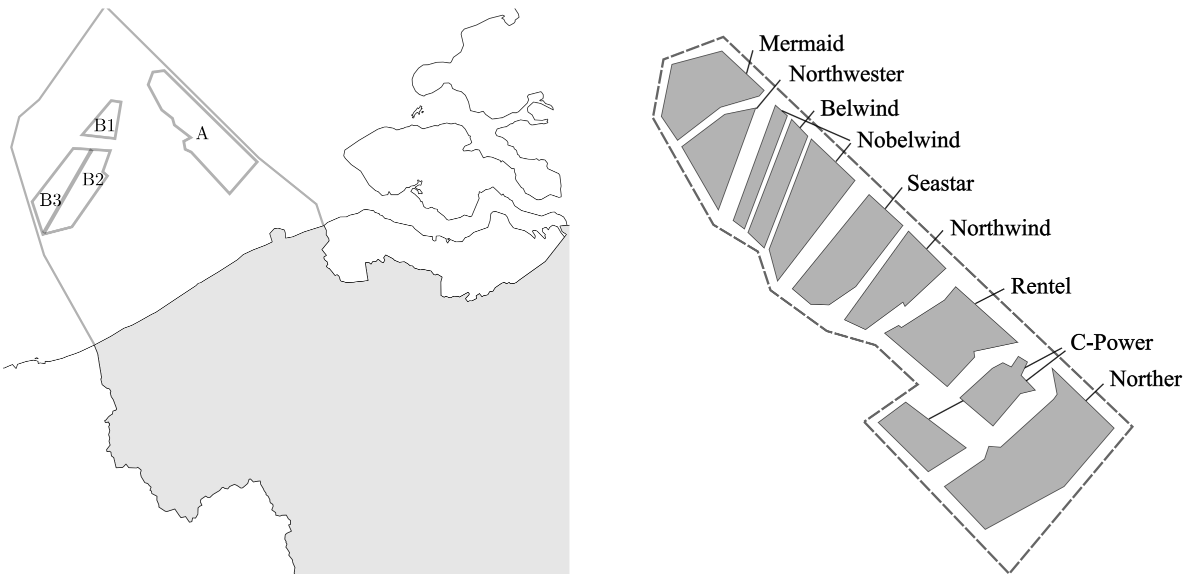
2.2.2 Distributed conventional units

Small distributed conventional units are also considered in this study, but in an aggregated manner. Their total installed capacity is defined by [4] and totals 1.9 GW. Following the same hypothesis as Elia, three types of units are considered: small gas CHPs (1379 MW), biomass units (503 MW), and waste units (46 MW). They are forced to operate at a constant load factor of 60 % throughout the year. This corresponds to a constant production of 1.14 GW in every hour of the year. It is supposed that its nodal distribution is similar to the load one.

2.3 Renewable Energy Sources

2.3.1 Offshore Wind Farms

In the Belgian waters, 9 wind farms next to one another (see Fig. 3b) are present today, with a total amount of 2262 MW of installed capacity [9]. They are all connected to the Stevin substation.



(a) Zone A: existing - Zone B: Princess Elisabeth Zone (PEZ), to be constructed.

(b) Zoom on existing wind farms (Zone A)

Figure 3: The planned belgian offshore wind farms for 2030.

New wind farms are planned for installation in a new area called Princess Elisabeth Zone (PEZ), as shown in Fig. 3a [10]. It is assumed that this new zone will consist of 15 MW wind turbines, totaling 3500 MW: a first zone with 728 MW (49 turbines), and a second and third zone with a combined total of 2782 MW (185 turbines). These are detailed and listed in Table 17.
The MTTF and MTTR values for each single wind turbine is taken from a study [11].

Table 6: Failures rates, and mean time-to-repair for offshore wind turbines [11].

	Minor Repair	Major Repair	Major Replacement	All
Share	-	-	-	
Lambda [/turbine/year]	5.73	0.89	0.13	6.75
Repair time [hours]	16.11	82.16	498.58	34.21
MTTF [hours]	1528.8	9842.7	67384.62	1297.78

The number of failures per year regardless the severity is $\lambda = 5.73{+}0.89{+}0.13 = 6.75$ [failures/turbine/year]. The average repair time, considering the occurrence of each severity, is MTTR $= 34.21$ [hours]. From this, can be derived the MTTF $= \frac{8760}{\lambda} = 1297.78$ [hours].

2.3.2 Distributed Onshore Wind Turbines and Photovoltaic Panels

The forecast installed capacities for 2030 are 14.1 GW for photovoltaic and 5.3 GW for onshore wind turbines according to Elia [4].

It is assumed that the geographic distribution of future onshore wind turbines and photovoltaic capacities will be similar to the situation in mid-year 2022. The existing capacities of onshore wind turbines and photovoltaic are provided by province in [12] and [13] respectively and summarized in Table 7. To convert this provincial distribution to a nodal distribution, we follow this method: the installed capacity of a province is evenly distributed among each node of the system located within that province, provided the node is connected to a distribution network (excluding transfer nodes). For example, if x % of onshore wind turbines are installed in th province of Antwerp, and there are 4 distribution-connected nodes in that province, each node will be assigned x/4 % of the wind capacity. The nodal distribution is referenced in Table 12 and 13.

Table 7: Distribution of PV [13] and onshore wind power [12] at mid-year of 2022

Region	Abbreviation	Onshore Wind Turbines Installed Power [MW]	[%]	Photovoltaics Installed Power [MW]	[%]
Antwerpen	Antw	324.91	10.76	1402	19.51
Brabant wallon	BW	95.9	3.18	136	1.89
Hainaut	Hain	537.95	17.82	508	7.07
Liège	Liège	297.705	9.86	746	10.38
Limburg	Limb	313.6	10.39	759	10.56
Luxembourg	Lux	104.8	3.47	162	2.25
Namur	Nam	345.05	11.43	212	2.95
Oost-Vlaanderen	OV	674.05	22.33	1421	19.77
Vlaams-Brabant	VB	60.3	2.00	665	9.25
West-Vlaanderen	WV	264.86	8.77	1175	16.35
Total		3019.125	100.00	7186	100.00

2.3.3 Distributed Run-of-River Hydroelectric Generation Plant

This work is based on Antoine Gaignage's research.

According to *energie commune*, Belgium had 124 MW of hydro power installed, and distributed on 176 sites (119MW in Wallonia and 6 MW in Flanders) at the end of 2022. In Wallonia, 15% of the installed capacities are dams, and 85% run-of-river units.

2.4 Electrical Imports

Belgium has today, 12 HVAC and 2 HVDC connections with neighboring countries. In the ERAA 2023 study conducted by ENTSOE, the Net Transfer Capacity (NTC) [1] of the belgian interconnections with its neighbouring countries are listed in Table 8.

Table 8: Net Transfer Capacities for Belgium in 2024 [14]

Country	Bidding Zone	Imports	Exports	Type
France	FR	4300	2800	HVAC
Netherlands	NL	3400	2400	HVAC
Luxembourg	LUG1+LUB1	180	680	HVAC
Germany	DE	1000	1000	HVDC
United Kingdom	UK	2400	2400	HVDC

Although we have a single NTC between regions, multiple buses in the system can connect Belgium to another region, and several import points exist. To allocate the NTC to the different import points linking a particular region , we can distribute it proportionally based on the line capacities. The parameters of the individual HVAC lines are given in [1]. For each of these interconnections, we have the voltage level [kV] and the nominal current [A]. The theoretical maximum loading of these lines can be obtained by multiplying each nominal current by $\sqrt{3} * U_{nom}$. The parameters of the HVDC

[1]defined as NTC = TTC - TRM. Total Transfer Capacity (TTC) is the maximum exchange program between two adjacent control areas that is compatible with operational security standards applied in each system if future network conditions, generation and load patterns are perfectly known in advance. Transmission Reliability Margin (TRM) is a security margin that copes with uncertainties on the computed TTC values.

lines is not necessary because their nominal power is directly given. The existing HVDC lines are Alegro (Germany - 1 GW), and NemoLink (UK -1 GW). New interconnections are planned to be constructed in 2030, like the subsea hybrid interconnector between Belgium and the UK *Nautilus* which will interconnect on a first segment Belgium and the energy island (1.4 GW - HVDC), and on a second segment, the energy island and the UK (1.4 GW - HVDC). These theoretical maximum loadings will help us distribute the NTC among the different import points.
This sums up to 15 interconnections with neighboring countries which are identified and listed in Table 18. For each connections, additional data is required [2]: the import price, the maximum yearly energy imported at each connection, the mean-time-to-failure (MTTF), and mean-time-to-repair (MTTR).

2.4.1 Maximum yearly imports

A yearly maximum quantity of electricity is set for each interconnection. By analyzing the physical flows between Belgium and its neighboring bidding zone (France, Germany, Luxembourg, Netherlands, United Kingdom) for the last three years (2021,2022,2023) [15], we can extract the yearly quantity of electricity imported from each region, see Table 9. We select the maximum value for each region. However, multiple interconnections link the same regions, and thus to allocate a maximum value per interconnection, we can distribute it proportionally based on the line capacities. Concerning the new HVDC line Nautilus, we will authorize the same quantity as NemoLink multiplied by 1.4 (pro rata of th installed capacity).

Table 9: Yearly Imports [TWh] of Belgium with neighboring countries [15]

	Imports [TWh]		
	2021	**2022**	**2023**
France	4.35	0.85	7.59
Netherlands	5.24	6.23	6.21
United Kingdom	0.14	2.52	0.98
Luxembourg	0.06	0.11	0.04
Germany	2.57	3.23	2.47
Total	12.35	12.94	17.30

2.4.2 Maximum simultaneous imports

According to the [14] the maximum NTC position for Belgium in 2030 will be 2000 MW for exports and 8272 MW for imports.

2.4.3 Import price and import availabilities

Thanks to the wholesale day-ahead electricity price data for European countries, sourced from ENTSO-e and cleaned by [16], hourly prices are available for each region between 2015 and today [3]. Two alternatives of considering imports availabilities and prices [4] are proposed: Max and Random.

- Max: For each interconnection i, and each hour of the year t, we define a price c_{imp} by averaging the prices of the different years of the considered region:

$$c_{imp}(i,t) = \frac{\sum_{y \in \mathbb{HY}} \text{price}(re(i), y, t)}{n_{hy}} \tag{2}$$

  with price(r,y,t) being the price for region re, year y, and hour t, and $\mathbb{HY}$ the set consisting the n_{hy} different historical years. This results in a fixed hourly time serie for each interconnection depending on the region of interconnection. For each Monte Carlo year, we add to this time series a white noise. This white noise has a normal $\mathcal{N}(0, \sigma)$ with $\sigma = ...$ based on historical data.

[2] which has mainly collected by Thuy-hai Nguyen.
[3] The studied period is 01/01/2015 00:00:00 to 01/03/2023 00:00:00. Moreover, years 2021 and 2022 are excluded because way different than the others.
[4] The prices resulting from both methodologies has been proposed by my collegue Thuy-hai Nguyen.

Outages are considered with their respective MTTF/MTTR and imports are permitted at all time (price-signal) if the interconnection is available. As mentioned in section 2.1.4, for HVAC interconnections, the MTTR is set to 84 hours, and the MTTF to 61 076 hours. For the HVDC interconnections, the MTTR is set to 24 hours, and the MTTF to 3287 hours.

- Random: A single price per interconnection (similar for interconnections with the same region) constant all over the year. This price is the mean value of averaged day ahead price:

$$c_{imp}(i,t) = c_{imp}(i) = \frac{1}{8760}\sum_{t=1}^{8760}\frac{\sum_{y\in\mathbb{HY}}\text{price}(re(i),y,t)}{n_{hy}} \tag{3}$$

In this case, it is supposed that half of the year the interconnection is dedicated for imports, and the other half for exports. This gives a yearly availability of 50%. More over, during the available periods, we consider a uniform distribution of the neighbors available capacity [0,100] %. Thus, it sums to a yearly availability of 25%. To do so, we generate a random time series of 8760 elements between -1 and 1. The negative values are set to zero.

2.5 Storage

2.5.1 Pumped-Hydro-Storage

Two pumped-hydro storage are considered for Belgium:

- Coo power station can provide 1080 MW for six hours, with a start-up time of under two minutes [17]. So a storage capacity of 6*1080 = 6480 MWh. The round-trip efficency of the power station is 75% meaning that the input/output efficiency is of 86.6%.
- Plate-Taille power station can provide 144 MW and has a hydro reservoir capacity of 67.8 million m^3. [Trouver sources et données pour le potential energie] [18]. Ces deux données viennet de adequacy fx elia :

The data is grouped in Table 19.

2.5.2 Batteries

In [4], batteries are divided in two categories: 1) Large-scale batteries (industrial projects) whose charging/discharging profile is optimised within the formulation and 2) Small-scale batteries, also called residential batteries, which have can either have a predefined charging/discharging profile depending on the PV production, or an optimized operation just like large-scale batteries. It is assumed that in 2030, all residential batteries will have a market dispatch. The installed power and energy capacity of these two categories are referenced in Table 10. Also, all of the batteries are considered to have a round-trip efficiency of 85% which means an input/output efficiency of $\sqrt{85} = 92.19\%$

	Large-scale			Small-scalle	Total
	In service	Potential New Capacities	All	All	All
Total Power [MW]	330	2140	2470	511.5	2981.5
% of 2-hours duration	66.4	0	8.9	100	24.5
% of 4-hours duration	33.6	100	91.1	0	75.5
Energy [MWh]	881.4	8560.0	9441.4	1023	10464.4

Table 10: Large-scale and small-scale batteries for Belgium in 2030 - Elia estimation [4]

It has been assumed that their locations is distributed among all the industrial hubs (Gent, Antwerpen, Brussels, Hainaut, Liège) and at the shore (Zebrugge) equally. The details ar provided in Table 20.

2.6 Electrical demand

According to [4], the annual electrical demand in 2030 reaches 112.8 TWh. This ”englobe” the traditional electrical usage supposing to increase, the additional demand for industry heat, electric vehicles, heat-pumps, and electrolyzers. Because in the model used in this work, electric vehicles, heat pumps, and electrolyzers are treated as a different type of demand, they can be substracted from the total annual demand: 112.8 [TWh] - 5.13 [TWh] (EVs) - 2.9 [TWh] (HPS) - 0.6 [TWh] (electrolyzers) = 104.17 [TWh]. This annual electrical demand has to be distributed in the time (among the hours of the year) and space (among the different nodes of the system) dimensions.

2.6.1 Time distribution methodology

The hourly distribution of the annual demand is based on the total load time series of 2018 available online on Elia's data platform.

2.6.2 Space distribution methodology

Three types of transformers [5] connected to the VHV grid are identified and categorized as follows:

i) Phase shifters: when the high voltage side (380 or 220 kV) is equal to the low voltage side of the transformer.

ii) Step-down 380/220 transformers: when the high voltage side is 380 kV and the lower side is 220 kV, the transformer permits the connection of 380 and 220 kV lines.

iii) Load feeders: when the high voltage side is 380 or 220 kV and the lower side 150 kV or lower, then the transformer is a step-down transformer used to feed a load.

The load is then distributed to the pro-rata of the installed capacities of load feeders transformers (iii) at each node. An exception is made for the node Stevin where a consequent capacity (1260 MW) of ¡150 kV transformer are installed which are not load feeders per se. The installed power of load feeders are available in Table 12 and 13 and the corresponding load share as well.

2.6.3 Load Shifting

A certain quantity of load shifting is permitted. The quantity is limited in energy on a daily basis, and in power. The quantities are based on th studey .... : ... MWh/day and MW.

2.6.4 Voluntary Load Shedding

Voluntary shedding is authorized. This accounts for consumers that agree to curtail their demand, and diconnect from th grid in exchange with money.

2.7 Electric Vehicles

Electric vehicles are taken into account in this study. A total of 1.9 millions of EVS are planned to be in circulation by 2030 according to [4]. The annual demand from the EVs is calculated with the following assumptions [4]: cars travel 15000 [km/year], with a consumption of 18 [kWh/100 km]: 1.9 M x 15000 [km/year] x 0.18 [kWh/km] = 5.13 [TWh/year]. This annual demand is distributed equally among the days of the year ($\sim$14 GWh/day). However the distribution among the hours of the day is not uniform, and depends on the EV type.

Four types of electric vehicles can co-exist depending on their charging behavior :

1. V0: natural charging profile (pre-defined time series) with a peak in the evening (plain line in Fig. 4)
2. V1H: delayed charging profile (pre-defined time series) with a peak in the middle of the night (dashed line in Fig. 4)
3. V2H: bi-directional charging profile (pre-defined time series) where the EV has a battery behavior, charging during the night and restituting during the evening (dashdotted line in Fig. 4)
4. V1M: smart charging profile (result of the optimisation) concerning EVs that are flexible and produce optimally during the day. The share of the smart EV fleet connected to a flexible charger during the day is not constant and represented in Fig. 5.

[5] Transformers can be constituted of 2 or 3 windings. If three windings, the HV side is unique, and there exist two LV sides.

The following share is considered in 2030 according to [4] - V0: 30 % - V1H: 45 % - V2H: 4% - V1M: 21% [6]. Also, flexible chargers are supposed to have a power of 7 kW. The repartition among the nodes is set identical to the PV distribution.

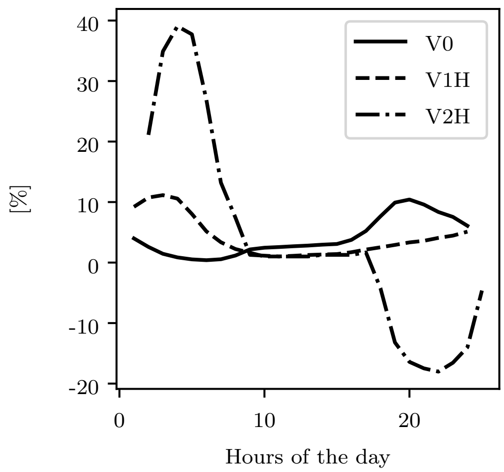


Figure 4: V0 (classical) and V1H (smart) charging profiles [4].

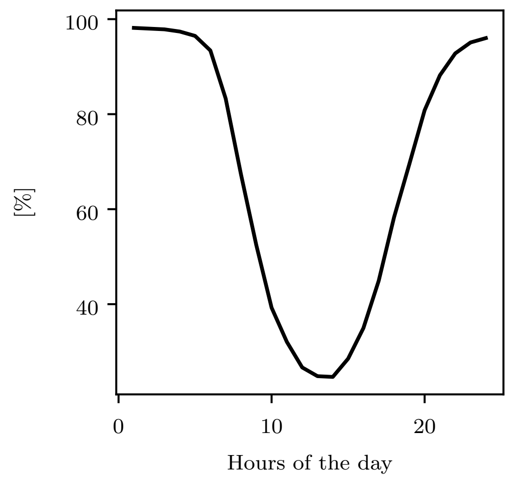


Figure 5: Share of the flexible EV fleet connected to a flexible charger during the day [4].

Their nodal distribution is considered to be similar to the photovoltaic distribution and is referenced in Table 12 and 13.

2.8 Heat-Pumps

Heat-pumps are taken into account in this study. A total of of 1.2 million heat-pumps are considered to be in operation by 2030 according to [4]. An annual demand of 2.9 [TWh/year] for the HPs operation is taken from [4]. This annual demand is distributed among the different months as shown in Fig. 6 and the distribution among the hours of the day depends on the HP type.
They are splitted into 3 categories depending on their behaviors:

1. HP0: natural profile (pre-defined time series) with a peak in the morning, and in the evening (plain line in Fig. 7)
2. HP1H: pre-heated profile (pre-defined time series) with an additional peak (compare to HP0) during the day, which reduces the evening peak (dashed line in Fig. 7)
3. HP1M: smart profile (result of optimisation) concerning HPs that are flexible and produce optimally during the day.

The following share is considered in 2030 according to [4] - HP0: 59 % - HP1H: 31 % - HP1M: 10%. Also, flexible HPs are supposed to have a thermal power 10 [kW_{th}], and a COP of 3 which amounts to an electrical power of 3.33 [kW].The repartition among the nodes is set identical to the PV distribution.

[6] In the study [4], smart vehicule-to-grid is also considered (V2M). However, the model used in this work does not permit V2G. Thus the share of V2M (1%) is given to the V2H category(3% $\longrightarrow$ 4%).

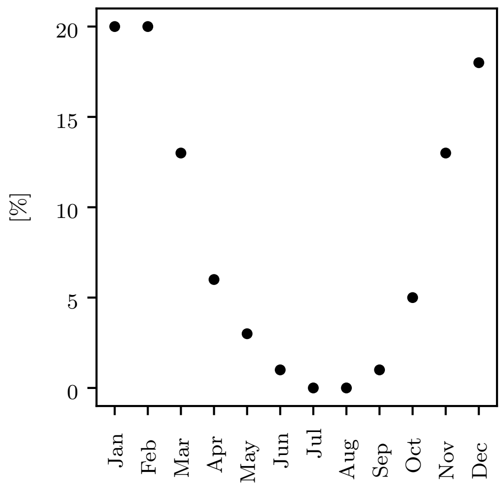


Figure 6: Monthly distribution of annual heat-pump demand inspired by [4] (simplification applied)

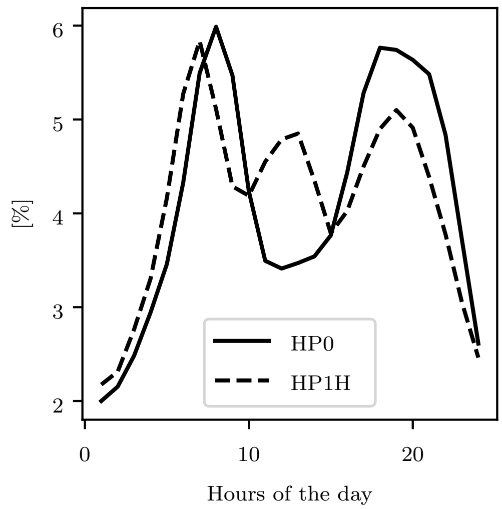


Figure 7: HP0 (classical) and HP1H (smart) charging profiles [4].

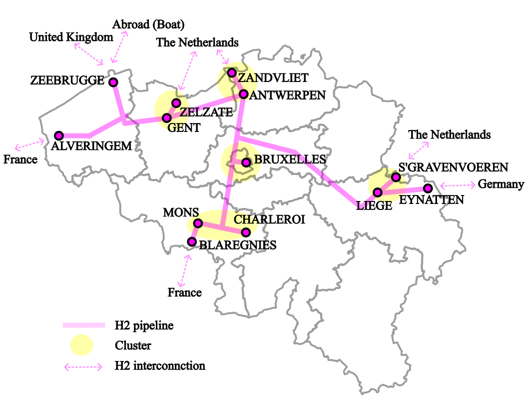
Their nodal distribution is considered to be similar to the photovoltaic distribution and is referenced in Table 12 and 13.

3 Hydrogen System

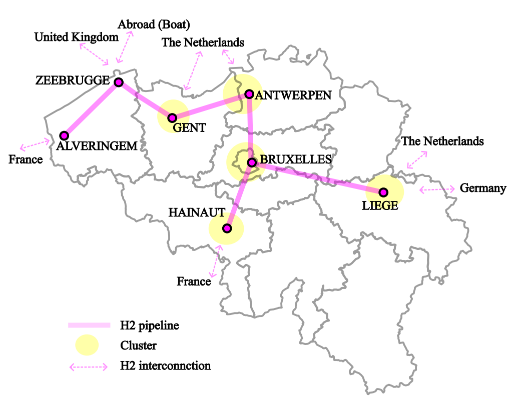
A future hydrogen system has been built:

- The hydrogen system is designed based on a document published by Fluxys [19] where they propose a first short-term (2030) network deployment for constructing the European Hydrogen Backbone, as illustrated in Fig. 8a. This network has been simplified using the following assumptions:
  - Clusters are grouped in one node
  - Pipelines joining elsewhere a node location are deviated towards a node
  - Eynatten considered in Liège cluster
  - Blaregnies considered in Hainaut cluster

  and can be visualized in Fig. 8b.



(a) Short-term option fo the deployment of the hydrogen backbone from Fluxys [19]



(b) Simplified hydrogen backbone considered for this work

Figure 8

The nodes of the hydrogen network are assigned to an existing node of the electrical system if there is:

- Alveringem: no corresponding node in area thus creation of a new node
- Zeebrugge: connected to Stevin (STEVN) node
- Gent: connected to Rodenhuize (RODE+) node
- Antwerpen: connected to Meractor (MERCA) node
- Bruxelles: connected to Bruegel (BRUEG) node
- Hainaut: connected to Houy (GOUY) node
- Liège connected to Rimière 220 (RIMIE220) node.

Moreover, based on the hydrogen pipelines specifications in [20] and summarized in Table 11, it assumed that the short-term hydrogen network deployment will consist in medium repurposed pipelines with a capacity of 3.6 GW. The hydrogen pipelines can be found in Table 21.

Table 11: Hydrogen pipelines specifications for the European Hydrogen Backbone [20]

Type		Capacity [GW]	Pressure operation [bar]
Small	new	1.2	50
	repurposed	1.2	50
Medium	new	4.7	50
	repurposed	3.6	50
Large	new	13	80
	repurposed	13	80

- Electrolyzers: Their installed capacity sum up to 447 MW according to Elia's study. We suppose that they are installed at shore (Zeebrugge), and at industrial hubs (hydrogen clusters): Gent, Antwerpen, Brussels, Hainaut, Liège with an even distribution. Their specificities can be found in Table 23.

- Hydrogen demand for 2030 can be derived in multiple ways:

  1. End-use demand method: Today, hydrogen is used as a primary feedstock in the industry sector for the production of end-use demands such as: the high-value chemicals (HVC), methanol, and ammonia. To derive the hydrogen demand from these end-use demands, various assumptions about the processes involved and their efficiencies has to be made.
  2. Models method: Future hydrogen demands are derived by several studies for 2050, this including the industrial demands, but also other end-use demands from the electricity, heat, or mobility sectors that could be satisfied by hydrogen in the future. Usually, these reports define a demand for 2050, so a linear interpolation shall be made for the 2030 demand.
  3. Up-bottom approach: Today's hydrogen demand is estimated at ... Mt, and it can be supposed that this demand will remain constant till 2030.
  4. The hydrogen demand has been estimated for very country in the world for 2050 in [21] based on the *Net Zero scenario of IEA in 2050* [22]. Among all the countries, the predictions for Belgium is 48.2 TWh/year (vs. 16 TWh/year in 2020). If we consider a lower-heating value of hydrogen of $LHV_{H_2} = 33.33$ [MWh/t], this demand is of 1.44 Mt/year. To define the demand for 2030, we can interpolate, and suggest that the consumption will be of $1/3 * (48.2 - 16)[TWh/year] = 26.7[TWh/year] = 0.8[Mt/year]$.

  In this study, the fourth manner is used, and the yearly demand is set to 800 [kt/year] = 26.6 [$\mathrm{TWh_{H2}}$/year]. The yearly demand is evenly distributed among the industrial hubs, i.e. Antwerpen, Ghent, Bruxelles, Hainaut, and Liège, and the nodal distribution is referenced in Table 12 and 13.

- Hydrogen-to-power units: no projects of this type s planned for Belgium. However, for th sake on curiosity, and study, we will consider a 100 MW unit is located at the shore, and a 150 MW unit located in Antwerpen. Ther specifcties can be found in Table 24.

- Hydrogen storage units: are located nearby each electrolyzers unit, with the same installed power, and a storage capacity of 10 hours, i.e. 10*P. The specificities are detailed in Table 25.

- Hydrogen imports: the quantity of imported hydrogen is not limited. However, the hourly quantity is limited at each interconnection by the pipeline capacity of 3.6 GW. This is detailed in Table 22.

4 Tables

Table 12: Buses 1/2

Node	Name	Full Name	Province	Type	V [kV]	Transfo [MVA]	Load [%]	PV [%]	WT_o [%]	Hydro [%]	DistGen [%]	Hp [%]	Ev [%]	H2 [%]
1	ACHEN	Achène	Namur	Load	380	270	1.54	1.75	5.80	0.00	1.54	1.75	1.75	0.00
2	ALVERINGEM	Alveringem	WV	H2	-	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	AUBAN220	Aubange 220kV	Lux	Load	220	240	1.37	0.56	0.86	2.20	1.37	0.56	0.56	0.00
4	AUBAN380	Aubange 380 kV	Lux	Load	380	30	0.17	0.00	0.00	0.00	0.17	0.00	0.00	0.00
5	AVLGM	Avelgem	WV	Load	380	1035	5.91	8.11	4.37	0.00	5.91	8.11	8.11	0.00
6	AWIRS	Awirs	Liege	Load	220	560	3.20	0.65	0.89	11.00	3.20	0.65	0.65	0.00
7	BERN	Berneau	Liege	Transfer	220	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	BRUEG	Bruegel	VB	Load	380	1260	7.19	5.22	1.72	0.00	7.19	5.22	5.22	20.00
9	BRUME	Brume	Liege	Load	380	297	1.70	0.65	0.89	21.10	1.70	0.65	0.65	0.00
10	BUGG+	Buggenhout	OV	Transfer	380	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	CHAMP	Champion	Namur	Load	380	492	2.81	1.75	5.80	6.30	2.81	1.75	1.75	0.00
12	COO	Coo	Liege	Transfer	380	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	COURC	Courcelles	Hainaut	Transfer	380	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	DOEL	Doel	OV	Load	380	155	0.88	4.40	4.56	0.00	0.88	4.40	4.40	0.00
15	EEKLN	Eeklo Noord	OV	Load	380	465	2.65	4.40	4.56	0.00	2.65	4.40	4.40	0.00
16	GEZEL	Gezelle	WV	Transfer	380	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	GOUY	Houy	Hainaut	Load	380	930	5.31	3.87	8.89	0.00	5.31	3.87	3.87	20.00
18	GRAMM	Gramme	Liege	Load	380	600	3.43	0.65	0.89	7.70	3.43	0.65	0.65	0.00
19	HORTA	Horta	OV	Transfer	380	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	IZGEM	Izegem	WV	Load	380	980	5.59	8.11	4.37	0.00	5.59	8.11	8.11	0.00
21	JUPIL	Jupille	Liege	Load	220	860	4.91	0.65	0.89	23.30	4.91	0.65	0.65	0.00
22	LINT	Lint	Antw	Load	380	930	5.31	4.06	3.71	0.00	5.31	4.06	4.06	0.00
23	LIXHE220	Lixhe 220 kV	Liege	Load	220	350	2.00	0.65	0.89	17.50	2.00	0.65	0.65	0.00
24	LIXHE380	Lixhe 380 kV	Liege	Load	380	30	0.17	0.65	0.89	0.00	0.17	0.65	0.65	0.00
25	MAERL	Maerlant	WV	Transfer	380	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26	MARC+	Marcourt	Lux	Load	220	105	0.60	0.56	0.86	0.00	0.60	0.56	0.56	0.00
27	MASSE	Massenhoven	Antw	Load	380	465	2.65	4.06	3.71	0.00	2.65	4.06	4.06	0.00
28	MEERH	Meerhout	Antw	Load	380	1138	6.50	4.06	3.71	0.00	6.50	4.06	4.06	0.00
29	MEKI+	Mekingen	VB	Load	380	515	2.94	5.22	1.72	0.00	2.94	5.22	5.22	0.00
30	MERCA	Mercator	OV	Load	380	1170	6.68	4.40	4.56	0.00	6.68	4.40	4.40	20.00
31	NEMO	Nemo	WV	Transfer	380	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
32	RIMIE220	Rimière 220 kV	Liege	Load	220	160	0.91	0.65	0.89	0.00	0.91	0.65	0.65	20.00
33	RIMIE380	Rimière 380 kV	Liege	Load	380	80	0.46	0.65	0.89	0.00	0.46	0.65	0.65	0.00
34	RODE+	Rodenhuize	OV	Load	380	465	2.65	4.40	4.56	0.00	2.65	4.40	4.40	20.00
35	ROMSE	Romsée	Liege	Load	220	120	0.69	0.65	0.89	0.00	0.69	0.65	0.65	0.00
36	SENO+	Senochamp	Lux	Load	220	0	0.00	0.56	0.86	0.00	0.00	0.56	0.56	0.00
37	SERAI	Seraing	Liege	Load	220	280	1.60	0.65	0.89	0.00	1.60	0.65	0.65	0.00
38	SLIJKENS	Slijkens	WV	Transfer	380	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 13: Buses 2/2

Node	Name	Full Name	Province	Type	V [kV]	Transfo [MVA]	Load [%]	PV [%]	WT_o [%]	Hydro [%]	DistGen [%]	Hp [%]	Ev [%]	H2 [%]
39	STAM+	St-Amand	Hainaut	Load	380	645	3.68	3.87	8.89	0.00	3.68	3.87	3.87	0.00
40	STEVN	Stevin	WV	Transfer	380	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
41	TIHA1	Tihange	Liege	Load	380	570	3.25	0.65	0.89	10.90	3.25	0.65	0.65	0.00
42	VANYK	Van Eyck	Limburg	Transfer	380	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
43	VERBR	Verbrande Brug	VB	Load	380	1035	5.91	5.22	1.72	0.00	5.91	5.22	5.22	0.00
44	VILLE	Villeroux	Lux	Load	220	200	1.14	0.56	0.86	0.00	1.14	0.56	0.56	0.00
45	ZANDV	Zandvliet	Antw	Load	380	1085	6.19	4.06	3.71	0.00	6.19	4.06	4.06	0.00
46	ZELZATE	Zelzate	OV	H2	-	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
47	ZUTE+	Zutendaal	Limburg	Load	380	0	0.00	13.69	10.35	0.00	0.00	13.69	13.69	0.00

Table 14: Lines 1/3

Line	FromNode	ToNode	V [kV]	Length [km]	Inom [A]	R [ohm]	X [ohm]	Pmax [MW]	MTTF [hours]	MTTR [hours]
1	ACHEN	GRAMM	380	36.9	1999	1.14	12.10	1315.70	73397	26
2	AUBAN380	BRUME	380	104.4	2186	3.55	32.88	1438.78	73397	26
3	AVLGM	HORTA	380	39.7	1999	1.23	13.02	1315.70	73397	26
4	AVLGM	HORTA	380	39.7	2186	1.25	13.00	1438.78	73397	26
5	AVLGM	IZGEM	380	22.8	2186	0.71	7.48	1438.78	73397	26
6	AVLGM	IZGEM	380	22.8	2186	0.71	7.48	1438.78	73397	26
7	BRUEG	MEKI+	380	14.0	1999	0.45	4.63	1315.70	73397	26
8	BRUEG	COURC	380	47.3	2186	1.47	15.51	1438.78	73397	26
9	BRUEG	BUGG+	380	15.9	1999	0.61	5.11	1315.70	73397	26
10	BRUEG	BUGG+	380	15.9	2186	0.50	5.25	1438.78	73397	26
11	BRUME	GRAMM	380	44.3	1999	1.37	14.53	1315.70	73397	26
12	BRUME	GRAMM	380	44.3	2322	1.37	14.53	1528.29	73397	26
13	BRUME	COO	380	2.0	1999	0.06	0.66	1315.70	73397	26
14	BRUME	COO	380	2.0	1999	0.06	0.66	1315.70	73397	26
15	BUGG+	MERCA	380	15.5	1999	0.59	5.00	1315.70	73397	26
16	BUGG+	VERBR	380	21.7	2319	0.66	6.91	1526.32	73397	26
17	BUGG+	MERCA	380	15.5	2186	0.48	5.08	1438.78	73397	26
18	BUGG+	VERBR	380	21.7	2186	0.67	7.12	1438.78	73397	26
19	CHAMP	GRAMM	380	32.2	2186	1.00	10.56	1438.78	73397	26
20	CHAMP	COURC	380	44.1	2186	1.37	14.46	1438.78	73397	26
21	COURC	STAM+	380	12.6	1999	0.39	4.13	1315.70	73397	26
22	COURC	MEKI+	380	33.4	1999	1.03	10.95	1315.70	73397	26
23	COURC	GOUY	380	1.7	1999	0.05	0.56	1315.70	73397	26
24	COURC	GOUY	380	1.8	2186	0.06	0.59	1438.78	73397	26
25	DOEL	ZANDV	380	6.8	1999	0.24	2.40	1315.70	73397	26
26	DOEL	ZANDV	380	7.1	1999	0.07	2.57	1315.70	73397	26
27	DOEL	MERCA	380	22.8	1999	0.71	7.48	1315.70	73397	26
28	DOEL	MERCA	380	22.8	1999	0.71	7.48	1315.70	73397	26
29	DOEL	MERCA	380	22.2	2186	0.80	6.84	1438.78	73397	26
30	DOEL	MERCA	380	22.2	2186	0.80	6.84	1438.78	73397	26
31	EEKLN	HORTA	380	13.0	4560	0.40	4.26	3001.30	73397	26
32	EEKLN	MAERL	380	17.3	4689	0.28	4.07	3086.20	73397	26
33	GEZEL	MAERL	380	10.1	1635	0.09	2.24	1076.12	73397	26
34	GEZEL	MAERL	380	10.1	1635	0.09	2.23	1076.12	73397	26
35	GEZEL	MAERL	380	10.1	1635	0.11	2.21	1076.12	73397	26
36	GEZEL	MAERL	380	10.1	1635	0.11	2.21	1076.12	73397	26
37	GEZEL	STEVN	380	8.0	4644	0.13	1.90	3056.58	73397	26
38	GEZEL	STEVN	380	8.0	4644	0.13	1.90	3056.58	73397	26

Table 15: Lines 2/3

Line	FromNode	ToNode	V [kV]	Length [km]	Inom [A]	R [ohm]	X [ohm]	Pmax [MW]	MTTF [hours]	MTTR [hours]
39	GEZEL	NEMO	380	0.8	1635	0.01	0.07	1076.12	73397	26
40	GRAMM	LIXHE380	380	53.4	2051	3.04	20.03	1349.93	73397	26
41	GRAMM	ZUTE+	380	55.6	2000	1.85	17.45	1316.36	73397	26
42	GRAMM	TIHA1	380	2.6	2186	0.08	0.85	1438.78	73397	26
43	GRAMM	TIHA1	380	3.3	2186	0.10	1.08	1438.78	73397	26
44	GRAMM	STAM+	380	56.4	1999	1.75	18.50	1315.70	73397	26
45	GRAMM	TIHA1	380	2.9	1999	0.09	0.95	1315.70	73397	26
46	GRAMM	TIHA1	380	2.9	1999	0.09	0.95	1315.70	73397	26
47	GRAMM	RIMIE380	380	14.6	1999	0.45	4.79	1315.70	73397	26
48	HORTA	MAERL	380	29.0	4689	0.43	7.94	3086.20	73397	26
49	HORTA	MERCA	380	48.4	3400	1.58	15.19	2237.81	73397	26
50	HORTA	RODE+	380	14.2	2186	0.44	4.64	1438.78	73397	26
51	LINT	MERCA	380	21.1	2186	0.65	6.92	1438.78	73397	26
52	LINT	MASSE	380	14.1	2188	0.46	4.56	1440.10	73397	26
53	LINT	MERCA	380	21.1	2186	0.65	6.92	1438.78	73397	26
54	LIXHE380	VANYK	380	53.0	1999	2.07	16.53	1315.70	73397	26
55	MASSE	MEERH	380	32.5	2186	1.01	10.66	1438.78	73397	26
56	MASSE	MERCA	380	35.0	2186	1.09	11.54	1438.78	73397	26
57	MEERH	VANYK	380	57.5	2186	1.78	18.86	1438.78	73397	26
58	MERCA	RODE+	380	34.2	1999	1.07	11.21	1315.70	73397	26
59	VANYK	ZUTE+	380	31.1	1999	0.72	9.55	1315.70	73397	26
60	AUBAN220	VILLE	220	47.2	1063	4.01	14.16	405.06	73397	26
61	AWIRS	SERAI	220	6.6	1092	0.33	2.64	416.11	73397	26
62	AWIRS	RIMIE220	220	7.4	976	0.47	3.13	371.91	73397	26
63	JUPIL	RIMIE220	220	20.2	1092	0.61	4.52	416.11	73397	26
64	SERAI	RIMIE220	220	13.4	976	0.77	5.29	371.91	73397	26
65	MARC+	RIMIE220	220	38.0	1063	3.23	11.30	405.06	73397	26
66	MARC+	SENO+	220	26.8	1063	2.28	8.04	405.06	73397	26
67	RIMIE220	SERAI	220	11.4	1037	0.66	4.63	395.15	73397	26
68	ROMSE	SERAI	220	14.3	1037	0.83	5.81	395.15	73397	26
69	SENO+	VILLE	220	2.6	1063	0.63	2.15	405.06	73397	26
70	ROMSE	JUPIL	220	10.0	1000	0.60	4.00	381.05	73397	26
71	JUPIL	BERN	220	30.0	1000	1.80	12.00	381.05	73397	26
72	JUPIL	BERN	220	30.0	1000	1.80	12.00	381.05	73397	26
73	BERN	LIXHE220	220	10.0	1000	0.60	4.00	381.05	73397	26
74	BERN	LIXHE220	220	10.0	1000	0.60	4.00	381.05	73397	26
75	AUBAN380	AUBAN220	380/220	-	-	0.00	82.13	300.00	73397	26
76	AUBAN380	AUBAN220	380/220	-	-	0.00	80.53	300.00	73397	26

Table 16: Lines 3/3

Line	FromNode	ToNode	V [kV]	Length [km]	Inom [A]	R [ohm]	X [ohm]	Pmax [MW]	MTTF [hours]	MTTR [hours]
77	LIXHE380	LIXHE220	380/220	-	-	0.00	77.87	300.00	73397	26
78	LIXHE380	LIXHE220	380/220	-	-	0.00	77.87	300.00	73397	26
79	RIMIE380	RIMIE220	380/220	-	-	0.00	77.87	300.00	73397	26
80	RIMIE380	RIMIE220	380/220	-	-	0.00	77.87	300.00	73397	26
81	RIMIE380	RIMIE220	380/220	-	-	0.00	77.87	300.00	73397	26
82	GEZEL	SLIJKENS	380	18.0	2186	0.55	5.90	1500.00	73397	26
83	GEZEL	SLIJKENS	380	18.0	2186	0.55	5.90	1500.00	73397	26
84	GEZEL	SLIJKENS	380	18.0	2186	0.55	5.90	1500.00	73397	26
85	GEZEL	SLIJKENS	380	18.0	2186	0.55	5.90	1500.00	73397	26
86	SLIJKENS	IZGEM	380	20.0	2186	0.62	6.56	1500.00	73397	26
87	SLIJKENS	IZGEM	380	20.0	2186	0.62	6.56	1500.00	73397	26
88	SLIJKENS	IZGEM	380	20.0	2186	0.62	6.56	1500.00	73397	26
89	SLIJKENS	IZGEM	380	20.0	2186	0.62	6.56	1500.00	73397	26
90	AVLGM	COURC	380	84.8	2186	2.61	27.81	1500.00	73397	26
91	AVLGM	COURC	380	84.8	2186	2.61	27.81	1500.00	73397	26
92	AVLGM	COURC	380	84.8	2186	2.61	27.81	1500.00	73397	26
93	AVLGM	COURC	380	84.8	2186	2.61	27.81	1500.00	73397	26

Table 17: Offshore wind farms

Name	Node	Pmax [MW]	Nb WT [#]	MTTF [hours]	MTTR [hours]
Belwind	STEVN	171	56	1059	272
C-Power	STEVN	325	54	1059	272
Mermaid	STEVN	235	28	1059	272
Nobelwind	STEVN	165	50	1059	272
Norther	STEVN	370	44	1059	272
Northwester2	STEVN	219	23	1059	272
Northwind	STEVN	216	72	1059	272
Rentel	STEVN	309	42	1059	272
Seastar	STEVN	252	30	1059	272
P1_3500_15	SLIJKENS	728	49	1059	272
P23_3500_15	SLIJKENS	2782	185	1059	272

Table 18: Imports

Interconnection	Country	FromNode	ToNode	Type	NTC [MW]	Inom [A]	Unom [kV]	Pmax [MW]	MTTF [hours]	MTTR [hours]	Emax,year [TWh]	Price [€/MWh]
1	UK	NEMO	CANTERBURY	HVDC	1000	-	-	1000	31300	14	0.14	51.67
2	Netherlands	ZANDV	BORSSELE	HVAC	653.1	2499	380	1644.8	31300	14	1.31	41.67
3	Netherlands	ZANDV	GEERTRUIDENBERG	HVAC	653.1	2499	380	1644.8	31300	14	1.31	41.67
4	Netherlands	VANYK	MAASTRICHT	HVAC	571.3	2186	380	1438.8	31300	14	1.31	41.67
5	Netherlands	VANYK	MAASTRICHT	HVAC	522.4	1999	380	1315.7	31300	14	1.31	41.67
6	Germany	LIXHE380	ALEGRO	HVDC	1000	-	-	1000.0	31300	14	2.57	36.84
7	Luxembourg	AUBAN220	BELVAL	HVAC	90.0	1037	220	395.2	31300	14	0.03	36.84
8	Luxembourg	AUBAN220	SANEM	HVAC	90.0	1037	220	395.2	31300	14	0.03	36.84
9	France	AUBAN220	MOULAINE 1	HVAC	348.9	1160	220	442.0	31300	14	0.725	42.56
10	France	AUBAN220	MOULAINE 2	HVAC	348.9	1160	220	442.0	31300	14	0.725	42.56
11	France	GOUY	CHOOZ	HVAC	318.3	1058	220	403.2	31300	14	0.725	42.56
12	France	ACHEN	LONNY	HVAC	1038.7	1999	380	1315.7	31300	14	0.725	42.56
13	France	AVLGM	MASTAING	HVAC	1038.7	1999	380	1315.7	31300	14	0.725	42.56
14	France	AVLGM	AVELIN	HVAC	1206.5	2322	380	1528.3	31300	14	0.725	42.56
15	UK	SLIJKENS	UK1	HVDC	1000	-	-	1000	31300	14	0.14	51.67

Table 19: Pumped-hydro storages

Name	Node	Pmax [MW]	Emax [MWh]	eff_pump [-]	eff_turb [-]
Coo	COO	1161	5600	0.866	0.866
Plate-Taille	GOUY	144	700	0.866	0.866

Table 20: Batteries

Batt	Node	Pmax [MW]	Emax [MWh]	eff_batt_in [-]	eff_batt_out [-]
1	STEVN	497	1744	0.9219	0.9219
2	RODE+	497	1744	0.9219	0.9219
3	MERCA	497	1744	0.9219	0.9219
4	BRUEG	497	1744	0.9219	0.9219
5	GOUY	497	1744	0.9219	0.9219
6	RIMIE220	497	1744	0.9219	0.9219

Table 21: Hydrogen pipelines

Pipeline	FromNode	ToNode	Qmax [MW_{H_2}]
1	ALVERINGEM	STEVN	3600
2	STEVN	RODE+	3600
3	RODE+	MERCA	3600
4	MERCA	BRUEG	3600
5	BRUEG	RIMIE220	3600
6	BRUEG	GOUY	3600

Table 22: Hydrogen imports

H2Imp	Name	Node	Qmax [MW]	PriceH2Imports [€/MWh]
1	Alveringem	ALVERINGEM	3600	150
2	Zeebrugge	STEVN	3600	150
3	Zelzate	RODE+	3600	150
4	Zandvliet	MERCA	3600	150
5	S-Gravenvoeren	RIMIE220	3600	150
6	Eynatten	RIMIE220	3600	150
7	Blaregnies	GOUY	3600	150

Table 23: Electrolyzers

Electrolyzer	Location	Node	Pmax [MW]	MTTF [hours]	MTTR [hours]
1	Zeebrugge	STEVN	74.5	2000	50
2	Gent	RODE+	74.5	2000	50
3	Antwerpen	MERCA	74.5	2000	50
4	Bruxelles	BRUEG	74.5	2000	50
5	Hainaut	GOUY	74.5	2000	50
6	Liège	RIMIE220	74.5	2000	50

Table 24: Hydrogen-to-Power units

H2P	Location	Node	Pmax [MW]	eff [-]	MTTF [hours]	MTTR [hours]
1	Zebreugge	STEVN	100	0.43	2000	50
2	Antwerpen	MERCA	150	0.43	2000	50

Table 25: Hydrogen storage

H2Sto	Location	Node	Pmax [MW_H2]	Emax [MWh_H2]	eff_in [-]	eff_out [-]
1	Zeebrugge	STEVN	74.5	745	1	1
2	Gent	RODE+	74.5	745	1	1
3	Antwerpen	MERCA	74.5	745	1	1
4	Bruxelles	BRUEG	74.5	745	1	1
5	Hainaut	GOUY	74.5	745	1	1
6	Liège	RIMIE220	74.5	745	1	1

Table 26: Generators 1/2

Gen	Name	Node	Pmax [MW]	Type	Fuel	Efficiency [-]	VOM [€/MWh]	Fuel Cost [€/MWh_{fuel}]	CO_2 Emissions [t_{CO2}/MWh_{fuel}]	MTTF [hours]	MTTR [hours]
1	AALTER TJ	EEKLN	18	TJ	Oil	0.26	4	70.6688	0.2665	2607.5	130
2	AMERCOEUR 1R GT	GOUY	289	CCGT-GT	Gas	0.58	2.4	26.95	0.2008	821.9	110
3	AMERCOEUR 1R ST_cur	GOUY	162	CCGT-ST	Gas	0.58	2.4	26.95	0.2008	821.9	110
4	BEERSE TJ	MASSE	32	TJ	Oil	0.26	4	70.6688	0.2665	2607.5	130
5	Beveren 2 Indaver	MERCA	21	IS	Waste	0.36	3.6	26.64	0.02664	2909.7	111
6	Beveren 3 Indaver	DOEL	24	IS	Waste	0.36	3.6	26.64	0.02664	2909.7	111
7	Beveren Ineos Phenol Chem	MERCA	25.1	OCGT (CHP)	Gas	0.41	13.2	26.95	0.2008	2909.7	111
8	Beveren Sleco	MERCA	41	IS	Waste	0.36	3.6	26.64	0.02664	2909.7	111
9	Biomassa Oostende	GEZEL	18	IS	Biomasse	0.36	3.6	26.64	0.0118	2909.7	111
10	Biostoom Oostende	GEZEL	19.4	IS	Waste	0.36	3.6	26.64	0.02664	2909.7	111
11	Borealis Kallo Cogen GT_ST	MERCA	32	CCGT (CHP)	Gas	0.45	2.4	26.95	0.2008	2909.7	111
12	CIERREUX TJ	BRUME	18	TJ	Oil	0.26	4	70.6688	0.2665	2607.5	130
13	DROGENBOS GT1	MEKI+	150	CCGT-GT	Gas	0.52	2.4	26.95	0.2008	821.9	110
14	DROGENBOS GT2	MEKI+	150	CCGT-GT	Gas	0.52	2.4	26.95	0.2008	821.9	110
15	DROGENBOS ST	MEKI+	160	CCGT-ST	Gas	0.52	2.4	26.95	0.2008	821.9	110
16	EDF Luminus Angleur GT31	SERAI	25	OCGT	Gas	0.3	13.2	26.95	0.2008	731.2	221
17	EDF Luminus Angleur GT32	SERAI	25	OCGT	Gas	0.3	13.2	26.95	0.2008	731.2	221
18	EDF Luminus Angleur GT41	SERAI	64	OCGT	Gas	0.42	13.2	26.95	0.2008	731.2	221
19	EDF Luminus Angleur GT42	SERAI	64	OCGT	Gas	0.42	13.2	26.95	0.2008	731.2	221
20	EDF Luminus Ham GT31	RODE+	58	OCGT	Gas	0.42	13.2	26.95	0.2008	731.2	221
21	EDF Luminus Ham GT32	RODE+	58	OCGT	Gas	0.42	13.2	26.95	0.2008	731.2	221
22	EDF Luminus Ham STEG	RODE+	39	CCGT	Gas	0.45	2.4	26.95	0.2008	821.9	110
23	EDF Luminus Ringvaart STEG	RODE+	385	CCGT	Gas	0.55	2.4	26.95	0.2008	821.9	110
24	EDF Luminus Seraing GT1	SERAI	150	CCGT-GT	Gas	0.52	2.4	26.95	0.2008	821.9	110
25	EDF Luminus Seraing GT2	SERAI	150	CCGT-GT	Gas	0.52	2.4	26.95	0.2008	821.9	110
26	EDF Luminus Seraing NEW	SERAI	885	CCGT	Gas	0.61	2.4	26.95	0.2008	821.9	110
27	Euro-Silo	RODE+	12.9	CCGT (CHP)	Gas	0.45	2.4	26.95	0.2008	2909.7	111
28	E-wood	MERCA	22	IS	Waste	0.36	3.6	26.64	0.02664	2909.7	111
29	Flémalle NEW	AWIRS	890	CCGT	Gas	0.61	2.4	26.95	0.2008	821.9	110
30	Fluxys LNG Zeebrugge WKK	GEZEL	40	OCGT (CHP)	Gas	0.41	13.2	26.95	0.2008	2909.7	111
31	Greenpower Oostende	GEZEL	20	IS (CHP)	Waste	0.36	3.6	26.64	0.02664	2909.7	111
32	HERDERSBRUG GT1	GEZEL	157	CCGT-GT	Gas	0.51	2.4	26.95	0.2008	821.9	110
33	HERDERSBRUG GT2	GEZEL	156.3	CCGT-GT	Gas	0.51	2.4	26.95	0.2008	821.9	110
34	HERDERSBRUG ST	GEZEL	167	CCGT-ST	Gas	0.51	2.4	26.95	0.2008	821.9	110
35	INESCO GT1	MERCA	44.8	CCGT-GT (CHP)	Gas	0.58	2.4	26.95	0.2008	2909.7	111
36	INESCO GT2	MERCA	44.8	CCGT-GT (CHP)	Gas	0.58	2.4	26.95	0.2008	2909.7	111
37	INESCO ST	MERCA	48.5	CCGT-ST (CHP)	Gas	0.58	2.4	26.95	0.2008	2909.7	111

Table 27: Generators 2/2

Gen	Name	Node	Pmax [MW]	Type	Fuel	Efficiency [-]	VOM [€/MWh]	Fuel Cost [€/MWh_{fuel}]	CO_2 Emissions [t_{CO2}/MWh_{fuel}]	MTTF [hours]	MTTR [hours]
38	Intradel Herstal IS	JUPIL	32	IS	Waste	0.36	3.6	26.64	0.02664	2909.7	111
39	Ipalle Thumaide	GOUY	34	IS	Waste	0.36	3.6	26.64	0.02664	2909.7	111
40	ISVAG	MERCA	12	IS	Waste	0.36	3.6	26.64	0.02664	2909.7	111
41	IVBO	GEZEL	16	IS	Waste	0.36	3.6	26.64	0.02664	2909.7	111
42	IZEGEM	IZGEM	20	CCGT (CHP)	Gas	0.45	2.4	26.95	0.2008	2909.7	111
43	Jemeppe-sur-Sambre GT1	STAM+	48	CCGT-GT (CHP)	Gas	0.45	2.4	26.95	0.2008	2909.7	111
44	Jemeppe-sur-Sambre GT2	STAM+	48	CCGT-GT (CHP)	Gas	0.45	2.4	26.95	0.2008	2909.7	111
45	Jemeppe-sur-Sambre ST	STAM+	10	CCGT-ST (CHP)	Gas	0.45	2.4	26.95	0.2008	2909.7	111
46	Lillo Degussa GT1	MERCA	43	CCGT-GT (CHP)	Gas	0.45	2.4	26.95	0.2008	2909.7	111
47	Lillo Degussa GT2	MERCA	32	CCGT-GT (CHP)	Gas	0.45	2.4	26.95	0.2008	2909.7	111
48	Lillo Degussa ST	MERCA	10	CCGT-ST (CHP)	Gas	0.45	2.4	26.95	0.2008	2909.7	111
49	Marcinelle Energie TGV	GOUY	413	CCGT	Gas	0.52	2.4	26.95	0.2008	821.9	110
50	Monsanto Lillo WKK EBL	MERCA	43	OCGT (CHP)	Gas	0.41	13.2	26.95	0.2008	2909.7	111
51	NOORDSCHOTE TJ	IZGEM	18	TJ	Oil	0.26	4	70.6688	0.2665	2607.5	130
52	Oorderen Bayer	MERCA	43	OCGT (CHP)	Gas	0.41	13.2	26.95	0.2008	2909.7	111
53	SAINT-GHISLAIN STEG	GOUY	378	CCGT	Gas	0.51	2.4	26.95	0.2008	821.9	110
54	Sappi Lanaken GT	ZUTE+	43	OCGT (CHP)	Gas	0.41	13.2	26.95	0.2008	2909.7	111
55	SCHAERBEEK SIOMAB ST1	VERBR	15	IS	Waste	0.36	3.6	26.64	0.02664	2909.7	111
56	SCHAERBEEK SIOMAB ST2	VERBR	15	IS	Waste	0.36	3.6	26.64	0.02664	2909.7	111
57	SCHAERBEEK SIOMAB ST3	VERBR	15	IS	Waste	0.36	3.6	26.64	0.02664	2909.7	111
58	Scheldelaan Exxonmobil	MERCA	140	CCGT (CHP)	Gas	0.45	2.4	26.95	0.2008	2909.7	111
59	STORA LANGERBRUGGE WKK1	RODE+	10	CL (CHP)	Biomasse	0.38	3.6	26.64	0.0118	2909.7	111
60	STORA LANGERBRUGGE WKK2	RODE+	40	CL (CHP)	Biomasse	0.38	3.6	26.64	0.0118	2909.7	111
61	Syral Aalst GT	BRUEG	43	CCGT-GT (CHP)	Gas	0.45	2.4	26.95	0.2008	2909.7	111
62	Syral Aalst ST	BRUEG	5	CCGT-ST (CHP)	Gas	0.45	2.4	26.95	0.2008	2909.7	111
63	TAMINCO Gent WKK	RODE+	6.3	OCGT (CHP)	Gas	0.41	13.2	26.95	0.2008	2909.7	111
64	T-Power	MEERH	425	CCGT	Gas	0.58	2.4	26.95	0.2008	821.9	110
65	Wilmarsdonk Total GT1	MERCA	43	OCGT (CHP)	Gas	0.41	13.2	26.95	0.2008	2909.7	111
66	Wilmarsdonk Total GT2	MERCA	43	OCGT (CHP)	Gas	0.41	13.2	26.95	0.2008	2909.7	111
67	Wilmarsdonk Total GT3	MERCA	43	OCGT (CHP)	Gas	0.41	13.2	26.95	0.2008	2909.7	111
68	Zandvliet Power	ZANDV	419	CCGT (CHP)	Gas	0.57	2.4	26.95	0.2008	821.9	110
69	Zedelgem TJ	GEZEL	18	TJ	Oil	0.26	4	70.6688	0.2665	2607.5	130
70	Zeebrugge TJ	GEZEL	18	TJ	Oil	0.26	4	70.6688	0.2665	2607.5	130
71	Zelzate 2 Knippegroen	RODE+	305	CL	Gas	0.42	3.6	26.95	0.2008	2909.7	111
72	Zelzate TJ	RODE+	18	TJ	Oil	0.26	4	70.6688	0.2665	2607.5	130
73	Zwijndrecht Lanxess GT	MERCA	43	CCGT-GT (CHP)	Gas	0.45	2.4	26.95	0.2008	2909.7	111
74	Zwijndrecht Lanxess ST	MERCA	15	CCGT-ST (CHP)	Gas	0.45	2.4	26.95	0.2008	2909.7	111

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