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Consideration of Material Criticality for Battery Sub-technologies in an Energy System Optimization Model for Belgium and the Netherlands

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Abstract

This research focuses on the consideration of material criticality for battery sub-technologies in an energy system modelling framework. By employing a multi-objective optimization methodology, the research seeks to minimize the overall cost of the system while simultaneously minimizing the criticality. The criticality factor is based on the methodology of the EU and is implemented for the following battery types: Lithium Nickel Cobalt Manganese Oxide (NMC-111), Lithium Iron Phosphate (LFP), Lead Acid and Redox Flow. The REMix framework has been utilized and adapted to represent a fully renewable electricity system in the Netherlands and Belgium and include a pareto front for the optimization. First, a base scenario on cost optimization was developed and used as a comparison scenario. The difference in the sub-technologies, when the criticality is considered, results mostly in a reduction of storage capacity which was substituted by the import of electricity. There are minor changes in the choice of sub-technology, which result from an adaptation of storage need. In conclusion, the implementation of the criticality factor for one technology class has an influence on the design of the energy system. Nevertheless, a larger change is expected when the criticality factor is implemented for all technologies.

Table of Content

1. Introduction

The global CO2 emissions from energy combustion and industrial processes have reached another peak with an annual level with 36.3 Gt in 2021 [2]. In the European Union (EU), the energy sector accounts for more than 75% of the greenhouse gases (GHG) emitted [3]. Nevertheless, the global share of renewable energy supply increased to 12,3% in 2022 [4] with 40% of the electricity being generated by low-emission sources and the development of wind and solar energy is rising steadily until 2030 [2]. The EU has established a binding renewable energy target of at least 32% in 2030 with a provisional agreement on raising that target to at 42.5% in 2030 [3]. To reach the goal, the development of renewable energy technologies needs to increase from 2,990GW installed capacity in 2020 to 26,600GW in 2050 [5].

However, an increasingly fast development of renewable energy sources implies an equal increase in the raw material requirements for clean technologies, such as PV panels, wind turbines or storage technologies to cope with the intermittency of those renewable sources. The demand for those materials will grow substantially which raises concerns about the availability and possible restrictions for the energy transition [6]; [7]; [8].

In 2023, the European Commission already created a list of Critical Raw Materials (CRM) which is constantly updated. The fifth edition consists out of 34 CRMs in 2023 [9]. The main parameters used in the assessment are the level of economic importance for the EU and the potential risk of supply disruptions. Additionally, there are numerous studies that focus on the material supply for renewable energy technologies and potential bottlenecks for raw materials.

Valero et al. [10] assessed the risk of potential bottlenecks by comparing future demand with geological availability. They identified 13 metals to have a potentially very high or high risk of supply shortage. These included cadmium, chromium, cobalt, copper, gallium, indium, lithium, manganese, nickel, silver, tellurium, tin, and zinc. Consequently, this would have an impact on the development of solar photovoltaic, electric vehicles, wind turbines with permanent magnets, and solar thermal power [10]. This is supported by Moreau et al. [11] who assessed potential metal supply constraints for a fully renewable energy system in 2050. They concluded that the reserves of 8 out of the 29 necessary metals might deplete before 2050, but the energy industry only accounts for a small additional demand compared to other existing industries. However, for cadmium, cobalt, lithium and nickel, the largest demand is in the renewable energy sector and their potential depletion varies across renewable energy scenarios [11].

In another study, Junne et al. [11]assess the demand for neodymium, dysprosium, lithium, and cobalt in power generation, storage and transport technologies in regard to six global energy scenarios with the timeframe of 2050. Their results show that the required materials increase with increasingly ambitious scenarios. The maximum annual primary material demand exceeds the current extraction volumes of all metals, with lithium having the highest difference [12]. Schlichenmaier & Naegler [13] analyse 25 potentially scarce materials resulting from an energy scenario based on the 1.5 °C target, as well as the risk of short- and medium-term shortages. Their results show that the demand for lithium, dysprosium, tellurium, and cobalt is clearly dominated by energy and transport technologies. Furthermore, the cumulative emand for the energy and transport technologies is exceeding the actual reserves for cobalt and lithium, and potentially for tellurium, nickel, and iridium. The demand is even further exceeding the current production when non-energy sectors are considered as well. Therefore, an increase in production is required for almost all materials included in their study.

This implies that the availabilities of raw materials for clean energy technologies, and their potential influence on supply chains and price developments, becomes increasingly important. Due to the fact that different sub-technologies of renewable energy technologies often use different materials, the composition of materials and their level of criticality should be considered in the choice of technologies for the design of energy systems.

Energy system modelling focuses on the design and optimization of energy systems and has been developed through the need of representation of the complex interactions and layers within modern energy systems [13]. Large optimization models with a bottom-up approach that are based on detailed technical data have been in use since the 1960s and focus on providing scenarios of how an energy system could develop in the future [14]. They are usually applied to a range from regional to continental systems and can be helpful for decision makers to plan the processes of the energy transition.

In some of the previously mentioned studies, it has been pointed out that current energy system modelling is predominantly focused on cost-optimization. Nevertheless, it would be beneficial to also implement the material requirements for a better understanding of the role potential bottlenecks in the material supply may have on potential transition paths and the global energy transition [13]. Furthermore, the need to not only focus on a technology class but also the material requirements for different sub-technology has been indicated [12]. Accordingly, it is the current research gap that this research is aiming at.

The objective of this research is to integrate the criticality of one technology class into an energy system modelling framework to perform a multi objective optimization focused on the cost of the system cost and the systems criticality. Furthermore, the objective is to analyse how the design of the of two European countries, Belgium and the Netherlands, differs when the criticality factor for different sub-technologies is included in the optimization process. For the scope of this research, only batteries for utility-scale energy storage systems are considered.

This research project will be focused on answering the following research question:

How do designs of a fully renewable energy system in Belgium and the Netherlands differ if they are optimized to minimize the system cost and criticality of different battery technologies in utility-scale energy storage systems?

2. Methodology

This section provides an overview of the data and methods used for this research.

2.1. Data

First, information about sub-technologies of batteries has been gathered to determine the selected sub-technologies and identify their techno-economic data.

The selection of sub-technologies for batteries has been determined by the projected importance for future energy systems, which was based on current reports on market developments [15], [16] and on the opinion of an expert working in battery research. Additionally, the availability of data for sub-technologies was also taken into consideration.

Currently, the global battery market is dominated by lithium-ion batteries and lead acid batteries. The market development is driven by electric mobility applications; however, it also includes other application like stationary storage systems [17]. Consequently, lithium-ion and lead batteries are also the leading technologies for storage systems.

Redox Flow batteries are also commercially available and their only application so far are energy storage systems (ESS), with the first large-scale projects installed successfully [18]. The future market relevance will be dependent on the price per kWh and advances in the chemistries but their main application will be stationary storage systems [18]. The market for utility-scale storage is expected to be led by lithium ferrophosphate (LFP) batteries while nickel-manganese-cobalt (NMC) batteries will cover the remaining demand for batteries.

LFP und NMC batteries are both lithium-ion batteries, however they differ in the chemistry of their cells. LFP batteries are using iron phosphate as the active material in the battery, while NMC batteries are using different compositions of nickel, manganese and cobalt. The equal distribution of the materials is referred to as NMC-111. In order to decrease the amount of the expensive cobalt, different combinations are used for NMC batteries which are represented in the number combination. For example, NMC-532 utilizes five parts of nickel, three parts of cobalt and two parts of manganese [19]. While NMC 111 and NMC 532 are predominantly used in domestic storage solutions, NMC 622 and NMC 811 are shifting towards the electric vehicles market. Additionally, redox flow batteries are expected to take over a moderate share after the step of commercialization is reached [15].

According to Dennis Koplja, head of battery technology group at the DLR Institute of Engineering Thermodynamics, the battery types most suitable for stationary storage system are LFP, Lead Acid, Redox Flow and Sodium-ion batteries (personal communication, 21. September 2023).

According to the previously stated arguments, the selected battery types are NMC, LFP, Lead Acid and Vanadium Redox Flow.

2.1.1. Lithium nickel cobalt manganese oxide (NMC-111)

Lithium batteries have become the most common battery type and account for more than 90% of energy storage installations in 2018 [16], and lithium nickel cobalt manganese oxide (NMC) batteries remain dominant in the market with a share of 60% [20]. NMC batteries have a high level of energy density, a high capacity and a high level of output voltage. The nickel in the battery improves the capacity but is also connected to a low chemical and thermal stability. The cobalt improves the charging and discharging, however the mineral is also considered critical due to its high cost and short supply. The manganese improves the overall stability of the battery, and the overall thermal stability and capacity retention is improved when moving from NMC-811 to NMC-111. Their current main application are electric vehicles and portable electronic devices [16]. NMC batteries are not considered to be the leading technology for ESS, however as the current main battery type it is included in the research as a comparison. Out of the different compositions of NMC batteries, NMC-111 batteries are mostly used for storage solutions which is why this sub-technology was chosen for this research.

2.1.2. Lithium iron phosphate (LFP)

Lithium iron phosphate (LFP) batteries has the second largest market share with just under 30%. The chemistry in the battery is not based on nickel, manganese and cobalt like NMC batteries but rather on iron and phosphorus [20]. This results in a higher chemical and thermal stability, a longer cyclability, a constant output voltage as well as non-toxic materials. On the other hand, it also results in a lower capacity compared to NMC batteries and a lower energy density [16]. However, energy density is not a critical factor for stationary applications which makes them a promising alterative for ESS. Additionally, LFP batteries have a lower cost than NMC batteries and profit from similar production requirements to lithium-ion batteries [15].

2.1.3. Lead Acid

In 2021, the global lead-acid battery market accounted for $38BN and the total production was 375 GWh, of which $11BN and 75 GWh account for stationary applications. Even though, the sales of lithium-ion exceeded lead-acid batteries, the amount of produced GWh was similar, due to a lower cost of lead-acid batteries. Lead-acid batteries have been commonly used for energy storage systems before and are designed to provide a constant voltage over a long lifetime [21]. Even though the technology is familiar, there is remaining potential to improve the power and lower the production costs [22].

2.1.4. Redox Flow

Redox Flow batteries differ from other electrochemical storage technologies as they do not rely on solid electrodes. A battery consists out of two electrolyte tanks that contain redox couples, a battery cell for the conversion of energy and pumps to circulate the electrolytes through the battery cell. For this type of battery, the energy and power can be scaled separately by scaling the electrolytes tanks or the electrode are in the battery cell respectively, which makes it easily adjustable to specific requirements of different systems and applications. Additionally, it has a high cycle stability and its electrolyte materials are recyclable. The energy density is lower than for lithium-ion batteries, however this is not a critical factor for stationary applications. As of now, redox flow batteries are solely used for ESS and offer a broad range from a few kWh up to several hundred MWh. Vanadium redox flow batteries are the most mature category of redox flow batteries, which also makes it the type of redox flow battery included in this research [18].

The data about the material composition of the selected sub-technologies has been taken from Schlichenmaier & Naegler [13] and the references therein. It includes the amount of raw materials for each sub-technology in kg/kWh.

Figure 1 provides an overview of the material composition of the selected batteries. It includes the materials for the battery as well as for the stationary periphery. The exact data can be found in Appendix 1.

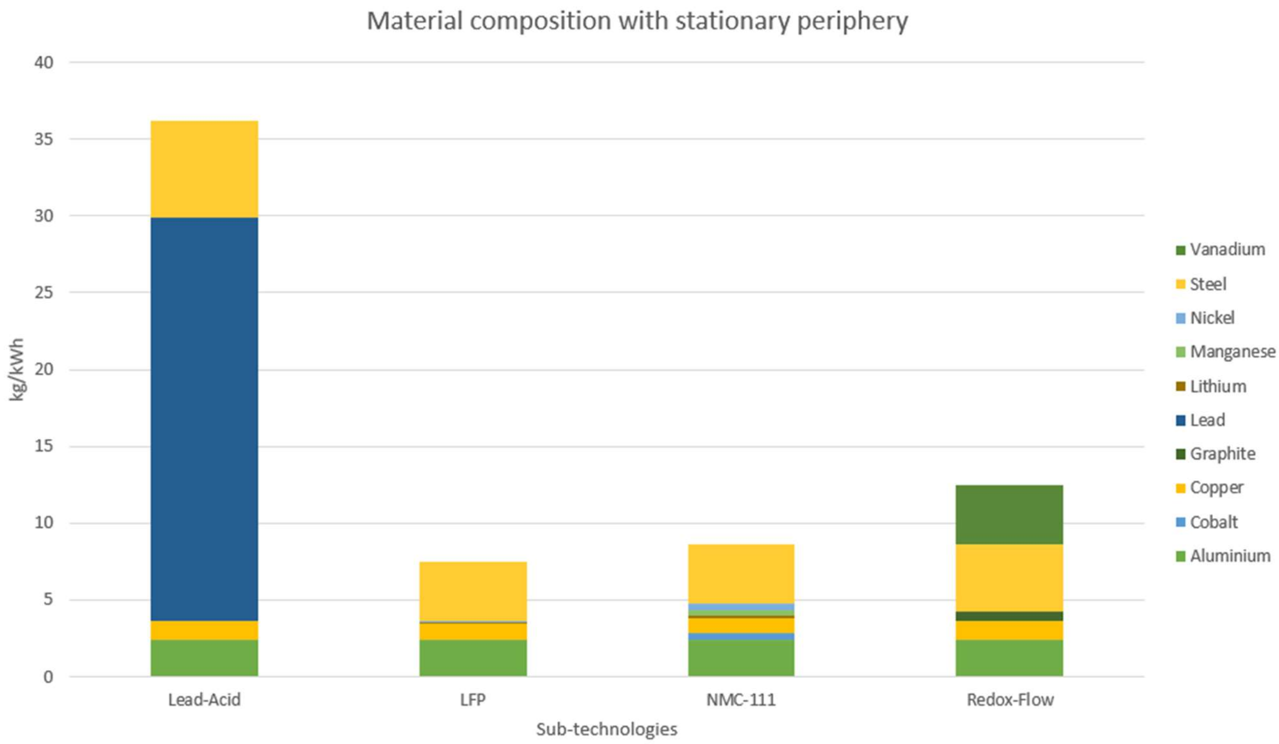

Figure 1: Overview of material composition of sub-technologies given in kg/kWh

A total overview of the data can be found in Appendix 7.1.

2.1.5. Techno-economic data

The data for the technical and economic parameters has been retrieved from the Pacific Northwest National Laboratory [23] and include a cost and performance assessment of the selected sub-technologies for 2020 and 2030. Because of the uncertainty of future price developments in the battery market as well as technological developments, the data for 2020 was chosen in order to avoid further uncertainty. The economic data was given in USD and have been converted to EUR [24] based on the conversion of 0.92€ per 1$ on the 18.11.2023.

The cost of the selected sub-technologies has been divided by the costs for the storage units and the converter units. The costs for the storage units is comprised out of the investment costs for the storage block and the balance of the system, as well as the fixed operation and maintenance (O&M) costs. The costs for the converter include the investment costs for the power equipment. Because this research is focused on large storage systems, the data for a 200MWh application has been used. The techno-economic data for the included storage technologies can be found in Appendix 7.2.1.

The techno-economic data for the generating technologies of solar and wind energy was taken from Simon & Xiao [25]. It provides the life duration, as well as investment costs and the fixed operation & maintenance costs for both technologies from the year 2020. The data can be found in Appendix 7.2.2.

2.2. Criticality

In order to perform a multi objective optimisation, a factor for the criticality of the respective sub-technologies needs to be established.

The German Aerospace Center (DLR) is currently running the project MaTiC-M which is, among other objectives, aiming at determining an estimate of the risk of supply bottleneck for minerals needed for technologies included in the projects. For such an analysis, it is differentiated between criticality on two levels: the material level and the technology level. The criticality on a material level is solely focused on the respective raw material, while the criticality on a technology level is defined by the criticalities of the materials within the technology [26]. This research is focused on criticality on a technology level as it is more suitable for a comparison of sub-technologies. Accordingly, the criticality factor on a technology level from the MaTiC-M project was used for this research.

The project is comparing several methodologies that have been developed to determine a criticality factor, and is basing its current calculation on the methodology from the European Commission. The European Commission defines raw materials as critical when they have a high level of economic importance, a high risk of supply risk disruptions and a lack of appropriate substitutes [27]. Hence, there are two indicators: the Supply Disruption Probability (SDP) and the Economic Importance (EI). A material is assumed to be critical if both indicators surpass a certain threshold. The EI indicator focuses on a maximum damage estimation to the overall economy. Due to this focus, it is not as applicable for a criticality analysis on technology level and the criticality factor that has been developed in the project is based on the SDP indicator of the EU. The SDP indicator includes the concentration of suppliers and their political situation, the recycling rate of a material and the ability to substitute. Below, the formula can be seen [26]. However, the ability to substitute has not been taken into account for the criticality factor used in this research.

$$SDP = HHI_{WGI,t} \cdot (1 - EoL_{RIR}) \cdot SI_{SR}$$

Equation 1: Formula for the SDP indicator

$HHI_{WGI,\,t}$:	Herfindahl-Hirschman Index, proxy for concentration of supplier countries
WGI :	Scaled World Governance Index, proxy for the political situation
t :	Trade-related parameter (accounts for export taxes, export quota, export prohibitions, etc.)
EoL_{RIR} :	End-of-Life Recycling Input Rate
SI_{SR} :	Substitution Index related to supply risk, proxy for ability to substitute (accounts for (co-)production and criticality of substitutes, the share of the considered material in all end-use applications and the sub-share of each substitute in all end-use applications. The substitute-cost-performance is not accounted for)

The criticality of a sub-technology was then identified by calculating the sum of the criticalities of the materials in the technology.

$$CS_{technology,\ funtional\,unit} = \sum_i CS_i * w_i$$

Equation 2: Sum of material criticality in a considered technology

i :	Materials used in a functional unit
$CS_{technology,\ functional\ unit}$:	Criticality (or SDP) indicator of a considered technology
CS_i :	Criticality (or SDP) indicator of constituent material i
w_i :	Weights

It can be weighted according to different aggregation methods [26]. The criticality factor on technology level that was used in this research was the mass weighted SDP for the year 2023. The cost of the materials is also represented in the cost of the storage system and the power equipment. Hence, the mass weighted criticality factor has been preferred over the alternative cost weighted method in order o avoid potential double accounting.

The mass weighted criticality factor has been weighted as following:

$$w_i = m_i$$

Equation 3: Mass weighing of criticality factor

w_i: Weighting factor for mineral i

m_i: Mass (kg) of mineral i per functional unit

In Figure 2, the criticality factor for the chosen sub-technologies is shown, developed from the criticality of materials used in sub-technology. Based on the SDP and the mass weighted approach, redox flow batteries have the highest criticality factor while LFP batteries have the lowest criticality.

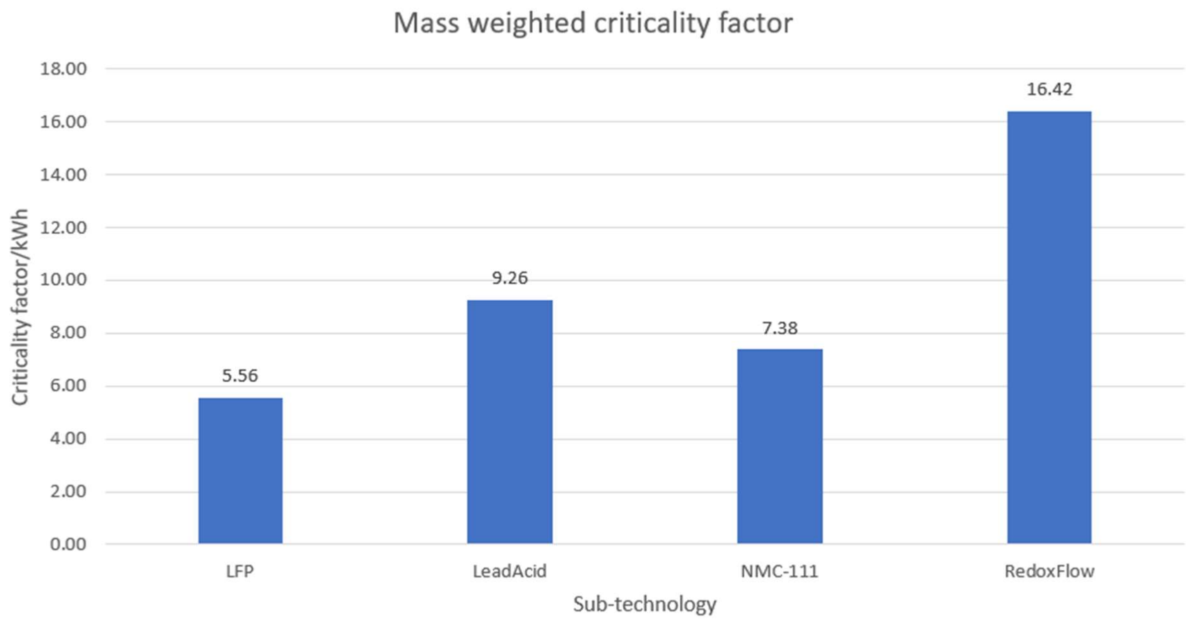

Figure 2: Criticality factor of sub-technologies *[26]*

Appendix 7.3 includes the criticality factor of different aggregation methods for the selected sub-technologies.

2.3. Energy system modelling

2.3.1. REMix

In order to meet the objective of this research, the energy system optimization framework REMix (Renewable Energy Mix) by the department of Energy System Analysis of the German Aerospace Center (DLR) has been chosen and applied [28]. The framework can be used to evaluate the interplay of technologies to determine the most cost-effective expansion and operation of the system. It has been applied to establish the needed infrastructure for energy systems which are solely or predominately based on variable renewable energy sources [29].

The features of the framework include a technological, a temporal and a regional scope which can be aggregated from high spatial detail to simplified networks in order to address computational complexity. The data handling and the interfaces are built the programming language Python while the mathematical optimization is done with the modelling software GAMS [30]. The objective function is determined by establishing one indicator to be either minimized or maximized which has primarily been the cost of the system.

REMix has recently been made publicly available on GitLab [31], where more detailed information about the framework and its structure can be found.

2.3.2. Scope

The scope of the REMix model set up used for this research is a simplified representation of the current energy system in Belgium and the Netherlands. It is focused on how batteries as an energy storage system would behave in a completely renewable energy system built from greenfield to demonstrate the impact of considering material criticality in energy system planning.

The energy system is solely focused on electricity and the renewable energy generating technologies in this framework were limited to solar photovoltaic and wind turbines, due to their establishment nowadays and their importance in future energy systems as well as to create an appropriate scope for this research. Their intermittency also secures a certain need for electricity storage in the system to require a sufficient amount of battery capacity needed. The year to be optimised was 2023 to represent the current criticality factor for the storage sub-technologies.

2.3.3. Data

The database for this application of the framework consists out of a publicly available, large-scale dataset which aims at enabling the modelling of predominantly renewable European electricity systems [32]. The dataset is comprised out of three static components, namely the network, generators and the installed capacity of renewables, and three dynamic components which are the demand signal, the renewable production forecasts and the renewable production signals.

Data	*Description*
Network data	1,494 buses & 2,156 lines
Load signal	Hourly power demand
Solar/Wind signal	Hourly capacity factor
Solar/Wind layout	Assigned capacity at 100% gross penetration of renewables

Table 1: Overview of used data from the RE-Europe dataset *[32]*

The regional scope of the framework is defined through the network which consists out of 1,494 electricity network nodes that are connected through 2,156 transmission lines. The original dataset includes nodes for mainland Europe. For the following evaluations the regional scope is limited to the Netherlands and Belgium in order to keep computation times at a manageable level. This results in 49 network nodes that spatially have been aggregated to two nodes, one for each country and the transmission lines that start and end within both countries have been included which results in 51 lines that have been aggregated to one transmission line between Belgium and the Netherlands.

The provided load signal consists out of data for each node hour by hour for three consequent years, 2012-2014. Because only one year was to be optimized in this framework, the data for 2013 has been selected as 2012 was a leap year which results in an additional day, and then filtered and aggregated to one node for Belgium and the Netherlands respectively. Figure 3 shows the total demand in Belgium and the Netherlands over the year 2013, respectively.

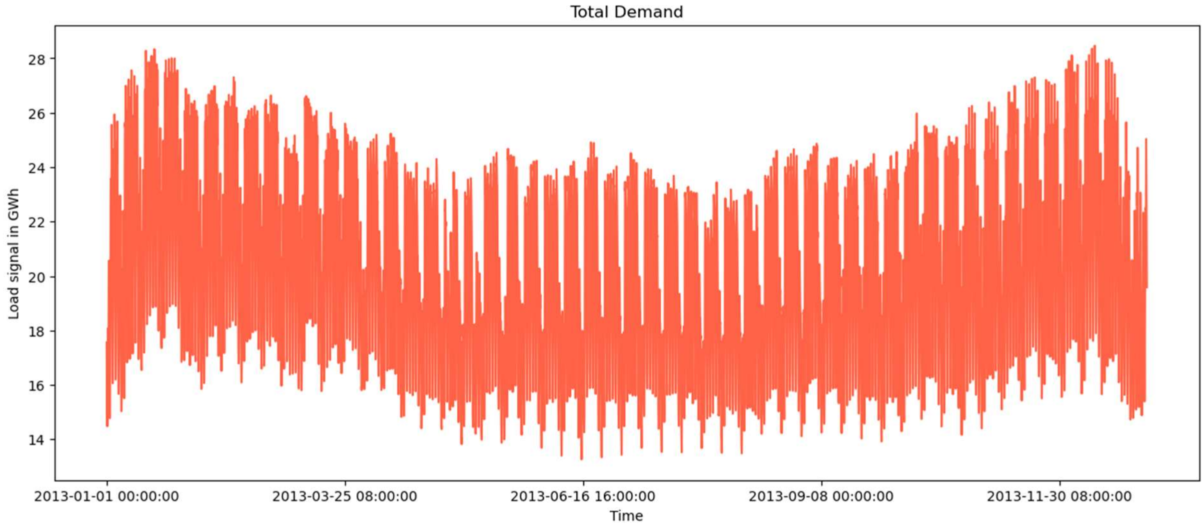

Figure 3: Total demand in Belgium and the Netherlands in 2013, given in GWh

There are several electricity generating technologies included in the dataset, both renewable and fossil fuel based, but only the datasets about the wind and solar signals as well as the capacity layouts have been used. The production signals can be seen in Figure 4 and Figure 5 respectively, and were given relatively to the installed capacity for which a uniform and proportional layout were given. The first layout represents a uniformly spread capacity while the latter focuses on layout more proportional to the renewable production capacity. The second layout has been chosen for this research and while implementing it directly it represents the 100% gross penetration of renewables that has been chosen as the scope. The following figures show the solar and wind signals for both countries based on the proportional layout.

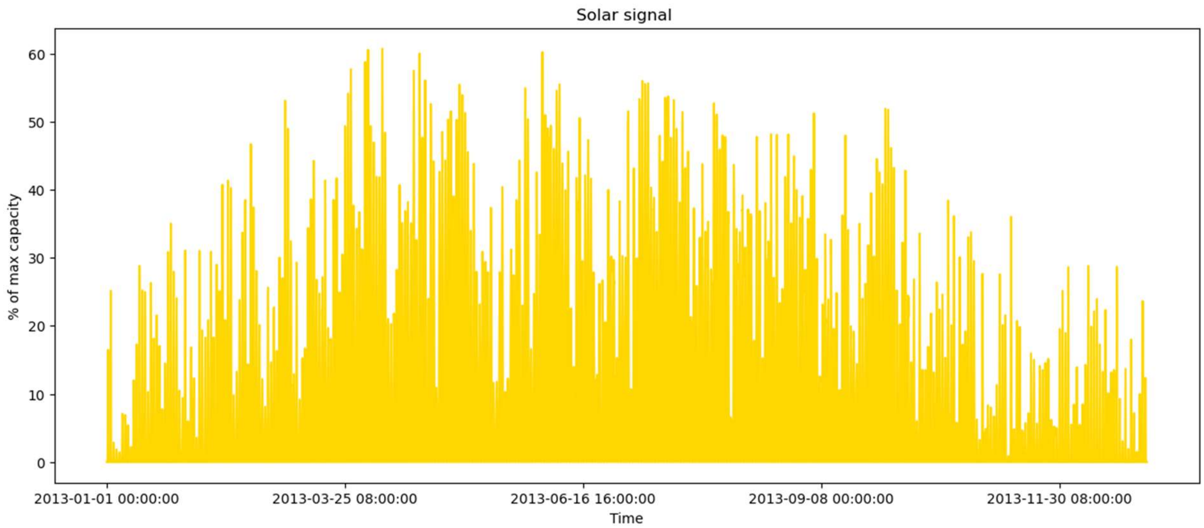

Figure 4: Solar signal of Belgium and the Netherlands in 2013, given in GWh

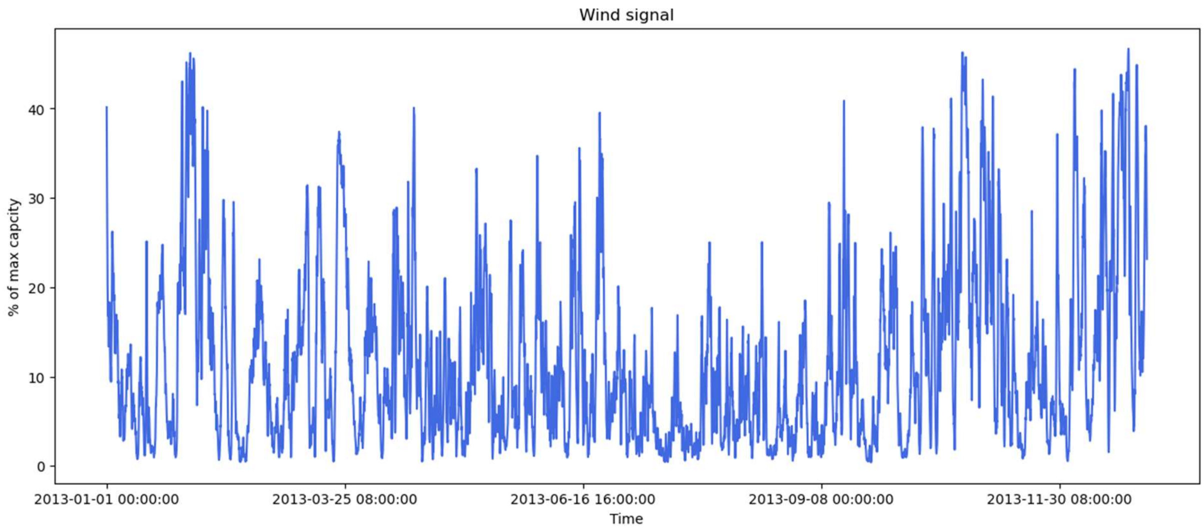

Figure 5: Wind signal for Belgium and the Netherlands in 2013, given in GWh

The gathered techno-economic data for the sub-technologies has been implemented to the framework to establish the costs, efficiency, life time and size of one storage unit.

In the REMix framework, storage technologies are comprised out of two components: the component for charging and discharging, which is the power converter, and the storage component itself that holds the energy, namely the storage. The input data for the converter consists out of the costs for the power equipment (i.e. power inverter), while the input data for the storage is comprised out of the costs for the storage system, as well as the technological data. To connect the converter to the storage unit, the energy to power ratio (e2p) is used which can also be defined as the discharge at rated capacity or how fast the battery can charge or discharge its electricity. It is calculated by dividing the energy storage capacity for one unit by the charging capacity for one unit. For that, a typical storage and output capacity for one unit has been used [33]. The biggest variation between the sub-technologies have Redox Flow batteries due to their different chemistry and their differentiation between scalability of power and energy. Hence, Redox Flow batteries have an e2p factor of 4, while the remaining batteries have an e2p factor of 0.3. Because NMC-111, LFP and Lead Acid batteries have similar conditions, the calculation for the e2p factor was based on the same data. The size of one converter is set to one as a default setting which results in a converter unit size of 1 GW. Based on the e2p factor, the size of one storage unit of Redox Flow batteries is 4 GWh and the size for a storage unit of the remaining sub-technologies is 0.3 GWh. The economic data that was given in €/kWh has been conversed accordingly to represent the cost for one storage unit or one converter unit.

Because the model is not including several generating technologies from the original European dataset while the total demand remains the same, the generating capacity from the remaining technologies, including batteries for storage, is not sufficient to cover the total demand of both countries. Hence, the possibility for the import of electricity was included in the model in order to enable a feasible model run. By electricity import, the supply from outside of Belgium and the Netherlands, and consequently the systems boundaries, is meant. The cost of importing electricity was based on the cost of electricity on the spot market on November 24, 2023 [34] for Belgium and the Netherlands.

2.3.4. Indicators

To include the material criticality in the modelling framework, the indicator of criticality has been implemented as a separate indicator in addition to the established indicator of system cost.

Below the parameterization of the original objective function, as well as the arguments to run the optimization with GAMS can be seen.

```
accounting_indicatorBounds.loc[idx["global", :, "SystemCost"], "obj"] = -1

m.run(
    resultfile="cost",
    lo=3,
    postcalc=1,
    roundts=1,
)
```

resultfile="cost"	Defines the folder where the result file will be located
lo=3	Log option of GAMS to ensure the visibility of the output file
postcalc=1	Default setting to do a post-calculation
roundts=1	Instruction to automatically round after-comma digits in large time series files

Table 2: Overview of arguments used to run the optimization with GAMS

The system costs are comprised of the investment costs and fixed operation and maintenance cost (O&M) of each technology, including generating and storage technologies. The criticality indicator consists out of the criticality factor for each technology. Due to the scope for this research, the criticality factor was only implemented for the storage technologies and does not include the converter or generating technologies.

The goal of the multi-objective optimisation is the minimization of both the cost and the criticality of the energy system. This was done by using a REMix built-in method for a pareto front which aims at providing the pareto efficient solutions for both indicators. Therefore, a cost-minimal solution is computed first. The result of the objective value is then relaxed by a so-called pareto factor and used for constraining several model runs that minimize the systems criticality. The number of model runs is defined by pareto points. A solution is pareto efficient when no alternation is available that improves one indicator without aggravating the other one [35].

The modelling framework was set to include five pareto points with a pareto factor of 1.02, hence the framework will generate five pareto efficient solutions with a maximal deviation of 2% compared to the minimal system costs solution.

Below, the adapted objective function and commands can be seen:

```
accounting_indicatorBounds.loc[idx["global", :, "SystemCost"], "obj"] = -1
accounting_indicatorBounds.loc[idx["global",:, "Criticality"], "pareto"] = -1

m.run(
    resultfile="criticality",
    lo=3,
    names=1,
    postcalc=1,
    roundts=1,
    method="pareto",
    paretopoints = 5,
    paretofactor = 1.02,
    )
```

2.4. Analysis

The results of the modelling framework were analysed to identify potential changes in the design of the energy system.

As a first step, the framework completed a model run solely on the objective of cost minimisation with the techno-economic data for the sub-technologies included. It serves as a base scenario to analyse the potential changes after the implementation of the criticality factor. The analysis was focused on the following parameters: system cost, system criticality, storage units build, generating technologies build, and annual commodity balance.

2.5. Limitations

There are several limitations to the data that has been used in this research.

First, the techno-economic data for the sub-technologies of battery storage is from 2020. Due to the global political and economic developments in recent years, it can be assumed that the cost of storage systems has changed since the assessment has been made. Nevertheless, the dataset has been used as it provided a detailed breakdown of the cost assessment and a comparable source for all selected sub-technologies.

The methodology for the criticality factor is also one of several approaches that can be taken to analyse the criticality of technologies. As it is focused on the supply disruption risk, it does not take into account the ability to substitute nor other factors that influence raw materials like available reserves or the environmental impact. Hence, the criticality factor used in this research also has its limitations.

Finally, the data that was used to define the scope of the European REMix model has its limitations as it was published in 2017. It contains the load profile and the wind and solar production signals from 2012 to 2014 which do not reflect the current situation completely accurate. Furthermore, the transmission line is not included in the adapted data and remains on a default setting. Hence, it is not represented in the indicator system cost.

3. Data Analysis

3.1. Base scenario

This section elaborates on the results from the cost minimization scenario which does not include the criticality factor and serves as comparison scenario. The objective is to minimize the cost of the overall system while implementing the chosen renewable technologies and meeting the overall demand by balancing the fluctuating power generation with the different battery technologies.

3.1.1. System cost

The system cost is comprised out of the investment cost and the fixed O&M costs for all included technologies.

The composition of the system costs varies greatly among Belgium and the Netherlands. In the Netherlands, the system cost is 60,827,900 Kilo-Euros (k€) of which 82% originates from the investment costs. The composition of the investment costs is driven by the costs of wind turbines and redox flow batteries. The total composition of the investment costs between technologies can be seen in Figure 6. The total O&M costs are 10,731,200 k€ and account for 18% of the system cost. The O&M costs are distributed according to the investment cost. The total cost of imported electricity is 3,364 k€, which makes up less than 1% of the total system cost. Accordingly, the generating capacity in the Netherlands, combined with storage applications, is able to cover the bulk part of the demand.

The total system cost in Belgium is 20,470,700,000 k€, which is significantly higher than the system cost of the Netherlands. The investment cost consists out of 17,083,300 k€, and are mainly comprised out of the costs for LFP batteries and wind turbines and the total O&M cost are 1,676,470 k€. Nevertheless, both the investment costs and the O&M costs only make up a marginal share of the system costs as it mainly consists out of the cost for importing electricity with a total of 20,452,000,000 k€. The overall capacity of electricity generation based on the provided solar and wind signals has been reached in both countries and the generation capacity of Belgium lies considerably below the demand. Hence, the vast majority of the demand is covered by the import of electricity from outside of the modelled energy system which consequently makes up the dominant share of the system cost in Belgium.

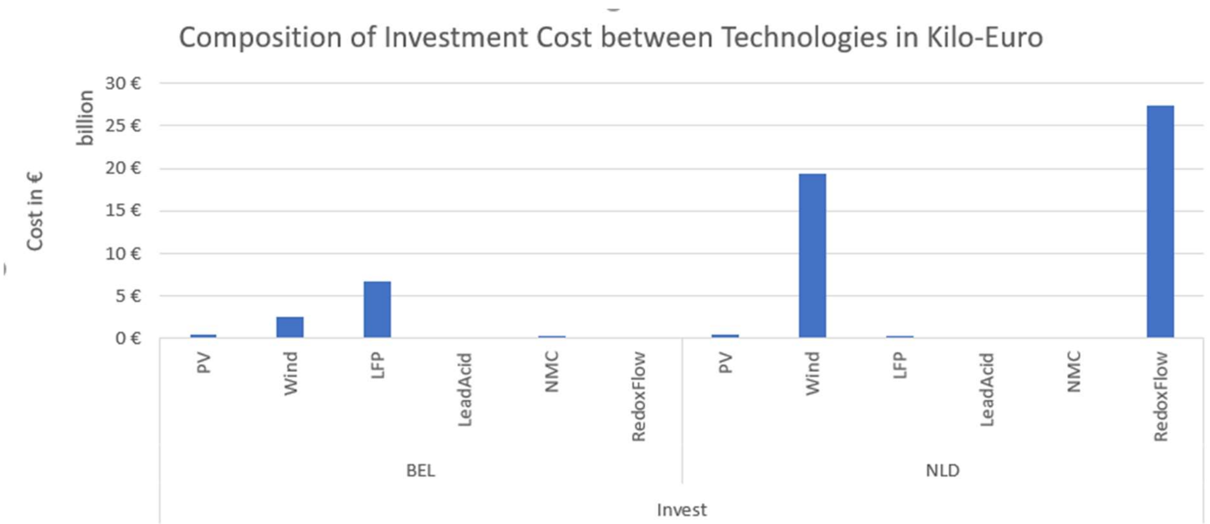

Figure 6: Composition of investment costs between technologies in Belgium and the Netherlands in millions of k€

3.1.2. Generation technologies

The REMix output parameter of converter units provides an overview over the installed generation technologies, in this case for PV panels and wind turbines.

In both countries, the full potential of electricity generation based on the given solar and wind signals was developed. As it can be seen in Figure 7, the expansion of PV panels and wind turbines differs between Belgium and the Netherlands. The deployment of power generation technologies is much lower in Belgium than in the Netherlands, as the full capacity is lower for both energy sources. While Belgium has a similar expansion between wind and solar technologies, the Netherlands have significantly more installed wind turbines. Consequently, this has the major share in the total units of generating technologies. This distribution is also reflected in the costs which was show above (Figure 6).

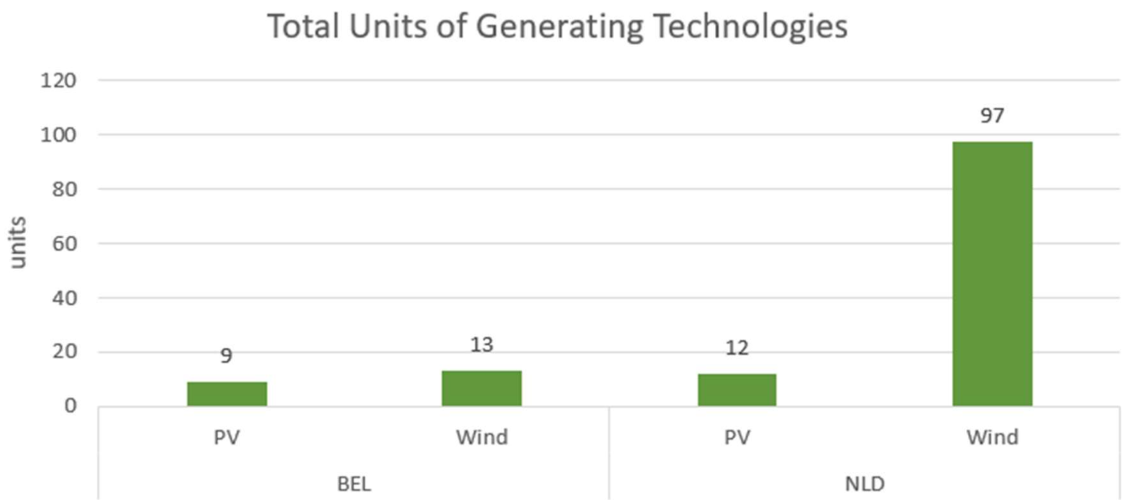

Figure 7: Total units build of generating technologies for the Netherlands and Belgium

Due to the geographic location and weather circumstances, wind energy is available in both countries in a more abundant way than energy generated from the sun. Accordingly, wind energy has a much larger share in the total electricity generated which can also be seen in Figure 8. In the Netherlands, the total electricity generated by wind is 281 931 GWh and the total amount generated by solar is 12 488.3 GWh. Accordingly, wind energy makes up 96% of the total electricity supply, while solar energy contributes the remaining 4%. In Belgium, the total amount of electricity generated by wind is 28 947.8 GWh and the total electricity generated by solar is 14 041 GWh, which results in 67% and 33% of the electricity generation, respectively. Even though the Netherlands have more units built of PV, the electricity generation from PV is higher in Belgium. This could be due to fact that the majority of the demand in the Netherlands is already satisfied by wind energy, which can be seen in the electricity balance in Figure 9.

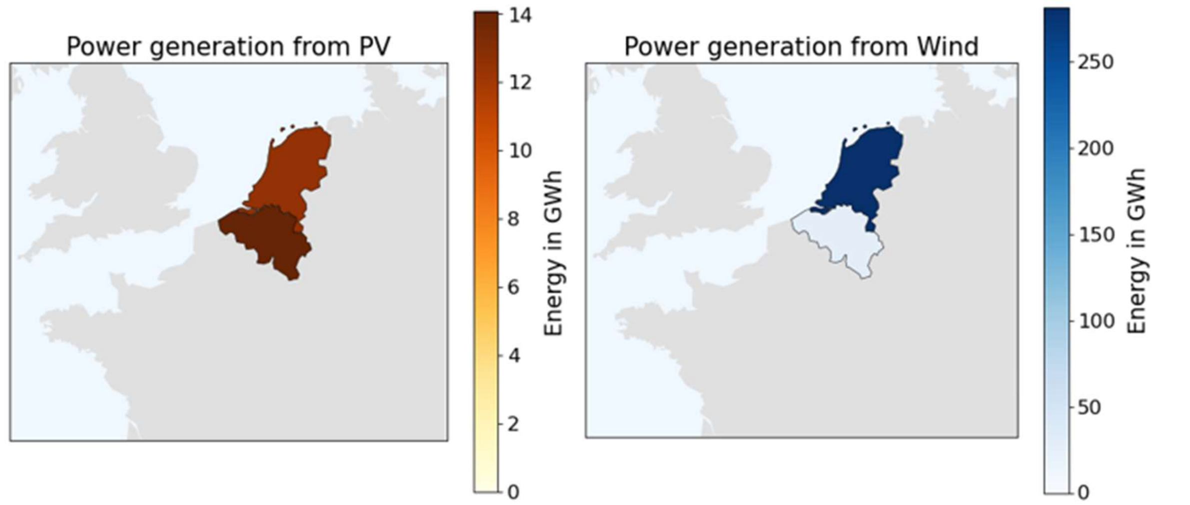

Figure 8: Power generation from PV and Wind in Belgium and the Netherlands in GWh

Overall, the generation from wind is significantly higher in both countries than the generation from PV. The total electricity generated in both countries results in 26 529.3 GWh from PV panels and 310 879 GWh from wind turbines, with a percentage of 8 and 92 respectively. This results in a total of 337 408.3 GWh produced electricity.

3.1.3. Power balance

The REMix output parameter of commodity balance represents the electricity balance within the energy system.

The total demand in the Netherlands is 101 088 GWh. The total electricity generated by wind and solar is 294 419.3 GWh which covers the demand most hours of the year. It can also be seen that most of the demand is covered by wind energy which is why the total generation from PV panels is lower in the Netherlands than in Belgium, regardless of the number of units. However, there are some hours in which the demand is not fully covered by the electricity generation technologies. To demonstrate the small gaps in the electricity, a closer look at the electricity balance between the hours 1000 and 1400, which is the time frame from 11.02.2013 15:00:00 until 28.02.2013 07:00:00, is provided in Figure 9. It shows the electricity balance of the Netherlands, including the demand, electricity generated by wind and solar and slack, which represents the import of electricity from outside of the modelled system, hence not Belgium or the Netherlands.

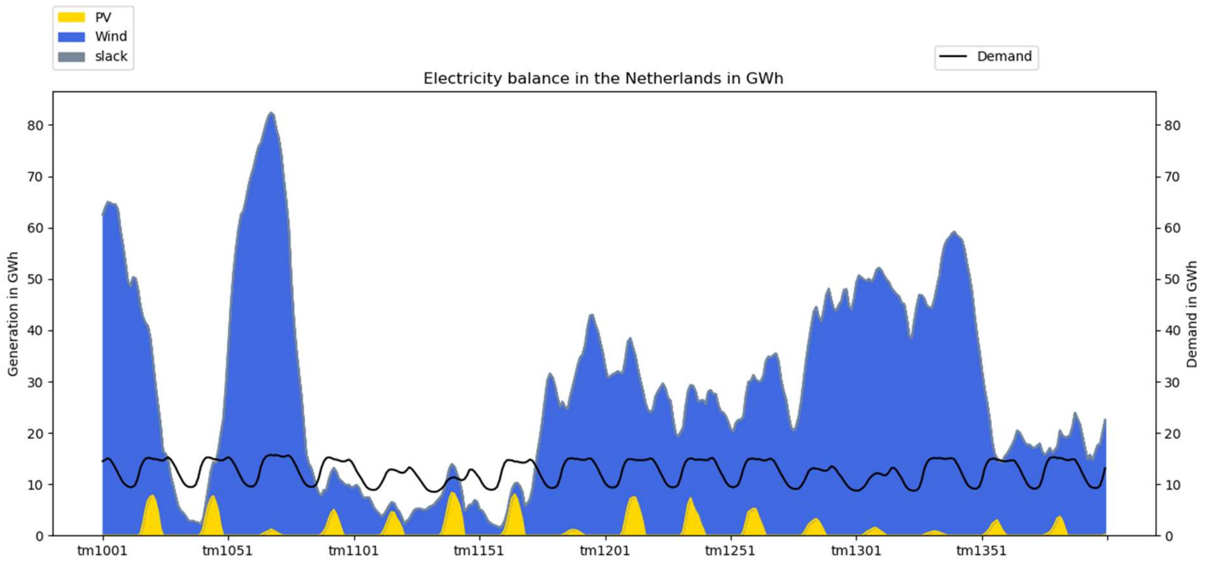

Figure 9: Electricity balance between 11.02.2013 and 28.0.2013 in the Netherlands in GWh

It can clearly be seen that there are several time steps in which the demand cannot be covered which demonstrates the need for storage technologies in order to balance the system and cover the demand in the Netherlands.

The demand in Belgium is 79 919.3 GWh and the total electricity generated by renewable technologies is 42 988.8 GWh. Consequently, the demand in Belgium can not be fully covered by its generation capacity of renewable sources. Hence, the import of electricity is needed, as well as the import of electricity from the Netherlands via AC transmission. The electricity supply from the transmission line acts a base load in the electricity balance and the total amount of electricity received from the AC line is 11 125.2 GWh. Figure 10 shows the electricity balance of Belgium in the same time frame as shown in the previous figure.

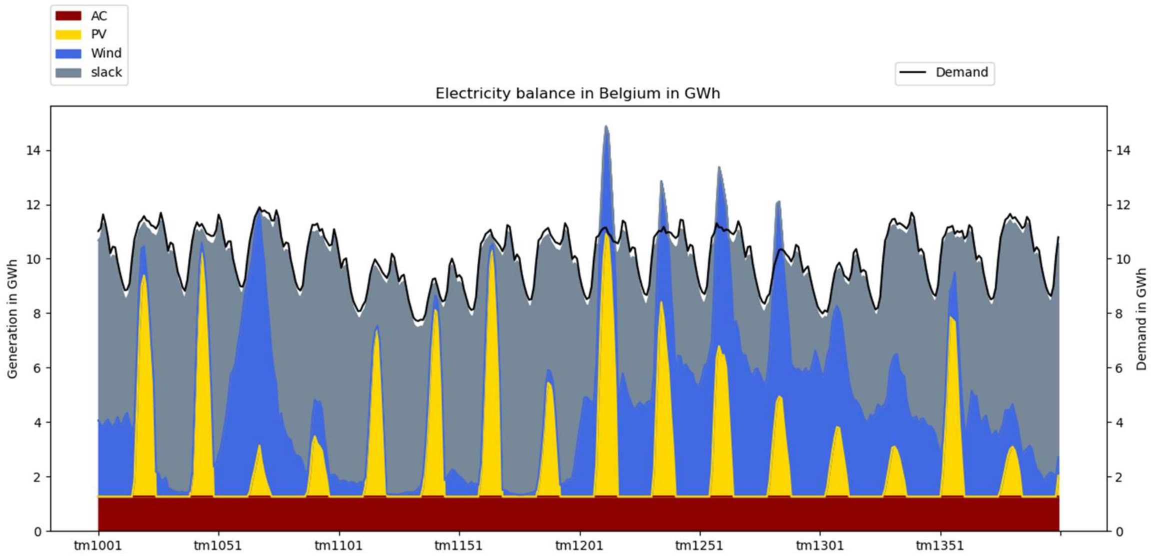

Figure 10: Electricity balance between 11.02.2013 and 28.0.2013 in Belgium in GWh

It can be seen that the demand is almost fully covered by the combination of generating technologies, the AC line and the imported electricity. Nevertheless, a pattern of gaps in the electricity supply can be seen which shows the need for storage capacity in Belgium.

3.1.4. Storage technologies

As discussed in the previous section, Belgium and the Netherlands are relying on storage capacity to fully cover their demand.

Figure 11 shows the total units of storage technologies installed in Belgium and the Netherlands. It can be seen that the installed units vary significantly between countries

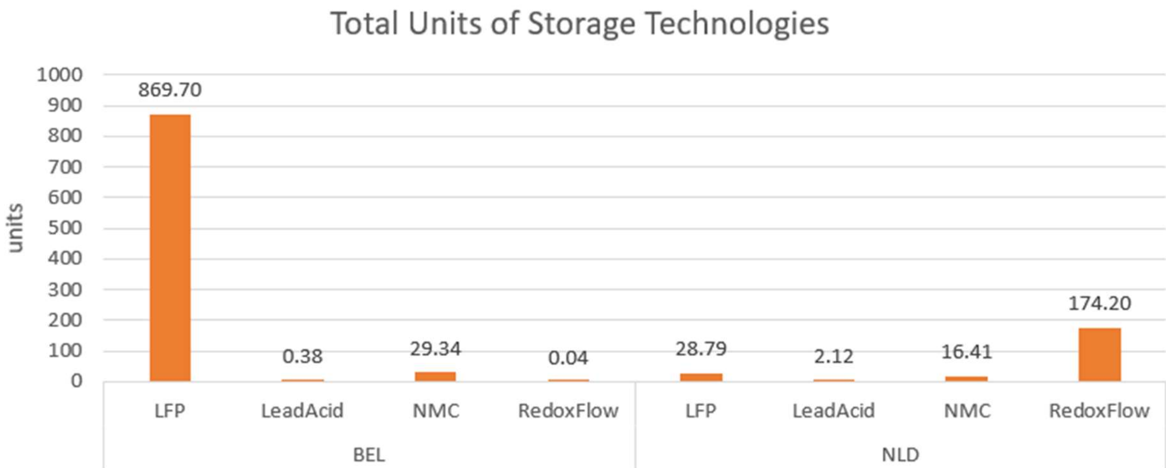

Figure 11: Total storage units for the Netherlands and Belgium

The main sub-technology of batteries installed in the Netherlands are redox flow batteries with 174.2 units. As redox flow batteries have a capacity of four GWh per unit, it results in a storage capacity of 696.817 GWh. Furthermore, 28.79 units of LFP batteries have been installed with a total capacity of 8.637 GWh, 16.41 units of NMC batteries with a total capacity of 4.924 GWh, as well as 0.635 GWh capacity of lead acid batteries which results in 2.12 units. The unit size of LFP, NMC and lead acid batteries is lower than for redox flow batteries with a capacity of 0.3 GWh per unit. Accordingly, the total storage capacity in the Netherlands amounts to 711.013 GWh.

Even though lead acid batteries are the least expensive technology, it is also the least installed sub-technology. Yet, the cost difference to LFP and NMC batteries is minimal and the higher efficiency of LFP and NMC batteries might be decisive for the optimal solution. Redox flow batteries are the preferred sub-technology in the cost minimizing scenario, even though the technology has the highest investment and O&M costs. In order for the model to prefer redox flow batteries, other characteristics as the higher lifetime and the higher e2p ratio are of potentially larger influence. The high share of redox flow batteries in the Netherlands likely relates to the high share of wind energy in the electricity supply. As mentioned above, redox flow batteries have a higher e2p ratio, hence the discharge at rated capacity is higher and the battery can charge and discharge faster. Additionally, the adjustment to different requirements is easier. These characteristic fit well with the fluctuations of electricity supply by wind power and the storage level of redox flow batteries somewhat resembles the spikes visible in the wind signal, which can be seen in Figure *12*5.

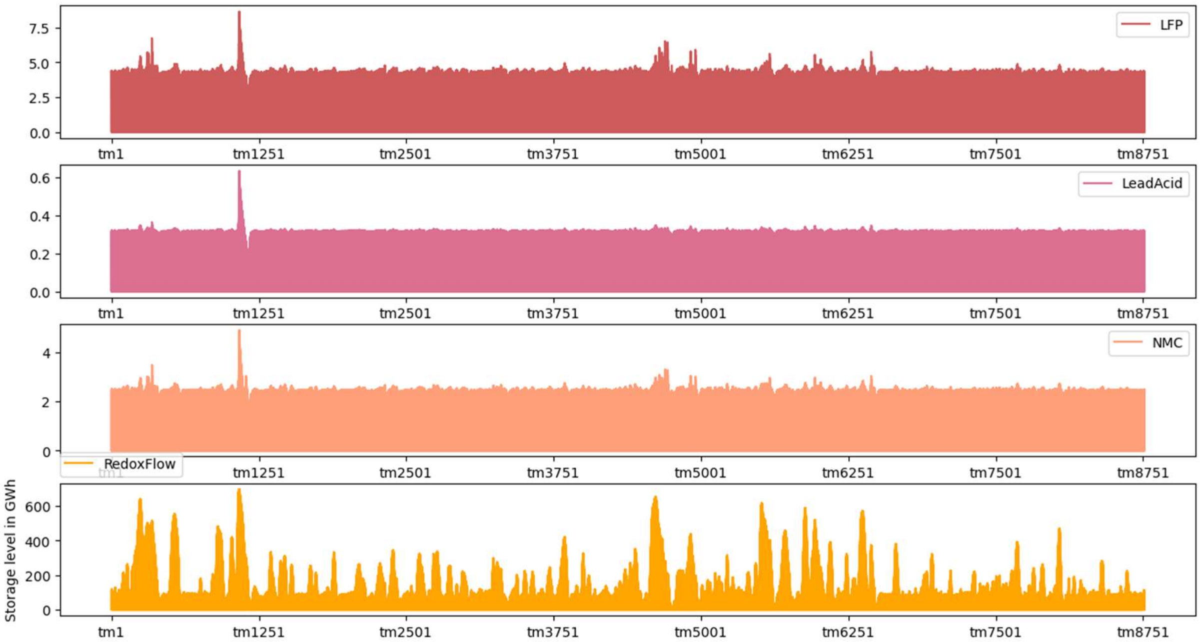

Figure 12: Storage level of all sub-technologies in the Netherlands given in GWh

In comparison, the storage level of the remaining sub-technologies remains mostly stable. LFP batteries have the second highest peaks in the storage level, followed by NMC batteries, which matches the number of installed units as shown above.

Hence, redox flow batteries are the first choice in order to cover the intermittency of electricity generated by wind turbines, followed by LFP batteries to support additional needed capacity for a more stable storage level with slower discharge.

In Belgium, LFP batteries have certainly the largest share among the sub-technologies. The total number of 869.7 units result in a total storage capacity of 260.909 GWh. NMC have the second largest share, which is significantly lower with 29.34 units and a capacity of 8.802 GWh. Additionally, there are 0.38 units of lead acid batteries installed with a total capacity of 0.113 GWh and 0.04 units of redox flow batteries which amounts to a capacity of 0.166 GWh. Here it is clearly visible that redox flow batteries have a higher capacity per unit than the other sub-technologies as the total capacity exceeds the capacity of lead acid batteries, despite the lower number of units. Overall, Belgium has lower storage capacities than the Netherlands with a total of 269.99 GWh. Because the vast majority of the electricity supply in Belgium is covered by electricity imports, the need for storage capacity is lower due to the higher controllability of import in comparison to intermittent renewable energy sources.

When comparing the costs of the sub-technology, a similar development can be seen as in the Netherlands. LFP batteries are the dominant technology, followed by NMC, even though lead acid batteries are the least expensive. Again, the choice of not preferring the least expensive sub-technology stands in relation to the marginal cost difference and higher difference in efficiency. Additionally, Belgium also installed capacity of redox flow batteries, yet at a significantly lower level than the Netherlands due to the lesser peaks.

The storage level of the sub-technologies in Figure 13 show that lead acid and redox flow batteries almost are constantly having a storage level at almost maximal capacity. At the same time, the storage levels of LFP and NMC batteries have significantly more variation over the year and act similar to the pattern in the electricity balance. In addition to the higher scale of storage levels for NMC and especially LFP, this indicates that those batteries are mainly in use while lead acid and redox flow batteries are more used for backup storage capacity.

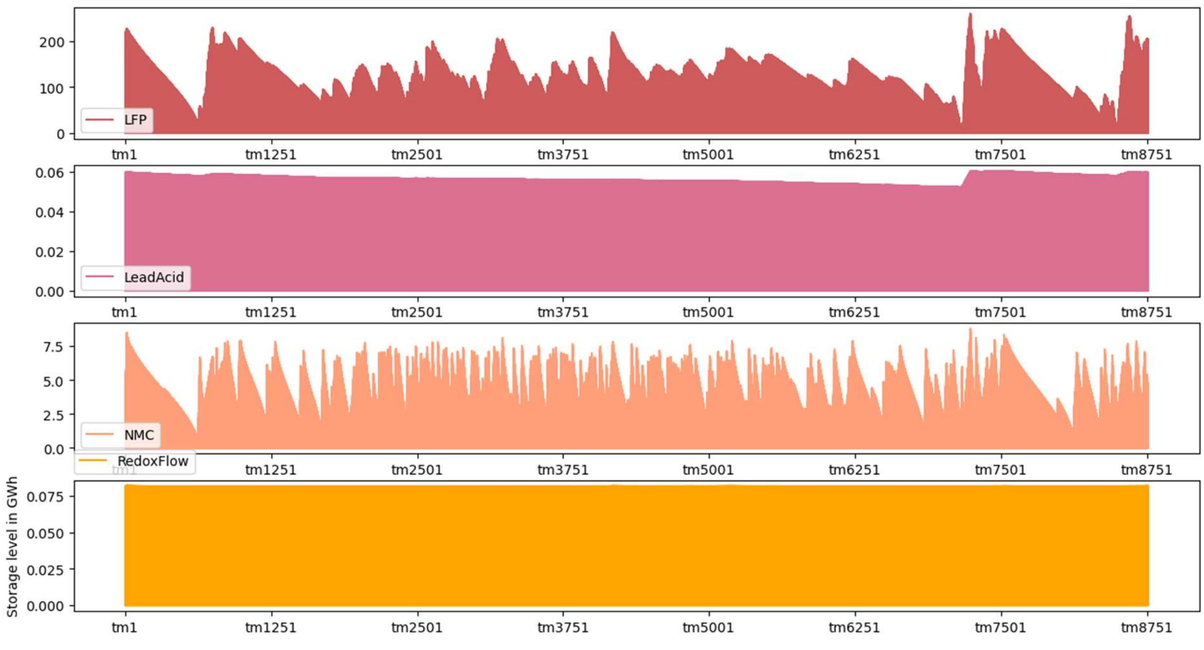

Figure 13: Storage level of all sub-technologies in Belgium given in GWh

Because Belgium is coping with a less intermittent electricity supply, it is reflected in the choice of sub-technology. LFP and NMC batteries have a slower discharge rate which makes them less suitable for high fluctuations than redox flow batteries. Nevertheless, the fast discharge is not as vital in the case of Belgium which is why the less expensive sub-technologies were selected.

In total, the storage capacity for Belgium and the Netherlands is 981.002 GWh. Redox Flow batteries have the highest share with 71%, followed by LFP batteries with a share of 28%. NMC and lead acid batteries both have a marginal share with 1% and less then 1% respectively.

3.2. Criticality scenario

In the following section, the outcomes of the criticality scenario with five pareto fronts will be analysed. Pareto zero represents the optimization solely based on costs which was presented in the previous section under base scenario. The criticality scenario has the same scope and data input as the base scenario but it also includes the criticality factor for the storage sub-technologies, and has the objective to minimize both the cost and the criticality of the system while still meeting the demand.

3.2.1. SystemCost & Criticality

This section will look at the behaviour of the indicators SystemCost and Criticality.

The pareto front in Figure 14 shows that the indicator of SystemCost is increasing steadily while the indicator of Criticality is decreasing.

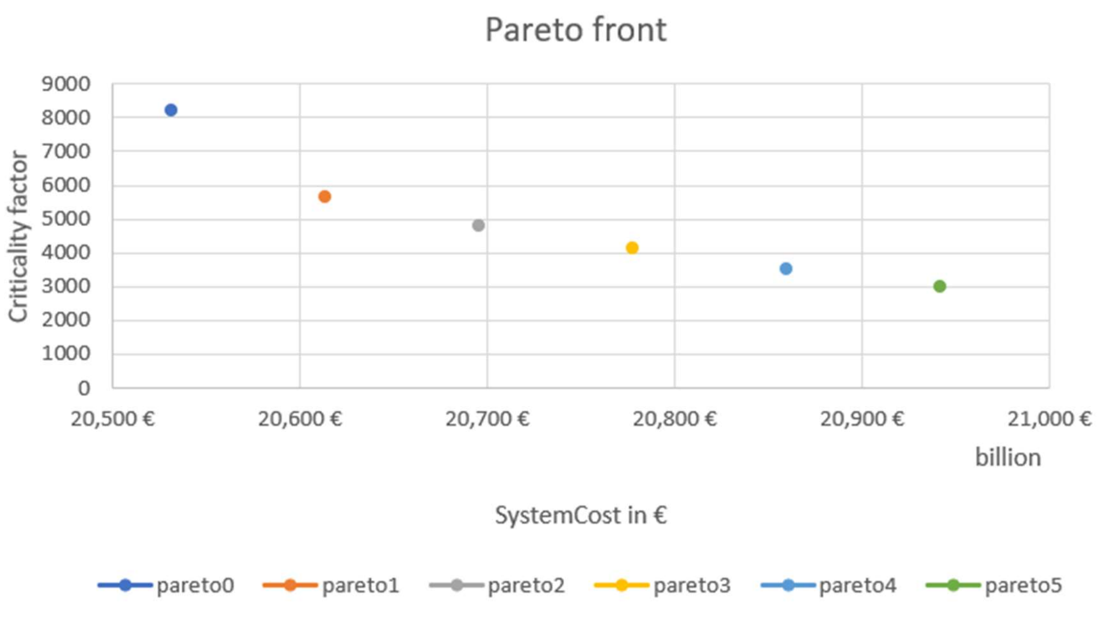

Figure 14: Pareto front of the indicators SystemCost and Criticality

The SystemCost have a 2% increase from 20 531 500 000 k€ in pareto 0, which is representing the base scenario, to 20 942 200 000 k€ in pareto 5 which is the pareto pint with the highest SystemCost. Pareto 0 has a criticality factor of 8216.68 for the entire energy system while the system design in pareto 5 has a criticality factor of 2977.23 which is a significant decrease of 63.7%. This shows that a significant decrease in the criticality of the system can be achieved, however, it is accompanied with an increase in the cost.

The following sections provide an overview of the development of the indicators over the pareto front. More details are provided for pareto 5, to enable the comparison between the point with the lowest criticality and the base scenario with the highest criticality.

As it can be seen in Figure 15, the composition of the investment costs has a similar focus of technologies in all pareto points. Nevertheless, there are two developments in regard to the share in investment costs. The first development is the share of redox flow batteries in the Netherlands, which is decreasing over the pareto points. Additionally, the share of LFP batteries in Belgium is decreasing steadily over the pareto points.

In pareto5, the total cost of the system in the Netherlands is 196,038,000 k€, with an investment cost of 34 830 300 k€ that makes up 18% of the total costs, and an O&M cost of 9 412 030 and a percentage of 5. In addition, the share of electricity import in the total costs has risen substantial to 77% from 3,364 k€ to a cost of 151 796 000k€. The decrease in investment cost is 30%, compared to the base scenario. This development is driven by the reduced usage of redox flow batteries, as the omitted capacity needs to be substituted. In this case with the use of electricity import due to the fact that it does not have a criticality factor attached and the capacity for electricity generation was already fully exhausted. In total, the cost of the system in the Netherlands has an increase of 222% which is significant.

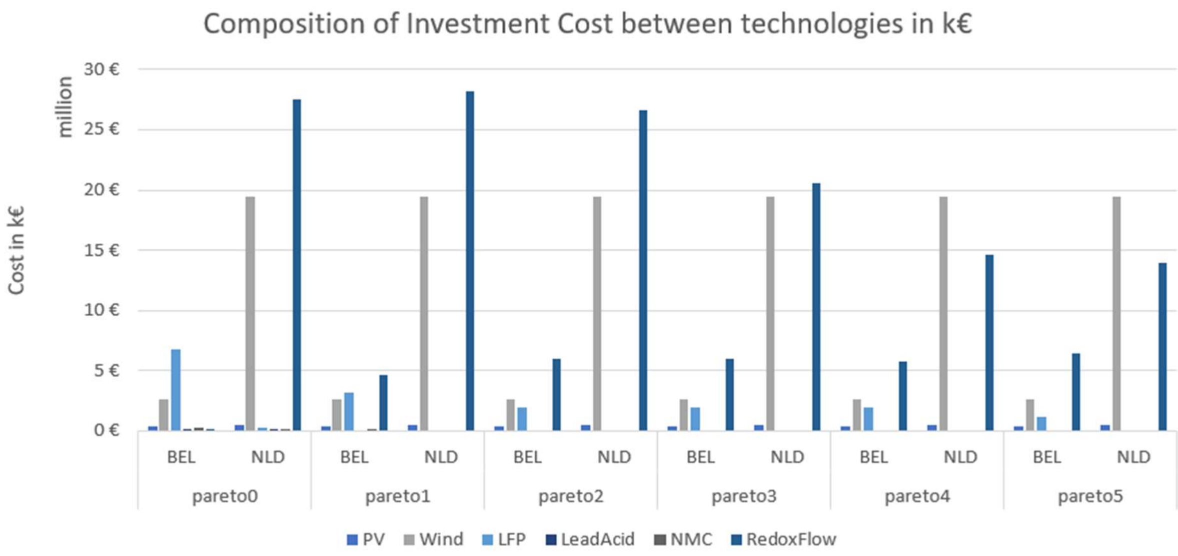

Figure 15: Composition of investment costs between technologies in Belgium and the Netherlands, given in k€

In Belgium, the total system cost in pareto 5 are 20 746 100 000 k€ of which the vast majority is related to electricity import with a cost of 20 732 000 000 k€. The investment cost amount to 12 279 400 k€ which is a 28% decrease in comparison to the base scenario, which is driven by the increase in redox flow batteries. The total system cost in Belgium increased slightly by 1.4%. Accordingly, the increase of the indicator SystemCost is mainly driven by the increase in the Netherlands.

In pareto5, the total criticality of the system in the Netherlands is 1446.81 while the system in Belgium has a criticality factor of 1530.42. The criticality in the Netherlands is clearly driven by redox flow batteries, as the sub-technology is also the main batterie type installed in the Netherlands. In Belgium, the criticality factor is dominated by LFP batteries. However, redox flow batteries are also contributing as their share of units increases. Because redox flow batteries have the highest criticality factor among the sub-technologies (see Figure 2), it can be assumed that the in- or decrease in units has a considerable impact on the criticality factor of the system. Because, LFP batteries have a lower criticality, the impact of changes in total units in expected to have a lower impact of the overall criticality. This can also be seen in the overall development of the criticality in the pareto points which is shown in *Figure 12*Figure 16.

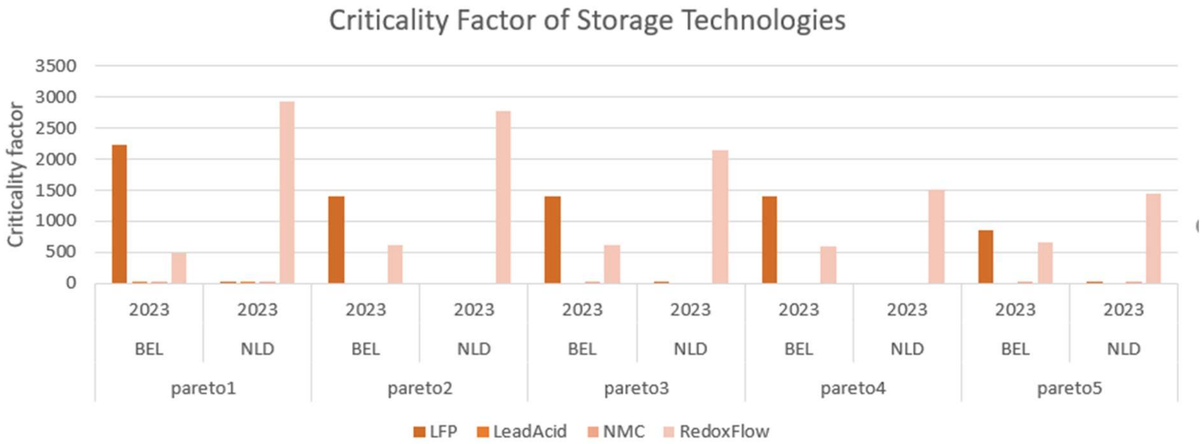

Figure 16: Criticality factor of Storage Technologies over all pareto points in Belgium and the Netherlands

3.2.2. Generation Technologies

The development of generating technologies was not influenced by the implementation of the criticality factor. Hence, potential changes within the pareto fronts would not result from a minimization of criticality but could rather be seen as a reaction to the differences in the storage technologies.

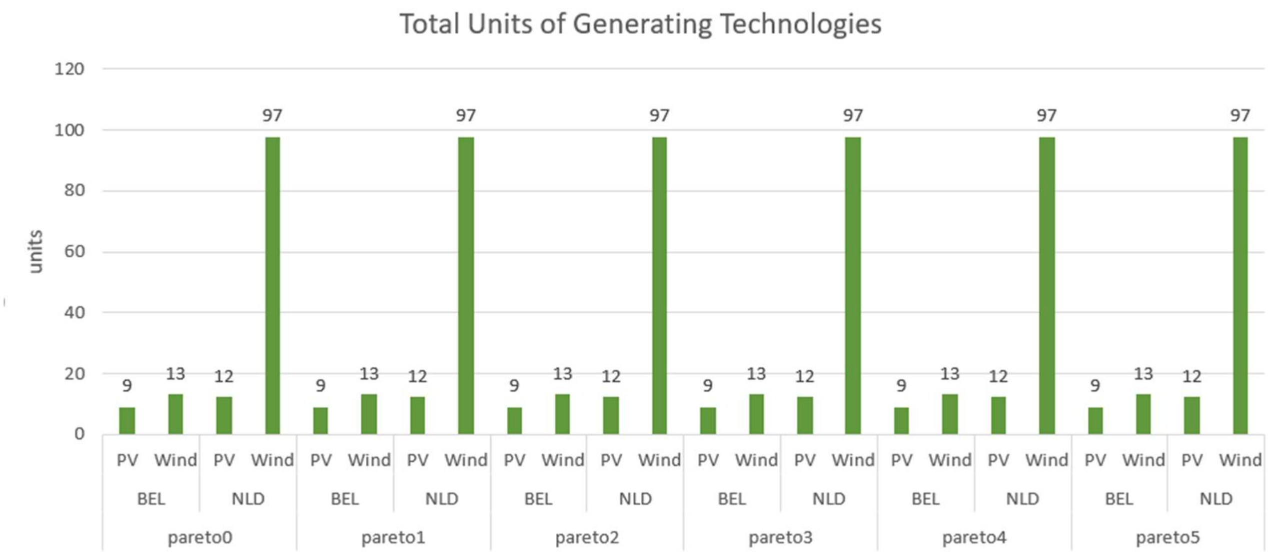

Figure 17: Total Units of Generating Technologies in Belgium and the Netherlands in all pareto points

Nevertheless, it can be seen that the total number of units of generating technologies is not affected in the pareto points and remains the same (

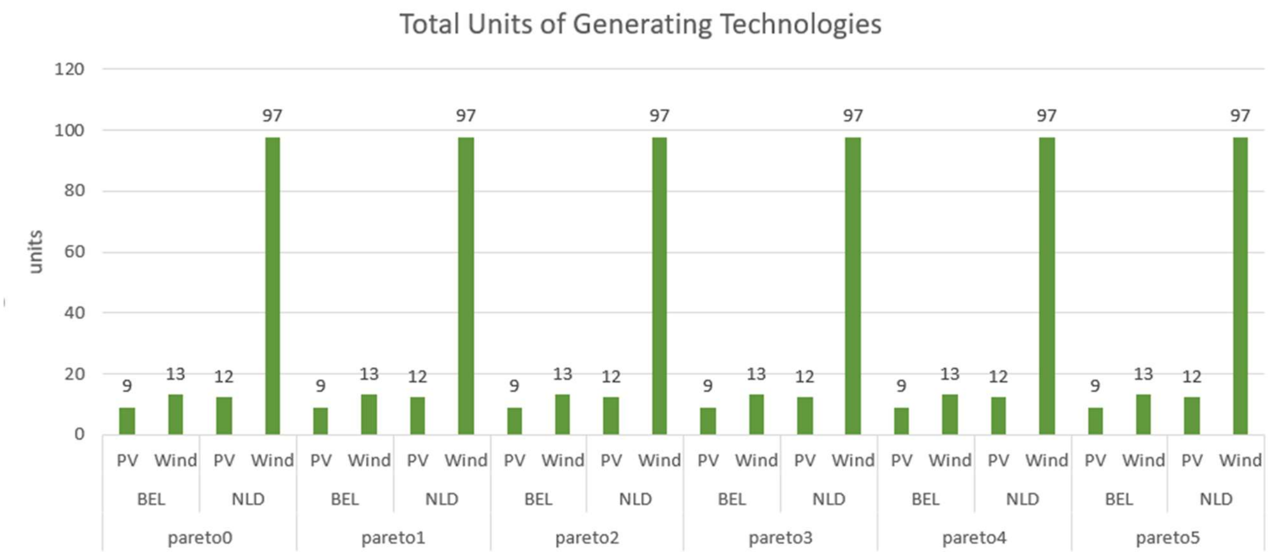

Figure 17), which also applies to the generation capacity. This lack of development is also due to the fact that the full capacity of electricity generation is already reached, so an increase in generation is not possible. Consequently, the shifts in the power balance are compensated with the import of electricity

3.2.3. Power Balance

The increase in electricity import can also be seen in the electricity balance of the countries. For comparison, the same time frame as in the base scenario has been visualized.

In the Netherlands, the gaps between electricity supply and demand are still prominent, yet the amount of electricity import to minimize the gaps is increasing in comparison to the base scenario. This can be seen in Figure 18 which shows the electricity balance in the Netherlands for the same time frame.

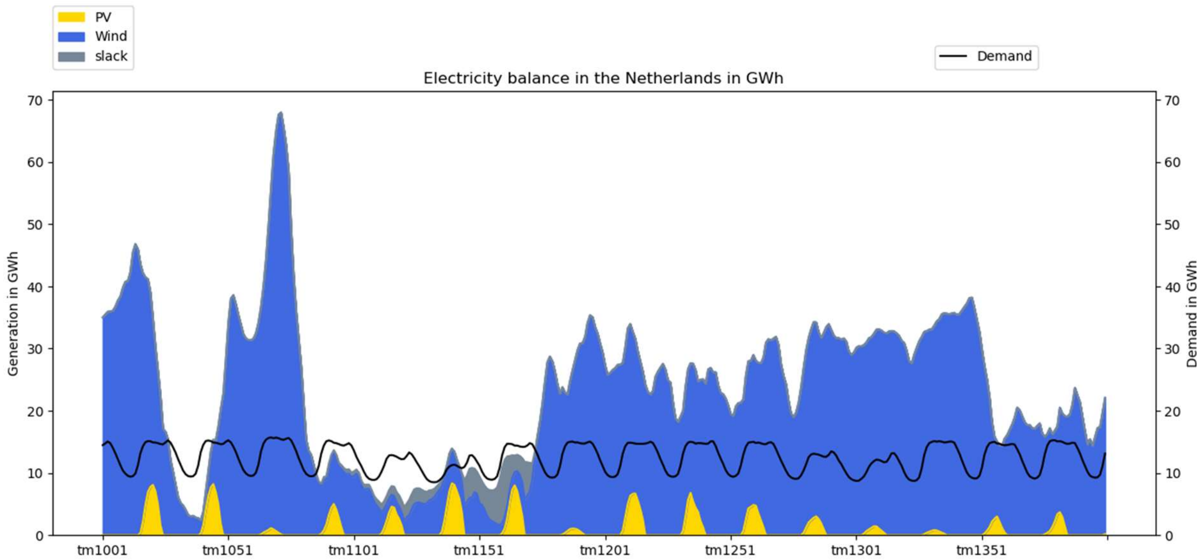

Figure 18: Electricity balance between 11.02.2013 and 28.02.2013 in the Netherlands in GWh for pareto5

A similar development can be detected in the electricity balance of Belgium. The gaps between the demand and total supply are smaller, which demonstrated the increase in imported electricity. Additionally, the supply of electricity via AC transmission is decreasing to 11048.3 GWh from 11125.2 GWh which results in a decrease of 0.7%. Hence, the decrease is not significant, yet it has a small impact on the electricity balance.

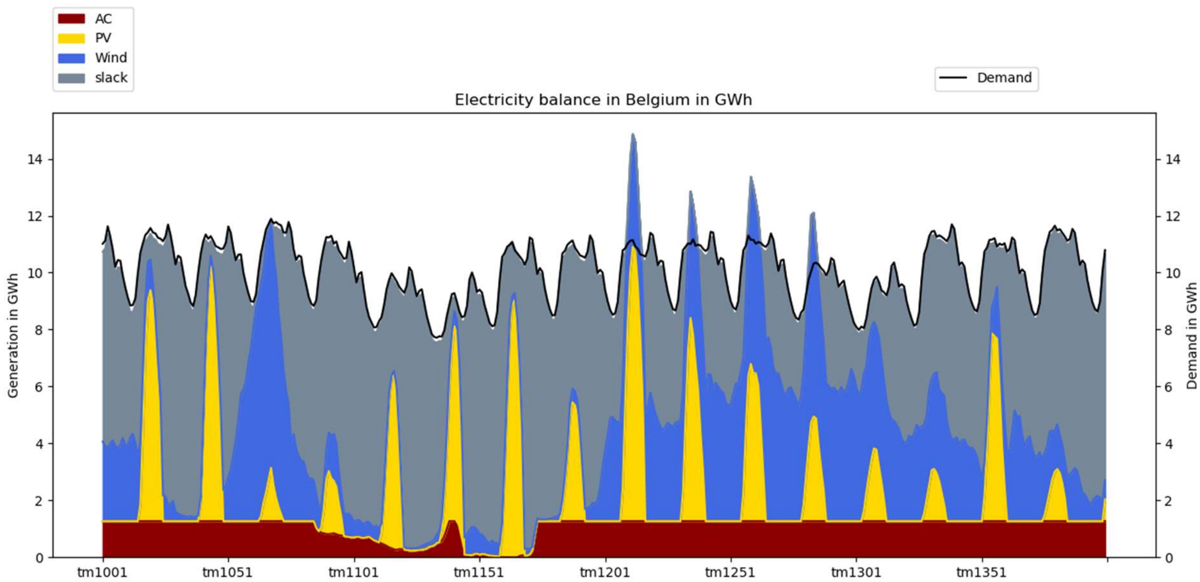

Figure 19: Electricity balance between 11.02.2013 and 28.0.2013 in Belgium in GWh for pareto5

3.2.4. Storage Technologies

As discussed in previous sections, the number of storage units is decreasing over the pareto points which can be seen in Figure 20. Due to the fact that the criticality is only implemented for storage sub-technologies, the changes in the storage units are influencing the criticality of the system and a reduction in storage units results in a lower system criticality. The developments seen in the composition of investment costs (Figure 15) are validated by the number of units for the sub-technologies, which can be seen in Figure 20.

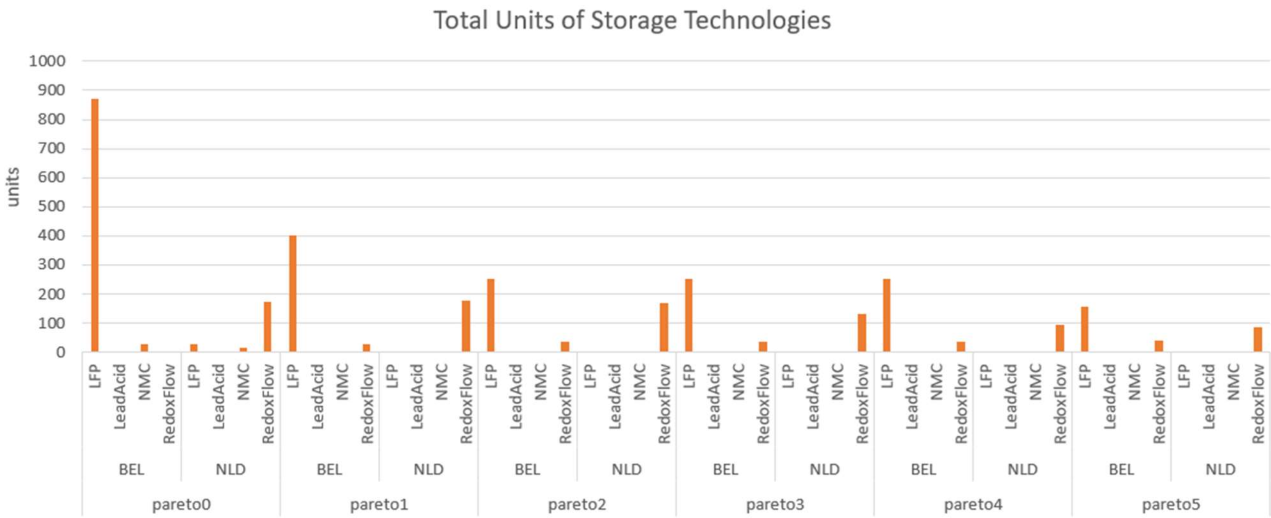

Figure 20: Total Units of Storage Technologies over the pareto point in Belgium and the Netherlands

The amount of redox flow batteries in the Netherland is decreasing over the pareto points and no other storage sub-technology is substituting the capacity. In pareto5, the number of redox flow units is 88.11 with a total capacity of 352.422 GWh which is a decrease in capacity of 49% compared to the base scenario. Additionally, the storage units for LFP, NMC and lead acid batteries are also decreasing drastically which results in a capacity of 92.191 kWh, 43.494 kWh and 61.431 kWh, respectively. It is noteworthy that the capacity of LFP, NMC and lead acid is given in kWh instead of GWh which demonstrates the vast reduction in capacity. This reduction can also be seen in Figure 21 which shows the storage level of the sub-technologies in the Netherlands. As seen in the base scenario, the storage level of redox flow batteries is dominated by peaks which indicates its usage to cope with the intermittency of the dominate energy source of wind. The storage level of the other sub-technologies remains stable beside two peaks in the start of the year. This also indicates the minimal usage of the batteries, supported by the very low level of storage capacity.

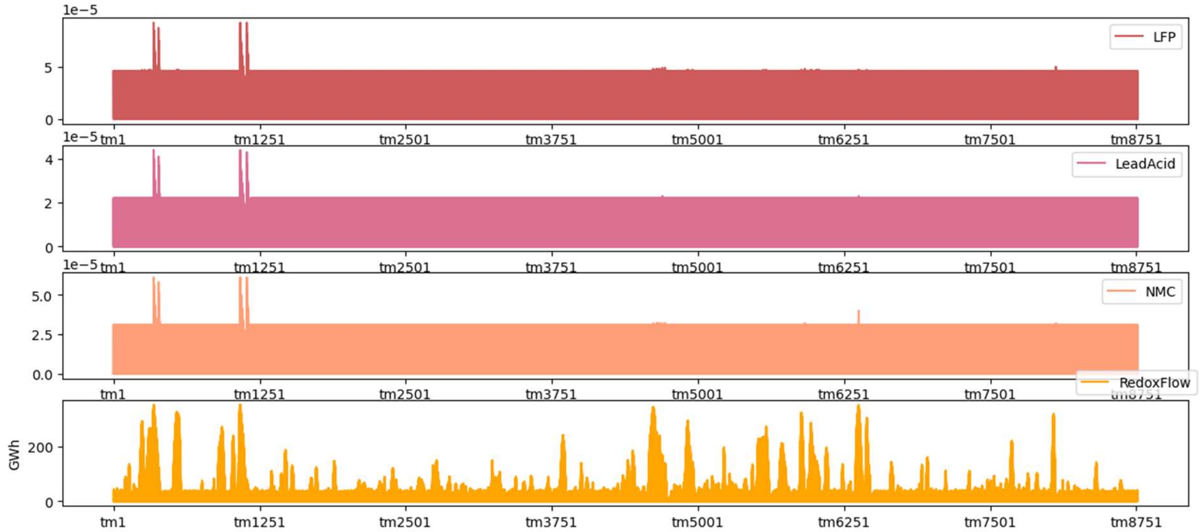

Figure 21: Storage level of all sub-technologies in the Netherlands given in GWh for pareto5

The system criticality in the Netherlands is defined by redox flow batteries. Therefore, the criticality is reduced by a reduction in the installed redox flow units as no other storage sub-technology is used as a substitution. However, additional reduction is achieved through the minimisation of the remaining sub-technologies, predominantly LFP batteries.

In Belgium, the dominant storage technology is LFP batteries which are decreasing in units. In pareto5, the total number of LFP units is 155.16 which results in a capacity of 46.547 GWh. Accordingly, the capacity of LFP batteries decreased by 82% compared to the 260.909 GWh in the base scenario. In contrast to the Netherlands, another sub-technology for storage is increasing instead. Redox flow batteries have a total number of units of 40.68 with a capacity of 162.715 GWh, compared to 0.167 GWh in the base scenario. Accordingly, it can be seen that the storage capacity which was reduced for LFP batteries, is partially shifting towards capacity of redox flow batteries which makes it the dominant sub-technology. Additionally, the units for lead acid and NMC batteries have decreased significantly, with a remaining capacity of 39.648 kWh and 145.256 kWh, respectively. In can be seen that both capacities are given in kWh as well which indicates the level of minimization which is also visualised by Figure 22. The figure also shows that the storage level of all sub-technologies is fluctuating over the year which indicates that the remaining storage capacity is solely used to cope with the intermittency of renewable energy.

This development would also explain the choice of sub-technology in regards to criticality.

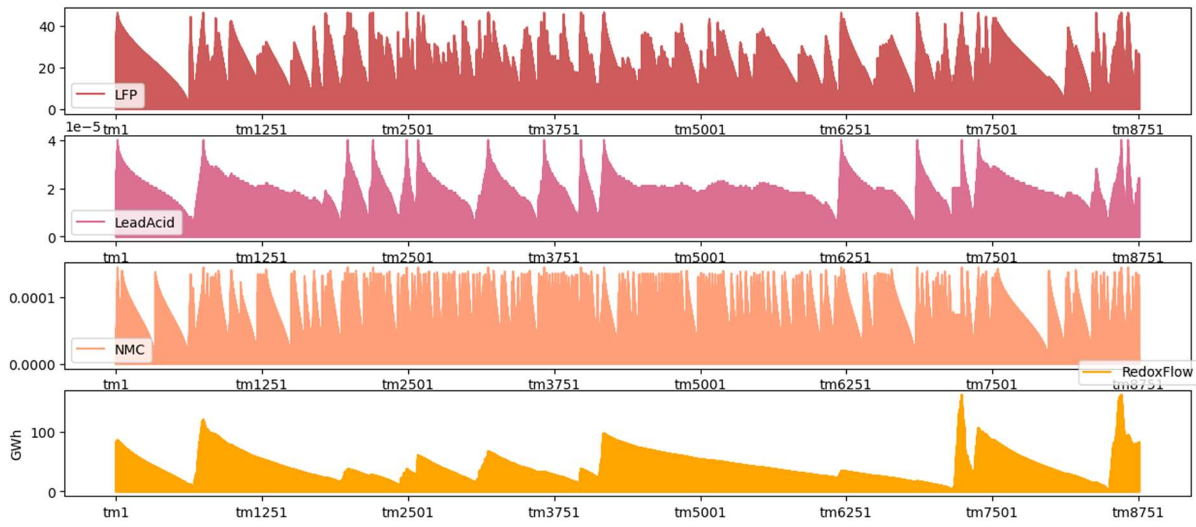

Figure 22: Storage level of all sub-technologies in Belgium given in GWh for pareto5

This development would also explain the choice of sub-technology in regards to criticality. LFP batteries have the lowest criticality factor of all sub-technologies with 5.56 per kWh while redox flow batteries have the highest criticality factor with 16.42 per kWh. Hence, the usage of LFP batteries is optimal for a minimization of the systems criticality and with the reduction in units, the criticality of LFP batteries is decreasing from 4833.96 in the base scenario to 1530.42 in pareto5. The criticality of NMC and lead acid batteries is also decreased significantly due to drastic reduction in capacity. Nevertheless, the installation of redox flow batteries instead of LFP batteries seems counterintuitive due to is high criticality factor. However, due to the fact that the criticality factor was implemented per unit in the REMix model and the capacity of one redox flow unit is considerable higher, the overall criticality of redox flow batteries in Belgium is lower than the criticality of LFP batteries with a factor of 667.99, even though the overall capacity is exceeding LFP batteries. Additional characteristics of redox flow batteries like the fast discharging capacity support the choice of sub-technologies, as this still results in the lowest criticality.

Overall, it can be said the implementation of a criticality factor for storage sub-technologies has a visible effect on the design of the energy system. The criticality depends on the usage of storage technologies and a steady reduction of storage units is possible with a slight increase in the costs of the system. The implementation of criticality is not only reducing the overall storage capacity, it is also shifting the capacity among the sub-technologies as it can be seen in Belgium. Additionally, the size and specific characteristic of a storage unit has a strong impact on the usage as well, as it can be seen in the exploitation of redox flow batteries.

4. Discussion

This research was a first approach at analyzing the design differences of energy systems when the criticality of sub-technologies is included in the optimization parameters. Several limitations exist, which will be discussed below.

The first limitation arises from the chosen criticality factor that was used. As mentioned above, there are several methodologies to derive a criticality factor, either on a material or technology level. The criticality factor used in this research is solely focusing on criticality based on the probability of supply disruptions. However, there are other factors which also have a potential influence on the availability of raw materials and could impact the criticality factor. These factors include the ability to substitute materials or technologies and to recycle materials, as well as the actual reserves and resources and the environmental impact the exploitation potentially has.

One uncertainty of this research is that the selected sub-technologies were based on the current distribution in the market. With technological developments and the commercialisation of new battery types, the number of sub-technologies should be largened. One promising technology that was mentioned in the reviewed the literature were sodium-ion batteries, which are expected to be a promising and widespread technology. Compared to lithium-ion batteries, they have lower material costs and a lower environmental impact, mostly due to the absence of critical materials like cobalt, nickel and copper. It can be used in various applications including electric vehicles (EV) and long-term storage applications. Even though, lithium-ion batteries have a better performance at the moment, in some areas, sodium-ion batteries could be an attractive alternative to LFP or Lead Acid batteries [18]. The technology is especially considered to be a substitute for lithium-ion batteries, as sodium is available at a lower cost than lithium. The technology is still in the development phase but is expected to be a potential key solution for grid electricity storage applications [36]. Due to the fact that the current state of technology is not developed and commercialized enough to retrieve the necessary data on a comparable level as with the previous mentioned technologies, the sub-technology of sodium-ion batteries will not be included in this research. Nevertheless, due to its widespread potential, it is recommended to include it in further research regarding the role of ESS in energy systems.

Another uncertainty in this research is the cost development of batteries as storage solutions. It was commonly stated by market development reports and the consulted expert, that the price development is unpredictable due to several factors like material prices or production capacities. However, the focus of this research was less on identifying the exact numbers of the cost of energy systems but more on identifying changes in the proportions between technologies and the overall system design. Nevertheless, it is recommended to include that uncertainty in future research.

As this was a first step, the potential to upscale the modelling framework in terms of countries as well as technologies is immense. To come closer to a representation of the actual electricity system in Europe, all generation, distribution and storage technologies would need to be included with the current techno-economic data as well as the criticality factor. Because the criticality was only implemented for one technology class, the implementation for all technologies is likely to have a significant influence on the overall system design, including the choice of technologies and the power balance of the system. Additionally, the import of electricity would need to be accounted for as well, as it acts as a substitute for the development of electricity generation.

5. Conclusion

In order to successfully transition into an energy system based on renewable energy sources, the amount of raw materials needed for green technologies is rising immensely. Consequently, concerns about raw material availability and the potential criticality of materials are increasing. Yet the majority of energy optimisation modelling frameworks are solely focus on the cost minimisation of the system.

Based on this research gap, the objective of this research is to implement the criticality factor into a multi-objective optimisation in the energy system modelling framework REMix for Belgium and the Netherlands. Furthermore, the objective is to analyse the differences in the energy system design when it is optimized to minimize cost and criticality. The research focuses on the sub-technologies of batteries for utility-scale storage system which are considered to play an essential role in the future energy system, namely LFP, NMC, lead acid and redox flow batteries. The energy generation technologies are PV panels and wind turbines with the addition of one AC transmission line between Belgium and the Netherlands.

An optimization solely towards cost minimisation is presented as a base scenario in order to analyse the potential changes. In the base scenario, the demand in the Netherlands can mainly be covered by wind and solar energy, which have already reached their full capacity, yet minor gaps require the use of electricity storage. The main battery technology installed in the Netherlands are redox flow batteries, due to their ability to cope with strong fluctuations in the electricity balance caused by the intermittency of renewable energy sources. In Belgium, the larger share of electricity import requires less storage capacity and lower discharge rates. Hence, the dominant sub-technology is LFP batteries, followed by NMC batteries, due to their lower cost and higher efficiency.

In the criticality scenario, the criticality factor was implemented for all storage technologies and includes five pareto points. The criticality of the overall system is decreasing over the pareto points while the cost of the system is increasing slightly. Hence, the fifth pareto point has the lowest system criticality but the highest system costs.

After the implementation of the criticality factor, the overall units of storage technologies are decreasing which consequently leads to a decrease in criticality. The distribution of sub-technologies in the Netherlands did not change and redox flow batteries remained the prominent batterie type, even though the technology has the highest criticality factor. Yet, its capacity to cope with high intermittency is crucial for the selection and the reduction in criticality has been achieved through an overall decrease in storage capacity. The missing capacity in the electricity balance has been substituted by electricity import. In Belgium, the overall capacity in storage has decreased as well which reduced the system criticality. However, a shift from the dominant LFP batteries, towards redox flow batteries can be seen. This potentially relates to the change of usage for storage applications which shifted towards coping with renewable energy sources. Even though redox flow batteries have a considerable higher criticality than LFP batteries, the criticality is implemented per unit for which redox flow have more capacity than LFP. Together with the substantial reduction in LFP batteries, as well as for NMC and lead acid, the increase in redox flow batteries still results in a lower criticality.

In conclusion, it can be said that the implementation of a criticality factor in the modelling framework has an influence on the design of the energy system, even if it is considered for only one sub-technology. It can be seen that the change in design was mostly focused on reducing the storage capacity in order to reduce the criticality, yet some changes in the choice can be seen that result in a lower system criticality. Nevertheless, the substitution for technologies which are not influenced by the criticality has a big share in the optimization of the system and this can be expected to change when more technologies will be included in further research.

Consequently, the research of this thesis can also be upscaled in different ways to represent a more realistic European energy system. An upscaling in spatial scope would result in adding other European countries or implementing the framework for all 26 EU member states. Furthermore, the technologies, for which the criticality factor was implemented, needs to be broaden to include all generating, storage and distribution technologies. As a next step, the criticality for PV panels and wind turbines would need to be included. Additionally, a differentiation between sub-technologies, as done in this research with a focus on batteries, should continue to be included for additional technologies. This way, differences in the criticality due to use of raw material within a technology class can also be identified. Also, different methods for the calculation of the criticality factor can be used in further research, focused not only on the potential supply disruption probability but also potential recyclability or the potential to substitute, as well as different weighing methods. As it was presented in the results, the implementation of the criticality factor per unit affected the outcome, hence other methods of the implementation of the criticality factor would be interesting for further research. Furthermore, the settings of the multi-objective optimization in the REMix framework could be adapted to include more pareto points or a higher pareto factor which could give the framework a larger range.

All in all, this research showed a first approach at implementing the criticality of technologies within an energy system modelling framework for one technology class. Accordingly, the research can be expanded in many directions that will further look at the impact of material criticality on the choice of technologies for the design of energy systems.

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7. Appendices

7.1 Material composition of storage sub-technologies

Below, the material composition of the selected sub-technologies can be seen.

Subtechnology	Mineral	kg/kWh (2023)	kg/kwH (2023) with periphery
LFP	Aluminium	0	2.431677952
	Cobalt	0	0
	Copper	0	1.005200909
	Lithium	0.129356234	0.129356234
	Manganese	0	0
	Nickel	0.0645	0.0645
	Steel	0	3.818932737
	Sulfur	0	0
	Titanium	0	0
	Vanadium	0	0
Lead-Acid	Aluminium	0.0037	2.435377952
	Cobalt	0	0
	Copper	0.1852	1.190400909
	Lead	26.2962963	26.2962963
	Lithium	0	0
	Manganese	0	0
	Nickel	0	0
	Steel	2.5	6.318932737
	Sulfur	0	0
	Vanadium	0	0
NMC-111	Aluminium	0	2.431677952
	Cobalt	0.406475536	0.406475536
	Copper	0	1.005200909
	Lithium	0.149285714	0.149285714
	Manganese	0.361892308	0.361892308
	Nickel	0.413953333	0.413953333
	Steel	0	3.818932737
	Sulfur	0	0
	Vanadium	0	0
Redox-Flow	Aluminium	0.016840789	2.448518741
	Cobalt	0	0
	Copper	0.206935009	1.212135918
	Graphite	0.600161002	0.600161002
	Lithium	0	0
	Manganese	0	0
	Nickel	0	0
	Steel	0.510944191	4.329876928
	Sulfur	0	0
	Vanadium	3.895	3.895

7.2. Techno-economic data

Below the techno-economic data for the included technologies can be found.

7.2.1 Storage technologies

Technology	Parameter	Year	Unit	Value
LFP_charger	Invest	2020	€/kW	59.64
NMC_charger	Invest	2020	€/kW	59.64
LeadAcid_charger	Invest	2020	€/kW	108.87
RedoxFlow_charger	Invest	2020	€/kW	108.87
LFP	Efficiency	2020	%	86
NMC	Efficiency	2020	%	86
LeadAcid	Efficiency	2020	%	77
RedoxFlow	Efficiency	2020	%	68
LFP	Life time	2020	years	10
NMC	Life time	2020	years	10
LeadAcid	Life time	2020	years	12
RedoxFlow	Life time	2020	years	15
LFP	OMFix	2020	€/kWh-y	1.97
NMC	OMFix	2020	€/kWh-y	2.02
LeadAcid	OMFix	2020	€/kWh-y	2.65
RedoxFlow	OMFix	2020	€/kWh-y	3.87
LFP	Invest	2020	€/kWh	197.97
NMC	Invest	2020	€/kWh	204.49
LeadAcid	Invest	2020	€/kWh	195.97
RedoxFlow	Invest	2020	€/kWh	394.51

7.2.2. Generation technologies

Technology	Parameter	Year	Unit	Value
Utility PV	Investment Cost	2020	2018 €/kW	589
Utility PV	O&M	2020	%	1.8
Offshore Win	Investment Cost	2020	2018 €/kW	3406
Onshore Winc	Investment Cost	2020	2018 €/kW	1397
Wind	Investment Cost	2020	2018 €/kW	2401.5
Offshore Win	O&M	2020	%	3.7
Onshore Winc	O&M	2020	%	3.1
Wind	O&M	2020	%	3.4
Utility PV	Life time	2020	years	25
Offshore Win	Life time	2020	years	23
Onshore Winc	Life time	2020	years	21
Wind	Life time	2020	years	22

7.3. Criticality factor

Below the criticality factor for 2023, based on different aggregation methods can be seen.

Subtechnology	Aggregation_method	2023
LFP	Cost weighted SDP	68.68975854
	Cost weighted average SDP	1.467406838
	Mass weighted SDP	5.5583470
	Mass weighted average SDP	0.746120115
	Max SDP	2.021276596
	Mean SDP	0.902197097
Lead-Acid	Cost weighted SDP	15.76643814
	Cost weighted average SDP	0.223742983
	Mass weighted SDP	9.264626028
	Mass weighted average SDP	0.255639304
	Max SDP	1.279069767
	Mean SDP	0.511810182
NMC-111	Cost weighted SDP	122.12408
	Cost weighted average SDP	1.667479074
	Mass weighted SDP	7.384179745
	Mass weighted average SDP	0.859883532
	Max SDP	2.857142857
	Mean SDP	1.224018334
Redox-Flow	Cost weighted SDP	245.5842236
	Cost weighted average SDP	2.17065613
	Mass weighted SDP	16.42126879
	Mass weighted average SDP	1.31520688
	Max SDP	2.5
	Mean SDP	1.256593064