D1.1_Technical Flexibility Potential and Belgium Energy System Impact

GALILEO

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1. Technical potential of industrial flexibility

This report explores the technical potential of industrial flexibility within the Belgian context, as examined in the GALILEO project. Industrial flexibility refers to the ability of industrial processes to adjust their electricity or thermal consumption in response to implicit and explicit signals, such as market prices, tariffs, grid constraints signals, or flexibility products.

We focus here on the technical feasibility of such adjustments: which processes could, in principle, offer flexibility given their physical characteristics, operational constraints, and energy profiles? This chapter does not yet assess the economic viability or system value of such flexibility as these aspects are covered in a later phase of the project.

Through a combination of literature review, industry engagement, and structured data collection, we aim to map out the relevant technologies and flexibility mechanisms in five key industrial sectors. The resulting insights support both the modelling efforts in GALILEO and the development of realistic flexibility roadmaps.

Within the Galileo project we will make use of different modelling approaches to model the use of industrial flexibility within the Belgian industry. The different models each have their own scope in terms of level of technological detail, geographic detail, time resolution, etc. What they all have in common is a need for data on related technologies to model the industrial processes in a way that matches each model's respective scope. As such, our first step in the Galileo project, by means of this deliverable, is to take stock of the information available on these technologies. The models used in the Galileo project are spread across the spectrum of energy models. We present a short overview of them below.

The ***Belgian TIMES energy system model*** (TIMES-Be) is a long-term (up to 2050) capacity and dispatch optimization model. The model optimizes investment and dispatch decisions for all technologies in all sectors (industry, power sector, residential, etc.) related to all energy flows (electricity, gas, oil, etc.) in Belgium. Due to the large scope of the model, the time resolution is more limited and individual industrial sites are grouped with similar activities across the Belgian territory.
The ***Bidding Strategy Model*** optimizes bidding strategies for industrial flexible assets participating in energy markets. It consists of five modular and interconnected sub-models corresponding to a detailed representation of the industrial process constraints, market participation constraints, scenario generation, and risk measures. By combining detailed operational modelling of industrial processes with scenario-based market forecasting and risk assessment, the library facilitates the decision-making process across various energy markets and services. This ensures bidding strategies that are both technically feasible and economically sound.
The ***Energy market simulator*** is a tool designed to replicate and analyze the functioning of energy markets, while also enabling the testing of new market designs and products. The simulator includes detailed representations of electricity markets, such as the day-ahead market and the manual Frequency Restoration Reserve (mFRR) market. Beyond electricity, it can also model markets for other energy carriers like heat and gas, making it a versatile model for studying the effects of market design changes across different energy systems.
The ***Energy Cost Hedging Model*** supports industrial consumers in designing cost-effective and resilient long-term energy procurement strategies to mitigate

volatile electricity cost risks they face during electrification. It consists of 3 modules that simulate industrial load profiles, renewable generation (solar and wind) and market price scenarios. It evaluates different Power Purchase Agreement (PPA) designs, such as baseload, pay-as-produced, and profile-matching under historical market conditions. By combining time-series matching analysis between load, renewables, and storage with techno-economic performance metrics and risk-based scenario analysis, the model identifies optimal combinations of PPAs, on-site renewable investments, and flexible operations. The model ensures effective hedging against price fluctuations and supports informed investment decisions.

In this report, accompanied with an overview excel, we present the initial findings of the technology stocktake conducted for the GALILEO project. As the project progresses, these findings will be updated and refined to reflect newly available data and evolving insights. The level of detail available varies considerably across sectors. This variation is due to differences in industrial composition, the diversity of processes within each sector, the availability and quality of public data, and the current state of electrification. As a result, some sectors are described in greater technical depth than others — not due to analytical choices, but because of the inherent characteristics of each sector and the information currently accessible through our partners.

1.1 Methodology for data collection

To take stock of the technology data for industrial flexibility, we make use of a five-step approach:

1. First, we have set up an analysis team per industrial sector covered in the Galileo project. Each analysis team consists of one research institute and one industrial partner.

Partner activity	Industrial sector	Research partner	Industrial partner
Various activities	Chemicals	VITO	Tessenderlo group
Stainless steel production	Iron and steel	VITO	Aperam
Sugar refinery	Food	VITO	Tiense Suikerraffinaderij
Zinc smelting	Non-ferreous metals	Entras	Nyrstar
Data centers	Commercial sector	KULeuven	LCL

2. Secondly, the research partner conducts a literature review of the technology data for industrial flexibility in the relevant sector.
3. Thirdly, the results of the literature review are cross-referenced with the industrial partner. Additional information is provided by the industrial partner if possible and if confidentiality allows for it.
4. Fourthly (optional), the results are cross-referenced with the sector federation of the relevant sector.
5. Fifthly, the results are documented in a structured way in data sheets.

To structure the data collection, data collection templates or data sheets have been designed[1]. The type of data collected is techno-economic in nature. These sheets capture the techno-economic characteristics required for modelling the technical potential of industrial flexibility. The technological parameters provide the necessary details for accurately representing industrial processes within the models used in the GALILEO project. The economic data is equally important, as most models aim to identify cost-optimal pathways, meaning that both capital and operational costs strongly influence model outcomes.

Wherever quantitative data is provided, the unit of measurement is clearly specified. When possible, the original data source is also cited to ensure transparency and traceability.

For all cost-related parameters, both the currency and the reference year are indicated. If the year is explicitly stated in the source, it is used directly; otherwise, the publication year of the source is applied as a proxy. The inclusion of the reference year allows for appropriate cost comparisons across sources using standard discounting techniques.

Each technology sheet has attributes grouped under different sections:

- General information: Includes the technology name, its purpose, and the industrial process it applies to.
- Capacity attributes: Covers existing and potential capacity levels, technical lifetime, investment cost estimates, and fixed O&M costs.
- Operational attributes: Describes typical operating regimes, energy and material inputs, variable costs, and the share of total process consumption.
- Flexibility at Constant Annual Production: Assesses the potential for shifting load in time while maintaining total yearly output (i.e. time-shifting without volume change).
- Flexibility with Variable Annual Production: Explores flexibility when total production volume can vary across the year (i.e. up- or downscaling of output).

This structure ensures that each technology is assessed in a consistent, model-ready format, while also capturing sector-specific differences in process design and flexibility potential.

1.2 Flexibility per Industrial Sector

Industrial energy flexibility, as defined by the International Energy Agency (IEA), is the ability of a production system to adjust its energy demand in response to external signals, such as grid conditions, price signals, or the availability of renewable energy. In the context of the energy transition, such flexibility plays a key role in balancing supply and demand, enabling system adequacy, and integrating variable renewables. Flexibility strategies can be classified into three categories:

1. Organizational: Measures related to planning, logistics, and workforce management. These typically require little to no capital investment, but can unlock flexibility by rescheduling operations or reorganizing production flows.

2. Operational-technical: Measures that rely on existing assets or processes to actively modulate energy use. This includes demand-side management (DSM), advanced process control, load shifting, and the exploitation of thermal or material buffers.

3. Infrastructure-based: Strategies that require the addition of new assets, such as batteries, e-boilers, or thermal buffers. These typically involve significant capital

[1] The data sheets with collected technology information can be referenced in annex.

expenditures and long-term planning, but can offer structural and scalable flexibility in the long term..

A range of flexibility mechanisms exists within these categories. As shown in Figure 1-1, flexibility can take different forms depending on the operational context and system needs:

- Peak clipping: Reducing peak demand through direct load control.
- Valley filling: Increasing off-peak electricity consumption.
- Load shifting: Rescheduling energy-intensive processes to off-peak hours.
- Energy efficiency improvements: Reducing overall electricity consumption.
- Flexible load shaping: Using predictive forecasting and reliability-based demand control.

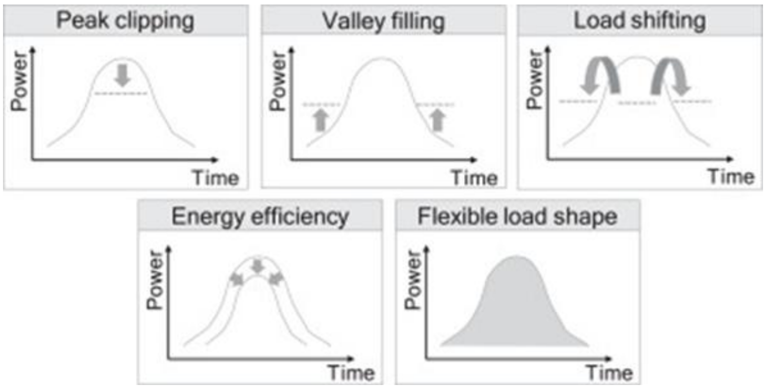

Figure 1-1. Load-shape measures within demand side management [1].

Some sustainable technologies gaining traction across all industries contribute significantly to energy flexibility by enhancing efficiency, optimizing energy use, and enabling demand-side management. These include:

- Heat exchangers.
- Cogeneration/Trigeneration.
- Heat pumps.
- Sorption chillers.
- Organic Rankine Cycles.
- Variable Speed Drives on motors.
- Carbon capture, storage and utilization.
- Vapor recompression systems.
- Production of biogas via organic waste.

In the next sections we provide a sectoral deep dive into how flexibility manifests across key industrial sectors in Belgium.

1.2.1 Chemical Sector

1.2.1.1 Introduction

The Belgian chemical sector is the largest industrial consumer of electricity in the country, playing a crucial role in both the national economy and the broader European industrial landscape. Accounting for approximately 33,5 TWh of electricity and 2,8 TWh of gas annually in 2023 [2]. As seen in Figure 1-2, the sector represents a significant portion of Belgium's total industrial energy demand, with most of the consumption concentrated in Flanders, particularly in the Port of Antwerp, which houses some of the largest petrochemical complexes in Europe. The presence of multinational corporations such as BASF, INEOS, and ExxonMobil have established Belgium as a key hub for chemical production, leveraging the country's strategic location, advanced logistics infrastructure, and access to global markets.

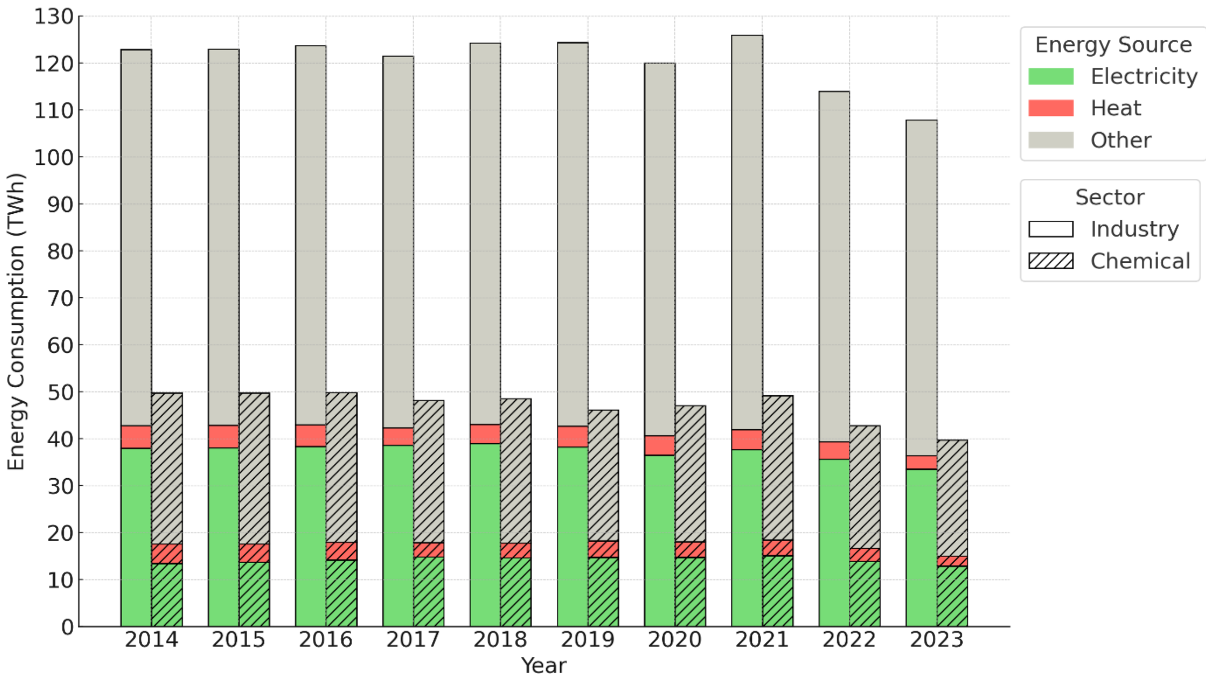

Figure 1-2: Energy consumption in Belgium for the entire industrial sector compared to the chemical sector [2].

Energy consumption within the chemical sector is dominated by continuous, high-load processes that require a stable and uninterrupted electricity supply. Given the nature of chemical production, many facilities operate around the clock only shutting down for maintenance, making energy efficiency and cost optimization critical concerns. Among the most energy-intensive processes are chlor-alkali electrolysis, steam cracking, and high-temperature reactors, each of which demands vast amounts of electricity.

This high demand profile presents both challenges and opportunities, particularly as Belgium seeks to integrate more renewable energy sources and enhance grid stability. Chemical producers are increasingly exploring ways to optimize energy consumption through demand-side response (DSR) mechanisms, shifting certain energy-intensive operations to periods of lower electricity prices or higher renewable generation availability. Additionally, many companies are adopting on-site energy generation and storage solutions, such as hydrogen production and cogeneration plants, to mitigate price volatility and reduce dependence on fossil fuels.

As Belgium moves towards climate neutrality by 2050, the role of the chemical industry in achieving energy flexibility will become even more crucial. Despite the complexity of large-scale, continuous operations, optimizing energy use and incorporating flexible electricity consumption strategies will be essential in balancing economic competitiveness, sustainability, and grid reliability.

1.2.1.2 Flexibility Potential

A deeper understanding of the sector's flexibility potential is outlined in the European Chemical Industry Council's (cefic) paper: Cefic Views: Understanding and Facilitating Industrial Flexibility in the Chemical Industry [3]. This paper highlights the complexity of chemical production systems and challenges the basic assumptions about their ability to provide demand-side flexibility.

One of the primary structural limitations is the interconnectedness of processes. Chemical plants often operate as integrated systems, where one unit's output serves as the input for another. These cascading linkages mean that modifying the load profile of a single process can trigger a chain of disruptions across an entire facility. In some cases, the inflexibility of one process effectively restricts the flexibility of all others on-site.

In addition to process interdependence, technical and safety limitations significantly constrain the scope for dynamic operations. Many chemical reactions have minimum capacity thresholds, below which safe operation cannot be guaranteed. Equipment such as reactors and compressors also have limited ramping capabilities and require extended periods to safely start up or shut down [4]. These constraints are compounded by risks to product quality, plant longevity, and contractual obligations—factors that make abrupt or frequent operational changes economically and technically undesirable.

Another key issue is storage capacity. While some energy flexibility could, in theory, be unlocked by overproducing during low-price periods and storing outputs, or conversely underproducing and storing inputs, many chemical compounds, particularly hazardous substances like chlorine, hydrogen, and many acids and bases, are subject to strict legal and physical storage limits. As such, even when upstream processes are flexible, downstream bottlenecks or storage constraints may prevent full utilization of that flexibility.

Overall, industrial flexibility in the chemical sector must be understood as site-specific, voluntary, and constrained by complex trade-offs between operational stability, safety, efficiency, and economics. While flexibility can be increased through targeted investments, such as on-site storage or grid-interactive systems, this will only occur when aligned with broader competitiveness and regulatory frameworks that appropriately value the unique characteristics of the sector.'

1.2.1.3 GALILEO application

As in other energy-intensive sectors, unlocking the flexibility potential of the chemical industry requires a detailed examination of the core technologies that dominate electricity and thermal energy use. The nature of chemical production, characterized by continuous processes, tightly integrated systems, and strict product quality requirements, means that flexibility is often highly contextual. It is shaped not only by the design and operation of individual units, but also by their interdependencies, control systems, and economic role within the broader plant environment.

In Belgian chemical manufacturing, two prominent process categories illustrate the range of opportunities and challenges for flexible operation: electrolysis and steam-based electricity generation. Both play an important role in the sector's energy profile and offer distinct pathways for contributing to grid stability and market participation.

The analysis begins with one of the most energy intensive processes in the industrial sector: **electrolysis**. Here, specifically, the electrolytic chlor-alkali process is reviewed, in contrast to electrolysis in other industrial sectors, such as electrowinning of zinc in the nonferrous sector. Chlor-alkali electrolysis is a cornerstone process in the chemical industry, producing chlorine, hydrogen, and caustic soda via the electrolysis of brine [5]. This process operates continuously under high power demand and represents around 16 TWh electricity consumption in Europe in 2023 for the production of chlorine [4], [6].

Despite this stable operation, electrolysis systems, especially modern cell stacks, exhibit a high level of controllability. They can modulate their power consumption relatively quickly, allowing for participation in ancillary service markets such as frequency containment and restoration reserves. Indeed, they remain among the few industrial processes capable of delivering such fast-response services without extensive retrofitting.

However, the deployment of electrolysis-based flexibility is bounded by several factors. Rapid or frequent adjustments in power input can accelerate the degradation of key components, such as membranes, and may induce pressure or flow variations that compromise process safety or product quality. Moreover, economic feasibility is not guaranteed. The provision of flexibility must be carefully balanced against potential losses in efficiency or output and only becomes viable when market signals are strong enough to justify the associated operational costs.

A second significant avenue for flexibility lies in the use of **steam turbines** powered by recovered heat from chemical reactions—such as those found in sulfuric acid production. In these processes, excess thermal energy from exothermic reactions is harnessed to generate high-pressure steam, which in turn drives turbines to produce electricity. These turbines have typically been operated in baseload mode, offering a stable and continuous supply of electricity either to internal operations or the grid. Nonetheless, with appropriate system configuration, they can also provide rapid downward modulation of power output through steam bypass mechanisms. This enables responsive curtailment of electricity generation without affecting the upstream chemical processes.

Realizing the full flexibility potential of such systems requires overcoming technical and organizational barriers. Many steam turbines and associated control systems were originally designed for constant operation and thus lack the automated dispatch capabilities needed for active market engagement. Furthermore, without clear internal incentives or key performance indicators aligned with flexibility objectives, such capabilities often remain untapped. Enhancing dispatch control logic, integrating forecasting tools, and exploring synergies with auxiliary systems such as electric boilers are all ongoing efforts to make these assets more dynamic and responsive to external energy conditions.

Together, these examples illustrate the layered complexity of estimating and unlocking flexibility in the chemical sector. While many processes possess inherent technical capabilities to provide flexibility, their deployment is constrained by a combination of operational, economic, and systemic considerations. Accurately assessing this potential requires a multidisciplinary approach, one that integrates process engineering, energy market analysis, and system-level planning. Only through this kind of integrated perspective can industrial flexibility be effectively harnessed to support decarbonization, system adequacy, and market efficiency.

1.2.2 Iron and Steel sector

1.2.2.1 Introduction

Belgium's steel sector covers primary, secondary, and stainless-steel production. Each of these products requires different production processes and energy consumption. The sector consumes 5,8% (4,4 TWh) of the total final electricity consumption, which represents 12% of the energy it consumes. The electricity produced from blast furnace gas is nearly 2 TWh. Table 1-1 shows an overview of the entire sector, as well as the production routes and sections of the supply chain, without deducting the emissions allocated to the power sector due to the use of blast furnace gas.

Primary steel is produced in one site in Ghent, owned by ArcelorMittal, where a Blast Furnace—Basic Oxygen Furnace (BF-BOF) configuration is used. In the case of secondary and stainless steel, an Electric Arc Furnace is the main process for steelmaking. The EAF are located in Genk, Châtelet (Aperam) and Charleroi (Thy-Marcinelle). For both production routes, after the steelmaking steps, continuous casting, rolling and finishing steps are used.

Table 1-1: Overview of energy consumption and CO2 emissions in the Belgian steel sector.

	unit	Steel sector	BF-BOF	EAF	Post processing	source
production	Mta	6,9	4,8	2,1	7,0	[7]
Total energy consumption	TWh	35,4	28,7	3,9	2,8	[8]
Electricity consumption	TWh	4,4	1,8	2,2	0,4	[8]
Electricity share	%	12%	6%	57%	16%	[8]
energy intensity	MWh/t	5,13	5,94	1,86	0,37	-
emissions	MtCO2	10.288	9.444	364	480	-
emissions (scope 2)	MtCO2	12.511	10.331	1.478	702	
CO2 intensity (scope 1)	tCO2/t	1,49	1,95	0,18	0,07	-
CO2 intensity (scope 2)	tCO2/t	1,81	2,14	0,71	0,10	Assuming 140kg/kWh
CO2/energy (scope 1)	tCO2/MWh	291	329	94	170	-
CO2/energy (scope 2)	tCO2/MWh	354	360	383	249	-

Additionally, within the steel sector, both in Eurostat energy balance and NACE[2] activities, other companies post-process or use steel but are not the main producers. Therefore, these are not covered in the current analysis, as they are more geographically scattered and are not as energy-intensive as steelmaking sites.

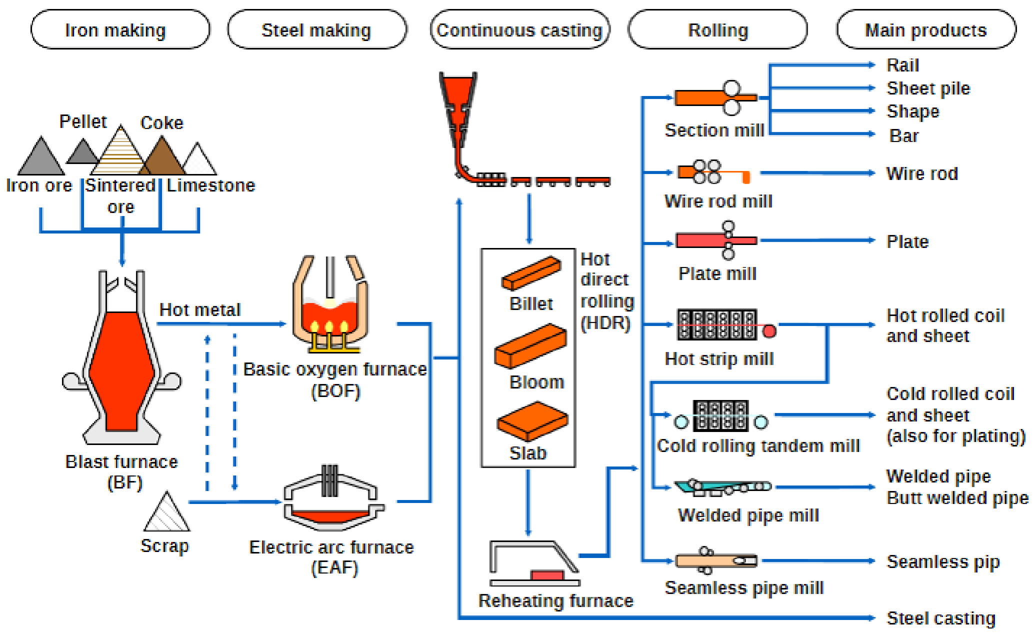

Figure 1-3: Steel supply chain [9].

[2] The NACE code indicates the type of economic activity, and it is designated by the European Union and each Member State. The list can be found at this link https://ec.europa.eu/competition/mergers/cases/index/nace_all.html

Current electricity-based processes as well as alternative technologies that allow further electrification of the steel sector are investigated. Table 1-2 includes a list of these technologies, which are described in more detail in the factsheets in the annex of this deliverable. The deployment of these technologies could offer the possibility to do partial or complete load shifting, response time, production timing and buffer storage (material and energy) without detrimental effects on the company's main economic activity.

However, the assets used in the steel sector are highly capital intensive which requires them to be operated most of the time. Nevertheless, steel production in Europe has decreased, losing market share to imports [10] in the context of global oversupply [11]. Therefore, energy prices will impact the competitiveness of the European industries. Industrial flexibility could impact the energy system cost, leading to benefits for all energy consumers, including industrial energy-intensive processes.

Table 1-2: Electric-based technologies in steel supply chain.

steel type	Supply chain section	Product	Technology	In use	Electrification type	Average capacity [MW]	fuel replaced	Electricity intensity [GJ/t]
primary	Iron making	pig irons	Blast Furnace	existing	-	33	-	0,2
		sponge iron	Direct iron reduction	alternative	indirect	2.243	coal	13,6
	Steel making	crude steel	Electrowinning	alternative	direct	2.267	coal	13,0
			Molten oxide electrolysis	alternative	direct	2.511	coal	14,4
			Plasma iron reduction	alternative	direct	2.825	coal	16,2
Secondary and stainless	Steel making	crude steel	EAF	existing	-	201	-	2,9
all	Rolling	steel coil	Furnace - resistance heating	alternative	direct	257	natural gas	1,1
			Furnace - induction heating	alternative	direct	279	natural gas	1,2

Primary steel

Flexibility in an interdependent production process is primarily influenced by technology. To enhance efficiency, the production of finished steel products should be divided into distinct and independent stages, including raw material handling, iron reduction, steelmaking, continuous casting, rolling, processing, and finishing. While each stage employs specific technologies, as outlined in **Error! Reference source not found.**, the entire industrial site operates under a structured schedule to maximize productivity. However, opportunities exist to decouple these stages, either through stockpiling—such as slabs—or by strategically scheduling production using the ladle as a short-term thermal energy buffer.

Currently, primary steel production relies heavily on fossil energy sources for both iron reduction and energy generation. In the BF-BOF (Blast Furnace–Basic Oxygen Furnace) route, carbon and coke are used to produce pig iron, which is then refined into steel in the BOF. This process generates significant amounts of blast furnace gas (BFG), which is commonly utilized for electricity production. However, the dependency on BFG constrains power turbine operations, limiting grid flexibility and dispatchability.

Electricity is primarily consumed in the rolling section, as well as in machine drives, control systems, and facility operations throughout the production process. The specific energy consumption of hot rolling mills ranges between 1,2 and 2,4 GJ/t, while cold rolling mills consume approximately 1,0 to 1,4 GJ/t [12]. It is estimated that electricity can represent up to 40% of the specific energy consumption in rolling mills, while the rest is thermal energy.

Although the H2-DRI is an alternative, this analysis does not include hydrogen production via electrolysis as a flexibility option from the steel sector. Thus, special attention is given to the current electric steel production. Nevertheless, low-TRL and promising electric-based technologies to produce steel are investigated as future alternatives.

Secondary and stainless steel

Secondary and stainless-steel production currently uses electricity as the main energy source to power Electric Arc Furnaces (EAF). EAF consumes around 80% of the electricity in this route, requiring 350-600 kWh/t of crude steel [13]. The electricity consumption in the continuous casting, rolling and complementary processes is mostly related to engines and supporting equipment. Therefore, the flexibility of the current EAF production route is concentrated on the operation and technical possibilities of the EAF. The EAF works in batches that usually take 40-60 minutes in clear steps such as melting, oxidation and reduction. Depending on the status of the melting process, the arc is set to different power levels, e.g. for the start-up process, melting scrap, the foam slag period or keeping the liquid steel warm. In addition to the technical possibilities of the different machines involved in the production chain, other aspects are relevant for the steel producer, such as impact on product quality, short tap-to-tap times and few unplanned interruptions.

In Germany and Belgium, network charges impact the way the production is scheduled to avoid all electric equipment in electric steelmaking sites being utilized at the same time to avoid excessive additional charges, for example, by load-shedding or delaying production [14].

1.2.2.2 Flexibility potential

Industrial flexibility in the steel sector is gaining attention to optimize energy use, reduce costs, and support grid stability. Case studies, such as ELIA's report on INDUSTEEL, demonstrate that some steel plants already possess inherent flexibility—for instance, over-dimensioned furnaces that allow load adjustments without disrupting production [15]. Access to real-time operational data is crucial for unlocking flexibility, with cost reduction and financial incentives being primary motivators for industrial participation.

From a technical perspective, flexibility is constrained by operational limits, including safety requirements and process dependencies. Economically, high opportunity costs and capital investments restrict long-term flexibility, though short-term load reduction—such as providing ancillary grid services—is already practiced in electric steelmaking. While load shifting in response to electricity prices has been used during crises (e.g., natural gas price surge in 2021 and 2022), frequent adjustments could damage equipment and lead to workforce logistics issues.

Further electrification and advanced technologies, such as AI-driven load optimization and hybrid furnace systems, could enhance flexibility. However, successful implementation requires balancing operational constraints, financial viability, and regulatory frameworks to ensure steel producers can adapt without compromising efficiency or competitiveness.

Figure 1-4 below schematically shows how the energy intensive part of iron and steel processes relate to flexibility. When in operation, they operate at high load-levels, with the possibility to reduce energy consumption on short notice. Increasing the energy consumption on short notice is less feasible due to the high load-levels when operational. It also shows how longer duration load balancing does not match well with the capital intensive nature of the installations. A prolonged downtime presents a disproportionally high loss of value versus the possible renumeration for flexibility.

Figure 1-4: Flexibility options iron and steel industry [16]

1.2.2.3 GALILEO application

The steel sector is among the most energy-intensive industries in Belgium, making it a crucial candidate for exploring demand-side flexibility. As discussed, steel production comprises several processes with potential flexibility, such as **EAFs**, **reheating furnaces**, and **casting lines**.

Electric arc furnaces in the context of Galileo are over-dimensioned in comparison with yearly production levels. They are already activated in function of the electricity price and available work in process stocks to feed downstream processes. In addition, procedures were implemented in the past to execute a complete shutdown of the EAF within a time span of 15 minutes. This make the EAF an excellent candidate for contracted flexibility, if the renumeration is right.

Casting lines can also provide a level of flexibility, although this adds additional complexity and efficiency losses. The metal in the casting lines would need to be reheated and re-liquified if operations are halted on short notice. This reheating represents and energy consumption that would not present if operations would continue uninterrupted.

The analysis requires a bottom-up modelling of steel production sites with system-level and market analyses. Simulating operational processes and identifying technical flexibility windows (e.g., load shifting, temporary halts, thermal inertia exploitation) becomes critical to better understand and capture the specificities of the sector and its operating conditions, which can limit or favour flexibility. Besides the technology selection in decarbonizing the sector (energy system perspective), energy market models could provide a complementary perspective from the company point of view, pinpointing the opportunities and risks of trading additional, or even new, energy market services. Simultaneously, the energy system perspective will capture the broader value of steel sector flexibility on other sectors, directly and indirectly.

Unlocking flexibility in the steel sector offers numerous benefits. For system operators and market participants, it provides additional balancing resources, particularly valuable during peak demand or dips in renewable generation. For steel producers, it opens up potential revenue streams from market participation and reduces exposure to volatile electricity prices. Despite its potential, important limitations must be considered. Flexibility in steel production is often constrained by process interdependencies, product quality requirements, and operational conditions.

1.2.3 Food Sector

1.2.3.1 Introduction

The food sector is one of the largest energy consumers worldwide, accounting for approximately 30 % of the total energy consumption. Energy is required for a variety of food processes, including heating, cooling, drying, refrigeration, processing, packaging, and transportation [17].

The food industry stands apart from other sectors due to its wide range of manufacturing activities, diverse product offerings, and varying energy requirements for production. Despite this complexity, it is feasible to outline a “general process framework” that encompasses all the typical stages in food production facilities [17]. Figure 1-5 proposes a distinctive block diagram illustrating the sequential chain of processes occurring within a generic food manufacturing industry. Segregating the different processes of all potential subsectors as such could provide a better understanding of the energy demand and how energy flexibility could be applied in some sections.

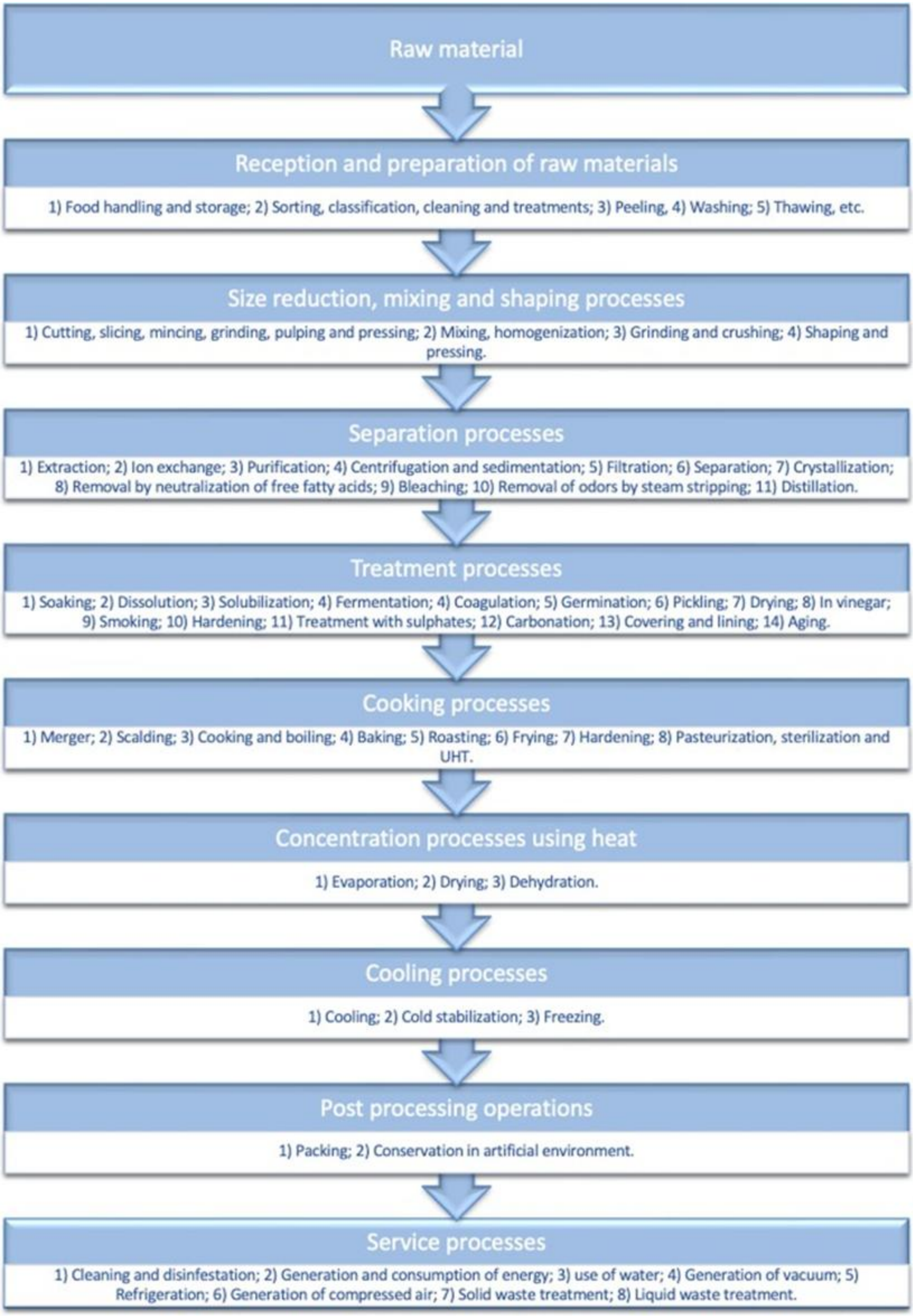

Figure 1-5. Flowchart of typical processes in a generic food facility [17].

In the Belgian context, the food industry is a crucial component of the country's economy. According to NACE-A38 coding, in 2023, the food industry accounts for 16,2% of the industrial added value, behind the pharmaceutical sector [18]. It includes key subsectors such as meat processing, dairy, chocolate, sugar, and beverages, all of which have strong ties to agriculture, retail, pharmaceuticals, chemicals, packaging, and logistics. The following figure showcases the number of companies per sub-sector.

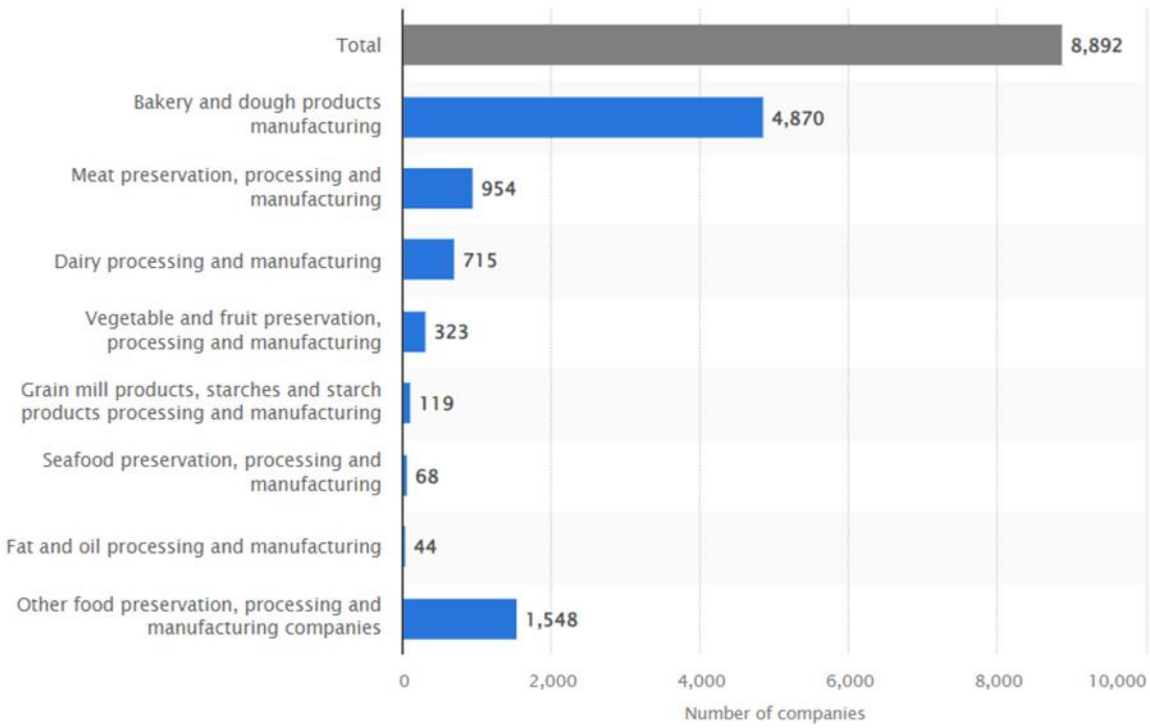

Figure 1-6. Number of companies in the food manufacturing industry in Belgium in 2021, by sector [36].

Belgian food industry is the third-largest energy consumer in the country's industrial sector, following chemicals and metallurgy. It consumed approximately 16% of Belgium's total industrial energy in 2023 [18]. The sector primarily relies on natural gas (59%) and electricity (30%), with the remaining portion coming from petroleum and other fossil fuels [19].

Internal sources indicate that some of the largest energy consumers in the food sector are those involved in sugar production, basic food ingredients, potato-based products, and dairy. More detailed insights into Belgium's 26 food industry subsectors could be obtained through Fevia, the Belgian food industry federation. As this information is not available at this time, a presumable sectoral similarity with the US and UK allows for basic insights. [17], [20]. Figure 1-7Figure 1-8 highlight electricity and natural gas consumption in the U.S. food industry. They showcase that electricity is primarily used for machine drives and cooling, while natural gas is mainly utilized for process heating and boilers. Although absolute consumption values differ from the ones in Belgium, the sectoral share distribution provides valuable insights into energy use across different subsectors. Developing a detailed energy consumption profile for Belgium's key food industry subsectors would improve the understanding of decarbonization pathways and help identify opportunities for integrating energy flexibility.

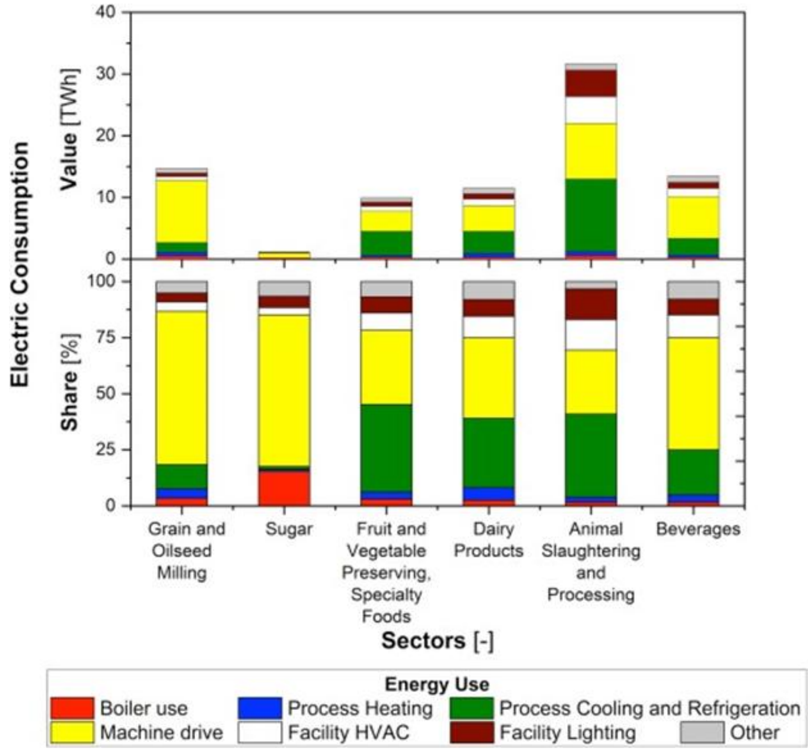

Figure 1-7. Electricity consumption in the Food Industry of the United States [17].

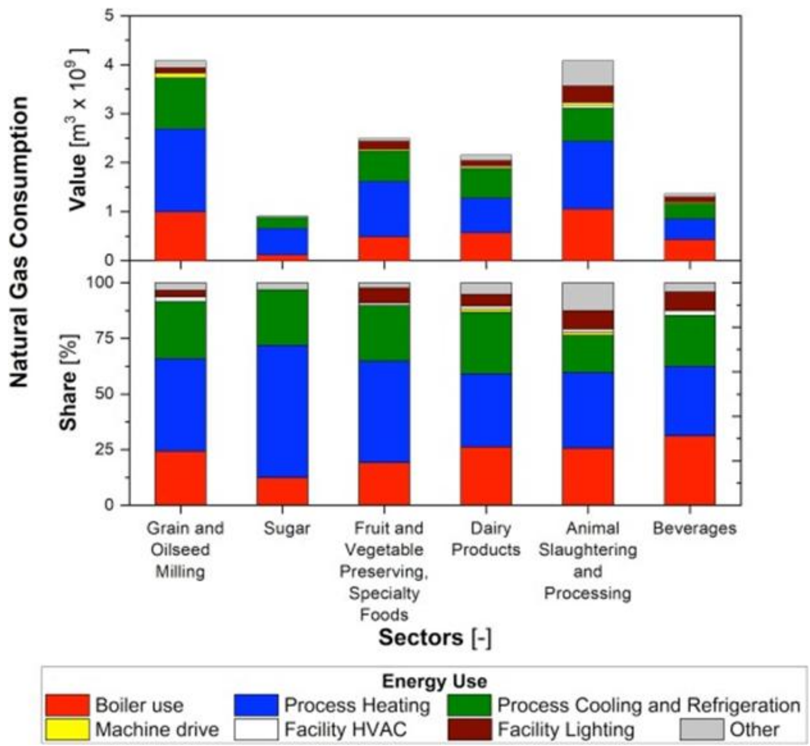

Figure 1-8. Natural gas consumption in the Food Industry of the United States [17].

Even though more detailed energy demand per subsector is not publicly available some general notes can be provided based on the main type of food industries present in the country:

- Meat processing is highly energy-intensive due to the demands of refrigeration and motor power drive. Additionally, the growing use of automated equipment, strict temperature control, and hot water for cleaning has further escalated energy consumption in slaughterhouses [20].
- Dairy processing involves concentrating raw milk and separating solids, relying on electricity for pumps, refrigeration, and separation, while thermal energy is used for cleaning, evaporation, and pasteurization [21]. Cleaning-in-place operations are highly energy-intensive due to strict hygiene requirements [22].
- Baking industry solutions include hydrogen burners, electric ovens, and dual-fuel flexibility. Energy efficiency can be improved by optimizing ovens, such as recirculating exhaust gases. Significant hot water and steam use occurs for temperature and humidity control in fermentation and cleaning. Boiler efficiency can be enhanced through proper sizing and process control [20].
- Sugar and Chocolate Production: Significant heat and electricity consumption for refining and processing. The sugar subsector is further explored in the study case section.
- Beverage Industry: High water and energy usage for brewing, distillation, and cooling.
- Frozen and Processed Foods: Extensive refrigeration and packaging requirements.

Overall, most processes in the food industry fall below the 500 °C threshold, presenting substantial opportunities for electrification and demand-side flexibility.

1.2.3.2 Flexibility Potential

Currently, no energy flexibility studies have been conducted specifically for the food industry. Nonetheless, some important observations can be made based on the sector's energy use characteristics.

The vast majority of energy-intensive processes in the food industry operate at medium to low temperatures (below 500 °C), including: Pasteurization, baking, fermentation, cleaning-in-place, refrigeration, evaporation and separation. This temperature range is crucial because it aligns well with mature and efficient electrification technologies, such as: Electric boilers, heat pumps, electric ovens, induction heating, mechanical vapor recompression (MVR) and high-efficiency motors and variable speed drives. These technologies can not only replace fossil fuel-based systems but also offer significant flexibility potential, particularly when integrated with digital process control, thermal storage, and flexible demand response strategies.

Beyond these general technologies and strategies already discussed for the industrial sector, several fully electric and flexibility-driven innovations are emerging in food processing. These advancements primarily aim to provide heat efficiently while ensuring food quality and hygiene. Some examples are:

- High-Pressure Processing (HPP): Uses pressure instead of heat for sterilization, preserving food quality while reducing energy consumption. Non-thermal processes like HPP require less water and heat, contributing to a lower environmental impact [23].
- Ohmic, Microwave and Infrared Heating: Faster and more energy-efficient than conventional heating methods. Microwave technology is already utilized for drying, thawing, and pasteurizing [23], [24].
- Ultrasound and Pulsed Electric Fields: Improve food preservation with minimal energy input.

- Ozone and UV Treatment: Reduce the need for chemical sanitizers and lower water consumption.

Investment costs remain a key barrier to widespread industrial adoption of all of these technologies [24] [25] Among these emerging technologies, UV light, microwave heating, and HPP have the highest potential for large-scale commercialization [23] [25]. Ongoing research focuses on refining process conditions and microbial safety protocols to support broader adoption within the food industry.

1.2.3.3 GALILEO application

One of the key partners in this project is Tiense Suiker, the largest sugar refinery in Belgium. The company produces up to 0,8 Mton of sugar per year. The following summary highlights key takeaways from meetings with the company, offering a comprehensive overview of the challenges and opportunities faced by businesses in the sector concerning flexibility integration.

The transformation of beets into sugar involves several key steps:

1. Harvesting and Cleaning: Sugar beets are harvested and transported to the refinery, where they are washed to remove dirt and debris.
2. Slicing and Juice Extraction: The beets are cut into thin strips called cossettes and mixed with hot water in diffusion tanks to extract sugar-rich juice.
3. Purification: The raw juice contains impurities, which are removed using lime and carbon dioxide in a process called carbonation. The resulting clear juice is then filtered.
4. Evaporation: The purified juice is concentrated by evaporating water, turning it into a thick syrup with a higher sugar content.
5. Crystallization: The syrup is further heated and seeded with sugar crystals to encourage crystallization. This results in sugar crystals forming within the thick syrup.
6. Separation and Drying: The sugar crystals are separated from the remaining liquid (molasses) using centrifuges, then dried and cooled before storage.
7. Final Processing and Packaging: The refined sugar is screened for quality, packaged, and distributed for commercial and consumer use.
8. Byproducts such as molasses and beet pulp are used for animal feed, bioethanol, or other industrial applications.

Up to 20 to 30% of total production costs for sugar consist of energy costs, with the main energy consumption sections of the process being the evaporation and crystallization.

The facility operates seasonally, from September to the end of January/February (dubbed “the campaign”). It can be extended with an additional 60 days for crystallization if so desired. While in operation, the installations are active 24/7. It is difficult to fully stop the installation and restart, as semi-finished product goes to waste or degrades by doing so. The process could be slowed down but that prolongs the campaign. February to July is dedicated to expeditions, including signing contracts to guarantee a beet supply during the campaign and contracting new labor. During this time, the focus is also on the packaging of the product. Energy consumption is much lower during this period. On the other hand, it is difficult to store beets, as they rapidly degrade. On top of that, there is not enough space to store the amount processed during a typical campaign. Sugary water, coming from putting the beets in contact with water, can be stored for up to one year. This leaves some room for flexibility, but the opportunity has not been explored in depth.

Several low-carbon alternatives are already being implemented to reduce fossil fuel consumption and enable a higher degree of flexibility, such as:

- Installation of Small Gas Boilers: Smaller gas boilers have replaced a high-capacity gas boiler, covering the existing steam demands. Additionally, the previous coal burner has been discontinued, further reducing emissions. These boilers offer some flexibility in steam generation, as they can be adjusted to meet fluctuating demand more efficiently than a single high-capacity boiler. However, their flexibility is limited by gas availability and ramp-up times.
- Combined Heat and Power (CHP) System: Steam is now produced using a CHP system, aligning electricity generation more closely with on-site consumption.
- Mechanical Vapor Recompression (MVR): MVR units are being installed in the evaporation and crystallization sections, expected to decrease gas consumption by 60% (equivalent to a reduction of 70,000 tons of CO_2). These systems, which operate at variable frequencies between 70% and 108%, are scheduled to be fully operational by 2026. However, as CHP usage decreases (leading to lower in-house electricity generation) and more electricity is required for recompression, overall electricity demand will increase, necessitating additional electricity purchases.
- Spirit Project – High-Temperature Industrial Heat Pump: Plans are underway for the installation of Europe's largest high-temperature industrial heat pump, designed to achieve temperatures of 135–160°C. This technology could enable full electrification of the process. However, a key challenge is its coefficient of performance (COP), estimated at 3–3.5, which is significantly lower than the COP of 6–7 achieved by Mechanical Vapor Recompression (MVR) systems.

Several emerging alternatives are being explored to enhance sustainability and energy flexibility, though their implementation faces significant challenges. Biogas production from organic waste and water treatment processes presents a viable path to full decarbonization, yet concerns over odors and decreasing European support have slowed its expansion. Hydrogen integration is also under evaluation, with plans to connect to the H_2 pipeline from Zeebrugge to Germany.

Additionally, while carbon capture technologies offer potential for emissions reduction, their high costs remain a major obstacle. In the realm of industrial byproduct valorization, fermentation for citric acid production using molasses (a syrup with 60% sugar content) is being explored. At the same time, waste heat recovery could enable the supply of excess heat to Tienen through a district heating network, but political backing and substantial investment are crucial for its realization. A key challenge across these initiatives is the lack of investment from the company's directing board, as well as the need for stronger governmental support in Belgium. Some other companies' next steps include exploring futuristic Power Purchase Agreements (PPAs), such as long-term baseload contracts spanning five to ten years, and evaluating new process technologies like vacuum crystallization to further improve efficiency and sustainability.

This case study highlights the key considerations for each subsector to enhance energy flexibility integration by:

- Determining the primary energy-intensive processes.
- Assessing daily and seasonal energy consumption patterns. For example, in the sugar industry, production is focused between September and February.
- Evaluating energy use per process block per unit of intermediate product, as well as total facility consumption per unit of final product.
- Analyzing how heat and electricity are supplied to each process unit. Can full electrification be achieved? What alternative technologies could replace current

systems? Are there more innovative, flexibility-friendly process units that could be integrated? What barriers hinder their implementation?

- Examining whether material buffer storage exists between process units.
- Assessing the degree of flexibility in energy consumption. To what extent can process units reduce energy use or be temporarily shut down without compromising product quality or causing losses?

In conclusion, energy flexibility is a critical enabler of sustainability and cost-efficiency in the Belgian food industry, helping to balance energy supply and demand while integrating renewable energy sources. Given the sector's significant energy consumption, adopting flexibility measures can enhance resilience, reduce operational costs, and support Belgium's broader decarbonization goals.

However, several barriers hinder the widespread adoption of energy flexibility. High investment costs, technological limitations, and the lack of tailored regulatory frameworks pose challenges for industrial players. Additionally, the diversity of the food sector—with its varying processing requirements, hygiene standards, and production schedules—complicates the implementation of standardized flexibility solutions.

Despite these challenges, certain "low-hanging fruits" offer promising opportunities for flexibility integration. The adoption of electrified heat technologies such as e-boilers and heat pumps, the optimization of cold storage flexibility, and the use of thermal and material buffers in production processes can significantly improve energy demand management. Additionally, emerging technologies like microwave heating, high-pressure processing (HPP), and membrane filtration can enhance energy efficiency while reducing reliance on fossil fuels.

1.2.4 Non-Ferrous Metals Sector

1.2.4.1 Introduction

The non-ferrous metals sector holds an important position in Belgium's industrial and economic landscape. Non-ferrous metals—including zinc, copper, aluminium, lead, tin, nickel, and precious metals—are indispensable inputs for numerous high-value applications across sectors such as transportation, electronics, construction, renewable energy, and defence. As the global economy accelerates its transition toward decarbonization and clean energy, the strategic importance of these materials is increasing. Metals such as lithium, nickel, copper, and rare earth elements are vital for enabling clean technologies, including electric vehicles, solar PV, wind turbines, and battery storage systems. Projections under the IEA's Sustainable Development Scenario (SDS) indicate a sharp rise in the demand for critical minerals by 2040 compared to 2020 levels (Figure 1-9). Moreover, the mineral intensity of selected clean energy technologies (Figure 1-10) highlights the mounting pressure on non-ferrous value chains to scale up production while ensuring resilience and sustainability.

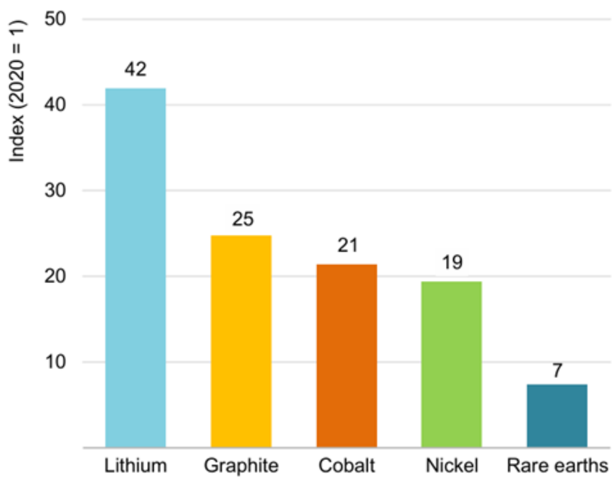

Figure 1-9: Growth of selected non-ferrous minerals in the SDS, 2040 relative to 2020 [1]

Belgium's non-ferrous metals industry not only contributes to the European supply of these critical materials—often through advanced refining and recycling processes—but also emerges as a potential enabler of energy system flexibility. With high energy consumption and growing renewable integration, Belgium's non-ferrous sector presents significant potential for energy flexibility. Industrial processes in the sector can adapt to fluctuating electricity supply, enhance grid stability, and support both national and EU climate goals.

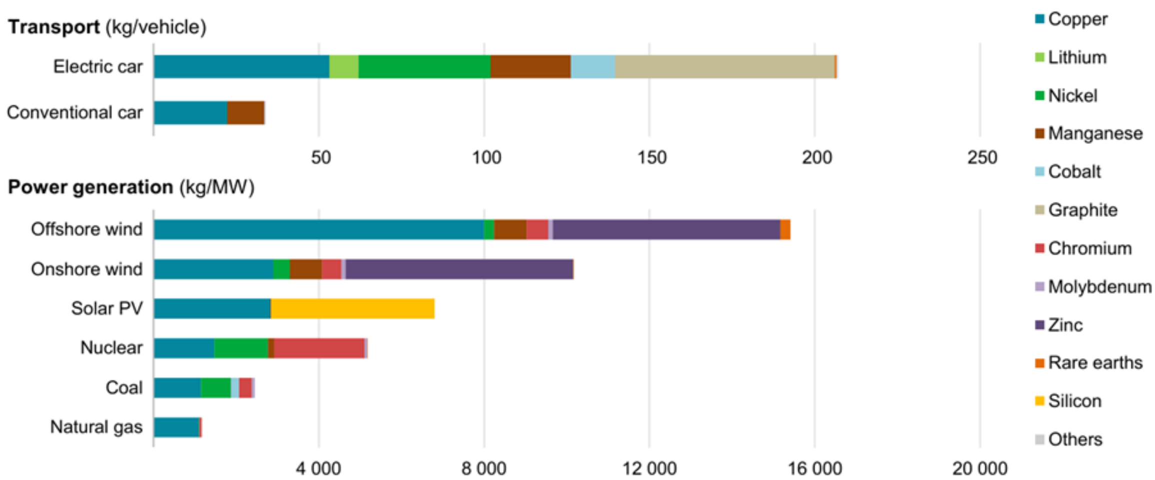

Figure 1-10: Mineral Requirements for Renewable Energy Technologies [1]

Belgium is home to several companies involved in the production, refining, and recycling of non-ferrous metals. These include Nyrstar (zinc production), Aurubis (copper smelting and recycling), Metallo (multi-metal recovery), and Umicore (precious metals and battery recycling). These companies constitute the backbone of the "Flanders Metals Valley," a regional industrial ecosystem known for its high concentration of metallurgical expertise, advanced recycling technologies, and systemic approach to circular material flows [2].

The relevance of the non-ferrous sector extends beyond national boundaries. It is embedded in critical European industrial value chains, particularly those linked to decarbonization and digitalization [3]. Metals such as aluminum and copper are essential for the electrification of transport, solar photovoltaic systems, wind turbine generators, and battery energy storage systems [4]. The presence of upstream and midstream non-ferrous metal operations in Belgium thus plays a vital enabling role in Europe's net-zero industrial strategy. In this context, Belgium's competitive advantage is underpinned by its geographical location, port infrastructure, integrated supply chains, and policy frameworks that support industrial innovation and sustainability. From an energy perspective, non-ferrous metals production is characterized by energy-intensive processes that rely heavily on both electrical and thermal energy. Electrochemical and high-temperature operations dominate the production chains, especially in the context of refining, electrolysis, melting, and casting [5]. The sector is among the top five industrial consumers of energy in Belgium, following chemicals, food, and steel [6].

Electricity is the dominant energy vector, especially in electrochemical processes such as electrowinning and electrorefining of zinc and copper. These operations require a consistent and stable power supply, with electricity accounting for a significant portion of operating costs. As shown in Table 1, electricity represents the largest share of energy use in the Belgian non-ferrous sector, accounting for an estimated 50–60% of total energy consumption. Zinc electrolysis, for instance, consumes approximately 4,17 MWh_e per ton of zinc produced [7], while aluminum smelting through the Hall–Héroult process can exceed 15 MWh_e/t [2]. Although Belgium does not have primary aluminum smelting, downstream aluminum processing and secondary refining (recycling) still require substantial energy input.

Thermal energy, primarily derived from natural gas, is used in melting, drying, roasting, and calcination stages. According to Table 1, natural gas constitutes roughly 30–40% of the energy mix. Furnaces, kilns, and rotary dryers are common in lead and copper metallurgy. In some facilities, recovered heat is utilized for ancillary services or integrated into other industrial processes [8]. Although the integration of waste heat recovery, cogeneration, and renewable energy sources—such as biogas or hydrogen—remains limited, it presents a significant opportunity for advancing decarbonization efforts in the future.

The non-ferrous metals sector is characterized by energy-intensive, high-load operations. These processes typically operate at continuous loads to maintain chemical and thermal stability, which poses challenges for demand-side flexibility. Unplanned interruptions or frequent load shifts can lead to inefficiencies, increased wear on equipment, and reduced product quality. Despite these challenges, there are opportunities for flexibility in the sector, particularly in processes that involve energy consumption and recovery.

The sector includes both primary and secondary production routes. In primary production, Nyrstar Balen is a key player, utilizing the Roast-Leach-Electrowin (RLE) process for zinc electrolysis—a multi-stage process illustrated in Figure 3. In secondary production, companies such as Umicore (Hoboken), Aurubis (Olen), and Metallo (Beerse) specialize in the recycling and recovery of copper, aluminum, and precious metals. These companies are essential to the sector's sustainability goals, contributing significantly to the circular economy through the reuse of valuable materials.

Table 1-3: Estimated Energy Use by Process Type in Belgian Non-Ferrous Sector

PROCESS TYPE	TYPICAL ENERGY USE	ENERGY FORM	BELGIUM EXAMPLE
ELECTROLYSIS **ZN, CU REFINING, BATTERY METALS**	3,5–5,5 MWh/t	Electricity	Nyrstar Balen/Overpelt
THERMAL SMELTING **PB, CU, ALLOY PRODUCTION**	1,5–3,0 MWh/t	Mostly fossil (gas, coke)	Metallo Beerse, Umicore
RECYCLING **MULTI-METAL RECOVERY**	2–4 MWh/t	Mixed (gas, electricity)	Metallo, Umicore
ROASTING/CALCINATION **ZN AND CU OXIDE PRODUCTION**	0,5–0,8 MWh/t	Heat (natural gas)	Nyrstar, Aurubis
MECHANICAL PRETREATMENT **SHREDDING, SORTING, GRINDING**	0,3–0,7 MWh/t	Electricity	Umicore, various shredders
ANCILLARY OPERATIONS **MATERIAL HANDLING, LOGISTICS, COOLING, WATER TREATMENT, AND FACILITY MAINTENANCE**	~5–10% of total plant energy	Mixed	All sites

Source: Estimation based on industrial benchmarks and corporate disclosures [7,8,9,10]

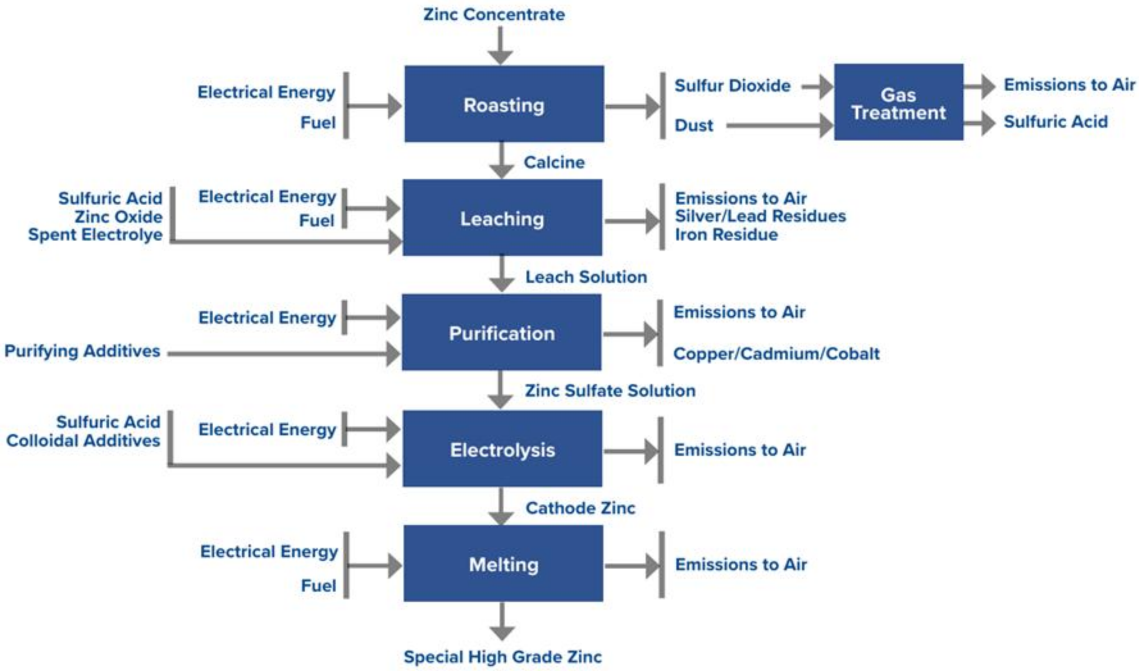

Figure 1-11: Process Flow - Zinc Production (Electrolysis Route) [11]

1.2.4.2 Flexibility potential

Key processes in the non-ferrous sector that are relevant to energy flexibility include:

- Zinc Electrolysis: This is a continuous process with high electricity consumption. Electrolysers have some load-following capability, making them potential candidates for demand-side flexibility services.
- Copper Recycling and Refining: This process involves thermal smelting and electro-refining stages. The batch processes in the smelting stage allow for production scheduling, providing some flexibility for load shifting.
- Aluminium Recycling: In this process, melting furnaces are used, which can be operated in a load-shiftable manner, depending on the type of furnace and its insulation. This provides an opportunity for flexible energy use.
- Battery and Precious Metals Recovery: This process involves high-temperature operations with integrated energy recovery systems, allowing for some load balancing through buffer storage. This flexibility helps to manage energy demand while maintaining production efficiency.

Each of these processes offers distinct opportunities for enhancing energy flexibility, despite the traditionally high-load nature of the sector. In addition, there exist several flexibility levers across the non-ferrous value chain:

- Electrolysis units can shift load within technical boundaries without affecting product quality.
- Melting furnaces in recycling operations offer batch operation options, allowing for off-peak operation.

- Material buffers, such as storage of intermediate products (e.g., molten metal, purified leachate), help decouple process steps.
- Energy recovery systems (e.g., from high-temperature furnaces) support self-consumption and can reduce peak grid demand.
- Participation in energy markets, as already demonstrated by companies like Nyrstar in demand response programs.

The flexibility potential of the non-ferrous metals sector is influenced by several interrelated factors, including technological configurations, contractual energy arrangements, and the degree of process integration. Flexibility measures under consideration include load shifting, participation in balancing markets, and scheduling operations in line with time-of-use tariffs. However, the implementation of such strategies is constrained by the continuous nature of many metallurgical processes, strict product quality requirements, and the high capital intensity of production equipment. To effectively identify and unlock viable flexibility options, a comprehensive techno-economic assessment is required—one that combines process-level analysis with real-time energy consumption data and the facility's capabilities for grid interaction.

1.2.4.3 GALILEO application

The non-ferrous metals sector faces significant challenges in managing energy consumption due to the energy-intensive nature. Nyrstar's zinc smelting facility in Balen, Belgium, represents a use case in project Galileo in which flexibility can be leveraged through the development of a "Virtual Battery". This initiative integrates process knowledge with energy market insights to provide valuable flexibility services to the grid while minimizing operational disruptions and enhancing economic competitiveness.

This case investigates how Nyrstar can optimize its energy usage and participate in various energy markets (such as Day-Ahead Market, Ancillary Frequency Regulation, and more) while ensuring that process safety and zinc production quality remain uncompromised. Through advance buffering techniques and an electrolysis process, Nyrstar aims to provide a range of services, including mFRR and aFRR, in addition to optimizing market participation in the Day-Ahead and Continuous Intraday Markets.

The zinc smelting operation integrates electrolysis as part of its zinc production process. The electrolysis process involves electrolyzing zinc from an aqueous solution of zinc sulfate. This process, typically consuming a substantial amount of electricity, is highly flexible, as it can respond to changes in grid conditions by shifting energy consumption. Nyrstar is exploring the potential of its existing Virtual Battery, powered by the electrolysis process, to deliver flexibility services across multiple energy markets.

Nyrstar's electrolysis process, spread across four halls, utilizes lead anodes and aluminum cathodes to extract zinc from an aqueous zinc sulfate solution. The flexibility of this process stems from its ability to adjust the rate at which it operates, providing both power and energy to the grid. With an existing flexibility of 90 MW, Nyrstar can deliver this capacity mainly in the mFRR market, with initial steps taken towards participating in the aFRR market.

To extend this flexibility, Nyrstar is implementing a fifth hall in its electrolysis facility, increasing its flexibility to 125 MW_e. This facility allows Nyrstar to shift production profiles significantly, offering up to 120 hours of maximum capacity operation and up to 70 hours of minimum capacity operation. Such prolonged flexibility makes Nyrstar's Virtual Battery a unique resource for balancing renewable energy fluctuations and grid stability.

The core of the Virtual Battery system lies in the installation of large buffer tanks (12.000 m³), which allow for extended energy shifts beyond the existing 10-hour production stop limit. These hybrid tanks can store both purified solution (rich in zinc) and spent acid (a byproduct of electrolysis). This flexibility is crucial for adapting production schedules to external energy market signals, enabling participation in balancing markets without interrupting zinc production.

By using these buffer tanks, Nyrstar can store large volumes of zinc solution during low-demand periods and release them when production demand is high. The capacity to store and shift production over extended periods (up to 120 hours) provides a level of energy flexibility rarely seen in industrial processes, offering a unique asset for grid balancing and market participation.

In this use case, the aim is to identify how Nyrstar can best allocate its available flexibility across various markets to optimize operations and economic returns. Several strategic considerations are key:

1. Volume of Flexibility: Nyrstar's Virtual Battery offers both high instantaneous power capacity (MW) and extended-duration energy flexibility (MWh). This enables participation not only in balancing markets (aFRR, mFRR) but also in short-term trading platforms like the Day-Ahead and Continuous Intraday Markets.
2. Value Stacking: Flexibility can be optimized through dynamic, selective bidding strategies, allowing the company to access multiple revenue streams across markets. By adapting its bidding behaviour based on real-time grid needs and price signals, the company can stack value from different services without compromising production efficiency.
3. Impact on Market Prices: Large-scale industrial flexibility has the potential to influence market clearing prices. By absorbing excess renewable energy or reducing demand during peak times, Nyrstar can contribute to market stability, making it an important player in the integration of variable renewable energy sources.

However, several barriers must be addressed to fully realize this potential. First, any load-shifting strategy must ensure that process integrity is maintained. Second, the economic viability of the Virtual Battery depends heavily on the structure of grid contracts and tariffs, which may not always incentivize flexibility. Finally, both electricity and zinc prices are volatile, introducing significant uncertainty into the business case. Continued optimization, robust forecasting, and the development of adaptive business models are essential to navigate this risk.

Looking ahead, this use case could serve as a blueprint for other energy-intensive industries seeking to decarbonize and increase competitiveness. As part of Belgium's broader industrial decarbonization efforts, Nyrstar's approach offers valuable insights into how flexibility can be embedded within core production processes and aligned with energy system needs.

1.2.5 Datacenters

1.2.5.1 Introduction

The Belgian data center sector has experienced a significant growth in recent years, which is expected to continue due to the digitalization of our economy and a rising demand for AI infrastructure and cloud investments. Today, the sector requires nearly 400 MW_e of IT power (excluding infrastructure load, see below) [26]. It is estimated that this translates into an annual electricity consumption of approximately 1,5 TWh_e [27]. Before looking at future projections and the flexibility potential of the sector, it is important to distinguish between three categories of data centers [28]:

- **Single-tenant or enterprise data centers**: Owned and operated by the company or organization they support. These are typically smaller data centers, such as those owned by a municipality or hospital.
- **Colocation data centers:** Rental of data center space to multiple parties. The colocation data center owner is responsible for non-IT infrastructure, such as cooling and power infrastructure. The tenants typically own, install, and operate their IT equipment. A colocation data center can house many customers and therefore benefit from economies of scale compared to enterprise data centers. Colocation data centers range in size from small to medium.
- **Hyperscale data centers:** Very large single-tenant data center (20MW_e or more, but campuses more than 100 MW_e are not uncommon). Typically owned by a major cloud providers or tech companies (Amazon, Google, Microsoft, etc.).

Table 1-4 shows the situation for the Belgian market in 2024. First, note that the table displays IT power, which is power consumption that is exclusively required by the IT-infrastructure. This metric therefore excludes the power required for cooling and any additional losses. The importance of these latter components has declined over time. Relatively older data centers require 0,6 - 0,8 MW_e of additional power per MW_e of IT-power, while modern data centers get by with about 0,3 MW_e (~0,1 MW_e for cooling and 0,2 MW_e losses) [28]. A major driver of this evolution is a reduced need for cooling, as modern IT infrastructure is better able to handle relatively higher temperatures.

As mentioned, enterprise data centers are typically smaller and distributed, but still account for 38% of IT-power (Table 1-4). Colocation data centers have recently crossed the 100 MW_e threshold and main operators in Belgium are Digital Realty, LCL, and Data center United [26]. Belgium currently hosts one hyperscale data center in Saint-Ghislain, owned and operated by Google [26].

Table 1-4: Belgian datacenters by IT Power (MW) size class in 2024 [26].

	Colocation		Enterprise		Hyperscale		Total	
IT power (MW)	companies	%	companies	%	companies	%	companies	%
0,05 - 0,5	11	46	215	81	0	0	226	78
0,5 - 1	1	4	28	11	0	0	29	10
1-5	6	25	16	6	0	0	22	8
5-20	4	17	5	2	0	0	9	3
20 or more	2	8	0	0	1	100	3	1
Total	24	100	264	100	1	100	289	100
	Total IT power (MW)		Total IT power (MW)		Total IT power (MW)		Total IT power (MW)	

	103	149	143	395

Two ongoing developments are noteworthy for situating the flexibility potential. First, the industry, and its demand for electricity, continues to grow. Second, colocation data centers are becoming more popular than single-tenant centers. Indeed, the overall demand for data center space is growing, and individual organizations are often choosing to stop investing in dedicated facilities and instead see more value in collocation. The Belgian Digital Infrastructure Association expects that colocation IT-power will grow from 103 MW_e today to 261 MW_e by 2029, an annual growth of 20% [26]. They furthermore expect that the hyperscale segment will even exceed this pace as Google has commenced construction of a new campus in Farciennes, set to host three new data centers.

1.2.5.2 Flexibility potential

Data centers could potentially leverage several mechanisms to provide flexibility. In what follows, we provide a brief overview of the different options and the extent to which different segments can deliver them. The overview below is loosely inspired by the work of Driesse et al. [28] and supplemented with information obtained during the interviews.

Data centers could **shift workloads over time**, i.e. increasing consumption when electricity prices are cheaper and vice versa. There is a growing body of literature that explores approaches to flexibility schedule IT loads, although many of these are stylistic case studies that do not attempt to quantify the practical flexibility potential [29], [30]. This potential is constrained by the type and schedulability of the workload, as well as the nature of the data center. First, time shifting can only be applied to workloads that are not time-sensitive, such as AI model training, video processing, backups, etc. There are many workloads that do need to be served in real time, such as banking transactions, streaming requests, internet traffic, etc. Second, shifting workloads remains difficult for colocation data centers because they do not directly operate the IT equipment in their facilities. Colocation owners would need to encourage their clients to flexibly schedule their IT-load. This could theoretically be done by passing on dynamic prices, but it remains a difficult proposition, and it is unclear whether this is worthwhile. As a result, colocation data centers have not implemented such mechanisms in practice and are not expected to do so in the near future. Hyperscale data centers, on the other hand, are actively experimenting with flexibility measures. Google, for instance, has implemented algorithms to shift non-urgent tasks in its hyperscalers and claims to have leveraged such measures to alleviate peak demand during the European energy crisis [31]. To the authors' knowledge, quantitative estimates of the flexibility potential of hyperscalers are not publicly available.

Data centers could **shift workloads over space**, i.e. shifting tasks from one location to another one where electricity prices are currently lower. Colocation data centers are unable to leverage this mechanism because they do not directly control their IT-loads, and even if a colocation center hosts a client at multiple locations, that client will typically prefer the closest data center for latency reasons. As such, this mechanism is again reserved for hyperscale data centers and specifically for those that have the capabilities to schedule loads at different locations. Riepin et al. [32] show that scheduling flexible IT loads across European facilities can significantly reduce the electricity procurement cost, but do not attempt to quantify which part of the load is eligible. Quantitative data on locational shifting remains proprietary.

Data centers could consider implementing **variable cooling strategies**, i.e. pre-cooling equipment when electricity prices (or imbalance prices) are favorable. Similar strategies are occasionally implemented for large cooling cells. However, as noted above, data centers are becoming more efficient because they can nowadays operate at relatively higher temperatures. Power requirements for cooling are decreasing (to about 10% of IT power), which diminishes the potential. Alternatively, data centers could consider thermal buffers, but it remains unclear whether this can be an economical option [28]. A likely more beneficial and reasonable option is to feed the heat into a (district) heating network. Such approaches are currently being implemented or pursued by several data centers but are beyond the scope of this report.

Finally, data centers make use of **Uninterruptible Power Supplies (UPSs) and backup generators** to safeguard availability. UPS systems could be considered for frequency containment reserves, whereas backup generators could be leveraged for mFRR markets and even for adequacy purposes. That being said, the flexibility potential of these assets is rather small because most UPS systems currently in place are not bi-directional, and because data center owners are generally unwilling to compromise reliability [33]. In other words, they prioritize guaranteed access and do not want to risk the unavailability of UPS systems and the data center at large. Likewise, backup generators are currently primarily fueled by diesel, which is typically not the most competitive asset in wholesale energy and reserve markets (apart perhaps for upward mFRR services). That being said, there do exist some practical examples of data centers leveraging their backup generators for flexibility services. Their number is furthermore increasing as more and more data centers can rely on their own generating assets [34].

In conclusion, colocation data centers are currently limited in their ability to provide flexibility services, primarily because they do not have direct control over their IT-power. To do so, their clients would need incentives to flexibly schedule non-urgent loads. At present, it is unclear what part of the colocation center load is not time sensitive. Either way, a fundamentally different approach (and pricing strategy) from colocation data centers would be required, which we deem unlikely in the near future. Hyperscale data centers, on the other hand, possess flexibility capabilities that are currently being operationalized in practice. Because these data centers are owned by major cloud providers or technology companies, data remains proprietary.

1.2.5.3 GALILEO application

LCL Data Centers is a Belgian provider of colocation services that owns five data centers with a collective IT power demand of 8 MW. The company furthermore owns and operates 1,5 MWp of PV generation and is investing in additional wind (6,9 MW) and PV (3,5 MW) capacity. These on-site renewable installations could create synergies with future flexibility strategies, such as optimizing on-site generation use or integrating storage solutions.

As a colocation data center, LCL does not directly control the IT workloads hosted in its facilities, which inherently limits its ability to provide demand-side flexibility through load shifting. LCL is furthermore subject to stringent Service Level Agreements (SLAs) that require guaranteed availability and prohibit many of the aforementioned flexibility mechanisms. Then again, LCL is exploring avenues to valorise flexibility. These avenues predominantly relate to leveraging their renewable assets optimally and matching their baseload demand profile with this intermittent production.

First, there are opportunities to be explored by integrating their renewable assets optimally into electricity markets. It is technically relatively easy to curtail PV production when electricity prices are negative. If curtailed, these assets can furthermore ramp up quickly to provide upward aFRR services. Second, LCL Data Centers is investigating the economic feasibility of battery installations to optimize the self-consumption of its assets. While optimizing self-consumption is valuable, integrating battery capacity into a broader market valuation strategy is likely more beneficial. For example, when electricity prices are negative, it could be beneficial to curtail a PV installation while drawing from the grid to (i) charge batteries and (ii) power IT workloads. Note that these strategies are not specific to the data center sector and require rather advanced contractual agreements with suppliers or BRPs. Then again, such strategies are valuable from a system perspective and would therefore, in principle, yield financial gains [35].

2. Belgian energy system scenarios

A deeper understanding of the role of flexibility and sustainable technologies in the Belgian industry sector over the coming years can be achieved through a national energy system cost optimization using software such as TIMES. VITO has developed and continues to expand its one region Belgian Energy System model, known as TIMES-BE. In the context of the GALILEO project, the TIMES-BE model could be further improved to better portray the sector and the influence of flexibility integration.

2.1. TIMES

TIMES is an advanced energy system modelling tool developed under the IEA-ETSAP framework. It enables both top-down and bottom-up modelling approaches and offers flexibility in spatial and temporal resolution. This allows analysts to simulate energy systems at different scales—ranging from hourly to multi-year time frames and from local to national or regional levels.

The model begins with predefined assumptions about service demands. These represent the energy services required by society, such as residential heating, lighting, industrial production of goods like steel and cement, and personal or freight transportation. TIMES does not generate these demands but uses them as fixed inputs to assess how best to meet them through various technology options.

At the core of the model lies a comprehensive representation of technological processes that can fulfill these energy demands. Each process includes conventional and low-carbon alternatives. For instance, steel production is modelled using both traditional coal-based blast furnaces and cleaner methods like hydrogen-based reduction, possibly coupled with carbon capture and storage or utilization. Similarly, road freight transport currently dominated by diesel can transition to electric, hydrogen, or biofuel-powered options. The model evaluates when and how to adopt these technologies based on economic and environmental factors such as CO_2 prices or climate targets.

To support this system-wide analysis, TIMES tracks the flow of energy carriers and materials—referred to as commodities—between processes. These flows include electricity, heat, fossil fuels, and synthetic fuels such as hydrogen or ammonia. The model also considers international trade where necessary, recognizing that a country like Belgium may need to import a portion of its energy supply.

TIMES carries out a cost optimization across the entire planning horizon. It integrates key economic parameters like capital investment, operational and maintenance costs, fuel expenses, and the efficiency of each process. This optimization is subject to physical and policy-based constraints. For example, the model ensures a balance between energy supply and demand in every time period and adheres to user-defined limits such as technology capacity caps, growth trajectories, and emissions reduction goals.

The model covers the full value chain, from the extraction or import of raw materials and energy, through transformation and distribution, to end-use consumption. All processes and commodity flows are assembled into a linear programming model that represents the energy system mathematically. Once optimized, the model outputs detailed results including installed capacity, energy and material flows, marginal production costs, CO_2 emissions, and the associated investments and operational costs required to meet demand in the most cost-effective way.

Overall, TIMES offers a robust, data-driven framework for exploring future energy pathways, informing policy decisions, and supporting the transition to more sustainable energy systems (see Figure *2-1*).

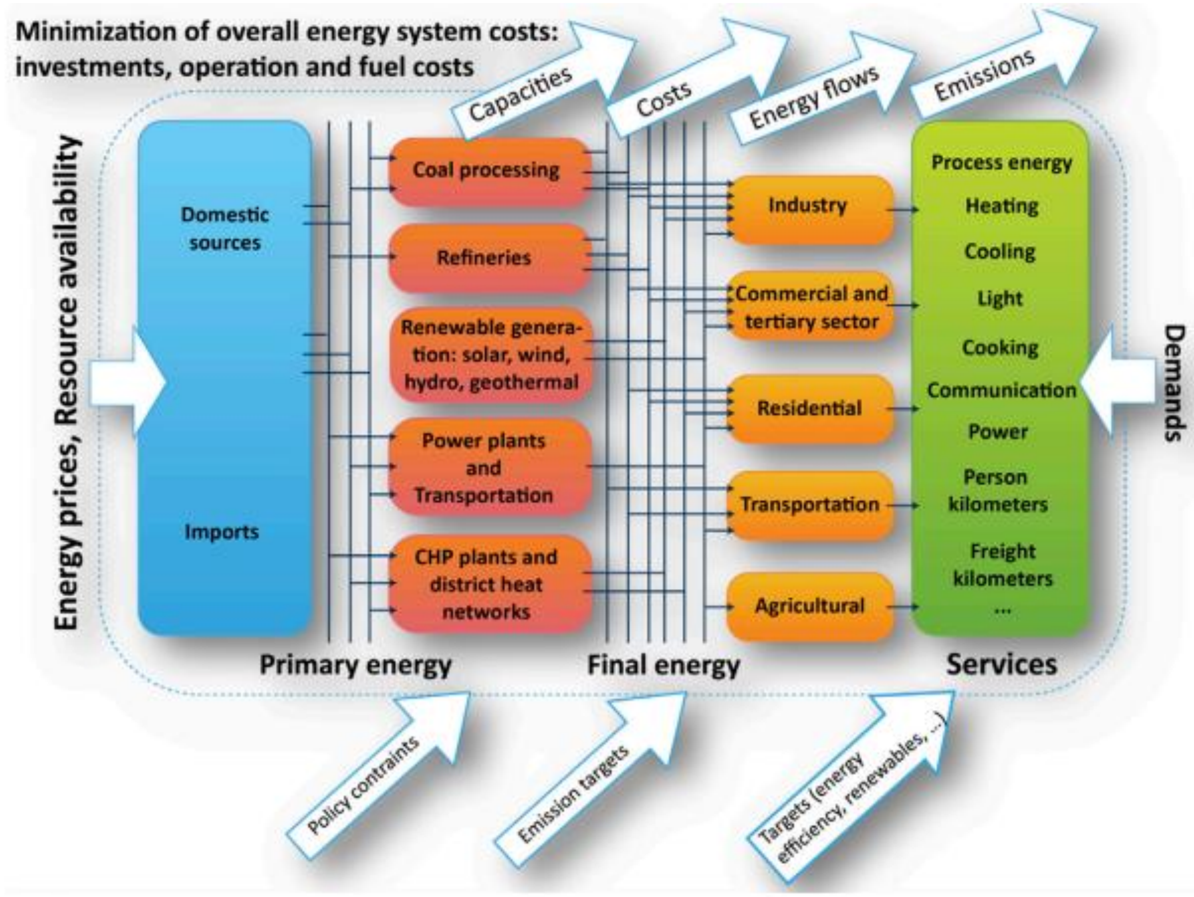

Figure 2-1. Schematic of TIMES inputs and outputs [25].

The TIMES modeling framework was employed to develop an energy system model for Belgium, known as TIMES-BE. This model enables the exploration of various long-term scenarios aimed at achieving net-zero CO_2 emissions by 2050 in a cost-optimal manner. Each scenario provides insights into potential technological pathways and policy strategies that could guide Belgium's energy transition.

For a comprehensive overview of the assumptions, data sources, and key inputs underpinning the development of TIMES-BE, we refer to EnergyVille's "Path 2050" report [25].

2.2. Improvements to the model and next steps

Several targeted improvements can be made to the TIMES model to enhance its capacity to represent energy flexibility within the Belgian industrial sector.

The current model adopts a relatively simplified representation of certain industrial sectors. However, findings from the literature review, along with feedback from industry stakeholders, indicate that a more detailed, sector-specific modeling approach is both feasible and highly beneficial. For example, further disaggregation of the food industry into subsectors such as baking and meat processing would allow for a more accurate depiction of energy consumption profiles and flexibility potentials at the subsector level. This can be achieved by collaboratively defining tailored process topologies with stakeholders. An initial example of such a topology—developed in collaboration with Tiense Suiker for the sugar production subsector—is presented in Figure 2-2. Arrows in red and yellow represent electricity and heat respectively.

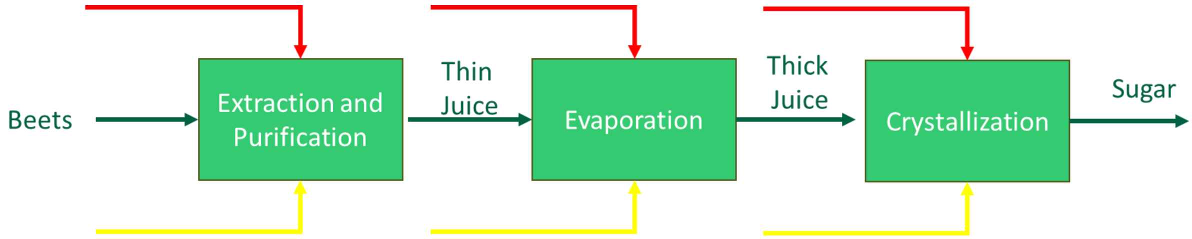

Figure 2-2. New proposed topology for the sugar production subsector.

It is also crucial to represent the typical daily energy use profiles and seasonal variability of industrial subsectors. Accurately capturing these temporal patterns is fundamental for modeling realistic energy demand and identifying flexibility opportunities such as load shifting and demand response strategies.

Moreover, the integration of new, sustainability-oriented and flexibility-enabling process and energy-supplying units is essential. This includes emerging technologies such as high-efficiency heat pumps, waste heat recovery systems, and biogas integration. Their inclusion would allow the model to simulate the dynamic impacts of these technologies on both energy demand and grid interaction.

To fully integrate energy flexibility, the TIMES framework should incorporate mechanisms to evaluate capital expenditure (CAPEX) trade-offs associated with flexible technologies, as well as efficiency losses where relevant. These enhancements would allow the model to better reflect the technical and economic dimensions of deploying flexible energy solutions.

Altogether, these refinements would enable the TIMES model to deliver a more comprehensive and realistic assessment of energy flexibility within the Belgian industrial context. Such improvements are vital to informing robust, evidence-based decision-making by policymakers and industry stakeholders.

3. Appendix

3.1 Technical flexibility potential data sheets

Overview in excel for each sector.

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