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Design of a Key Performance Indicator Framework for an In-LoCo Water Treatment Plant in the Natural Gas Sector: The Case of IGS S.p.A.

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Abstract

This thesis develops a structured Key Performance Indicator (KPI) framework for the new in-loco Water Treatment Plant (WTP) implemented at the IGS S.p.A. natural gas storage site. The project addresses the operational, economic, and environmental challenges associated with managing production water generated during gas withdrawal, replacing third-party disposal with a fully internal treatment process. Treating water on-site reduces logistics-related risks, increases operational continuity, and significantly decreases waste volumes, supporting the company's strategic, environmental, and cost-efficiency goals. To develop a new KPIs framework a hybrid methodology is adopted, combining ISO 22400 performance-measurement principles, insights from a systematic literature review, stakeholder interviews, and field-instrumentation analysis. The review identifies key operational performance dimensions: energy, chemical consumption, quality, waste, and reliability, while highlighting gaps in existing approaches, especially the absence of KPIs frameworks tailored to systems with strong seasonal variability and direct coupling with industrial production cycles. The resulting framework includes eleven KPIs organized across operational, economic, quality, and sustainability areas, with one mandatory regulatory indicator (water-quality compliance) and ten monitoring indicators. Each KPI is defined through context, design rationale, mathematical formulation, measurement requirements, and a conceptual dashboard widget. Normalization by treated volume ensures comparability across the highly variable operating conditions typical of gas storage facilities. The framework provides an integrated, real-time performance-monitoring architecture that supports regulatory compliance, operational stability, cost optimization, and strategic decision-making. Limitations and recommendations for future development such as automated data integration, uncertainty quantification, and advanced analytics are also discussed.

Key-words: Performance Measurement; KPI Framework Design; Water Treatment Plant; ISO 22400; Gas Storage; Process Optimization; Key Performance Indicators; Operational Efficiency

Abstract in Italiano

Questa tesi sviluppa un sistema strutturato di Key Performance Indicators (KPI) per il nuovo impianto di trattamento acque (WTP) realizzato in loco presso il sito di stoccaggio di gas naturale di IGS S.p.A. Il progetto affronta le sfide operative, economiche e ambientali legate alla gestione dell'acqua di produzione generata durante la fase di erogazione del gas, sostituendo il conferimento a terzi con un processo di trattamento completamente interno. Il trattamento in loco riduce i rischi logistici, aumenta la continuità operativa e diminuisce in modo significativo i volumi di rifiuto, supportando gli obiettivi strategici, ambientali e di efficienza economica dell'azienda. Per sviluppare il nuovo framework di KPIs è stata adottata una metodologia ibrida che combina i principi di misurazione delle performance della norma ISO 22400, i risultati di una revisione sistematica della letteratura, interviste agli stakeholder e un'analisi della strumentazione di campo. La revisione della letteratura individua le principali dimensioni prestazionali operative: energia, consumo di reagenti, qualità, rifiuti e affidabilità e mette in evidenza lacune negli approcci esistenti, in particolare l'assenza di framework di KPIs progettati per sistemi caratterizzati da forte variabilità stagionale e stretta interdipendenza con i cicli industriali principali. Il framework risultante comprende undici KPI organizzati nelle aree operativa, economica, qualitativa e di sostenibilità, con un indicatore regolatorio obbligatorio (conformità della qualità dell'acqua) e dieci indicatori di monitoraggio. Ogni KPI è definito attraverso contesto, pensiero dietro la progettazione, formulazione matematica, requisiti di misura e un widget per la visualizzazione. La normalizzazione rispetto al volume trattato garantisce confrontabilità anche in condizioni operative altamente variabili, tipiche degli impianti di stoccaggio del gas. Il framework fornisce un'architettura integrata di monitoraggio delle performance in tempo reale, a supporto della conformità normativa, della stabilità operativa, dell'ottimizzazione dei costi e dei processi decisionali strategici. Sono inoltre discusse le principali limitazioni e le raccomandazioni per sviluppi futuri, quali l'integrazione automatizzata dei dati, la quantificazione dell'incertezza e l'adozione di tecniche avanzate di analisi.

Parole chiave: Misurazione delle performance; Progettazione di un framework di KPI; Impianto di trattamento acque; ISO 22400; Stoccaggio del gas; Ottimizzazione dei processi; Indicatori di performance; Efficienza operativa

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Preface

Natural gas is an important part of global energy transition, being one of the most promising sources of energy (among the non-renewable ones) to meet the energy demand that is rising year by year, led by developing countries. Natural gas has several advantages over coal, with far better calorific power, which makes it a better source of electricity and thermal energy generation [1]. The use of natural gas allows a significant reduction of greenhouse gases emissions compared to coal, particularly carbon dioxide (CO₂), hence contributing towards mitigating climate change. This source of energy has become indispensable in most areas of daily life, since it is one of the major resources utilized to produce electricity, being one of the main drivers of power generation in most nations, including Italy, where natural gas is a pillar resource for the energy sector [2]. Natural gas is not only widely used in households, industries, and businesses for heating, cooking, and industrial processes, but also valued for its efficient storage properties. Natural gas storage is central to energy supply stability and security. During periods of low usage, gas is stored and subsequently drawn out and utilized during periods of peak usage, thus providing a consistent and continuous supply. Natural gas is stored in underground natural geological formations such as depleted gas fields, aquifers, and salt caverns. Natural gas is transported through an extensive network of pipelines, which is efficient and is a safe mode of gas transport from the production area to the consumption centers without causing traffic, noise, or exhaust emission. To reach locations not directly served by pipeline networks, natural gas can be liquefied to obtain Liquefied Natural Gas (LNG), where the volume of gas is reduced so that it can be stored in cryogenic containers, making possible for natural gas to be carried over long distances. The volume reduction, achieved through liquefaction, allows sea transportation to be more efficient without the use of costly and complicated land facilities. Natural gas, thus, not only satisfies current energy demand but also performs a central role in the process of transition to alternative energy sources [3]. During the growing focus on sustainability and emission reduction, natural gas serves as the bridge fuel between conventional and renewable energy sources. Being capable of flexible storage and transportation of gas, combined with its low carbon content, it has been proven to be a significant option for mitigating solar and wind volatility and intermittency, thus contributing to the development of a more robust energy system. As compared to other energy sources, for example, coal, which create solid wastes and combustion residues with complicated disposal procedures, natural gas burns considerably cleaner, with no ash or waste products to discard. This attribute, along with the fact

that it is versatile, accessible, and storable, makes natural gas a key element of a modern, sustainable energy system that is able to satisfy energy supply requirements in an era of increasing concern for energy security and the environment. One of the main issues in natural gas storage, faced by all players in the sector, is dealing with the so-called 'production water'. During the extraction phase, as will be addressed in the next paragraphs, natural gas comes mixed with underground water and chemicals added to prevent freezing in the pipelines. After being properly separated from the natural gas, the production water, which is full of chemical agents, is currently disposed of by third parties, impacting on economic and environmental performance and increasing operational risks. IGS has initiated a project to build a new Water Treatment Plant (WTP) to treat production water on-site, reducing dependence on third-party operators. My task was to define an appropriate set of KPIs to monitor the plant.

1 The natural gas industry

After a brief introduction to the gas supply chain, aimed at understanding the reasons behind the current market structure, this chapter presents and analyzes each step of the natural gas supply chain. A comprehensive overview will provide insights into natural gas storage, its role within the supply chain, and its strategic significance in the context of the energy transition.

1.1. The origin and its composition

In this paragraph, the role of natural gas in the energy landscape - both globally and nationally - is outlined, highlighting its contribution to the energy transition and its advantages over other fossil fuels. The following sources have been consulted in the preparation of this chapter: [1], [3], [4], [5], [6], [7], [8], [9], [10].

Natural gas is playing an increasingly central role in the energy transition. Compared to coal, it has a higher calorific value (measured in value kJ/kg), and it has lower environmental impact in terms of CO₂ emissions per unit of energy produced. In developed economies, coal use has been largely phased out, whereas it remains prevalent in developing countries, where heavy industry is a key sector. Today, natural gas is widely employed in both industrial settings for electricity generation and residential applications, primarily for heating. Natural gas is a mixture of light hydrocarbons formed through the anaerobic decomposition of organic matter. Its primary constituent is methane (CH₄), coexisting with lesser quantities of ethane, propane, butane, and trace amounts of other compounds, including nitrogen, hydrogen, radon, and krypton. Due to this significant predominance of methane, natural gas is commonly referred to as "methane gas". The contents or proportion of different components depend mainly on two factors: the geographical region where it is extracted and the geological processes determining the formation. These two factors affect the calorific value, i.e., energy released from combustion of 1m³ of gas and its commercial feasibility. For example, the gas composition must correspond, in Italy, to the UNI EN ISO 6976 standard with 99.5% methane, 0.1% ethane, and about 0.4% nitrogen. The purity of the gas and its calorific value depend significantly on the extraction location. The formation of methane follows two main theories (the different formation processes also determines the calorific value of the gas and, therefore, its commercial viability):

- Thermogenic Formation: The most accepted thermogenic theory assumes that fossil fuels result from the compression of organic matter under high pressure and temperature underground. Under these conditions, organic matter is

converted into complicated hydrocarbons, including natural gas. Gas produced by such conditions is called "thermogenic methane." In this process, organic particles, wrapped by layers of sediment and mud, are compressed little by little. The increase in pressure and temperature breaks the carbon bonds in organic matter; hydrocarbons are produced by this process. This can either be oil at lower temperatures, nearer to the crust of the Earth, or natural gas with higher temperatures at greater depths.

- Biogenic Formation: biogenic formation, also called the microbiological hypothesis, takes place in less depth and temperature. This is usually performed through the action of microorganisms-methanogenic bacteria-which chemically break down organic matter into methane gas, CH₄, by means of anaerobic digestion. This means the process can take place without the use of oxygen. Methane produced in this manner is common near the surface, eventually diffusing into the atmosphere. In some cases, however, it remains underground in such a way that methane can be retrieved as pure natural gas.

The accumulation of natural gas, as with oil, occurs in rocks which are conventionally known as reservoirs or deposits. The search for natural gas does not therefore occur in a different manner from the one performed to extract oil but forms part of the same activities in the search for hydrocarbons. In fact, only after drilling exploratory wells the nature of the deposit is identified. The term "*associated gas*" defines the natural gas that is dissolved in oil or forms the cap layer of an oil reservoir, whereas "*non-associated gas*" is a deposit almost completely composed of natural gas, as in the large fields in the North Sea and the Netherlands, or such as the Po Valley and the Adriatic offshore in Italy¹. For extraction, a vertical well is drilled. After confirmation of the presence of hydrocarbons, extraction proceeds. Long cemented steel pipes are inserted during drilling and serve to stabilize the well and prevent gas leakage, hence allowing the gas to flow the surface, where it is collected or stored. Since the pressure inside the reservoirs is very high, the gas will flow spontaneously to the surface. In the instances where the pressure inside the well drops due to the influx of water, compressors may be utilized to extract the gas.

1.2. The History of the Industry

The value chain for natural gas was traditionally vertically integrated, but in recent decades it has evolved towards a liberalized structure. The operations in the entire

¹ In the Adriatic Sea (IT) a reservoir has been discovered and called 'Alto-Adriatico'. It is situated 40 km from the Venice Lagoon and is one of the largest in terms of volume, with an estimated 40 bcm of gas. The Italian Government has blocked production under Article 8 of Law No. 133 of August 6, 2008, classifying it as a "subsidence risk" - i.e., land subsidence. Nowadays, the reservoir is fully exploited by the Croatian company Ina, which has completed extraction works in the Alto Adriatico through the commissioning of the Ivana D-1 platform [82],[83].

value chain laid under one single agent's control. In most of the natural gas markets, in the 1990s, monopolistic structures dominated the entire value chain, from production to distribution and sales to the final consumer, until the liberalization of the sector began, starting with production and gradually extending to distribution and sales. Vertically integrated utilities were those that undertook all key activities in the natural gas value chain, including production, transmission, distribution, and retail. In such a model, natural gas was produced, transported, and sold directly to end consumers by the same entity, which also owned and maintained the necessary infrastructure for distribution and transmission. In contrast, under the new liberalized model, natural gas can be produced or acquired in wholesale markets, while utilities mainly focus on developing and maintaining infrastructure, including distribution and transportation networks. A clear example of vertical integration can be found in Gazprom [11], a Russian company operating across all segments of the natural gas market, holding a dominant position throughout the value chain. Under such a structure, companies maintain exclusive control over retail activities and have significant influence in wholesale markets. Given such dominance, regulatory intervention by governmental or independent authorities becomes essential to prevent market abuse and protect consumers, through the establishment of legal and operational boundaries. In liberalized markets, these functions are typically carried out by national regulatory agencies which oversee pricing, competition, and infrastructure access. From being highly concentrated and monopolistic in character, natural gas markets have, over the last two decades, evolved towards deregulation and liberalization. This transformation was a precondition for the development and expansion of gas markets, which have gradually become more mature and stable, enabling genuine competition among industry operators. In turn, a deregulated gas market is a prerequisite for ensuring security of supply, as it allows for the diversification of both sources and routes of delivery. In fact, diversification can only be fully achieved within a genuinely competitive internal marketplace, which also provides incentives for investment in new technologies and infrastructure. This process of change in the sector was initiated by the United States, which played a pioneering role in opening natural gas markets during the 1980s through a series of deregulation measures aimed at enhancing competition within the industry. Deregulation in Europe began in the late 1990s, first in the United Kingdom and subsequently across continental Europe. This process has led to increasingly competitive markets, in which operators can access transmission and distribution infrastructure under fairer conditions, thereby contributing to greater efficiency and security of supply in Europe.

1.2.1. Liberalization in Italy – Letta Decree

In Italy, since January 1, 2003, the implementation of the Letta Decree - Legislative Decree 164/200, initiated the liberalization of the natural gas market, which, through

the introduction of free competition, encouraged investments and discouraging price competition, leading to lower prices for consumers. It is now allowed for consumers to choose which natural gas supplier best suits their needs with regards to efficiency and reliability. Before liberalization, the entire industry was a monopoly, and Eni (Ente Nazionale Idrocarburi) was the monopolist involved. The market was then restructured into clearly differentiated stages to favour efficiency and competitiveness. Nowadays, the national gas industry is often represented through the concept of the "*natural gas market supply chain*" providing a schematic and economic overview of the industry. The term represents all the production chain of natural gas, from the extraction - or importation from abroad, to the commercialization and final distribution to the final customers. Liberalization has resulted in the fragmenting of the supply chain into three main macro-phases:

- Upstream: It covers gas procurement activities to meet to the national energy demand;
- Midstream: Involved in all those infrastructure-related activities involving transport systems and facilities for storing gas extracted and which, therefore, functionally interconnect the upstream to the downstream sector of the industry;
- Downstream: Selling of natural gas to the final consumer.

Each step consists of several stages developed to make the process efficient, safe, and enduring. Such segmentation enables us to manage technical, logistic, and economic complications related to extracting, treating, transporting, and distributing natural gas. Starting from exploration, each step of the chain is planned and developed in such a way that it can minimize waste and optimize resources, following environmental and safety legislation. Moreover, this organization is essential to ensure that the service is provided, with both reliability and availability guaranteed to the final client, which means that natural gas supply is continuously meeting demand without cuts, meeting legislation and environmental requirements.

1.3. The role of natural gas globally

The importance of natural gas has grown significantly over the years. In developed countries, natural gas has already replaced coal as the primary energy source, while in non-OECD² countries, a growing trend will be expected, with a gradual transition from coal to natural gas. Worldwide the coal consumption is increased by 2,6% lead by non-OECD and non-OPEC³ countries. The global coal consumption is mainly attributed to the Asia-Pacific region, which accounts for 77% of global consumption. Moreover,

2 OECD – Organisation for Economic Co-operation and Development, international organization of mainly high-income countries promoting economic cooperation and development.

3 OPEC – Organization of the Petroleum Exporting Countries, intergovernmental organization coordinating petroleum policies of member countries.

natural gas is abundantly available in large underground reserves. According to the *World Energy Report 2024* [12] published by Eni, the currently known global reserves amount to 208,557 bcm⁴, marking a 0.5% increase compared to the previous decade and remaining nearly unchanged on an annual basis (+0.02%). Following a -1.25% decline in 2020, likely due to the reduction in exploration activities caused by the Covid-19 pandemic, reserves grew again between 2021 and 2022, recording a +2.3% increase before stabilizing in subsequent years. The largest natural gas reserves worldwide are primarily concentrated in Russia and the Middle East regions that continue to play a strategic role in global energy security. World natural gas production reached 4,084 bcm, up 0.3% year-on-year and down 2.0% compared to the previous decade. It is noteworthy that North America is currently the world's leading producer of natural gas. This achievement is made possible by the widespread adoption of shale gas⁵ extraction, which has been actively pursued since the early 2000s (Figure 1). The natural gas reserves in North America amounted to 10,997 bcm in 2015, and today they stand at 21,390 bcm. It maintains the top spot with a production of 1,232 billion cubic meters, accounting for around 30% of the world total. While conventional gas is in the porous cavities of permeable rocks, shale gas is confined in the pores of impermeable rocks. With the fracking technique, it is the rock formations that are fractured to become permeable and allow the gas to flow. However, relative to conventional gas, the extraction process of shale gas involves several additional risks and costs: fracking increases not only the cost because requires more wells compared to a conventional reservoir, but also raises the risk related to extraction with possible contamination of groundwater and potential induced seismic activities. The resulted produced gas using this technique has a lower quality compared to the conventional one. Another crucial pillar in the energy transition is energy efficiency: using less energy to achieve the same performance. From this perspective, it is also important to consider natural gas consumption, as it remains one of the primary sources of energy. As highlighted in the *World Energy Report* published annually by Eni [12], significant differences in energy trends emerge between developed and developing countries. As previously discussed, the global energy demand is mainly covered by fossil fuels: coal remains the primary energy source in developing countries due to its lower cost, while natural gas plays a dominant role in developed nations. Eni's report emphasizes that natural gas consumption is declining in Europe and, more broadly, in OECD countries, whereas it follows an increasing trend in developing nations, similarly to coal consumption in these regions. This trend underscores a global tendency toward optimizing energy use - so-called energy saving, which translates into a reduction in the consumption of the most widely used

⁴ bcm – *billion cubic meters*, unit of measurement for natural gas volumes.

⁵ Shale gas is natural gas trapped in low-permeability shale formations. Unlike conventional gas, found in more permeable and easily accessible reservoirs, shale gas is more challenging to extract and demands technologically complex infrastructure. Thanks to these technologies and extensive shale formations, the United States has dramatically increased shale gas production over the past two decades, surpassing many traditional producers of conventional gas and becoming the world's largest natural gas producer.

energy sources. This phenomenon represents a continuation of efforts undertaken in the energy transition process, with energy efficiency becoming a key factor in reducing CO₂ emissions. In Europe, most countries have reduced their natural gas consumption to levels equal to or below those recorded in 2010, indicating an overall decline in demand for this resource. This decline could partly be attributed to a shift towards other fossil fuels, such as oil, for economic reasons, but it also reflects a broader contraction in energy consumption. This trend is well illustrated by the overall energy consumption figures for Italy, as published by the Ministry of Environment and Energy Security (MASE) [13]. In 2023, Italy's gross energy availability defined as the total energy supply before accounting for losses and inefficiencies, which directly correlates with energy consumption, amounted to approximately 143,961 ktep⁶, marking a 4.4% decrease compared to the previous year (Table 1). Conversely, national energy production increased by 4.2%. In line with the declining demand, energy imports also contracted by 9.0%, from 152,251 ktep in 2022 to 138,664 ktep in 2023. The share of net imports relative to gross energy availability, a key indicator of the country's reliance on foreign energy sources, declined from 79.2% in 2022 to 74.6% in 2023. In Italy, natural gas demand fell by 10.3% compared to the previous year, significantly impacting imported gas volumes. The reduction in energy availability has been partially offset by a shift towards alternative energy sources - for instance, oil consumption in Italy increased by 1.5%. This shift, coupled with a decline in overall energy demand, serves as further evidence of the ongoing global trend toward energy efficiency. Total natural gas consumption amounted to 61.7 billion cubic meters, representing a reduction of 7 billion cubic meters year-on-year. Additionally, as of December 2023, gas storage levels were 0.5 billion cubic meters higher than in December of the previous year. The strategic management of gas storage, from both an economic and operational perspective, has proven effective in dependence on imported energy.

⁶ ktep – kilotonnes of oil equivalent (EN), tonne équivalent pétrole (FR), a unit of energy equal to one thousand tonnes of oil equivalent.

World Natural Gas Production Growth (2010-2023)

929.28 billion cubic metres

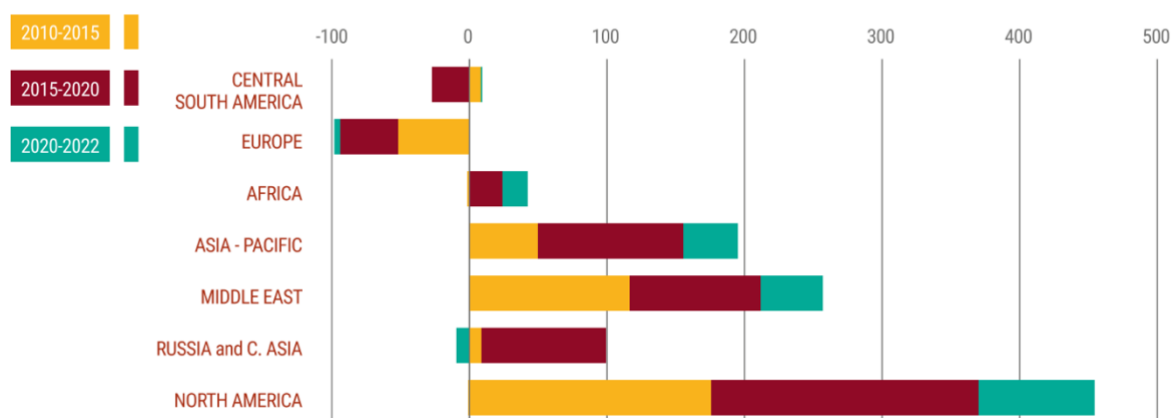


Figure 1: Horizontal bar chart showing World Natural Gas Production Growth. The chart highlights the growth rate of North America over the past 15 years, which has become the global leader in gas production thanks to shale gas [12]

Tabella 1: Il bilancio dell'energia in Italia – La disponibilità energetica lorda (ktep)

	2022	2023								
	Totale	Combustibili solidi	Petrolio e prodotti petroliferi	Gas naturale	Rinnovabili e bioliquidi	Rifiuti non rinnovabili	Calore derivato	Energia elettrica	Totale	Var % 23/22
+ Produzione	36.171	-	5.776	2.234	27.014		-	-	35.980	4,2%
+Saldo importazioni	138.565	4.864	76.327	50.630	2.052		-	4.692	138.644	-9,0%
- Saldo Esportazioni	31.220	184	28.074	2.145	531		-	285	31.220	-5,6%
+ Variazioni scorte	444	179	589	- 374	50		-	-	444	-113,3%
= Disp. En. lorda	150.531	4.859	54.618	50.345	28.586	1.146	-	4.407	143.849	-4,4%

Table 1: Energy Availability Balance in Italy. Source: MASE - Bilancio Energetico Nazionale - Metodologia Eurostat [13]

1.4. The natural gas chain

The term "*natural gas market supply chain*" refers to the entire production cycle of gas, which is divided into several stages, from procurement (based on both domestic

production and imports) to the infrastructures involved in transportation, storage, and distribution processes, and ending with its commercialization and distribution, both wholesale and retail. In this chapter, each phase of the supply chain will be analyzed. This paragraph has been written using information from the same sources: [4], [5], [7], [8], [9], [10], [14].

1.4.1. Upstream Phase: Exploration and Production

This phase includes all the activities related to the exploration and production of hydrocarbon resources. Exploration is the initial phase in the production cycle for the identification of the hydrocarbon reservoirs. It also consists of further sub-activities: area selection, acquisition of mining rights, and finally, geological surveys. Mining rights can be acquired by participating in the tender organized by the state, by agreement with companies holding the title, or by direct negotiations with the state. After the acquisition of rights, direct and indirect evaluations are conducted (e.g. study of the regional geology, acquisition and interpretation of seismic surveys, drilling of exploration wells) to build a geological model of the discovered reservoir in order to convert hypothetical reserves into proven reserves; the development of the reservoir is thus developed. After the exploration phase has been accomplished, production begins either onshore or offshore. In this stage the extraction wells are drilled. As identified earlier, the reservoirs are at high pressure (mainly due to their depth) therefore generally natural gas flows naturally through the wells to the surface. It is then directed, through the various channels formed during the exploration phase of the process, towards a treating facility. The natural gas extracted at this stage is called wet gas because, in contrast to dry natural gas, it is a mixture of methane combined with variable amounts of heavier hydrocarbons. Such composition makes it unfit for commercialization without preliminary treatment. This treatment separates methane from other components by using physical properties of different hydrocarbons, especially low critical temperature of methane. The separation includes:

- Cooling: Controlled cooling of the mixture to condense heavier hydrocarbons.
- Compression: Increasing pressure to facilitate the condensation and makes the process efficient.

The treatment produces:

- Dry natural gas principally composed of methane (CH_4), that meets commercialization specifications and thus it is ready for transportation and end use by pipelines.
- Liquid hydrocarbons like propane and butane are separated from the natural gas to meet the quality requirements and sold as a raw product for other uses.
- Water and acid gases removal: carbon dioxide and hydrogen sulfide.

Management and treatment of wet natural gas is considered one of the most important parts in the gas supply chain for the assurance of quality in the final product and maximization of the economic value of extracted resources. This process contributes to make the whole chain more efficient and sustainable. Coming to the national situation, the natural gas system is primarily supplied with gas produced in foreign countries, the domestic production (where the main player is ENI) covers only 5% of the total domestic gas demand.

1.4.2. Midstream Phase: Transportation and Pipelines

The upstream phase, by definition, includes exploration and production activities. However, gas imports, while representing a fundamental component of the supply mix, do not fall within this phase, as they constitute a subsequent step in the supply process. The imported gas, via pipelines or by sea in the form of LNG, falls into the midstream phase. In Italy, the most significant sources of supply are volumes from Azerbaijan, transported through the Trans Adriatic Pipeline (TAP), which connects the Shah Deniz fields in Azerbaijan to the Melendugno terminal in Southern Italy, and those from Algeria, conveyed through the Transmed submarine pipeline, which connects to the national network at Mazara del Vallo. Additionally, a substantial share of LNG is imported from Qatar and re-gasified at the floating terminal located off the coast of Veneto, near Rovigo. Once introduced into the national system, natural gas is distributed to end users through an integrated network of pipelines, divided into a national transmission network, which connects entry points to major consumption areas, and a regional network, dedicated to local distribution. This phase, defined as midstream, represents the bridge between the resource supply (any form of gas procurement) its actual utilization, ensuring the efficiency and security of the energy system as a whole. It consists mainly of transportation and storage activities. Natural gas is transported mainly in two ways:

1. Pipelines: they are a vast network of pipe systems that allows the transfer of natural gas from points of extraction or production to points of consumption with no additional need for intermediate loading or storage. This remains the most efficient method of moving natural gas at very low costs and at very high speeds. The pipes are lined with tar, bitumen, and synthetic resins in order not to suffer from corrosion. Every 100-200 km of the way, compressor stations restore the pressure to allow gas travelling with a speed of 20-30 km/h. The pressure should stand between 50 and 70 bar so that the losses on the route are compensated, and the requests of the final users are met. Pipelines also divide according to their purpose:
 - Accumulation pipelines: these transport gas from the extraction places to storage tanks or processing plants.

- Transmission pipelines: these transport the gas at high pressure towards the consumption areas. In transmission, gas is compressed, and as such, its volume reduces to give room for traveling at high speed. Transmission pipelines are further divided into primary lines which link the starting station with the consumption areas, and secondary lines which distribute the gas to various centers.
 - Distribution pipelines: these supply low-pressure gas directly to the consumer.
2. Transportation by sea: when the transportation of the gas by pipeline is not possible, the gas is liquefied and shipped using LNG carriers. At a temperature of -162°C , natural gas will liquefy, and its volume decreases to approximately 610 times less than in its gaseous state. A conventional LNG carrier (or ship) is able to carry about 130,000 cubic meters of liquefied gas, which is equivalent to 78 million cubic meters in its gaseous state. While the transportation of LNG by carrier is more costly, involving several transfers and complex logistics, the pipeline infrastructure is hardly ever available or feasible for long-distance international gas supply, particularly when crossing oceans or politically unstable regions. This limitation often makes LNG the only viable option for ensuring a diversified and secure energy supply, despite its higher costs. The chain of transportation in this regard involves the pipeline transportation of the gas to the coast, its liquefaction into liquid, and then loading it on board an LNG carrier fitted with thermally insulated tanks along with modern safety systems. After arriving at the import terminal, the liquefied gas, after a regasification process in a regasification plant and reaching the required level of pressure, is introduced into the pipeline network. The whole process, from extraction and liquefaction for transport by ships to regasification, is called the LNG chain, meaning Liquefied Natural Gas chain.

In accordance with the annual report of MASE, the Italian natural gas demand in 2023 amounted to 61.7 bcm (-10.3% compared to the previous year), covered by 5% from national production. National production, totaling 3.0 bcm, decreased by 9.9%, while imports, at 61.6 bcm, declined by 14.9%. Pipeline imports, totaling 45.0 billion cubic meters and representing 73.1% of total imports, decreased by 13.1 billion cubic meters compared to 2022. Specifically, imports from Russia decreased significantly to 2.8 billion cubic meters (-80%), from Northern Europe to 6.6 billion (-14%), while slight reductions were recorded in imports from Algeria (23.0 billion cubic meters, -2.2%), Azerbaijan (10.0 billion cubic meters, -3.3%), and Libya (2.5 billion cubic meters, -3.7%). LNG supply in 2023 amounted to approximately 16.6 billion cubic meters, accounting for 24.9% of total imports, with a 17% increase compared to the previous year (+2.4 billion cubic meters in absolute terms). Notably, LNG arrivals at national terminals were as follows: LNG Adriatic (Cavarzere) 8.9 billion cubic meters (+7.2%), GNL Italia (Panigaglia) 2.6 bcm (+18.0%), OLT (Livorno) 3.9 billion cubic meters (+3.8%). The

commissioning of the Piombino LNG terminal in the second half of 2023 (the fourth LNG terminal in Italy) contributed 1.2 billion cubic meters, representing 7.5% of LNG volumes and enhancing Italy's and Europe's supply security and diversification. The Italian gas transmission system [15], [16], forming the backbone of the national pipeline network, extends over 32,800 km with an injected volume of 75.40 bcm. Although the sector does not operate under a regulated monopoly, but due to the high fixed investments required for pipelines and compression/decompression stations—largely non-recoverable and generating economies of scale—this segment of the supply chain exhibits monopoly characteristics. Snam is the primary operator. Established in 1942 for the construction and operation of gas pipelines, Snam now manages over 64 bcm of natural gas injected into the national grid and operates more than 38,000 km of pipelines.

1.4.3. Midstream Phase: Gas storage and main components

Gas storage plays a critical role in the energy supply chain, serving a dual purpose: both as a technical necessity and as a strategic asset. The demand for natural gas exhibits significant fluctuations, driven primarily by daily and seasonal variations in temperature and weather conditions. These oscillations make the role of gas storage pivotal, as it provides a buffer that allows energy systems to adapt quickly to changes in consumption. As any other storages, during periods of low demand, gas can be stored, ready to be released during peak consumption periods, ensuring continuity of supply and stability in the energy market. On a macro scale, the importance of gas storage is highlighted by its ability to absorb unexpected supply and demand shocks. These shocks could be caused by several factors, including disruptions in supply chains, geopolitical crises, or sudden adverse weather events that affect consumption patterns. For example, in Italy, where over 95% of gas is imported, the strategic storage of gas enables the country to mitigate supply risks, responding efficiently to interruptions in gas delivery or sudden spikes in demand. From a technical perspective, gas storage enhances operational efficiency by facilitating a smooth balance between supply and demand. This is especially crucial in the context of daily fluctuations in consumption. The demand for gas tends to peak during weekdays, as industrial and commercial activities start up again. This is particularly true during the colder months, when energy demand for heating increases both in homes and industries. In contrast, weekends typically see a reduction in demand, as industries slow down or cease operations all together. This lower demand usually leads to a decrease in gas prices, creating an opportunity for operators to purchase gas at a lower cost. This price differential, occurring both on a daily and seasonal basis, forms the basis of temporal arbitrage. Temporal arbitrage refers to the practice of taking advantage of price fluctuations by purchasing gas during periods of lower prices (such as weekends or summer months) and storing it for later sale when prices rise, typically during weekdays or winter months. This practice not only helps to optimize

operational costs but also stabilizes prices within the market, thereby preventing extreme price spikes that could have a destabilizing effect on consumers and producers alike. In general, the winter months see a surge in prices due to increased heating demand, while summer months witness lower demand and, consequently, lower prices. Operators can capitalize on this by purchasing gas at lower prices during the summer, storing it in underground facilities, and selling it during the winter when demand and prices are higher. However, temporal arbitrage is not limited only to predictable seasonal fluctuations. It also includes the ability to respond to unexpected events that can create sharp, short-term price changes. Geopolitical crises, changes in production levels, or shifts in energy policy can all have significant impacts on gas prices, opening up new opportunities for operators who are well-positioned to take advantage of these changes. The growing complexity and the interconnections of global energy markets make gas storage even more critical, as operators must remain agile and responsive to rapid changes in market conditions. Moreover, gas storage plays an increasingly important role in supporting the transition to a low-carbon energy system. The growing integration of renewable energy sources, such as wind and solar power, has introduced variability into the energy grid. Gas storage can help smooth out the fluctuations in power generation from intermittent renewable sources, providing stability and reliability for the energy system. In this context, gas storage is not only a key enabler of energy security but also a critical asset in the shift toward cleaner energy sources, such as biogas or green gases, which are gaining importance in the energy sector. By enhancing the flexibility of energy systems, storage contributes to a more sustainable and circular energy system, where natural gas serves as a cleaner fossil fuel in the transition to greener alternatives. The strategic importance of gas storage is not limited to responding to market conditions or ensuring reliability during peak demand periods. It also serves as a crucial tool for managing supply crises. In times of disruption, whether due to geopolitical tensions, natural disasters, or infrastructure failures, gas storage enables countries to maintain reserves that can be deployed quickly to ensure continued supply. These reserves help mitigate the effects of unforeseen circumstances, reducing the risk of supply shortages and price volatility that could have detrimental impacts on the economy and society. In addition to these operational and strategic functions, gas storage also supports the economic stability of the energy market. By providing a mechanism for operators to purchase gas when prices are low and sell it when prices are higher, storage helps to reduce the volatility that is characteristic of energy markets. The ability to store gas during periods of low demand and sell it during high-demand periods reduces the likelihood of price spikes and market disruptions, thus improving price stability and contributing to a more predictable market environment. Gas storage can be classified into three main categories based on its function: strategic storage, modulation storage, and mineral storage.

- Strategic storage is designed to replace gas supplies during periods of scarcity or crisis, ensuring that reserves are available to mitigate the impacts of supply disruptions.
- Modulation storage is focused on balancing seasonal and daily fluctuations in demand, enabling the smooth operation of energy systems by responding to short-term variations in consumption.
- Mineral storage is necessary to support the extraction of natural gas from domestic reservoirs. addressing both technical and economic needs for domestic gas production. Mineral storage typically refers to the practice of injecting gas into underground formations, such as depleted gas fields or aquifers, to maintain reservoir pressure.

In summary, gas storage is a cornerstone of energy system stability and security. It enables operators to optimize supply and demand management, mitigate price volatility, and respond to unforeseen events that can disrupt the energy supply. As the energy landscape continues to evolve, particularly with the growing role of renewable energy sources, gas storage will become even more crucial in ensuring the reliability and sustainability of the energy system.

1.4.3.1. Gas Storage: its main components

The major components of a storage facility include the reservoir, the storage facility itself with compression and treatment plants, and the wells. The reservoir is the underground geological formation used in storing natural gas grid usually produced at great distances and injected into the national. These reservoirs are made up of permeable and porous rocks lying under impermeable cap rocks, such as clays, which avoid migration of hydrocarbons. The reservoirs already exploited may be converted for the storage of gas. The deposit of gas is built according to three key types such as:

- Conventional storage in gas depleted or partially depleted reservoirs.
- Semi-conventional storage, in depleted oil reservoirs or aquifers. Aquifers require suitable geological formations that can be identified through geological explorations or geophysical investigations. The cap rocks must be impermeable, such as clays, to contain the gas effectively. During the injection phase, the gas displaces water to form a 'gas bubble' within the porous rock. After several years, the gas occupies the upper portion of the reservoir, and the storage becomes operational.
- Specialized storage, carried out in artificially created cavities within salt formations or in abandoned coal mines. In salt formations, storage is achieved by dissolving salt to create cavities. Freshwater dissolves the salt, creating space for the gas, while the resulting brine solution is either re-injected or used for salt

extraction. These formations offer high levels of safety, as salt naturally forms a barrier that prevents gas leakage and ensures long-term stability and integrity.

The gas storage started in Italy in 1964 with the Cortemaggiore gas field, still in operation. Despite public debate on the subject, natural gas storage is a very safe practice that relies on the natural geological integrity of reservoirs. The same impermeable rocks making up these structures prevent leakage, thus tending to ensure safety and efficiency throughout the process.

1.4.3.2. Gas Storage: a highly regulated sector

Natural gas reservoirs have been proven naturally safe having stored gas for a period of a million years before being discovered and exploited. The reservoirs act as natural trap for hydrocarbons within leak-tight rocks or between geologic horizons, naturally providing a barrier for leakages. According to thermal genesis theory, geologic structures have been capable to trap natural gas for ages, demonstrating their capacity to securely store such resources. Today, underground gas storage operations are widely discussed, with increasing public awareness and debate. However, these activities remain under strict regulatory control, continuously monitored by institutions and subject to scientific research and technological advancements. In recent years, a growing area of research has focused on the possibility of storing hydrogen and CO₂ in salt caverns. As part of the energy transition, these storage solutions are being closely examined to assess their feasibility and long-term safety. Given their strategic role in decarbonization and energy security, underground reserves are undergoing extensive studies, ensuring that all phases - from approval and authorization to operational management - comply with the highest standards of safety, efficiency, and environmental protection. At the international level, underground gas storage is governed by widely recognized standards established by organizations such as the International Organization for Standardization (ISO) and the United Nations Economic Commission for Europe (UNECE). These institutions define the fundamental technical and safety requirements that must be met for the secure and efficient operation of storage facilities. Ensuring global consistency, these standards serve as a reference for both national and regional regulations. Within the European framework, gas storage is regulated by Directive 2009/73/EC, which establishes security and operational requirements for gas infrastructure. This directive, developed in collaboration with the Energy Community and the European Network of Transmission System Operators for Gas (ENTSOG), outlines the process for obtaining permits and managing underground storage operations. A key regulatory instrument in this context is the Network Code on Gas Storage (NCGS), developed in coordination with the European Union Agency for the Cooperation of Energy Regulators (ACER). The NCGS establishes rules for both underground and above-ground storage sites, ensuring transparent capacity management and compliance with

security and quality standards. Additionally, storage capacity assignments at the European level take place through auctioned markets under the supervision of ENTSOG, guaranteeing fair competition and efficiency in gas storage operations. In Italy, the regulatory framework governing gas storage is outlined in several Legislative Decrees and Laws which set out requirements to ensure operational safety and efficiency. Before a storage site can become operational, several authorizations and permits must be obtained. The authorization to the storage activities is granted in form of mining license (Concessione di Stoccaggio) released jointly by MASE and the competent Region. The license is released after a long procedure in which several authorizations and permits must be obtained. These include an Environmental Impact Assessment (VIA) and, in specific cases, an Integrated Environmental Authorization (AIA) to verify compliance with environmental regulations and prevent potential harm to ecosystems. Urban planning approvals are also required to ensure the project aligns with territorial and regional development policies. Furthermore, emissions permits must be secured to regulate atmospheric emissions and waste disposal during storage operations. In terms of safety, facilities must comply with geological and industrial risk prevention regulations, including those established by the Seveso Directive, aimed at protecting both workers and nearby populations. Throughout their operational life, storage sites must remain under constant supervision, with rigorous risk assessment and control measures in place. Regular inspections are required in compliance with the applicable Laws, ensuring continuous adherence to safety and environmental standards. Italian regulations are further aligned with Gas Infrastructure Europe (GIE) guidelines, reinforcing compliance with broader European regulatory frameworks. Finally, the allocation of gas storage capacity in Italy is subject to strict oversight by ARERA, which defines the terms and conditions to promote competition and transparency in the assignment process. This approach ensures that storage infrastructure remains efficient, secure, and capable of supporting the evolving energy landscape.

1.5. Downstream Phase: Gas delivering

Natural gas is transported through a few large-diameter pipelines within the national transmission network, and from there into thousands of small-diameter connection pipelines that distribute it to industries and households. Some 42% of the distributed gas in Italy is used for residential purposes and around 52% for industry and thermoelectricity. The distribution of natural gas displays wide geographical variations. The northern regions are consuming about 70% of the total distributed gas and manage about 60% of the medium- and low-pressure distribution network. These data reflect both the different degree of gasification of the country and the climatic differences between areas. Lombardy is the region with the highest consumption of

gas and with the most extended distribution network, while Sardinia is the only region without a gas distribution network. Distribution, as remarked above, represents a public service activity and as such is allocated by way of a public tender. The connection between the public administration granting the license and the operating company is governed by a service contract. The distribution activity does not see directly the figure of the final customer but, instead, it sees the seller because the distribution chain ends with the transportation of gas by local low-pressure networks. It also specifies that the distributor shall construct, manage and maintain the networks under the terms provided by law for the purpose of providing the distribution service to whatever sales company or wholesaler, in a neutral and nondiscriminatory form and according to the network code. Sales represent the final stretch of the chain and are constituted by the interface between final customers and the remainder of the chain. It is a commercial activity that remunerates all the other activities downstream in the supply chain, such as procurement of gas from the national market, operational marketing, commercial management, and billing, with the objective of retail sales to the final customers. Up to December 31, 2002, for residential customers and small consumers, there was a single subject acting both as a distributor and seller. Since 1 January 2003, all final customers are defined as eligible, hence free, to choose a supplier different from the distributor. In fact, the trade companies must be authorized by the Ministry for Economic Development, which issues the authorization if the applicant has a sufficient modulation service, proves the origin of the gas, guarantees the reliability of the transport conditions, and possesses enough technical and financial capacity. As a matter of fact, to date, there are 571 companies in Italy authorized to sell to end customers, based on data from the Ministry for Economic Development, updated to October 1st, 2016. As the Italian Regulatory Authority for Energy, Networks, and the Environment pointed out in the recent "Annual Report," the retail market for natural gas seems to be acquiring a good degree of openness, with consumption in the free market increasing and a decrease in the regulated market. This trend would show a good growth path and an opening to competition in the final market.

2 Internship at IGS S.p.A.

This chapter presents the company where the internship was carried out, outlining its history and analyzing the key drivers that motivated the investment in a new on-site WTP project. A brief description of the plant and its operations will also be provided. This will be helpful to better understand how the KPIs have been designed.

2.1. Players in the Italian sector

In Italy, there are 13 active storage sites, distributed across the entire peninsula. In this sector, the main player is Snam, which, through the acquisition of Edison Stoccaggio on March 3, 2025 (re-named Stogit Adriatica), and its subsidiary Stogit, manages 12 of the 13 active storage sites [17] .

2.2. The Company: IGS S.p.A

Ital Gas Storage (IGS) is an independent operator in the gas storage sector in Italy, managing a storage facility located in Cornegliano Laudense, Lodi Province. On March 15, 2011, the company was granted the gas storage concession for the “Cornegliano Stoccaggio” site by the Italian Ministry of Ecological Transition – Directorate-General for Mining Resources and Energy (UNMIG). In 2016, IGS initiated the conversion of the Cornegliano gas field into a natural gas storage facility. The Cornegliano gas field, discovered in 1951 by AGIP S.p.A. (now Eni), is located in the Po Valley, north of the Apennine Mountain range, and is bounded by reverse faults to the north and south. The reservoir consists of sands and clayey sands belonging to the “Sabbie di Caviaga” formation. During its production phase, the field yielded approximately 2.4 billion standard cubic meters (BSm³) of gas, calculated under standard operating conditions of temperature (20 °C) and pressure (1 atm). Drilling and well construction activities began in 1951 and concluded in 1997, when production ceased. The Original Gas in Place (OGIP) was estimated at 3.2 billion standard cubic meters (BSm³), calculated under standard conditions of pressure (1 atm) and temperature (15–20 °C), with a recovery factor of 74%. After the cessation of production, all 20 wells were plugged and abandoned in compliance with mining regulations, completing the decommissioning phase and preparing the site for its subsequent conversion. Following the concession grant in 2011 and the acquisition of all necessary authorizations, IGS commenced the conversion of the field in 2016. The project included drilling 14 new wells, distributed across two main clusters (Cluster A and Cluster B) each containing seven underground wells connecting the reservoir to the surface plant, minimizing land use. The current configuration of the field includes:

- 12 operational wells for storage activities (6 in each cluster)
- 2 wells dedicated to microseismical monitoring (A04 and B03)

The plant is connected to the Italian gas pipeline network via the Cervignano d'Adda junction, one of the most important in Italy, where major natural gas import and export pipelines converge. The entire storage plant site also includes a compression and treatment station, equipped with the necessary facilities for receiving gas from the network and subsequently injecting it into the reservoir through the wells. Additionally, it houses equipment for processing the extracted gas to meet regulatory standards before being reintroduced into the network, an interconnection pipeline between the Central Area-Cluster A and Cluster B, and a dedicated electrical substation serving the storage facility (SSE - IGS). Its construction has played a key role in reducing dependence on foreign import contracts and regasification programs. In the 2022-2023 heating season, it allowed the market to access a storage capacity of 230 million standard cubic meters (Sm³). The plant's core business is to offer gas storage services. It operates bidirectionally based on the needs of the national grid and customer demand. During the summer phase, in line with the laws of supply and demand, when gas prices are lower than the seasonal average, gas is injected into the reservoir via compressors. In the winter phase, gas is withdrawn and delivered back to the Italian gas pipeline network after proper treatment to remove water and humidity and following fiscal measurement. The production lasts 150 days each year, from mid-October to the end of March, while the injection phase lasts approximately 210 days each year. Each phase is carefully managed at every step, thanks to a fully automated control system that ensures 24/7 availability of a constant and accurate data flow to both the plant operators and customers, enabling full control over all gas handling operations in real time. In the production/extraction period, free water is separated from process gas, which is so dehydrated before being returned to distribution network.

2.3. The Project: an innovative way to dispose production water

As explained in the chapter addressing the various types of storage sites, the Cornegliano Storage site is classified as a conventional storage facility based on a water driven reservoir. The subsurface structure can be modeled as comprising three distinct layers:

1. Lower layer: A porous and permeable rock formation filled with formation water (aquifer).

2. Intermediate layer: A porous and permeable rock formation originally mineralized with natural gas, which in the case of the Cornegliano Storage Field consists of sandstone.
3. Upper layer: An impermeable cap rock composed of clay.

During the injection phase, the reservoir is charged with natural gas that displaces the formation water, clearing pore spaces in the permeable sandstone layer and forming a “gas bubble” within the porous rock. Conversely, during the production (or withdrawal) phase, particularly towards the end of the withdrawal season when the gas bubble occupies only a small portion of the porous rock, water tends to migrate towards the well due to a pressure gradient, filling the voids left by the extracted gas. As a result, the gas withdrawn during this phase is often highly saturated with water. Before the extracted gas can be reinjected into the distribution network, it must undergo proper treatment to meet the minimum quality requirements for injection into the national grid. Under specific pressure and temperature conditions, methane gas subjected to significant pressure and temperature differences (between the reservoir and the wellhead) is at risk of forming hydrate compounds – a gel-like hydrocarbon substance that could block pipelines and disrupt the gas flow. To prevent this, methanol is injected, which shifts the hydrate formation curve upwards, thereby mitigating the risk of hydrate formation. During the gas treatment phase, the formation water and previously injected methanol are separated from the natural gas. The presence of water during production is a critical performance indicator for the storage reservoir, as it reflects the efficiency of the withdrawal process. Weekly simulations are conducted to model and predict the reservoir’s behavior accurately. The management of produced water is also a key factor influencing operational performance and company-wide metrics. The produced water is currently transported off-site by truck and managed by external operators. This approach has significant implications for various performance indicators.

- Costs: relying on third-party providers entails direct operational expenses, while dependence on road transport makes costs highly sensitive to fuel price volatility, potentially leading to unforeseen increases.
- Environmental sustainability and local safety: CO₂ emissions emitted by the truck transportation are lower compared with the expected ones with the new plant related to the increased electricity bought to feed the plant and to the chemicals used to treat the water. As a result, the overall CO_{2-eq} emissions will increase. Thus, the local impact will be positive due to the reduction in the average number of trucks on the roads, leading to decreased combustion emissions and improved safety.
- Operational risk: the unavailability of transport vehicles, combined with the saturation of water containment buffers, could necessitate the suspension of production activities, temporarily affecting company operations.

Thus, during the construction phase and the initial operating cycles of the current gas storage facilities, IGS identified a higher-than-expected volume of separated water generated during gas extraction. To manage the separated water, the company has identified the opportunity to develop a dedicated Water Treatment Plant (WTP), to treat the production water in-loco. This strategic initiative enhances the flexibility of the storage plant's services, it reduces the environmental impacts while mitigating operational risks. Subsequently, IGS identified an improved environmental and operational solution: treating the separated water on-site through the dedicated WTP. This solution delivers three key benefits:

1. Reduction in liquid waste production and associated truck traffic. In the current approach the water used for the production process is treated as a waste and disposed of through third-part service. Conversely, with the implementation of the new plant, the production water will be used as a by-product as input to support the new plant's operations. As a results, the volume of the production water requiring disposal will be reduced. However, this new way to treat the production water will introduce a new waste stream. The expected different in waste volumes is substantial: on average from 50.000 tons of production water to an estimated 5 tons of different residual sludges will be expected with the new treatment plant.
2. Enhanced reliability of gas storage services, eliminating dependence on third parties for water management.
3. Lower overall operational costs in the medium to long term.

By implementing the WTP, IGS enhances environmental, risk, and economic performance indicators, reinforcing the sustainability and efficiency of its gas storage operations. Table 2 presents a comparison between the main benefits of the traditional approach and those of the in-loco WTP approach, analyzing their impact on operational efficiency, environmental sustainability, and cost performance. In the table environmental performance is assessed by quantifying greenhouse gas (GHG) emissions in terms of CO₂ equivalent, categorized as follows:

- Scope 1: Direct emissions from sources owned or controlled by the company, including those generated during standard operational activities.
- Scope 2: Indirect emissions resulting from the generation of purchased electricity consumed by the organization.
- Scope 3: All other indirect emissions occurring along the value chain, including business travel by employees.

Indicator area	Traditional approach	Approach with in-loco WTP
Operational costs	High: sensitive to fuel price volatility and expenses from external providers	Reduced: with more predictable costs and less reliance. Additionally, with a storage tank, water can be stored and treated when energy costs are lower, helping to optimize the energy consumption
Ghg production (CO2-eq)	Included as scope 3 in the annual report, increased by road transportations	Reduced: emissions are minimal due to on-site treatment. Scope 2 emissions can increase related to the electricity consumption and Scope 3 related to the use of chemicals
Operational risks	High: the risks of production interruption due to the unavailability of transport vehicles	Reduced: greater security in managing separated water and operational continuity
Waste production	The entire amount of the water produced during the production campaign was disposed by third-part trucks, thus representing a waste	The water produced is now used a by-product to feed the WTP. New type of waste to dispose are the sludges, so called residual sludges.
Environmental impact and local safety	Numerous trucks on the roads, increases pollution and local risks (accident risk)	Water produced will be treated on-site. The total number of waste trucks will decrease. However, the impact of the production of bought chemicals should be taken into account
Service reliability and flexibility	Dependence on external providers, risk of delays and interruptions	Greater reliability with autonomous management of water treatment

Table 2: Pro and Cons of the WTP compared to the as-is approach

2.4. The Project: Description of the phases

From the analyses conducted during the project engineering phase, the production water was found to have high concentrations of:

- Dissolved salts, mainly composed of chlorides, sodium ions, calcium, magnesium, and boron;
- Organic compounds (primarily methanol and acetic acid), which result in a high chemical oxygen demand (COD) and are associated with a high biological oxygen demand (BOD₅);
- Nitrogen compounds.

To comply with legal limits, each treatment stage has been designed to reduce the concentrations of these chemical agents, generating sludge that must be properly disposed. The entire process consists of six phases:

- Chemical Conditioning: Removal of metal ions and hardness reduction through precipitation, with the production and management of chemical sludge and partial COD reduction;
- Crystallization: Removal of salinity, with the production and management of saline sludge;
- Neutralization: pH adjustment through dosing of Na₂CO₃, NaOH (for acidic streams), and H₂SO₄ (for alkaline streams), ensuring optimal pH ranges for downstream biological treatment and compliance with discharge limits;
- Biological Treatment: Removal of BOD₅ and nitrogen compounds, with the production and management of biological sludge;
- Membrane Filtration: Complete solid-liquid separation through the filtration membranes, producing high-quality effluent with minimal turbidity and suspended solids, suitable for reverse osmosis feed;
- Reverse Osmosis: Final refinement through semi-permeable membrane filtration, mainly for boron removal and advanced purification.

Additionally, a further stage dedicated to exhaust air treatment is included, consisting of air extraction and purification. The WTP will receive and treat wastewater originating from both Cluster A and Cluster B. The treated effluent will be discharged into a local canal and will comply with the discharge limits established by Law D. Lgs. 152/06, Table 3, Annex 5, Part 3. The plant is designed with a single treatment line. An equalization basin is installed at the inlet of the WTP to smooth hydraulic peaks exceeding the treatment capacity of the downstream units and to homogenize fluctuations in influent pollutant concentrations. Figure 2 presents the block flow diagram illustrating the operating scheme of the WTP. The black line represents the

water stream, while the red line indicates the sludge stream. The air extraction and purification stream is not shown in the diagram.

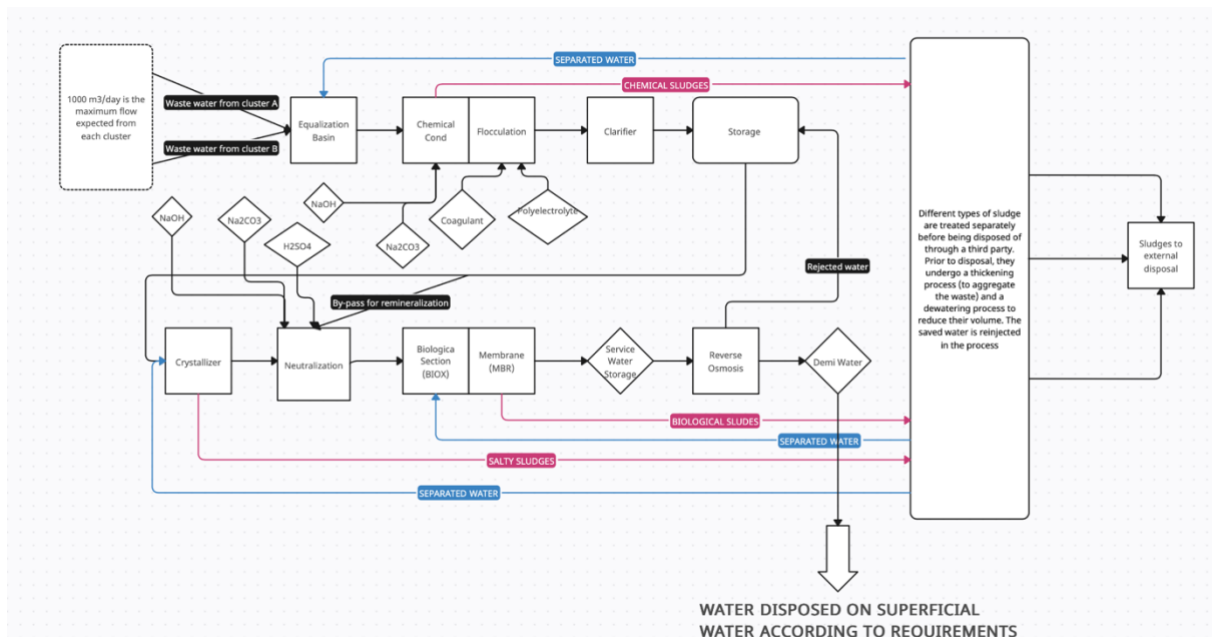


Figure 2: Block Flow Diagram

2.5. Water treatment in the oil and gas sector

The implementation of a water treatment plant within the gas storage site represents an innovative approach in the sector. In Italy, the main player in the industry - Snam, which controls 12 out of 13 active sites, manages production water as waste through third-party entities, lacking similar solutions for the treatment of process water. At an international level, water treatment technologies are widely used in the oil and gas industry, but mainly during extraction and refining phases, rather than in the storage sector. The integration of a WTP in this context therefore represents a significant innovation, capable of enhancing the operational and environmental sustainability of these facilities. This approach introduces a more efficient resource management system, in line with what is illustrated in Table 2 and could serve as a model for future implementations in the sector.

3 Literature Review

After a brief introduction to the sector and the project itself, this second part of the thesis focuses on the approach and methodology adopted to define an appropriate set of KPIs. Subsequently, each KPI will be presented and explained in detail. The paper concludes with an analysis of the adopted approach aimed at identifying its strengths and weaknesses, assessing its potential for further development and scalability, and clarifying its limitations as well as the conditions under which the tool can be extended and standardized.

3.1. Definition of performance and the role of measurement

The development of an effective performance measurement system requires a rigorous conceptual clarification of what constitutes "performance" in organizational and industrial contexts. Lord Kelvin's well-known statement:

"When you can measure what you are speaking about, and express it in numbers, you know something about it... otherwise your knowledge is of a meagre and unsatisfactory kind." — Lord Kelvin (1824–1907) [18]

captures the basic idea behind quantitative performance assessment: measurement turns subjective judgment into objective information, enabling rational decision-making and systematic improvement. Although organizational performance is widely discussed in both academic literature and managerial practice, its meaning remains conceptually ambiguous. The construct is inherently multidimensional and fragmented across different stakeholder perspectives, competitive contexts, and time horizons [19]. Moreover, performance is not defined by objective external standards, rather, it is shaped by managerial choices reflected in the measurement system itself. As a result, what an organization considers "performance" depends on how it chooses to define, measure, and prioritize its objective. In general terms, performance can be understood as the degree to which an organization achieves its planned objectives, considering both the resources employed and the outputs generated [20]. However, this broad definition requires further analysis to understand better multidimensional nature of organizational functioning.

3.1.1. Methodological Justification of the Synthetic Framework

Organizational performance is multidimensional by construction. However, most established performance management frameworks are built around a dominant

analytical perspective. While each model gives significant explanatory power, none of them, taken individually, captures the entire causal chain that links strategic decision-making, operational value creation, and the technical infrastructure that enables and constrains both. Adopting a single framework as the exclusive analytical view would produce a partial and structurally incomplete representation of organizational performance. This limitation is not a weakness of the individual models, but rather a matter of analytical scope. The Balanced Scorecard [21] provides a robust mechanism for aligning strategy with financial and process outcomes through its four perspectives. Nevertheless, it does not treat technological infrastructure as an autonomous performance dimension, it includes it indirectly within internal processes or learning and growth. Otley's [22] Performance Management System framework, later extended by Ferreira and Otley [23] offers a comprehensive structure for understanding how organizations design and use control systems. However, it mainly focuses on governance mechanisms and does not differentiate hierarchical performance levels separating strategic decision-making, operational processes, and technical infrastructure. The Performance Prism [24] focuses on stakeholder satisfaction and organizational capabilities, but it does not formalize the vertical causal relationship linking managerial choices to operational execution and, in turn, to enabling systems. In a similar way, the Three Levels of Performance model by Rummler and Brache [25] while conceptually close to a layered perspective, is oriented toward process and individual performance improvement rather than toward integrated measurement of aggregated organizational performance. None of these methodologies simultaneously covers the strategic-decisional, operational-process, and infrastructural-technical dimensions of performance. Using only one model would therefore create an analytical imbalance, giving too much weight to one aspect while giving too little to others, and ultimately weakening the ability of the performance analysis to explain results. The integration of complementary frameworks is widely discussed in the performance management literature, which demonstrates a trend toward integrative development. Ferreira and Otley [23] for instance, explicitly built their extended framework by combining Otley's original five questions with elements derived from Simons' Levers of Control [26], recognizing that their model was developed by combining existing academic research with insights drawn from practical experience. Another example from the literature comes from Chenhall [27] in his review of contingency-based management control research, saying that no single framework is able of capturing the full complexity of organizational control systems and suggests combining different perspectives to achieve a more complete view. Earlier, Venkatraman and Ramanujam [27] had already demonstrated that strategic performance measurement requires the simultaneous consideration of financial and operational dimensions, implicitly challenging mono-dimensional approaches. In this context, the synthetic framework proposed in this study is aligned with previous research and does not break with established theories. Its validity is based on three conditions: clearly recognizing the limits of existing models, being

transparent about the criteria used for integration, and ensuring internal consistency in the resulting framework. The three-part structure used here managerial, operational and technical performance is based on the idea of functional completeness. Rather than being an arbitrary classification, these three dimensions reflect essential and non-reducible functions that any organization must perform in order to operate in a sustainable way. The three identified functions are all necessary to describe organizational performance in a complete way. Together, they explain the entire performance chain, from strategic decisions to value creation, taking into account the role of infrastructure and capabilities. If the managerial dimension is removed, the organization may operate efficiently but without clear direction. If the operational dimension is missing, strategies remain intentions without practical execution. If the technical dimension is excluded, processes lack the tools, systems, and competencies required to function effectively over time. These three dimensions are also strongly interconnected. Managerial decisions set objectives and constraints for operational processes (top-down logic). Operational results, in turn, provide feedback that influences future managerial decisions (bottom-up logic). At the same time, technical capabilities shape both the efficiency of operational processes and the range of strategic options available, acting as both enabling and limiting factors. This interconnected structure reflects a systemic view of performance management, according to which the effectiveness of a performance management system depends on the alignment and balance among its components rather than on isolated elements. In this perspective, the synthetic framework proposed in this study does not seek to replace existing models. Instead, it builds on them at a higher level of abstraction, using their theoretical contributions to structure the three dimensions identified. The aim is to offer a simple but comprehensive analytical framework capable of representing the full causal chain of organizational performance, linking strategic choices, operational execution, and the technical conditions that support and constrain them.

3.1.2. Multi-Perspective Framework of Performance

Performance assessment can be articulated through three complementary analytical Perspectives [27], each illuminating a distinct layer of organizational effectiveness:

- Managerial Performance concerns the organization's capacity to translate strategic objectives into concrete results. It encompasses the alignment of decision-making processes, resource allocation mechanisms, and long-term priorities to ensure competitive positioning and stakeholder satisfaction. It is fundamentally linked to strategic coherence (the degree to which operational activities support overarching organizational goals) and goal accomplishment measured against predefined targets [21]. This perspective adopts a holistic, systems-level view, emphasizing outcomes rather than processes.

- Operational Performance refers to the efficiency and reliability of internal processes and workflows. This perspective focuses on the effectiveness with which activities are executed within the production or service delivery system. Operational performance is typically assessed through five competitive dimensions [28]: quality (conformance to specifications), speed (time to complete operations), dependability (reliability of delivery commitments), flexibility (adaptability to demand variations), and cost (resource consumption per unit output). This dimension-based framework provides a structured approach to evaluating process-level effectiveness.
- Technical Performance relates to the functioning, reliability, and capability of the physical and technological infrastructure supporting operations, including machinery, equipment, information and communication technology (ICT) systems, and automation technologies. Its metrics typically include availability (uptime), reliability (mean time between failures), maintainability (mean time to repair), and asset utilization rates. This perspective is particularly relevant in capital-intensive industries where equipment performance directly influences operational outcomes.

Although analytically distinct, these three perspectives are inherently interconnected within a hierarchical performance architecture. Managerial performance defines strategic direction and establishes performance targets; operational performance translates these objectives into executable processes and workflows; technical performance provides the enabling infrastructure that allows processes to function effectively and reliably. Together, they constitute a comprehensive framework linking strategy, operations, and technology in a coherent system [23].

3.1.3. The Fundamental Dimensions: Effectiveness and Efficiency

Regardless of the analytical perspective adopted, organizational performance is assessed through two fundamental dimensions that are the basis of any interpretation of success: effectiveness and efficiency. These concepts, while conceptually distinct, must be evaluated together to provide a complete assessment of performance. Effectiveness addresses the question of "doing the right things" that is, achieving expected outcomes, meeting customer and stakeholder expectations, and fulfilling strategic and operational objectives [24]. Effectiveness reflects the organization's capacity to produce results that matter, measured in terms of goal attainment, quality standards compliance, and value creation for stakeholders. An effective organization successfully accomplishes its mission, regardless of resource consumption. Efficiency, in contrast, concerns "doing things right" that is, achieving outcomes while minimizing the consumption of resources such as time, labor, materials, energy, and capital. Efficiency reflects the organization's capacity for resource optimization, measured through input-output ratios such as productivity metrics, cost per unit, or specific energy consumption. An efficient organization maximizes output per unit of input or,

equivalently, minimizes input per unit of output. The integration of effectiveness and efficiency provides an overall view of organizational performance. Effectiveness captures the external dimension of value creation defined as the ability to deliver results that satisfy stakeholder requirements. Efficiency captures the internal dimension of resource management: the ability to optimize operational costs and minimize waste.

3.1.4. Conceptual Framework for Performance Measurement

Any organizational action can be assessed along two fundamental dimensions: effectiveness, defined as the extent to which outputs meet stakeholder requirements, and efficiency, defined as the relationship between outputs and the resources consumed [29]. In order to translate this dual perspective into a coherent analytical structure, a systematic framework is required. Building upon the effectiveness and efficiency duality, a conceptual framework based on three main elements was proposed [30]:

- Performance measurement: the process of quantifying the efficiency and effectiveness of actions. This includes the systematic collection, processing, and analysis of data to generate performance information;
- Performance measure: a specific metric used to quantify efficiency and/or effectiveness referred to a specific dimension;
- Performance measurement system: the integrated set of measures used collectively to quantify efficiency and effectiveness across multiple dimensions of organizational performance. A measurement system comprises not only the individual metrics but also the data collection infrastructure.

This conceptual framework establishes clear definitional boundaries and provides the theoretical foundation for designing coherent performance measurement systems aligned with organizational objectives.

3.2. The Purpose and Importance of Performance Measurement

Performance measurement includes multiple critical functions within contemporary organizations, providing the informational foundation required to assess whether actions, processes, and decisions contribute to achieving intended results. While performance has multiple dimensions the act of measurement is what enables organizations to transform abstract strategic goals into quantifiable data, thereby supporting evidence-based decision-making and enabling systematic continuous improvement [31].

3.2.1. Hierarchical Functions of Performance Measurement

The organizational relevance of performance measurement is observed across multiple hierarchical levels and can be effectively conceptualized through a pyramidal architecture, where each level builds upon and depends on lower levels [29], [32]. The performance measurement pyramid operates through three hierarchical levels in order to create a comprehensive management framework that extend from operational execution to strategic direction [32]. At the base level lies the pyramid's fundamental role in enabling continuous improvement initiatives. As articulated by the quality management axiom often attributed to Deming, "You cannot improve what you do not measure" [33]. This principle establishes that improvement efforts must be grounded in empirical data to be effective and sustainable. Without an appropriate measurement system, organizations lose several critical improvement capabilities. Systematic measurement enables identification of performance gaps, process bottlenecks, and deviation from optimal operating conditions that might remain undetected [29], [34]. Beyond detection, measurement provides the empirical basis for assessing whether corrective actions and improvement initiatives have produced the expected effects, enabling evidence-based validation of interventions. Furthermore, documented performance data creates a knowledge base that enables organizations to learn from experience, identify best practices, and transfer knowledge across units and over time [30], [35]. The measurement plays motivational effects at the individual and team level, as empirical evidence suggests that individuals and operational teams perform more effectively when they understand which indicators are being monitored, how these indicators are operationally defined, what performance targets are expected, and how their actions influence measured outcomes [36]. This transparency creates accountability and aligns individual behavior with organizational objectives. Building upon this measurement base, the intermediate level of the pyramid supports operational management through systematic monitoring capabilities [21]. Monitoring, defined as the continuous observation of performance and its temporal evolution, enables organizations to detect deviations from expected patterns, assess process stability, and identify opportunities for targeted improvement interventions [37]. Performance indicators serve as reference points through which organizations can track progress by monitoring trends over time to assess whether performance is improving, deteriorating, or remaining stable relative to established baselines. These same indicators enable the detection of anomalies by identifying signals of underperformance, process instabilities, or emerging problems that require corrective action[38]. Additionally, monitoring facilitates benchmarking through comparisons of performance against internal standards across facilities, production lines, or time periods, as well as external references such as industry averages, best-in-class performers, or theoretical limits, thereby contextualizing performance levels and identifying improvement potential. This systematic monitoring transforms performance measurement from a retrospective reporting activity into a proactive

management tool that enables timely interventions before minor deviations escalate into significant problems. At the upper level of the pyramid, performance measurement provides strategic oversight by offering a comprehensive picture of organizational performance across multiple dimensions. At this highest level, measurement serves critical strategic functions that guide the entire organization. It ensures strategic alignment by maintaining coherence between daily operational activities and long-term strategic objectives, preventing the drift between stated strategy and actual operational priorities [21]. The comprehensive performance data provides the informational basis for resource allocation decisions regarding capital investment, capacity expansion, technology adoption, and organizational restructuring. Moreover, strategic-level measurement supports strategic planning by providing empirical data on current capabilities and performance trends, which provide information for scenario analysis, target setting, and strategic roadmap. Through this hierarchical architecture, from operational improvement at the base level, through tactical monitoring at the intermediate level, to strategic direction at the upper level, performance measurement ensures vertical coherence across organizational levels and enhances overall effectiveness [32], [36]. Each level depends on accurate, timely measurement, but the interpretation and utilization of performance information differ according to managerial scope and time horizon, creating an integrated system where base-level measurement capabilities enable intermediate monitoring functions, which in turn support upper-level strategic decision-making.

3.3. Key Performance Indicators in Industrial Systems: Conceptual Foundations

Having established the conceptual foundations of performance and performance measurement, it becomes necessary to examine how abstract performance concepts are operationalized into quantifiable metrics. This translation is accomplished through performance indicators, which serve as the methodological bridge between strategic objectives and measurable outcomes.

3.3.1. Defining Performance Indicators and KPIs

A performance indicator can be formally defined as a quantitative or qualitative variable that provides information about the status or evolution of a specific aspect of organizational performance [29]. Performance indicators translate abstract performance dimensions such as efficiency, quality, or reliability into observable, measurable variables that can be systematically monitored and analyzed. When indicators assume a central role in decision-making processes and strategic management, they are commonly designated as Key Performance Indicators (KPIs) [39]. KPIs therefore represent a critical subset of performance indicators that are

considered essential for monitoring and managing organizational performance effectively. The designation "key" implies that these indicators possess particular strategic relevance directly related to critical success factors [40], they inform high-priority decisions, or they monitor aspects of performance where deviations could have significant consequences. The distinction between general performance indicators and KPIs is not merely terminological but reflects a fundamental principle of measurement system design: not all measurable aspects of performance warrant equal managerial attention [34]. Effective performance measurement systems use selective measurement, focusing limited analytical resources on indicators that provide the greatest decision-making value.

3.3.2. Typological Classifications of Performance Indicators

The selection of an appropriate indicator subset is not methodologically defined, as different types of indicators are used for distinct analytical purposes and support different managerial activities. A first essential classification makes a distinction between indicators based on their temporal relationship to the phenomena they measure, differentiating between lagging and leading indicators [41]. Lagging indicators measure outcomes that have already occurred and are primarily used to evaluate historical performance, such as total operating costs for a completed period, cumulative energy consumption, annual production volumes, or end-of-period quality metrics. These indicators provide definitive assessments of past performance but offer limited predictive value for future outcomes, making them particularly valuable for retrospective analysis, performance reporting, and accountability assessment [41]. Leading indicators, in contrast, are forward-looking measures that capture trends, early signals, or precursor variables that anticipate future performance outcomes, including process parameter deviations, maintenance backlog accumulation, training completion rates, or customer satisfaction index. By providing advance warning of emerging problems, leading indicators enable proactive management and allow corrective interventions before performance deteriorates, thus proving particularly valuable for predictive management and preventive decision-making [41]. Effective measurement systems consequently integrate both temporal orientations: lagging indicators provide authoritative assessments of achieved results, while leading indicators enable anticipatory management and early intervention. A second fundamental classification distinguishes indicators based on their epistemological nature and measurement methodology, contrasting quantitative and qualitative approaches [42]. Quantitative indicators derive from numerical data obtained through direct measurement, automated data acquisition systems, or computational algorithms, and are widely adopted in technical and operational contexts due to their objectivity, precision, comparability across contexts, and amenability to statistical analysis [42]. Qualitative indicators, conversely, are derived from structured assessments, systematic observations, expert judgment, or categorical

classifications, and are typically employed to capture organizational, behavioral, safety-related, or contextual aspects that cannot be adequately represented through purely numerical metrics. assessments, maintenance quality ratings, or compliance status classifications. Although qualitative indicators can be more subjective than quantitative ones, they can capture important performance aspects that purely numerical metrics. These typological classifications collectively underscore a fundamental principle governing performance measurement system design: effectiveness depends not only on data availability, but rather on the coherent selection of indicators systematically aligned with organizational objectives, system characteristics, temporal requirements, and decision-making needs, ensuring that measurement frameworks effectively support their analytical and managerial purposes [29], [34].

3.3.3. Contemporary Developments: Data-Driven Approaches and International Standardization

The evolution of performance measurement in industrial systems has been characterized by two parallel yet complementary developments: the emergence of data-driven, process-oriented approaches enabled by advanced automation technologies, and the establishment of international standardization frameworks that provide methodological consistency across organizations and sectors [43]. Among these standardization efforts, ISO 22400, titled "Automation systems and integration" represents the principal international standard providing a structured, standardized approach to performance measurement in industrial systems. The standard's architecture is organized around several fundamental performance dimensions, all defined and formalized in ISO 22400-2 [44], that collectively capture the multifaceted nature of industrial operations. These dimensions include:

- availability, which addresses measures related to equipment uptime and operational readiness;
- effectiveness, which concerns measures related to output quality and process yield;
- efficiency, which focuses on measures related to resource utilization and productivity;
- reliability, which examines measures related to process stability and failure rates;
- quality, which includes measures related to conformance to specifications.

For each defined indicator, ISO 22400 specifies clear calculation formulas, required input data, measurement boundaries, and interpretation guidelines, thereby providing unambiguous methodological prescriptions [45], [46]. This standardization

enables several critical capabilities that extend beyond definitional consistency. Organizations can benchmark performance against industry standards using consistent definitions and approaches, ensuring comparability across different operational contexts. Stakeholders share a common understanding of indicator meanings and calculation methods, facilitating communication clarity across organizational boundaries and hierarchical levels [46]. Furthermore, organizations receive structured methodological guidance for developing measurement systems, reducing implementation uncertainty and enhancing systematic deployment. Critically, ISO 22400 does not prescribe a universal, fixed set of indicators to be applied identically across all contexts. Rather, it establishes conceptual guidelines based on three fundamental dimensions: the purpose of measurement, which addresses why indicators are needed and which strategic or operational objectives they serve, the scope of application, that delineates which organizational level or process is measured and the boundaries of the measurement domain and the role of indicators within the organizational performance management hierarchy, which clarifies how individual metrics contribute to broader performance assessment frameworks [47]. This flexible, principle-based approach recognizes that while standardization provides methodological consistency and ensures definitional rigor, indicator selection must ultimately be adapted to specific operational contexts, strategic priorities, and industry characteristics, thus balancing universal frameworks with contextual requirements.

3.3.4. Data-Driven and Process-Oriented Approaches

In parallel with these standardized frameworks, recent developments in performance measurement have emphasized data-driven approaches enabled by the proliferation of sensors, automation systems, and supervisory control and data acquisition platforms [48]. This technological evolution has facilitated a fundamental shift in KPIs development methodology: from top-down, theory-driven indicator selection toward bottom-up, empirically grounded approaches that leverage the massive volumes of process data generated by modern industrial systems [38]. These data-driven KPIs development methodologies are characterized by several distinctive features that differentiate them from traditional approaches. Rather than beginning with theoretical performance frameworks and subsequently identifying required measurements, data-driven approaches start with an inventory of available process signals and systematically derive indicators from existing data streams, thus inverting the conventional development sequence [48]. These approaches employ statistical analysis, data mining techniques, and process analytics to understand actual system behavior, identify performance-critical variables, and detect relationships between process parameters and performance outcomes through empirical investigation rather than theoretical postulation. By analyzing temporal patterns, process variations, and deviation from optimal operating conditions, data-driven methods can identify where inefficiencies arise and which variables most strongly influence performance losses,

thereby grounding performance measurement in observable operational realities. Moreover, as new sensors are installed or data quality improves, the indicator set can evolve organically, incorporating new measurements and refining existing metrics based on empirical validation, thus enabling continuous methodological refinement responsive to technological advancement [49].

3.3.5. Complementarity of Standardized and Data-Driven Approaches

These two methodological paradigms are not mutually exclusive but rather complementary in nature, each addressing distinct requirements within comprehensive performance measurement system design [29], [30]. Standardized frameworks provide conceptual structure that ensures theoretical coherence, establish methodological rigor that guarantees measurement validity, and enable external comparability that facilitates benchmarking across organizational boundaries [34], [44]. Data-driven approaches, conversely, ensure operational feasibility by working within existing technological constraints, leverage existing instrumentation infrastructure by utilizing already-deployed measurement capabilities, and adapt indicators to specific process characteristics by responding to empirical operational realities rather than generic theoretical constructs [38], [49]. The optimal approach consequently integrates both perspectives: employing standardized frameworks to establish the conceptual architecture and indicator taxonomy that provide theoretical foundation and ensure methodological alignment, while utilizing data-driven analysis to operationalize these concepts using available measurements and to identify context-specific indicators not captured by generic standards [30]. This hybrid methodology represents current best practice in industrial performance measurement system design, synthesizing deductive theoretical frameworks with inductive empirical analysis to produce measurement systems that are simultaneously methodologically sound and operationally feasible [29], [49].

3.4. Performance Measurement: State of the Art

Having established the general theoretical and methodological foundations of performance measurement, it becomes necessary to examine the specific application of these concepts within the domain of water and wastewater treatment systems. This chapter presents challenges for performance measurement due to the complexity of treatment processes, the multiplicity of performance objectives and the variability of operating conditions.

3.4.1. Systematic Literature Review: Methodology

A systematic literature review was conducted to identify established methodologies, performance measurement approaches, and operational efficiency assessment

methods in water treatment operations. The review followed the structured procedure proposed by Tranfield et al. [50], which articulates the process into three sequential phases: planning the review, conducting the review, and reporting the results. To ensure clarity and transparency in documenting the review process, the PRISMA 2020 statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), as updated by Page et al. [51], was adopted as the reporting framework.

3.4.1.1. Research question formulation and source identification

The review was designed to address the following research question: what are the established performance measurement approaches, indicators, and operational best practices adopted in industrial-scale water treatment facilities? The Scopus database was selected as the primary search platform due to its extensive coverage of peer-reviewed literature in engineering, environmental science, and water research disciplines. Scopus indexes over 27,000 active titles and is widely recognized as one of the most comprehensive bibliographic databases for systematic reviews in engineering and management domains [52]. The reliance on a single database constitutes a methodological limitation of the present review, however the disciplinary coverage offered by Scopus was considered sufficiently representative for the objectives of this work. The selection of search terms was defined in alignment with the objectives of the study and refined through an iterative review process aimed at ensuring thematic coherence and relevance to the research scope. Keywords were structured by combining water treatment process terminology with performance measurement and operational efficiency terms using Boolean operators.

3.4.1.2. Search query development

The search query was developed through an iterative refinement process designed to balance recall and precision in information retrieval. Recall refers to the ability of the query to capture the largest possible number of relevant studies, whereas precision denotes the proportion of retrieved records that are directly pertinent to the research objectives. During the calibration phase, preliminary exploratory searches were conducted to assess the behavior of different keyword combinations within the Scopus database. The inclusion of broad and cross-disciplinary terms such as “efficiency”, although conceptually related to performance assessment, produced an excessively large number of results, significantly reducing precision due to their widespread use across heterogeneous scientific domains. Conversely, the introduction of highly sector-specific expressions (e.g., “oil and gas”) was evaluated as a potential narrowing strategy; however, such terminology risked excluding relevant contributions from adjacent sectors, including municipal water treatment and desalination, where comparable performance measurement approaches are adopted. The final query was therefore calibrated to retain domain-specific terminology sufficiently precise to

capture the target literature while avoiding both excessive noises generated by overly generic terms and undue restriction caused by narrowly sector-bound expressions. The core search string combined water treatment domain terms ("water treatment", "wastewater treatment") with performance measurement terms ("performance indicator", "performance indicators", "KPI", "benchmarking") using Boolean operators. The search was performed in the Scopus database using the TITLE-ABS-KEY field, covering article titles, abstracts, and author keywords. Results were limited to publications between 2015 and 2026. The search query used is: (TITLE-ABS-KEY ("water treatment") OR TITLE-ABS-KEY ("wastewater treatment")) AND (TITLE-ABS-KEY ("performance indicator") OR TITLE-ABS-KEY ("performance indicators") OR TITLE-ABS-KEY ("KPI") OR TITLE-ABS-KEY ("benchmarking")) AND PUBYEAR > 2014 AND PUBYEAR < 2027. The initial search, conducted without temporal restrictions, returned 1,505 records. After restricting the temporal range to publications from 2015 onward, the corpus was reduced to 1,158 records. Following the removal of entries with undefined author profiles and restricting the results to English-language publications, the final dataset consisted of 1,125 documents.

3.4.1.3. Database filtering

According to the PRISMA methodology, the source selection process comprises three sequential stages [51] each one subject to potential bias due to personal judgement in the evaluation of relevance. To mitigate this risk, the selection criteria were defined prior to the execution of the review and applied consistently throughout the process, adopting a conservative inclusion principle (inclusion in case of doubt) at each stage to minimize the risk of excluding potentially relevant contributions. The initial search of the Scopus database, conducted without temporal restrictions, retrieved 1,505 records. Contributions for which relevant identification information was not available (undefined author profiles) were eliminated, and the results were restricted to English-language publications. The temporal range was further restricted to publications from 2015 onward, with the objective of concentrating the analysis on the most recent literature, representative of current operational practices, technological configurations, and regulatory frameworks in the water treatment domain. After applying these database-level filters, a set of 1,125 contributions was obtained. A thematic filter based on Scopus-indexed author keywords was then applied as a preliminary screening measure. The selected keywords "Benchmarking", "Wastewater Treatment", "Water Treatment", "Wastewater", "Water Quality", "Water Management", "Water Treatment Plants", "Pollutant Removal", "Water Pollutant", "Chemical Oxygen Demand", and "Sustainability" were chosen to include studies explicitly addressing water treatment processes, pollutant removal, and operational performance assessment. This filter was deliberately designed to be inclusive with respect to the type of treatment facility: studies addressing municipal wastewater and drinking water treatment were retained at this stage, as these facilities frequently employ

chemical treatment processes (such as coagulation, flocculation, biological treatment and pH adjustment) directly relevant to the performance measurement approaches investigated in this work. A more detailed evaluation of whether the studies were relevant to the specific industrial and operational context of this review was carried out during the later screening stages. A subject area exclusion filter was also applied to remove records classified under disciplinary domains outside the scope of the review, namely Arts and Humanities, Psychology, Health Professions, Veterinary Science, Pharmacology, Immunology and Microbiology, Medicine, and Social Sciences. After the application of these filters, 881 contributions entered the screening phase.

3.4.1.4. Title and abstract screening

The 881 records resulting from database filtered were subjected to a structured screening procedure based on title, abstract, and keyword analysis. Each record was assessed against four predefined inclusion criteria: (i) domain pertinence to water treatment processes in operational contexts; (ii) operational scale or explicit applicability to real facilities; (iii) performance orientation, namely relevance to the measurement, evaluation, or optimization of operational performance; and (iv) presence of quantitative data or numerical indicators. Rather than applying a strictly sequential binary exclusion protocol, a hierarchical multi-criteria classification approach was adopted. Criterion (i) was treated as a mandatory gateway condition: records lacking sufficient domain relevance were excluded irrespective of their performance on the remaining criteria. Among the records satisfying criterion (i), those meeting at least two additional criteria were classified as pertinent, yielding 499 contributions (56.6%). Records satisfying criterion (i) together with exactly one additional criterion were conservatively retained as borderline cases (168 records, 19.1%), following the principle that ambiguous records should be preserved to avoid premature exclusion of potentially relevant material. The remaining 214 records (24.3%) were excluded due to insufficient thematic alignment. Within the pertinent subset, criterion (iii) was almost universally satisfied (99.4%), followed by criterion (iv) at 88.2%, while criterion (ii) proved the most discriminating, being satisfied by 35.7% of pertinent records. This distribution reflects the predominance of modelling and simulation studies over empirical investigations conducted at full or pilot scale. A total of 117 records satisfied all four criteria simultaneously, among these, 33 were specifically situated within the oil and gas domain, addressing produced water treatment, offshore operations, or refinery wastewater processes. Contributions were organized into analytical clusters reflecting recurrent performance dimensions, as inferred from the performance indicators proposed, the methodological approaches adopted, and the operational contexts addressed. This clustering process forms the conceptual framework guiding the present review.

3.4.1.5. Thematic Clustering of Operational Performance Dimensions

The literature review identified five dominant thematic clusters that define performance in water treatment operations. While each cluster addresses a specific aspect of operational performance, they are functionally interdependent, as optimization decisions in one dimension frequently generate trade-offs or synergies in others.

- **ENERGY CONSUMPTION:** the first detected cluster is related to the energy consumption that represents a primary cost driver and environmental impact factor in water treatment operations. The literature [53], [54] on energy performance predominantly focuses on specific energy consumption as the primary indicator, defined as energy consumed per unit volume of water treated. This metric serves as a fundamental benchmark for comparing energy efficiency across different treatment configurations and technologies, allowing operators to identify optimization opportunities and assess the impact of operational modifications on overall energy request [55]. The standardization of energy performance through volumetric normalization enables meaningful comparisons between facilities with different capacities and treatment objectives, while also facilitating the identification of deviation from expected performance patterns that may indicate equipment degradation or process inefficiencies.
- **CHEMICAL CONSUMPTION:** closely related to energy consumption, chemical reagent utilization represents another major resource input with significant cost and operational implications. The literature on chemical efficiency emphasizes normalized consumption metrics that account for both treated volume and inlet water characteristics [56], [57]. Effective chemical management requires balancing competing objectives, as operators must minimize consumption to reduce costs while maintaining enough to ensure treatment effectiveness and avoiding over-quantity that increases downstream sludge production. This multi-objective optimization problem is further complicated by the nonlinear relationship between dosing rates and treatment outcomes, requiring process-specific calibration and continuous adjustment based on influent variability. The dynamic nature of influent water quality necessitates adaptive dosing strategies that respond to real-time conditions rather than relying on static operational parameters, presenting ongoing challenges for maintaining optimal chemical efficiency across varying operational scenarios [58].
- **QUALITY:** the ultimate objective of resource consumption in energy and chemical inputs is the achievement of target water quality standards, which constitutes the third major performance dimension. Water treatment facilities operate under strict regulatory frameworks specifying maximum

concentrations allowed for various contaminants in treated effluent. Quality performance indicators focus on both compliance verification and treatment margin assessment. These metrics serve dual purposes of demonstrating adherence to legal requirements and evaluating the robustness of treatment processes under different conditions. An important concept emerging from this literature [59], [60], [61] is over-treatment or non-remunerative quality excess, whereby achieving effluent quality substantially exceeding regulatory requirements may indicate inefficient resource utilization, as the incremental quality improvement provides any economic or regulatory value but rather it increases operational costs. However, maintaining modest treatment margins allows operations to provide operational buffer against influent variability and ensure consistent regulatory compliance. The opposite objectives between cost minimization and compliance assurance requires careful calibration of treatment intensity, with operators trying to identify the optimal operating point that reliably meets regulatory standards while avoiding unnecessary resource expenditure on quality improvements beyond what is legally or contractually required.

- **WASTE MANAGEMENT:** the operations generate waste streams, which constitute a fourth critical performance dimension. These streams are primarily in the form of chemical and biological sludges. Waste management performance addresses both waste minimization and resource recovery potential. The literature [62], [63] emphasizes that waste management represents both a cost center through disposal costs and a potential revenue source through resource recovery. Advanced treatment facilities increasingly adopt circular economy principles, recovering energy such as biogas, nutrients including phosphorus, or water from sludge dewatering from waste streams. This paradigm shifts from viewing waste as purely a disposal challenge to recognizing it as a potential resource changing the economic way in which the operation performance is computed, transforming what was traditionally considered an unavoidable cost into an opportunity for value creation and environmental sustainability enhancement [64].
- **RELIABILITY:** finally, an aspect that is common to all previously discussed performance dimensions is the need for sustained operational reliability. This reliability represents a fifth performance area that integrates the others. Rather than focusing only on performance at a specific point in time, treatment plants must operate in a stable and reliable manner over extended periods. Reliability indicators are used to evaluate process stability, equipment availability, and operational continuity. Sustained performance therefore requires not only meeting treatment targets at a given moment but also maintaining consistent operation over time horizons ranging from days to months and years. The literature [65], [66], [67] further distinguishes between planned downtime for scheduled maintenance and unplanned outages caused by equipment failures

or process disturbances. Planned maintenance can usually be scheduled during periods of lower demand or managed using backup systems, whereas unplanned outages often lead to service disruptions, emergency costs, and potential regulatory non-compliance, resulting in impacts that extend beyond immediate operational performance.

3.4.2. Gap Analysis: Water Treatment Performance Measurement

While the literature provides substantial guidance on performance measurement for municipal wastewater treatment and industrial water treatment several significant gaps emerge when considering the specific operational context of water treatment integrated with gas storage facilities:

- Gap 1: Seasonal Variability and Load Factor Management: municipal and most industrial treatment facilities operate with relatively consistent inlet volumes and characteristics throughout the year. In contrast, water production in gas storage operations exhibits extreme seasonal variability, with peak production during gas withdrawal periods (typically winter months) and minimal production during injection periods (summer months). No identified studies address KPI design for treatment facilities operating under such pronounced seasonal load variation;
- Gap 2: Integration with Primary Industrial Process: existing literature treats water treatment as either a standalone utility function or as a supporting process for continuous industrial operations. The gas storage context presents a fundamental different relationship: water treatment is directly coupled to the primary industrial process, creating interdependencies not addressed in existing frameworks. For instance, gas withdrawal rate fluctuations directly affect water production rates, potentially requiring dynamic adjustment of treatment process parameters;
- Gap 3: Application of ISO 22400 Principles to Water Treatment: while ISO 22400 is extensively applied in manufacturing contexts, its adoption in water and wastewater treatment remains limited. The reviewed literature predominantly employs sector-specific performance metrics developed within the water industry, with minimal reference to standardized KPI frameworks from other industrial sectors. This represents a missed opportunity for methodological transfer and limits the comparability of water treatment performance with other industrial operations;
- Gap 4: Real-Time Monitoring and Predictive Indicators: much of the existing literature focuses on retrospective performance analysis using daily, weekly, or monthly aggregated data. With increasing availability of real-time sensor data and SCADA integration, there is limited guidance on developing leading

indicators that enable predictive performance management and early detection of process degradation in water treatment contexts;

- Gap 5: Multi-Objective Optimization Frameworks: water treatment performance involves multiple, sometimes conflicting objectives: regulatory compliance, cost minimization, environmental impact reduction, and operational reliability. While individual performance dimensions are well-studied, integrated frameworks that explicitly address trade-offs and enable multi-criteria decision-making are underdeveloped in the literature.

3.4.3. Adopted Approach: Synthesis and Justification

This systematic literature review reveals a fundamental paradox in the current state of knowledge regarding performance measurement in water treatment operations. While performance measurement frameworks for water treatment have been extensively studied and documented across various configurations and scales, the specific operational context characterizing this project represents a configuration not directly addressed in existing literature. Specifically, the integration of industrial water treatment operations with gas storage facilities creates unique operational requirements and constraints that distinguish this application from conventional water treatment scenarios examined in the reviewed publications. The identified knowledge gaps necessitate a methodological approach that synthesizes multiple complementary frameworks rather than adopting any single existing model. The approach developed for this thesis combines three distinct conceptual foundations to address the limitations identified in the literature. First, standardized performance measurement principles derived from ISO 22400 manufacturing operations management standards provide methodological rigor and ensure that the resulting framework is aligned with the best practices for KPIs design, enabling potential cross-industry comparability and offering a structured classification framework for organizing diverse performance indicators. Second, water treatment methodologies extracted from the reviewed literature ensure that the specific indicators developed remain technically appropriate for the physical, chemical, and operational characteristics of treatment processes, incorporating sector-specific knowledge regarding energy consumption patterns, chemical efficiency optimization, quality assurance requirements, waste management strategies, and reliability assessment approaches. Third, context-specific adaptations address the unique operational requirements of gas storage-integrated facilities, particularly accounting for seasonal demand variability, process coupling between treatment and storage systems, and the distinctive cost-benefit calculus that emerges when treatment operations serve critical infrastructure with intermittent but high-consequence operational requirements. This integrated approach, grounded in international standards, informed by sector-specific technical literature, and adapted to unique operational constraints, represents a pragmatic methodological response to the knowledge gaps identified through the

systematic review. The resulting framework allows the development of a KPIs system that maintains theoretical rigor through adherence to established performance measurement principles while ensuring practical relevance through incorporation of water treatment domain knowledge and responsiveness to the specific operational context of gas storage facilities. The subsequent sections of this thesis detail the implementation of this hybrid methodology, presenting the specific KPIs developed for the case study facility, explaining their mathematical formulation and calculation methodologies, identifying the data requirements and measurement protocols necessary for their operationalization, and describing their integration into a real-time monitoring platform that enables continuous performance assessment and supports data-driven operational decision-making.



4 Methodological Application and KPIs Development at IGS S.p.A.

The development of an effective KPIs framework for industrial water treatment facilities represents a critical challenge in contemporary process engineering, particularly when considering new applications such as water management in gas storage facilities. The present study addresses this challenge through the systematic design and implementation of a comprehensive KPIs system for a WTP under construction, serving a gas storage operation.

4.1. Plant Characteristics and Operational Context

The WTP under construction presents operational, technological, and managerial characteristics substantially different from existing gas injection and withdrawal facilities. From an operational standpoint, most of the water to be treated is produced during the winter season, corresponding to the gas withdrawal or delivery period, when the plant operates at maximum capacity. However, the presence of an initial basin serving as a storage element enables the stabilization of the treatment plant's operational regime, decoupling it from the seasonal variability of water production. From a technological perspective, the substantial plant-level differences necessitate the adoption of specific KPIs to ensure effective monitoring of operational and economic performance. To identify the main performance drivers and define KPIs design requirements through a top-down approach, semi-structured interviews were conducted with nine key stakeholders involved in the plant's strategic planning, engineering, construction, and operation. The interviewees included: senior management representatives responsible for finance and corporate strategy (2), the plant manager (1), the project manager overseeing construction and Power BI implementation (1), process engineers and control room operators currently responsible for plant operations (2), an electrical engineer (1), a maintenance operator (1), an HSE manager responsible for environmental compliance, safety, and regulatory reporting (1), and a procurement department representative (1). The interviews revealed that the primary cost drivers of the plant are electrical energy consumption, chemical reagent utilization, and waste production and disposal.

4.2. Methodological Framework

Building upon the theoretical framework and gap analysis presented in Chapter 3, this section describes the specific methodology adopted. The methodology followed during the internship for defining an appropriate set of KPIs necessary for daily monitoring and plant optimization integrates three complementary approaches: international standardization principles, academic literature synthesis, and practical field-based analysis. This triangulation approach ensures both strong theoretical foundations and practical use, meeting the two main needs of performance measurement systems in complex industrial settings: following well-established methodologies documented in water treatment literature and adapting to site-specific operational constraints.

4.2.1. International Standardization Framework: ISO 22400 Application

The KPIs developed in this study have been designed in accordance with the principles established by ISO 22400, which provide a standardized framework for performance measurement in industrial systems [68], [69]. This international standard represents a fundamental reference for organizations seeking to implement structured performance management systems, offering a methodologically sound approach to indicator design and deployment. ISO 22400 does not prescribe a fixed set of indicators to be universally applied across all industrial contexts. Rather, it defines conceptual guidelines based on three fundamental dimensions: the purpose of measurement, the scope of application, and the organizational role of indicators within the performance management hierarchy. The standard articulates a structured indicator framework, explicating their function within the broader performance measurement system and establishing clear boundaries to prevent the inappropriate reduction of KPIs to purely optimization-driven metrics. This standardized approach proves particularly suitable for complex industrial plants where multiple operational objectives must be simultaneously addressed. In such environments, performance monitoring, regulatory compliance verification, process stability assurance, and environmental impact minimization are often equally critical as traditional cost efficiency objectives. The ISO 22400 framework explicitly recognizes this multi-objective nature of industrial performance, providing methodological guidance for developing balanced indicator systems that capture all the requirements. The adoption of this international standard ensures methodological consistency with established industrial practices while maintaining the flexibility necessary to address the specific characteristics of water treatment operations in gas storage facilities that is a context not explicitly covered by existing standardized KPI frameworks. The ISO 22400 framework was operationalized through the following systematic process:

- Performance dimension mapping: Each KPI was assigned to one or more ISO 22400 performance dimensions to ensure comprehensive coverage of performance aspects;
- Purpose clarification: For each indicator, the measurement purpose was explicitly defined;
- Hierarchical positioning: Indicators were classified according to their organizational level.

4.2.2. Stakeholder Engagement and Interview-Based Definition of KPI Requirements

Recognizing that an effective KPIs system must address the differentiated informational needs of organizational actors, a stakeholder-oriented approach was primarily adopted to support the top-down definition of performance indicators for the WTP. To this matter, semi-structured interviews were conducted with key stakeholders involved in the strategic planning, engineering, construction, and operation of the plant. The semi-structured format was selected to ensure comparability across interviews through predefined thematic areas, while preserving sufficient flexibility to explore role-specific concerns, emerging insights, and context-dependent performance priorities. The interview protocol was structured around four core analytical dimensions:

- Decision-making contexts – Identifying which strategic, operational, or technical decisions would be informed by performance data;
- Performance prioritization – Determining which aspects of plant performance were considered most critical by different stakeholder groups;
- Threshold definition – Establishing acceptable performance ranges, targets, and alarm levels for key indicators;
- Organizational alignment – Involving stakeholders in KPI system design to promote subsequent adoption, accountability, and effective utilization.

A total of nine stakeholders were interviewed. The selection followed a purposive sampling logic to ensure representation across strategic, operational, technical, regulatory, and procurement functions. Table 3 summarizes the stakeholder categories and their contribution to KPIs system design.

Stakeholder Category	Organizational Role	Primary Perspective	Contribution to KPI design
Senior Management (n=2)	Finance and Corporate strategy	Investment decisions, cost	Identification of economic KPIs and strategic

		drivers, financial sustainability	performance priorities
Plant Manager (n=1)	Overall plant operations oversight	Operational continuity and efficiency	Integration of strategic and operational performance indicators
Project Manager (n=1)	Construction Phase Coordination and Performance Monitoring Implementation	KPI measurability and reporting architecture	Alignment between KPI framework and digital monitoring tools
Process Engineer (n=1)	Process design and optimization	Treatment efficiency and process stability	Definition of technical and optimization-related KPIs
Control Room Operator (n=1)	Real-time plant monitoring	Anomaly detection and operational control	Definition of alarm thresholds and monitoring requirements
Electrical Engineer (n=1)	Electrical systems management	Energy efficiency and load management	Development of energy-related performance indicators
Maintenance Operator (n=1)	Equipment reliability and maintenance	Failure prevention and lifecycle cost	Definition of maintenance and reliability KPIs
HSE Manager (n=1)	Environmental compliance, safety, and regulatory reporting	Regulatory adherence and risk mitigation	Identification of mandatory compliance and safety-related KPIs
Procurement Representative (n=1)	Supplier and contract management	Chemical procurement and cost control	Definition of cost-efficiency and consumption indicators

Table 3: Stakeholders Involved in the Semi-Structured Interview Process

4.2.3. Thematic Analysis of Interview Results

Interview responses were analyzed through a structured thematic synthesis aimed at identifying recurring performance priorities across stakeholder groups. The analysis focused on extracting and consolidating key performance dimensions explicitly mentioned during the interviews. Interview notes were reviewed and performance-related statements were coded according to their underlying managerial or technical concern (e.g., energy consumption, regulatory compliance, plant availability) [70]. Similar codes were then grouped into broader thematic clusters representing distinct performance dimensions. Each theme was subsequently verified against the interview content to ensure consistency and coherence with the original stakeholder perspectives. Given the qualitative nature of the study and the limited number of interviews (n = 9), the objective of this analysis was not statistical generalization. Instead, frequency counts were used to identify areas of convergence among stakeholders and to support the prioritization of KPI categories within the proposed framework. Accordingly, the frequencies reported in Table 4 should be interpreted as indicators of thematic alignment across interviewed stakeholders rather than statistically representative measures of a broader population. Table 4 summarizes the main performance dimensions that emerged from the interviews and the number of stakeholders who explicitly identified each dimension as critical.

Performance Dimension	Description of Concern	Frequency (out of nine interviewed)
Effluent Quality Compliance	Compliance with discharge limits for release into surface water bodies	9/9
Electrical Energy Consumption	Energy cost, efficiency, load management	8/9
Chemical Reagent Utilization	Dosage optimization and procurement cost control	7/9
Plant Availability	Operational continuity and uptime	6/9
Waste Production & Disposal	Sludge management and disposal costs	7/9
Equipment Reliability	Failure prevention and predictive maintenance	5/9
Real-Time Monitoring & Alarm Management	Immediate anomaly detection and response	7/9

Safety and Environmental Risk Control	Prevention of environmental and safety incidents	4/9
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Table 4: Emergent Performance Dimensions and Frequency of Occurrence

4.2.4. Interpretation and Implications for KPI Design

Effluent quality compliance emerged as the only one identified priority (9/9), confirming its classification as a mandatory KPI category. Compliance with discharge standards represents a non-negotiable constraint, as failure to meet regulatory thresholds prevents water discharge and may result in operational or legal consequences. Among economic drivers, electrical energy consumption and chemical reagent utilization were the most recurrently cited dimensions, reflecting their significant impact on operational expenditure. Waste production and disposal costs were also consistently identified as relevant cost components. Operational stakeholders emphasized plant availability and equipment reliability, highlighting the importance of continuity and preventive maintenance within the KPI architecture. Meanwhile, real-time monitoring and alarm management were particularly relevant for operational roles directly involved in plant control. These findings directly informed the prioritization and weighting of performance dimensions within the final KPI framework, ensuring alignment between strategic objectives, regulatory constraints, and operational realities.

4.2.5. Field-Based Instrumentation Analysis

Contemporary KPIs systems in process industries are increasingly built upon real-time data streams provided by distributed sensor networks and supervisory control and data acquisition systems [71], [72]. This evolution reflects a broader shift in performance measurement philosophy, from periodic retrospective assessment toward continuous, data-driven monitoring [29]. Recognizing this technological reality and considering that the WTP under study is equipped with comprehensive instrumentation for safety monitoring purposes, the available field instrumentation formed the empirical foundation for KPIs development. The methodological approach adopted can be characterized as bottom-up [73]: rather than defining idealized indicators and subsequently identifying the required measurements, the analysis commenced with a systematic inventory of available process measurements derived from the project engineering phase and progressed toward the formulation of indicators derivable from these measurements. This data-driven orientation contrasts with top-down frameworks, such as the Balanced Scorecard [21], where strategic objectives dictate measurement selection. The pragmatic rationale behind this choice reflects the ultimate implementation objective: deploying KPIs on a real-time

monitoring platform accessible to operations personnel and management [39]. This approach ensures that the resulting KPIs framework is not only theoretically sound but also practically implementable within the constraints of existing instrumentation infrastructure. Furthermore, by grounding KPIs development in actual field signals rather than idealized data assumptions, this methodology enhances the robustness and reliability of performance measurements, consistent with the principle that effective indicators must be anchored to measurable and accessible process variables.

4.2.6. Methodological Integration and Justification

The three methodological pillars described above ISO 22400 standardization, stakeholder requirements, and field instrumentation analysis were integrated through an iterative design process. This integration addresses the specific gaps identified in the literature review. The resulting hybrid methodology represents a systematic response to the research gaps and provides a replicable framework for KPIs development in similar complex industrial contexts.

4.3. KPIs Categorization: Plant Characteristics and Operations

To ensure clear KPIs categorization and facilitate interpretation by different stakeholders, the developed indicators have been organized according to two complementary classification schemes: a functional categorization based on performance dimensions, and a regulatory classification based on the role of the indicator. In this context, regulatory KPIs refer to mandatory indicators required to ensure compliance with environmental legislation governing wastewater discharge into surface water bodies. These indicators are not primarily designed to monitor operational efficiency, but to verify adherence to legally imposed discharge limits. Failure to comply with these parameters results in the impossibility of releasing treated water and the need for additional treatment. The KPIs have been further divided into five macro-areas, each addressing a distinct dimension of plant performance and serving specific stakeholder groups:

- **Operational Area:** This area contains KPIs aimed at monitoring plant operations and identifying potential anomalies from a preventive perspective. A critical aspect is compliance with parameters for water discharged into surface water bodies, as non-compliance could result in administrative sanctions and environmental damage. The primary users of these KPIs are control room-operators who require real-time visibility into process status and early warning of emerging issues;

- **Economic Area:** This area includes the majority of KPIs, as economic performance represents the ultimate objective of plant management. The primary recipients are senior management and operations managers responsible for cost control and operational optimization. KPIs in this area concern energy consumption, chemical reagent utilization, waste production, and equipment utilization patterns that influence operational costs. For greater analytical clarity, the economic area has been subdivided into four subcategories: energy efficiency is assessed through a set of indicators aimed at quantifying electrical energy consumption, chemical reagent consumption is monitored through indicators that track the use of reagents across the various treatment stages, where specific consumption metrics support the identification of optimization opportunities and the early detection of process drift.
- **Maintenance performance** is evaluated by means of indicators usage and degradation, the utilization of parallel processing trains as it directly influences equipment degradation rates and, consequently, maintenance frequency and associated costs. Finally, waste production is characterized through indicators quantifying sludge generation, waste disposal volumes, and the related disposal costs, thereby addressing the third major cost driver emerging from the stakeholder analysis.
- **Quality Area:** This area is aimed at monitoring treated water quality and ensuring regulatory compliance. As discussed in Section 3.4.1 the literature identifies a critical balance between ensuring compliance and avoiding "non-remunerative over-quality" (give-away). Interviews conducted with process stakeholders revealed a possible correlation between water quality, chemical reagent utilization, and overall economic impact. Specifically, achieving water quality significantly exceeding regulatory specifications entails additional operational costs without providing any direct economic or regulatory value. The most impactful indicator is the compliance with discharge limits (Legislative Decree 152/06, Table 3, Annex 5, Part Three)
- **Sustainability Area:** This area includes KPIs related to the plant's environmental impact beyond regulatory compliance. Aspects considered include energy consumption (in quantitative terms and by supply source), chemical reagent utilization intensity, and sludge waste production. These indicators support environmental reporting, corporate sustainability objectives, and potential future carbon accounting requirements.

4.3.1. Regulatory Classification: Mandatory versus Monitoring KPIs

A fundamental distinction has been made between two classes of indicators based on their relationship to regulatory requirements and operational imperatives. Mandatory

KPIs include performance measures directly related to regulatory compliance requirements or operational safety constraints, where non-compliance may result in regulatory violations, environmental damage, operational shutdowns, or license revocations. The primary mandatory KPI is water quality compliance, specifically the requirement that treated water meet discharge standards for discharge into surface water bodies, along with plant availability targets specified in operational permits and safety-related performance thresholds. On the other side, monitoring KPIs represent performance measures aimed at continuous improvement and achieving maximum operational efficiency. While not subject to external regulatory enforcement, these indicators remain internally critical for cost optimization, process optimization, predictive maintenance, benchmarking and performance trending, and strategic planning. This distinction between mandatory and monitoring KPIs carries important implications for alarm configuration, reporting frequency, and management attention allocation. Mandatory KPIs typically require more strict monitoring protocols, faster response times, and formal escalation procedures due to the potential consequences of non-compliance. Monitoring KPIs, by contrast, support optimization activities that can be prioritized according to operational circumstances and identified improvement opportunities, thereby enabling a more flexible and strategic approach to performance enhancement.

4.3.2. Complete KPI Framework

Table 5 presents the complete set of KPIs developed for the WTP, categorized by process area, functional macro-area, and regulatory role. The Process Area column identifies the specific treatment unit to which each KPI refers; indicators classified as "Overall Plant" are not associated with a single treatment stage but rather characterize the overall plant performance. This comprehensive framework results from the integration of ISO 22400 principles, methodologies documented in water treatment literature and context-specific requirements identified through the adopted methodology.

N. KPI	PROCESS AREA	NAME	ROLE	AREA
1	Overall Plant	Water Treated & Treatment Efficiency	Monitoring	Operational
2	Overall Plant	Water Quality Compliance	Mandatory	Quality
3	Chemical Conditioning	Chemical Conditioning – Specific Chemical Consumption	Monitoring	Economic/Environmental
4	Chemical Conditioning	Chemical Conditioning – Specific Process Cost	Monitoring	Economic

5	Crystallizer	Crystallizer – Specific Process Cost	Monitoring	Economic
6	Neutralization	Neutralization – Specific Chemical Consumption	Monitoring	Economic/Environmental
7	Neutralization	Neutralization – Specific Process Cost	Monitoring	Economic
8	Biological treatment	Biological Treatment – Specific Chemical Characteristics	Monitoring	Operational
9	Biological treatment	Biological Treatment – Specific Chemical Consumption	Monitoring	Economic/Environmental
10	Biological treatment	Biological Treatment – Specific Process Cost	Monitoring	Economic
11	Reverse Osmosis	Reverse Osmosis – Specific Chemical Consumption	Monitoring	Economic - Chemical Reagent

Table 5: Comprehensive KPI Framework for Gas Storage-Integrated Water

This framework encompasses 11 primary KPIs distributed across the five macro-areas, with particular emphasis on economic performance reflecting the cost-driven priorities identified in stakeholder consultations. The single mandatory KPI reflects the paramount importance of regulatory adherence, while the 10 monitoring KPIs provide comprehensive visibility into operational and economic performance.

4.4. Analytical Scope and Exclusions

The analysis conducted in this thesis focuses exclusively on KPIs directly correlated with operational efficiency, economic performance, and plant availability of the WTP in the context of gas storage operations. Several categories of performance indicators, while implemented in the corporate monitoring system, are not addressed in this paper as they represent standardized metrics not requiring specific methodological elaboration for the application context.

4.4.1. Energy KPIs by Plant Section

At the time of this study, dedicated energy meters for individual plant sections had not been implemented. Such instrumentation was under evaluation for future implementation to enable more granular energy performance analysis. In the absence of direct sectional measurements, energy consumption by plant section can be estimated through a simplified approach based on equipment nominal power ratings and operating hours. However, this estimation method presents inherent limitations:

- Assumes constant operation at nominal power, neglecting partial load operation;
- Does not account for variable frequency drives and load-dependent efficiency;
- Ignores real utilization factors and cycling patterns;
- Cannot capture conversion losses and auxiliary consumption.

Since the methodology for calculating sectional energy consumption is well-established in engineering practice and extensively documented in standards such as ISO 50001 (Energy Management Systems) [74], [75], [76], this aspect will not be further elaborated in this thesis. Future implementation of sectional energy metering will enable more sophisticated energy performance analysis, including identification of optimization opportunities at the subsystem level.

4.4.2. Reactive Maintenance KPIs

Metrics such as Mean Time To Repair (MTTR) and Mean Time Between Failures (MTBF) represent standardized indicators for characterizing system reliability and maintainability. These KPIs are implemented in the corporate monitoring system following definitions and calculation methodologies established in international technical standards:

- IEC 60050-192:2015 - International Electrotechnical Vocabulary;
- IEC 61703:2016 - Mathematical expressions for reliability, availability, maintainability and maintenance support terms;
- ISO 14224:2016 - Petroleum, petrochemical and natural gas industries: Collection and exchange of reliability and maintenance data for equipment.

These standardized reliability metrics are well-documented [77], [78], [79] in the reliability engineering literature and do not require context-specific adaptation for water treatment applications. Therefore, while MTTR and MTBF are included in the broader performance monitoring system, they are not analyzed in detail in this thesis, which focuses on KPIs requiring specialized design or adaptation for the gas storage-integrated WTP context.

4.4.3. Health, Safety, Environment and Human Resources KPIs

Indicators related to Health, Safety, and Environment (HSE) management and human resources have been excluded from this analysis. These include:

- Personnel absence rates and turnover
- Injury frequency rate and severity rate
- Near-miss reporting frequency
- Safety walks completion rates
- Training compliance metrics
- Contractor safety performance

While these metrics are fundamental for workplace safety management and organizational monitoring, they follow well-established standards and frameworks. These standardized HSE metrics fall outside the specific scope of this thesis, which concentrates on technical and process performance of the water treatment system itself. HSE performance monitoring follows corporate and industry standards applicable across all operational facilities, not requiring water treatment-specific adaptations.

5 Detailed KPIs Presentation

5.1. Introduction to KPI Presentation Framework

In the previous chapter the theoretical foundations and methodological approach used to develop a comprehensive performance measurement system approach have been presented. Chapter 4 provided a rigorous conceptual framework, articulating the multi-dimensional nature of organizational performance throughout the definition of effectiveness and efficiency and it has brought these theoretical concepts into a hybrid methodological approach integrating ISO 22400 standardization principles, stakeholder requirements and field-based instrumentation analysis, ended up with a definition of an indicator framework organized across five functional macro-areas and classified according to regulatory role. This chapter represents the logical next step in the design process, moving from methodological architecture to detailed technical specification and its primary objective is to provide comprehensive, implementation-ready specifications for each of the KPIs identified in Table 5, ensuring that the abstract performance concepts articulated in the theoretical framework can be translated into concrete. The presentation of individual KPIs in this chapter follows a consistent four-part structure intended to ensure clarity, methodological soundness, and practical applicability. This structure is applied uniformly throughout the chapter and serves both educational and practical purposes. It begins with five plant-level indicators giving a strategic oversight of overall performance, including treatment efficiency, regulatory compliance, energy consumption, equipment utilization, and waste generation, incorporating normalization mechanisms to address the seasonal variability inherent in gas storage operations. The presentation then proceeds sequentially through process-specific sections (chemical conditioning, crystallization, neutralization, biological treatment, and membrane processes) each one introduced with comprehensive technical overviews that establish the operational context necessary for meaningful indicator interpretation, necessary for meaningful interpretation of the indicators, reflecting the idea that effective performance measurement requires understanding not only what is measured, but also why it is important within the overall process.

5.1.1. Methodological Note on Visual Display and Dashboard Widget

The dashboard widget figures included in each KPI subsection are not screenshots extracted from an operational monitoring platform. At the time of writing, the water treatment plant examined in this thesis has not yet been commissioned, and the related SCADA and data visualization infrastructure is still in the engineering development phase. Consequently, no live operational data stream is currently available from which

authentic system captures could be obtained. The visual representations presented were generated using artificial intelligence tools as conceptual mock-ups to support the specification of functional and visual requirements. These artefacts are consistent with the prototyping approach adopted during the internship at IGS S.p.A., where AI-assisted visualization was employed to define dashboard design in the absence of a deployed system. Within a design science research framework, high-fidelity prototypes and representative mock-ups constitute legitimate design artefacts prior to implementation. The figures included in this chapter should therefore be interpreted as design specifications encoding the intended structure, logic, and graphical configuration of each KPI widget, rather than as empirical records of system operation.

5.2. Plant-Level KPIs

5.2.1. Section Overview

The plant-level performance indicators represent the highest level of the hierarchical measurement architecture, providing aggregate visibility into the water treatment facility's overall operational effectiveness, economic efficiency, regulatory compliance status, and environmental performance. These indicators fulfill the strategic oversight function offering senior management and external stakeholders a summarized view of plant performance that goes beyond the detailed process-level information needed for daily operations, but that might hide wider trends if considered on its own. The main reason for introducing this hierarchical measurement structure derives from established performance management theory, which emphasizes the necessity of multi-level indicator systems capable of serving diverse stakeholder needs across different organizational echelons and decision-making time horizons [36], [80]. Plant-level KPIs address fundamentally different analytical questions compared to section-specific indicators: rather than detecting localized process inefficiencies or optimizing individual unit operations, these aggregate metrics assess whether the integrated treatment system achieves its broad mission of converting produced water from gas extraction into compliant discharge effluent while minimizing operational costs and environmental impacts. The distinctive characteristic of plant-level indicators in the context of gas storage-integrated water treatment is their necessary accommodation of extreme seasonal load variability, a phenomenon largely absent from conventional municipal wastewater treatment facilities or continuous industrial process applications that dominate the water treatment performance measurement literature reviewed in Section 3.4. The gas storage operational cycle imposes pronounced seasonality on water production rates, with winter gas withdrawal periods generating water production approaching design capacity while summer gas injection periods reduce production to minimal levels, creating load factor variations that can span an order of magnitude across the annual cycle. This operational reality necessitates

careful consideration of normalization strategies within plant-level KPI formulations to ensure that performance can be meaningfully compared across periods of dramatically different throughput, distinguishing genuine efficiency variations from artifacts of capacity utilization. The plant-level measurement framework integrates contributions from all constituent process sections through a data aggregation architecture that preserves essential performance information while reducing dimensionality to manageable levels suitable for strategic decision-making. This aggregation process is not merely arithmetical summation but rather involves sophisticated weighting, normalization, and contextual adjustment procedures that account for process interdependencies, operational constraints, and the physical laws governing water treatment unit operations. The theoretical basis for such aggregation methodologies derives from multi-criteria decision analysis frameworks which provide rigorous mathematical foundations for matching heterogeneous metrics into coherent overall measures while keeping them easy to understand and avoiding misleading levels of accuracy. The aggregation methods chosen for each plant-level KPI reflect a balance between the ideal theoretical approach and what can realistically be implemented in practice, favoring clear and transparent calculations that help stakeholders understand and trust the measurement system, rather than complex combined indicators that are difficult to understand.

5.2.2. KPI 1: Water Treated & Treatment Efficiency

5.2.2.1. Context and Relevance

The water treated and treatment efficiency indicator constitutes the foundational performance metric of the entire measurement system, quantifying both the absolute volumetric throughput of the water treatment plant and the conversion efficiency with which influent produced water is transformed into compliant treated effluent suitable for discharge. This indicator addresses the effectiveness dimension of the efficiency-effectiveness framework articulated in Section 3.1.2, assessing the degree to which the treatment system accomplishes its primary operational mission while simultaneously providing the normalization denominator upon which numerous downstream specific consumption indicators depend. The strategic importance of this KPI derives from its dual function as both an independent performance metric and a foundational calculation input since numerous other section-level indicators are formulated as ratios normalizing consumption or production quantities by treated volume, such that measurement accuracy and consistency of the water treated indicator directly propagates to the reliability of the entire dependent indicator set. In gas storage operations that include water treatment, this indicator is especially important because the amount of water produced during gas extraction changes a lot with the seasons. As documented in and elaborated in the gap analysis of Section 3.4.2, water production rates in gas storage facilities exhibit extreme seasonal variation driven by the gas

withdrawal-injection cycle, with winter withdrawal periods generating water production approaching design capacity while summer injection periods reduce production to minimal levels. These operating conditions mean that the treatment plant must maintain effective performance across an order of magnitude variation in throughput, from periods of maximum capacity utilization requiring all parallel processing trains to be operational simultaneously, through transitional periods of moderate loading, to summer months where minimal water production demands only partial plant activation. The impact of these fluctuations is partly reduced by the plant layout, which includes an upstream buffer basin designed to flatten flow peaks before the treatment stages. In this context, the water treated indicator is a key tool for monitoring the overall efficiency of the treatment plant, as it allows evaluation of plant performance under varying loads and supports the assessment of capacity use, maintenance planning during low-load periods, and verification that treatment efficiency remains stable despite large variations in treated water volumes. The treatment efficiency component of this indicator addresses a performance dimension largely absent from conventional water treatment benchmarking literature, which typically focuses on influent characterization and effluent quality rather than systematic quantification of volumetric process losses. In multi-stage water treatment systems employing membrane filtration and reverse osmosis, substantial fractions of influent water are consumed through legitimate process mechanisms including ultrafiltration backwash cycles, reverse osmosis concentrate rejection, biological treatment evaporative losses from aeration, and chemical sludge dewatering water content, with aggregate process losses typically ranging from 15-30% of influent volume depending on treatment configuration and operating condition. These losses are not inherently inefficient but rather represent necessary consequences of treatment process operation; however, losses exceeding expected ranges may indicate process degradation warranting investigation. The treatment efficiency metric therefore provides a system-level indicator of process integrity, with deviations from expected efficiency ranges signaling potential issues such as ultrafiltration membrane integrity failures increasing backwash losses, reverse osmosis recovery degradation from scaling or fouling. The primary stakeholder groups served by this indicator encompass senior management requiring visibility into overall production capacity and resource utilization, operations managers responsible for day-to-day throughput management and equipment deployment decisions, process engineers monitoring system performance and identifying optimization opportunities, and compliance officers requiring confidence that treatment capacity is adequate to process all produced water without bypassing treatment stages. The indicator supports multiple decision-making contexts including capacity planning for anticipated gas production schedules, maintenance scheduling that exploits low-load periods for equipment servicing, equipment activation sequencing decisions when transitioning between seasonal loading regimes, and investigation prioritization when treatment performance deteriorates.

5.2.2.2. Design Rationale

The indicator was conceptualized as a composite metric combining two complementary sub-indicators rather than a single value, based on the recognition that throughput volume and conversion efficiency address fundamentally different performance questions that, while related, require independent monitoring and cannot be adequately captured through a single aggregated metric without loss of essential information essential for operational management. The absolute throughput component (volume of water treated per unit time) was formulated using the inlet flow measurement located downstream of the initial storage basin and upstream of the chemical conditioning section as the reference measurement point, rather than the raw water production measurement at the gas extraction wellhead or the final discharge flow measurement at the plant outlet. This boundary selection reflects several methodological considerations. The initial storage basin serves as a decoupling element between the inherently variable gas production rate and the treatment plant operational regime, absorbing short-term production fluctuations and providing a stabilized flow to the treatment. Selecting the inlet rather than outlet flow as the throughput reference aligns with standard industrial practice for production rate metrics, which conventionally measure feedstock input rather than product output, enabling the separate efficiency metric to capture the distinction between input and output volumes. The off-specification water sub-indicator is measured downstream of the analytical sampling pit, where treated water quality is checked against discharge limits before the final routing decision. At this point, instruments compare effluent quality with regulatory standards and automatically divert non-compliant water away from discharge. The corresponding flow measurement therefore represents the volume of fully treated water that does not meet discharge requirements, providing clear and direct information on the extent and duration of quality deviations, which is essential for regulatory compliance and internal analysis. Thus, under the hypothesis of no other inefficiencies such as water evaporation or hydraulic loss the water discharged (or outlet flow) sub-indicator is defined as the difference between treated water and off-specification water. This approach is based on a verified mass balance, as treated water has only two possible paths: discharge or diversion as off-spec water. The treatment efficiency component was formulated as the ratio of outlet treated water volume to inlet water volume over equivalent measurement periods, expressed as a percentage. This volumetric efficiency ratio provides a direct quantification of the fraction of influent water successfully converted to treated effluent, with the complement (100% - efficiency) representing aggregate process losses across all treatment stages. The design decision to express efficiency as a simple volumetric ratio rather than a more sophisticated metric incorporating water quality transformation (such as a quality-adjusted efficiency incorporating both volume conversion and contaminant removal effectiveness) reflects the principle of indicator simplicity and interpretability of the performance measurement, in which effective indicators must

be sufficiently transparent in their calculation methodology to enable straightforward interpretation by target stakeholder groups without requiring specialized technical expertise. The volumetric efficiency provides an immediately comprehensible metric whose deviation from expected values can be readily interpreted as indicating either increased process losses requiring investigation or improved recovery performance following optimization interventions.

5.2.2.3. Technical Specification

The mathematical formulation of the Water Treated and Treatment Efficiency indicator comprises three sub-metrics connected by a mass balance identity, each calculated from instrumentation identified through the field-based analysis with explicit specification of input measurements, calculation algorithms, dimensional consistency, and expected value ranges.

Sub-indicator 1: Water Treated

It is the absolute volume of water entering the treatment process over a defined measurement period is calculated by integrating the volumetric flow rate measured at the system inlet over the aggregation interval:

$$V_{treated} = \int_{t_0}^{t_1} Q_{in}(t) dt$$

Where $Q_{in}(t)$ represents the instantaneous volumetric flow rate measured by electromagnetic flowmeter at the outlet of the initial storage basin and inlet to the chemical conditioning section, expressed in m³/h. For discrete digital implementation in the SCADA system with sampling interval Δt , the integral is approximated using discrete numerical integration:

$$V_{treated} = \sum_{i=1}^N \frac{Q_{in}(i) + Q_{in}(i-1)}{2} \times \Delta t$$

Where N represents the number of sampling intervals within the aggregation period. The output unit is measured as m³ per aggregation period.

Sub-indicator 2: Off-Specification Water (V_off-spec)

The volume of water that has completed the treatment process but does not satisfy discharge quality requirements over a defined measurement period is calculated by integrating the volumetric flow rate measured downstream of the analytical sampling pit (dry-pit) over the same aggregation interval:

$$V_{off-spec} = \int_{t_0}^{t_1} Q_{off}(t) dt$$

Where $Q_{off}(t)$ represents the instantaneous volumetric flow rate measured by the Flow Transmitter located downstream of the dry-pit, capturing the water diverted from discharge due to non-compliance with quality specifications established in Legislative Decree 152/06. The discrete digital implementation follows identical trapezoidal integration methodology as specified for $V_{treated}$:

$$V_{off-spec} = \sum_{i=1}^N \frac{Q_{off}(i) + Q_{off}(i-1)}{2} \times \Delta t$$

Sub-indicator 3: Water Discharged ($V_{discharged}$)

The volume of treated water actually discharged to the receiving surface water body is not measured independently but is derived from the mass balance relationship governing the physical routing of water through the discharge control system. The two measurement points selected for independent instrumentation define the boundaries of a closed system wherein water has precisely two possible destinations: compliant discharge or off-specification diversion. The discharged volume is therefore obtained by subtraction:

$$V_{discharged} = V_{treated} - V_{off-spec}$$

No independent flow measurement is required at the discharge point, and none is specified, for the reasons of logical consistency and measurement reliability articulated therein.

Sub-indicator 4: Treatment Efficiency ($\eta_{treatment}$)

The volumetric conversion efficiency from influent water to compliant discharged effluent is calculated as the ratio of discharged water volume to treated water volume over equivalent measurement periods:

$$\eta_{treatment} = \frac{V_{discharged}}{V_{treated}} \times 100\%$$

Substituting the mass balance identity for $V_{discharged}$, the equivalent formulation is:

$$\eta_{treatment} = \frac{V_{treated} - V_{off-spec}}{V_{treated}} \times 100\% = \left(1 - \frac{V_{off-spec}}{V_{treated}}\right) \times 100\%$$

The complement of treatment efficiency ($100\% - \eta_{treatment}$) represents the aggregate volumetric losses across all treatment stages due to off-specifications water quality.

5.2.2.4. Visual Display and Dashboard Widget

The widget uses a chart designed to clearly and immediately show the trend of the plant's main operational parameters. The representation combines different graphical elements that, together, make it possible to follow both the water volumes handled and the efficiency and cost indicators, offering a complete view of the plant's behaviors over the observed period. The main part of the visualization consists of a set of vertical bars on a Cartesian plane that indicate the volume of treated water on a daily basis. This choice allows the operator to easily recognize how treatment levels change over time and to visually compare each day with the next. Shown on top there are three lines: the blue line shows the trend of discharged water, the red line represents the volume of off-specification water and the green dashed line indicates the plant's efficiency in percentage terms. The efficiency line uses a separate scale on the right side of the chart, so that it can be compared with the physical volumes without creating visual confusion. A horizontal dashed line is shown above the bars to indicate the daily treatment target. This visual reference helps the operator immediately understand whether the recorded values meet expectations or deviate from the target. Above the chart, three summary indicators provide an overview of incoming flows and an internal level measurement: volume of water coming from cluster A, volume from cluster B, and an average level for buffer basin at the beginning of the water treatment plant. These metrics haven't been discussed because they are linked to the gas storage plant and already present in the system. Overall, the widget provides a complete and well-structured representation that brings together water quantities and efficiency indicators thus the economic data in a single view. Even though it contains several layers of information, the chart is organized so that the operator can easily spot changes, compare different days, and identify relationships between variables. This makes the tool useful both for a quick check and for more detailed analysis of how the plant is operating. The overall widget layout follows the principle that the most operationally urgent information occupies the most visually prominent positions, while contextual and supplementary information is accessible but does not compete for attention during normal operations when all parameters are within expected ranges. The design intent is that under normal conditions an operator glancing at the widget for two seconds can confirm that the plant is operating within expected parameters, while under abnormal conditions the same two-second glance immediately flags the nature and severity of the deviation requiring attention.

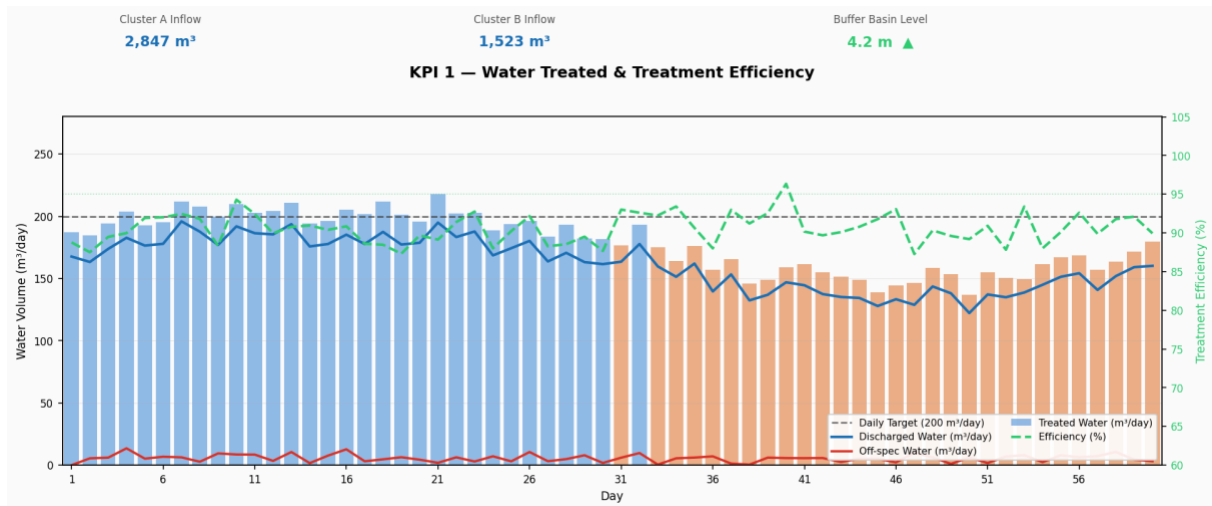


Figure 3: Conceptual dashboard mock-up for KPI 1 (AI-assisted design prototype; not based on operational data)

5.2.3. KPI 2: Water Quality Compliance

5.2.3.1. Context and Relevance

The water quality compliance indicator constitutes the single mandatory KPI within the entire performance measurement framework, directly linking operational performance to regulatory obligations and environmental protection requirements. Unlike all other indicators in the system, which serve internal optimization and continuous improvement objectives, this KPI addresses an external compliance boundary whose violation carries immediate legal, environmental, and reputational consequences including administrative sanctions, potential operational shutdown, environmental damage to the receiving surface water body, and license revocation. The regulatory framework governing discharge quality in this application is established by Italian Legislative Decree 152/06 (Table 3, Annex 5, Part Three), which specifies maximum permissible concentrations for a defined set of water quality parameters that must be continuously satisfied by treated effluent before the discharging.

The mandatory nature of this KPI reflects the fundamental principle that regulatory compliance represents a non-negotiable operational constraint rather than an optimization objective. The operational significance of continuous quality monitoring derives from the dynamic nature of the treatment process and the multiplicity of upstream factors influencing effluent quality. Each treatment section contributes to the overall quality transformation of the water, from initial particulate removal in chemical conditioning through dissolved species reduction in crystallization and biological treatment to final polishing in membrane filtration and reverse osmosis.

Degradation in any upstream section can propagate to effluent quality, potentially causing exceedance of one or more discharge parameters.

The produced water characteristics from gas extraction operations additionally exhibit variability driven by reservoir conditions, drawdown pressure, and seasonal factors, introducing influent quality disturbances that the treatment train must accommodate while maintaining compliant output. The continuous monitoring provided by this KPI at the dry-pit therefore serves as the final quality verification gate, detecting any condition where the integrated treatment system fails to achieve compliant effluent regardless of the underlying cause, and triggering the diversion mechanism that prevents non-compliant water from reaching the receiving water body.

The indicator serves multiple stakeholder groups with distinct informational needs. Compliance officers require continuous confidence that discharge standards are being met, supported by documented measurement records suitable for regulatory reporting. Operations managers need early warning of emerging quality excursions to enable rapid investigation of upstream treatment sections before ongoing non-compliance occur. Process engineers utilize quality parameter trends to identify correlations between upstream process conditions and effluent quality, informing optimization of treatment chemical dosing and process parameters. Senior management requires visibility into compliance status as a key operational risk indicator, given the potential severity of regulatory enforcement actions and the reputational implications of environmental incidents. The indicator therefore has a central position within the KPI framework, connecting with almost all other performance areas because upstream process performance directly affects final effluent quality.

The relationship between this KPI and the previous one (Water Treated & Treatment Efficiency) is particularly direct: when quality monitoring at the dry-pit detects non-compliant effluent, the discharge control system diverts the water, generating the off-specification volume that enters in the KPI 1 calculations. This coupling ensures that quality excursion events are captured both as compliance events and as volumetric losses, providing complementary perspectives on the same operational condition and enabling cross-referencing between quality and throughput performance when investigating process upsets.

5.2.3.2. Design Rationale

The formulation of this indicator required addressing a fundamental design challenge inherent to multi-parameter compliance monitoring: the translation of numerous individual quality parameters, each with its own regulatory threshold and distinct physical meaning, into a coherent indicator system that serves both regulatory

verification and operational diagnostic purposes without sacrificing transparency or obscuring critical information through inappropriate aggregation. From a regulatory standpoint, compliance is assessed on a per-parameter basis: any single parameter exceeding its regulatory limit constitutes non-compliance regardless of how well other parameters perform.

A composite index employing compensatory aggregation (such as weighted arithmetic or geometric means) could mask individual parameter violations within an acceptable aggregate score, creating a false impression of compliance that would be both technically misleading and legally indefensible [81]. The design therefore maintains individual parameter identity throughout the monitoring and reporting system, presenting each measured concentration against its respective regulatory threshold as an independent compliance assessment. The selection of monitored parameters reflects the intersection of two requirements: the parameters specified as mandatory discharge limits by Legislative Decree 152/06 and the parameters measurable by the online analytical instrumentation installed at the dry-pit. The eight parameters continuously monitored (turbidity, conductivity, pH, redox potential, temperature, dissolved oxygen, ammonia, and nitrates) represent the subset of regulatory parameters for which reliable online continuous measurement technology is available and appropriate for the process conditions at the discharge point.

The measurement location at the dry-pit was selected as the monitoring point for several reasons converging on the requirement that quality assessment occurs at the last possible point before the routing decision between discharge and diversion is executed. This location captures the effluent quality after all treatment stages have been completed. Monitoring upstream of this location would risk detecting quality conditions that are subsequently corrected by natural processes or final treatment adjustments, potentially triggering unnecessary diversions, while monitoring downstream of the routing decision would defeat the purpose of preventive diversion by allowing non-compliant water to reach the discharge before quality is verified. The dry-pit therefore represents the physically and logically optimal monitoring location, balancing comprehensive treatment coverage against detection timeliness. The design decision to present each parameter as an independent value alongside its regulatory limit, rather than expressing parameters as treatment margins or normalized ratios relative to limits, reflects the operational transparency objectives of the KPIs framework.

Operators and compliance officers are most familiar with absolute concentration values in the units specified by regulatory documentation, and the direct comparison between measured concentration and regulatory limit in consistent units enables immediate comprehension of both compliance status and the quantitative margin available before exceedance. While treatment margin analysis (expressing the

difference between measured value and regulatory limit as a percentage of the limit) provides useful information for process optimization, this analytical perspective is better addressed through dedicated process optimization indicators rather than complicating the primary compliance monitoring display with derived quantities that may obscure the fundamental measured values. The alarm and routing logic governing the discharge control system operates on individual parameter thresholds rather than aggregate compliance scores, consistent with the per-parameter compliance philosophy described above. When any single monitored parameter exceeds its regulatory limit, the control system executes diversion of the effluent stream regardless of the status of all other parameters. This conservative approach ensures that any non-compliant discharge cannot occur through the online monitoring system, though it necessarily introduces some degree of precautionary diversion in cases where measurement uncertainty or transient sensor fluctuation causes momentary apparent exceedance that does not reflect genuine non-compliance. The measurement uncertainty margins incorporated into the alarm thresholds address this consideration by establishing alarm setpoints slightly below the regulatory limits, providing a buffer that accounts for measurement accuracy while maintaining a safety margin against genuine exceedance.

The temporal characteristics of the monitoring system reflect the distinct timescales relevant to quality compliance. Some parameters exhibit rapid dynamics requiring high-frequency monitoring to detect transient excursions of short duration, for example, pH can change substantially within minutes during process upsets in the neutralization section, while others evolve more slowly and are adequately characterized by less frequent measurement cycles. The sampling frequencies assigned to each parameter reflect these distinct dynamic characteristics, balancing detection capability against measurement reliability and sensor maintenance requirements. The analytical instruments installed at the dry-pit operate on independent measurement cycles, with each sensor providing readings at its characteristic sampling interval regardless of the status of other sensors, ensuring that a malfunction or maintenance requirement affecting one instrument does not compromise monitoring of other parameters.

5.2.3.3. Technical Specification

The Water Quality Compliance indicator comprises eight independently monitored parameters, each assessed against its respective regulatory threshold established by Legislative Decree 152/06. No composite calculation or aggregation formula is applied: each parameter value is provided directly by its dedicated online sensor at the dry-pit, and compliance status is determined by independent comparison of each measured value against its regulatory limit. The following specifications define the measurement characteristics, regulatory thresholds, and alarm configurations for each parameter. The parameter tracked are the following:

- Turbidity (Turb): it quantifies the optical scattering properties of the water resulting from suspended particulate matter, providing an indirect indicator of suspended solids concentration and treatment effectiveness in particulate removal stage (UoM: NTU, regulatory limit: 10 NTU);
- Conductivity (Cond): it measures the electrical conductivity provides an indirect measure of total dissolved ionic species concentration, sensitive to variations in salinity resulting from upstream. In chemical treatment processes and reverse osmosis performance (UoM: μS , regulatory limit: 2500 $\mu\text{S}/\text{cm}$);
- pH: it quantifies the hydrogen ion activity in the treated effluent, with both excessively acidic and alkaline conditions constituting regulatory violations and potential environmental hazards to the receiving water body. The regulatory framework establishes a permitted range rather than a single upper limit, requiring the monitoring system to verify compliance against both lower and upper bounds simultaneously (UoM: pH, regulatory limit: 6.0–9.5 pH);
- Redox Potential (Redox): it represents the oxidation-reduction potential characterizes the electrochemical state of the water, providing information regarding the presence of reduced or oxidized species and serving as an indirect indicator of biological treatment process conditions and disinfection status (UoM: mV, regulatory limit: Site-specific, defined in environmental permit);
- Temperature: water temperature at the discharge point affects the ecological conditions of the receiving water body, with elevated temperatures reducing dissolved oxygen capacity and potentially stressing aquatic ecosystems. The regulatory framework establishes maximum temperature limits or maximum temperature increase relative to receiving water conditions (UoM: $^{\circ}\text{C}$, regulatory limit: 30 $^{\circ}\text{C}$ absolute or $\Delta T \leq 3$ $^{\circ}\text{C}$ relative to receiving water);
- Dissolved Oxygen (O_2): the concentration of dissolved oxygen in the discharge effluent affects the oxygen availability in the receiving water body, with excessively low values indicating incomplete aerobic treatment or oxygen depletion conditions that could create anaerobic conditions in receiving waters (UoM: mg/L, regulatory limit: ≥ 4.0 mg/L);
- Ammonia (NH_4^+): the ammonia concentration in the effluent reflects the effectiveness of the biological nitrification process in the biological treatment section, with elevated ammonia indicating nitrification failure or insufficient biological treatment capacity. Ammonia is toxic to aquatic organisms at concentrations exceeding regulatory limits and contributes to eutrophication of receiving waters (UoM: mg/L as NH_4^+ , regulatory limit: 10 mg/L as NH_4^+);

- Nitrates (NO_3^-): the nitrate concentration in the effluent reflects the effectiveness of the biological denitrification process and contributes to eutrophication of receiving waters through nutrient loading. Elevated nitrate levels may also indicate incomplete biological nitrogen removal or excessive nitrification without corresponding denitrification in the biological treatment section (UoM: mg/L as NO_3^- , regulatory limit: 10 mg/L as NO_3^-).

The overall compliance status at any given time is determined by the logical AND of all individual parameter compliance assessments: the discharge is considered compliant only when all eight monitored parameters simultaneously satisfy their respective regulatory limits. A single parameter exceedance, regardless of the margin or duration, constitutes non-compliance triggering effluent diversion. The compliance status is updated each time any individual parameter completes a new measurement cycle, with the system maintaining the most recent measurement for each parameter and continuously evaluating the composite compliance condition. When all parameters return to compliant values following an exceedance event, the discharge routing system reverts to normal discharge mode, and the duration and volumes associated with the exceedance event are recorded for regulatory reporting and incident investigation.

5.2.3.4. Visual Display and Dashboard Widget

Each of the eight monitored parameters is displayed on an independent Cartesian plane showing the temporal trend of the measured parameter value over the selected observation period. The regulatory limit applicable to each parameter is represented by a horizontal reference line on the respective chart, providing immediate visual context for interpreting measured trends relative to the compliance threshold. To the left of the trend charts, a summary table reports, for each parameter, the regulatory limit and the most recent measured value in adjacent columns. Under normal operating conditions, the measured value is displayed in standard formatting; in the event that the latest measurement exceeds the prescribed limit, the value would automatically switch to red formatting, thereby generating an immediate visual alert of a non-compliance condition without requiring detailed inspection of the individual trend charts. This integrated representation supports both rapid compliance verification during routine monitoring and more detailed diagnostic analysis in the presence of quality excursions.



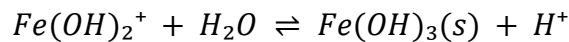
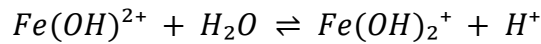
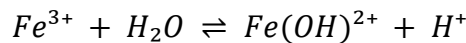
Figure 4: Conceptual dashboard mock-up for KPI 2 (AI-assisted design prototype; not based on operational data)

5.3. Chemical Conditioning Section KPIs

5.3.1. Section Overview

The chemical conditioning section is the initial treatment stage where physicochemical processes are employed to destabilize and aggregate colloidal particles and suspended matter present in the produced water from gas extraction operations. This section satisfies critical functions within the integrated treatment system including removal of turbidity-causing particulates, reduction of organic matter through co-precipitation mechanisms, precipitation of dissolved metals, and preparation of the water matrix for effective performance of downstream biological and membrane treatment stages. The importance of chemical conditioning comes from its protective role for downstream membrane systems: inefficient conditioning performance allowing particulate matter or colloidal substances to pass through to membrane filtration stages results in accelerated membrane fouling, increased cleaning frequency, making the membrane lifespan shorter thus increasing operational costs propagating through the entire treatment chain. The chemical conditioning section therefore highlights the strong interconnections typical of multi-stage water treatment processes, where optimization at the individual section level needs to consider effects on downstream performance rather than focusing on isolated local efficiency goals.

The chemical conditioning process operates through sequential application of coagulation and flocculation unit operations, each addressing distinct physicochemical mechanisms for particle destabilization and aggregation. The section is typically composed of two mixing tanks arranged in sequence. The first tank provides rapid and intense mixing to ensure uniform distribution of chemical coagulants, which destabilize colloidal particles by neutralizing their electrostatic repulsion forces and initiating aggregation. The predominant coagulant employed in this facility is ferric chloride (FeCl_3), selected based on jar test optimization studies conducted during commissioning. Upon addition to water, ferric chloride undergoes hydrolysis reactions that generate positively charged iron species:



These hydrolysis reactions progressively form amorphous ferric hydroxide precipitate while releasing hydrogen ions at each step, inducing pH decreases proportional to coagulant dose. This requires the influent water to have sufficient alkalinity to keep the pH within a suitable range for effective particle removal. Under these conditions, ferric hydroxide forms solid particles that capture suspended matter and dissolved contaminants as they settle. The second tank operates with slower and gentler mixing, creating conditions that allow particles to collide and combine in a controlled way, forming stable flocs without breaking them apart. During this flocculation stage, polymer flocculants are often added to help particles stick together and to increase floc strength. The larger and heavier flocs formed can then be efficiently removed in the subsequent clarification units. Chemical dosing in this section is usually set in proportion to the incoming water flow and adjusted based on expected water quality. This approach supports stable operation under typical conditions; however, changes in influent characteristics such as pH, temperature, or the amount of suspended and dissolved material may require dose adjustments to maintain treatment performance, as these factors directly influence both particle aggregation and the efficiency of chemical reactions.

Chemical conditioning is also the main source of sludge generation within the treatment plant. The amount and properties of the sludge produced depend on the type and quantity of chemicals used as well as the nature of the contaminants removed. For this reason, decisions aimed at reducing chemical consumption must consider not only reagent costs but also the implications for sludge handling and disposal. From a system perspective, effective chemical conditioning reduces the load on biological processes and limits membrane fouling in filtration stages, thereby improving overall plant reliability and reducing operating costs. On the other side,

insufficient performance in this section can affect in a negative way downstream units and increase total system costs. Chemical conditioning should therefore be evaluated and managed as an integral part of the overall treatment system, with performance assessed in terms of its contribution to plant-wide efficiency and cost control.

5.3.2. KPI 3: Chemical Conditioning - Specific Chemical Consumption

5.3.2.1. Context and Relevance

The specific chemical consumption indicator for the chemical conditioning section addresses one of the three primary operational cost drivers identified through stakeholder interviews, quantifying the intensity of coagulant and flocculant utilization per unit volume of water treated. Chemical reagents are a significant operational expenditure in water treatment facilities, with chemical conditioning typically representing almost half of the total chemical costs across the entire treatment train due to the substantial dosing rates required for effective coagulation and flocculation. The operational significance of monitoring specific consumption rather than absolute consumption comes from the need to distinguish real efficiency variations from throughput-driven consumption changes regarding seasonal load variability. The normalization by treated volume through the specific consumption formulation enables meaningful performance comparison across different loading conditions, supporting identification of real efficiency degradation or improvement independent of seasonal throughput variations. The chemical section can directly influence the effectiveness and costs of all downstream treatment stages. The optimization of chemical consumption in this section therefore involves complex trade-offs extending beyond the direct reagent costs: underestimate the quantity to minimize chemical expenses may increase downstream operational costs through accelerated membrane fouling, increased biological treatment loading, or reduced overall treatment effectiveness requiring increased processing of off-specification water, while overdosing provides robust treatment performance and membrane protection but generates excessive sludge volumes increasing disposal costs and potentially breaking the "non-remunerative quality excess" principle, saying that treatment quality substantially exceeding regulatory requirements provides no value while incurring unnecessary costs.

The indicator serves multiple stakeholder groups with distinct analytical needs. Operations managers utilize specific consumption trends to detect deviations from expected dosing patterns that require further investigation, check whether dosing changes made in response to variations in influent quality are appropriate and effective, and identify ways to optimize dosing by balancing chemical costs with downstream effects. Procurement personnel require consumption rate data for inventory management, establishing chemical reorder points and quantities to

maintain adequate supply without excessive stock levels, and forecasting annual chemical requirements to support budget planning and supplier contract negotiations. Process engineers analyze consumption patterns related to influent water quality characteristics and downstream treatment performance to optimize dosing algorithms, calibrating feedforward-feedback control systems, and develop operational guidelines for adapting chemical doses to seasonal or operational variations. Senior management monitors chemical consumption as a key operational cost metric contributing to overall plant economic performance assessment and benchmarking against industry standards or peer facilities.

The relationship between KPI 3 and other indicators in the framework reflects the systemic nature of multi-stage treatment performance. Chemical consumption in conditioning influences sludge production, with the stoichiometric and empirical relationships between coagulant dose and sludge generation rate providing a basis for cross validating these two indicators and investigating sludge production trends. The conditioning performance indirectly affects membrane cleaning frequency, as inadequate conditioning allowing particulate matter or colloidal substances to reach membrane stages accelerates fouling development. The water quality achieved through conditioning contributes to the biological treatment loading and nutrient balance, with organic matter co-precipitation during conditioning reducing the biochemical oxygen demand entering biological treatment. These interdependencies emphasize that chemical consumption cannot be optimized in isolation but must be evaluated within the broader context of system-level performance captured through cross-sectional analysis.

5.3.2.2. Design Rationale

The formulation of this indicator required addressing several design challenges specific to the chemical conditioning context: the selection of appropriate normalization denominators, the treatment of multiple chemical species with distinct functions and costs, the incorporation of storage inventory visibility to support operational decision-making, and the temporal resolution appropriate for detecting meaningful consumption variations while filtering measurement noise. Each design choice reflects the intersection of theoretical considerations regarding performance measurement methodologies documented in water treatment literature and pragmatic constraints coming from instrumentation capabilities and operational information requirements.

The specific consumption metric was formulated as the ratio of chemical mass consumed to water volume treated, expressed in kg/m^3 or g/m^3 depending on typical dosing magnitudes, following established conventions in water treatment performance measurement. This volumetric normalization enables direct comparison

of dosing intensity across different time periods regardless of throughput variations, addressing the seasonal load variability challenge identified as Gap 1.

An alternative formulation considered during indicator design involved normalization by influent contaminant load to provide a more direct measure of treatment efficiency independent of influent quality variations. However, this contaminant-normalized approach was rejected due to practical implementation challenges: influent turbidity and other relevant quality parameters are not measured continuously with sufficient accuracy to support reliable real-time calculation, the relationship between influent contaminant characteristics and optimal chemical dose is highly nonlinear and influenced by numerous factors beyond simple mass balance, and the resulting metric would be less intuitive to operations personnel accustomed to thinking in terms of dose per volume treated. The volumetric normalization was therefore considered as the primary formulation, with the understanding that interpretation of consumption trends must account for influent quality variations documented through periodic laboratory analysis or inferred from correlation with upstream process indicators.

The incorporation of chemical storage tank inventory levels as background information within the KPI visualization reflects operational requirements for supply chain management and consumption verification extending beyond the primary performance monitoring objective. The chemical storage tanks provide buffer capacity enabling continuous operation despite discrete delivery schedules from suppliers. Monitoring inventory levels serves multiple operational purposes: enabling timely reorder before stock-out risks leading to operations interruption, providing independent verification of consumption measurements through mass balance, detecting potential leaks or unidentified consumption through unexplained inventory decline, and supporting delivery scheduling optimization to minimize storage costs while maintaining adequate supply security. The design decision to present inventory information as background bar charts on the chemical consumption trend charts rather than as separate independent indicators reflects the auxiliary nature of this information: inventory itself is not a performance metric but rather operational context supporting interpretation of consumption trends and enabling supply chain management. The dual-axis configuration with consumption trend on the primary axis and inventory level on the secondary axis enables operators to visualize both patterns simultaneously, facilitating correlation analysis between consumption rate changes and inventory drawdown rates. The water volume treated in the chemical conditioning section is presented as a third component of the visualization to complete the triad triple-view enabling decomposition of chemical cost variations into their constituent drivers. Chemical costs in any given period are determined by the product of three factors: the volume of water treated (throughput), the specific consumption rate (efficiency), and the unit cost of chemicals (procurement). Variations in observed

total chemical costs can arise from changes in any of these three factors or combinations of some of them, and effective cost management requires distinguishing which factor is responsible for observed trends. The inclusion of treated volume in the visualization alongside consumption and cost trends enables this decomposition: if costs increase while treated volume and specific consumption remain stable, procurement cost variation is indicated; if costs and specific consumption both increase while treated volume remains stable, genuine efficiency degradation has occurred; if all three increase proportionally, the cost increase is simply a throughput effect requiring no corrective action. This diagnostic framework operationalizes the principle stating that effective KPI systems must support root cause analysis rather than merely reporting the effects.

5.3.2.3. Technical Specification

The Specific Chemical Consumption indicator includes consumption monitoring for four distinct chemical reagents employed in the chemical conditioning section, each measured through instrumentation appropriate to its physical form and dosing characteristics. No composite aggregation across chemical species is performed; each reagent consumption is tracked separately to preserve functional and economic distinctions between these chemically and operationally distinct treatment inputs. The consumption measurement methodology differs between liquid and solid chemicals based on available instrumentation and practical measurement capabilities. Liquid chemicals delivered through metering pumps employ dual-measurement verification combining dosing pump totalizers (primary measurement) with storage tank level drawdown (secondary verification). Solid chemicals lacking pump-based dosing employ storage tank level measurement as the only consumption measurement.

For each of the substances involved in the chemical process (ferric chloride - liquid form, polymer flocculant - liquid form, Na_2CO_3 - solid powder form, NaOH , liquid form) the following calculation method has been followed: the specific consumption is calculated as the mass per unit volume of water treated in the chemical conditioning section over the aggregation period:

$$SCC_i = \frac{M_i}{V_{treated,CC}} \times 1000$$

Where M_i represents the total mass of substances consumed during the aggregation period, expressed in kilograms, and $V_{treated,CC}$ is the volume of water treated in the chemical conditioning section over the same period, expressed in cubic meters. The factor 1000 is applied to convert the resulting value from kilograms per cubic meter to grams per cubic meter, which is the conventional unit used to express specific chemical consumption. The mass of each substance is determined through two complementary measurement approaches providing mutual verification. The primary measurement

employs totalizing flowmeters integrated within the coagulant dosing pumps, which accumulate volumetric dose delivered and convert to mass through the known density of the coagulant solution. The secondary measurement employs level transmitters on the storage tank, calculating mass consumption from inventory drawdown over the measurement period accounting for any deliveries received:

$$M_i = (L_0 - L_1) \times A_{tank} \times \rho_i + M_{delivered}$$

Where L_0 and L_1 are initial and final tank levels, A_{tank} is the tank cross-sectional area, ρ_i is solution density, and $M_{delivered}$ represents any supplier deliveries received during the period.

Sub-indicator 1: Specific Coagulant Consumption

The specific consumption of coagulant (ferric chloride, liquid form) is calculated as the mass of coagulant consumed per unit volume of water treated in the chemical conditioning section over the aggregation period.

Sub-indicator 2: Specific Polyelectrolyte Consumption

The specific consumption of polyelectrolyte (polymer flocculant, liquid form) is calculated identically to coagulant consumption, employing the same dual-measurement verification approach.

Sub-indicator 3: Specific Sodium Carbonate Consumption

The specific consumption of sodium carbonate (Na_2CO_3 , solid powder form) is calculated from storage tank level drawdown, as this reagent is not delivered through metering pumps but rather batch-fed to process streams or dissolution tanks.

Sub-indicator 4: Specific Sodium Hydroxide Consumption

The specific consumption of sodium hydroxide (NaOH , liquid form) is calculated using dual-measurement verification combining dosing pump flowmeters and storage tank level drawdown.

Sub-indicator 5: Chemical Storage Inventory

The chemical storage tank inventory levels are monitored continuously for all four reagents to support supply chain management and provide independent consumption verification where applicable. Inventory is expressed as absolute volume (m^3) and as days of supply at current consumption rate:

$$I_{chemical} = L_{current} \times A_{tank}$$

$$Days_{supply} = \frac{I_{chemical} \times \rho_{chemical}}{M_{chemical,daily}}$$

Where $M_{chemical,daily}$ represents the rolling 7-day average daily consumption for the respective chemical, providing a smoothed estimate of consumption rate less sensitive to day-to-day variations than single-day consumption values.

Sub-indicator 6: Water Treated in Chemical Conditioning Section

The water volume treated in the chemical conditioning section is measured at the section inlet using identical methodology as the plant-level water treated indicator but reported independently to enable section-specific normalization. Under normal operation $V_{treated,CC}$ equals the plant-level $V_{treated}$ as the chemical conditioning section is the first treatment stage; however, they may diverge if the plant operates in bypass mode or if recirculation streams are activated.

5.3.2.4. Visual Display and Dashboard Widget

The widget employs a vertically grouped three-chart configuration designed to enable fast visual decomposition of chemical cost variations into their constituent drivers through merged presentation of related metrics sharing a common time axis. This arrangement makes it easier to compare the data, so operators can visually line up events across the three charts and see cause-and-effect relationships.

The first top panel is related to the chemical costs; it displays the total daily chemical cost for the conditioning section as a continuous line trend over the selected time horizon. The cost is calculated as the sum of coagulant and flocculant costs, where each component equals the product of mass consumed and unit cost from the most recent procurement pricing. A critical characteristic of this cost metric is its composite nature: cost variations can arise from three distinct mechanisms that cannot be disaggregated from the cost trend alone: (1) changes in water throughput affecting total chemical demand at constant specific consumption and constant unit prices, (2) changes in specific consumption at constant throughput and constant unit prices, or (3) changes in chemical unit prices from supplier pricing variations at constant throughput and specific consumption.

The widget design addresses this ambiguity through the coordinated presentation with Charts 2 and Charts 3, which provide the throughput and specific consumption information necessary to diagnose cost variation causes. The inability to separately display procurement-driven cost variations within this visualization reflects a fundamental limitation: chemical unit prices are updated in the system only when new supplier contracts are executed or price adjustments occur (typically quarterly or semi-annually), and intra-period price variations are not tracked at daily resolution.

Consequently, procurement cost effects appear as step changes in the cost trend coinciding with contract updates rather than smooth variations. The chart in the middle shows a dual-axis configuration presenting specific consumption as the primary visualization and storage inventory as contextual background information. The specific consumption for the four chemicals, coagulant (SCC_coag), polyelectrolyte (SCC_poly), sodium carbonate (SCC_Na₂CO₃), and sodium hydroxide (SCC_NaOH) are displayed as continuous line trends on the primary vertical axis. The chemical species are color-coded to maintain visual distinction. These trend lines show the daily specific consumption in g/m³ over the selected time horizon, enabling operators to identify consumption pattern changes, detect gradual trends indicating process drift or influent quality evolution, and verify that consumption rates remain within expected ranges established through design specifications and operational experience. The differentiation between the four chemicals serves important process purposes. Coagulant and polyelectrolyte consumption patterns typically track output variations under stable influent quality, exhibiting proportional relationships with treated volume. In contrast, sodium carbonate and sodium hydroxide consumption patterns reflect influent water chemistry variations (alkalinity and pH respectively) that may be independent of throughput. An operational scenario in which coagulant and polyelectrolyte consumption increase proportionally with throughput while sodium carbonate consumption remains stable indicates normal seasonal load variation without influent chemistry change. Conversely, increasing sodium carbonate consumption at stable throughput and stable coagulant usage signals an influent alkalinity deficit requiring investigation of upstream conditions or adjustment of crystallizer lime dosing which affects alkalinity balance. Displayed in the background of the same chart, vertical bar graphs represent the storage inventory volumes for all four chemical tanks, referenced to a secondary vertical axis with units of cubic meters. The four-chemical presentation employs grouped bars with each chemical in a lighter shade of its corresponding trend line color, maintaining color coding consistency between consumption lines and inventory bars. The horizontal dashed lines drawn across the inventory bars show the reorder level and critical low-level alarm, calculated dynamically based on the current rolling average consumption rate for each respective chemical. These reference lines help the operators to visualize and assess the inventory: the bars extending well above the reorder threshold indicate comfortable supply margins, bars approaching the reorder threshold signal procurement action requirement, and bars approaching or below the critical threshold indicate urgent supply risk requiring immediate attention.

The dynamic calculation of days-of-supply thresholds is particularly important for chemicals with highly variable consumption rates where the same absolute inventory volume may represent dramatically different operational buffer depending on current influent water chemistry conditions.—This integrated presentation of consumption efficiency (trend lines) and supply availability (inventory bars) serves multiple

operational purposes. First, it enables verification of consumption measurements through inventory drawdown consistency for liquid chemicals equipped with both dosing pump flowmeters and tank level transmitters: the cumulative consumption indicated by the trend lines over a multi-day period should correspond to the inventory decrease shown by the bars, with significant discrepancies indicating potential measurement errors or unidentified consumption leading to investigation. Second, it supports inventory management by providing consumption rate context for interpreting inventory levels: the same absolute inventory volume represents different days-of-supply depending on current consumption rates, and the dynamic reference lines adjust accordingly. Third, it facilitates investigation of consumption anomalies by enabling operators to correlate consumption spikes with inventory drawdown events, distinguishing genuine consumption increases from measurement purposes. The last chart, at the bottom of the panel shows the total water treated in the chemical conditioning section over a period of time: a trend line is displayed in a neutral gray color to distinguish them from the chemical-specific color coding employed in Charts 1 and 2. A horizontal dashed reference line indicates the design capacity of the chemical conditioning section providing visual context for capacity utilization. The inclusion of throughput information as the third component of the stacked visualization completes the diagnostic triad enabling decomposition of cost trends into constituent causes. Overall, the widget design philosophy prioritizes visual pattern recognition and correlation analysis over numerical precision, reflecting the operational reality that chemical consumption monitoring serves primarily diagnostic purposes (detecting abnormal patterns requiring investigation) rather than requiring exact quantitative assessment for every time period. The three-chart stacked configuration, consistent color coding, dynamic reference lines, and coordinated time axis create a coherent analytical tool enabling operators to rapidly assess chemical consumption performance and identify issues requiring attention or opportunities for optimization.

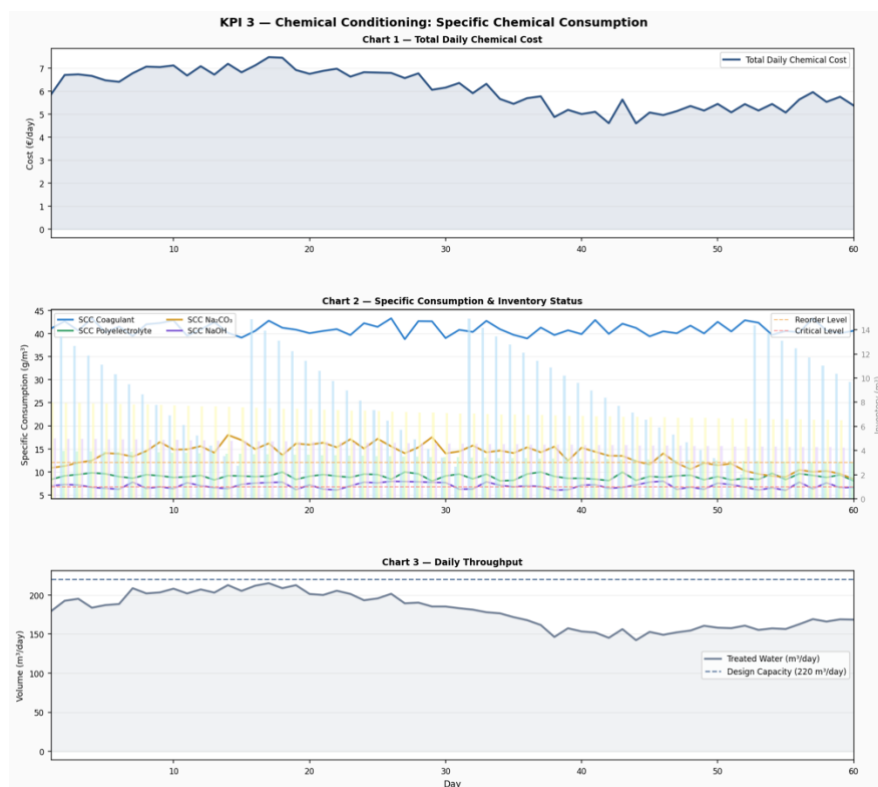


Figure 5: Conceptual dashboard mock-up for KPI 3 (AI-assisted design prototype; not based on operational data)

5.3.3. KPI 4: Chemical Conditioning – Specific Process Costs

5.3.3.1. Context and Relevance

The chemical conditioning process costs indicator provides comprehensive economic visibility into the total operational expenditure associated with the chemical conditioning section, integrating chemical reagent costs, energy consumption costs, and expressing the aggregate as a unit cost normalized by treated water volume. While the KPI 3 presented in the previous chapter quantifies the physical efficiency of chemical utilization in mass per volume terms, the one presented in this chapter translates these consumption patterns into economic impacts while additionally incorporating energy costs that are not captured in the consumption-focused indicator. The distinction between physical efficiency monitoring and economic cost monitoring reflects a fundamental principle in performance measurement: physical and economic optimization objectives may diverge due to price variations, cost structure differences between input factors, and trade-offs between capital expenditure and operational expenditure that require explicit economic analysis rather than purely technical assessment.

The cost structure comprises three principal components: chemical reagent procurement costs for the four chemicals employed, electrical energy costs for

operating mixing equipment and chemical dosing systems and allocated overhead costs for maintenance and labor though these latter components are typically excluded from real-time KPI calculations focusing on variable costs subject to operational control. The chemical costs themselves exhibit substantial variability driven by global commodity markets for base chemicals and specialty chemical markets for synthetic polymers. Energy costs similarly vary with electricity market conditions, time-of-day pricing structures where applicable, and seasonal demand patterns affecting wholesale electricity prices. The operational complexity of cost management in chemical conditioning derives from the multifactorial nature of cost drivers and the indirect relationships between controllable operational parameters and resulting costs. Total costs in any period equal the product of three independent factors: throughput volume (m^3 treated), specific consumption rates (g chemical/m^3 or kWh/m^3), and unit costs (€/kg chemical or €/kWh electricity). Variations in observed total costs can arise from changes in any factor or combinations of some of them, and effective cost management requires distinguishing which factors are responsible for observed trends to enable appropriate response. A cost increase driven by throughput variation seasonal load increase requires no corrective action as it represents normal operational scaling, while a cost increase driven by degraded efficiency (increased specific consumption) leading to process investigation and optimization, and a cost increase driven by procurement price changes may trigger supplier negotiations or hedging strategies. The inability to distinguish these causes from aggregate cost data alone motivates the multi-component visualization approach described in the chapter 5.3.3.4 Visual Display section, wherein cost trends are presented alongside the constituent factors enabling diagnostic decomposition. The relationship between this KPI and the previous one is direct but non-redundant: KPI 3 monitors the physical efficiency of chemical utilization independent of procurement economics, while KPI 4 translates efficiency into economic terms while adding the energy cost dimension absent from the consumption-focused indicator. Both indicators serve complementary purposes and target different decision-making contexts. KPI 3 supports process optimization focused on minimizing chemical usage through improved dosing control, influent quality management, and treatment effectiveness, while KPI 4 supports economic optimization that may involve trade-offs between chemical costs and energy costs. The primary stakeholder groups served by this indicator includes senior management requiring visibility into operational cost drivers for budgeting and financial performance assessment, operations managers responsible for cost-conscious operational decisions balancing treatment effectiveness against economic constraints, procurement personnel evaluating supplier performance and negotiating contracts based on actual consumption and cost data, and finance personnel responsible for cost accounting, variance analysis, and operational budget management.

5.3.3.2. Design Rationale

The formulation of this indicator required addressing the challenge of presenting multi-factor cost information in a format enabling rapid diagnostic decomposition while maintaining clarity and avoiding visual complexity that would limit rather than support operational decision-making. The fundamental design principle adopted is the separation of total process costs into their constituent drivers through coordinated visualization of three complementary metrics presented in vertically stacked charts: chemical unit costs as the procurement pricing factor, energy consumption as the operational efficiency factor for electrical usage, and total unit cost alongside treated volume as the integrated economic performance metric combining all cost components. This three-chart structure enables systematic investigation of cost variations by isolating each major cost driver in dedicated displays that can be visually correlated through their shared time axis. The decision to express process costs as a unit cost (€/m³) rather than absolute cost (€/period) reflects the normalization principle applied throughout the KPI framework to address seasonal load variability. Absolute costs increase proportionally with throughput under constant efficiency and pricing conditions, making direct comparison across periods of different loading difficult and hiding real efficiency changes within seasonal cost fluctuations. The unit cost formulation removes throughput effects by construction, enabling meaningful comparison of cost efficiency across different operational periods. However, the unit cost alone provides incomplete information for budget management and financial planning, which require absolute cost projections and actuals; consequently, both unit cost and absolute cost (derived as unit cost × treated volume) are calculated and available through the widget interface, with unit cost emphasized in the primary visualization and absolute cost accessible through tooltip or summary displays.

The three-chart configuration follows a logical diagnostic sequence.

Chart 1 isolates chemical unit costs, which represent less frequent changes outside operational control reflecting procurement contracts and market conditions rather than operational efficiency. By presenting these costs independently, the visualization enables operators to immediately identify when cost variations originate from pricing changes versus consumption efficiency changes that are stable in Chart 1.

Chart 2 presents energy consumption in absolute terms, capturing the operational efficiency of the section's electrical equipment including mixing systems and dosing pumps. Energy consumption varies with throughput due to both proportional loads (flow-dependent pumping) and fixed loads (mixing equipment maintaining constant intensity regardless of flow rate within operating trains), requiring merged interpretation with throughput data to distinguish load-dependent from efficiency-driven variations.

Chart 3 integrates all cost components into the comprehensive unit cost metric (€/m³) while simultaneously displaying treated volume, enabling the final synthesis in which total economic performance is assessed in context of throughput variations and correlated with the upstream cost driver charts to complete the diagnostic decomposition. The incorporation of sludge disposal costs within the total unit cost calculation reflects the operational reality that chemical conditioning generates the majority of treatment plant sludge, with sludge production rates directly coupled to chemical consumption through stoichiometric and empirical relationships. The attribution of sludge disposal costs to the chemical conditioning section recognizes this section as the primary sludge generation point and enables complete economic accountability for the section's operational impacts. The sludge cost component is calculated from average unit disposal costs obtained from waste management contractor invoices, entered manually into the system on a periodic basis (typically monthly following receipt of invoices). The unit cost represents the blended average disposal cost per tons of dry solids accounting for actual disposal volumes and invoiced amounts during the billing period. An important operational consideration is that some sludge fractions may be recovered as feed-in materials for external industrial processes rather than disposed as waste, with such recovery arrangements potentially involving zero disposal cost or even modest revenue generation offsetting disposal expenses for non-recoverable sludge fractions. The sludge unit cost parameter therefore reflects the net economic impact of sludge management including both disposal costs for waste fractions and any cost offsets from material recovery, with the net value entered as the effective sludge cost used in the total unit cost calculation. The treatment of chemical unit costs within the KPI calculation framework required addressing the challenge that unit prices are not measured continuously but rather updated episodically when procurement contracts are renewed or supplier pricing adjustments occur, typically quarterly or semi-annually. The design approach adopted employs the most recent unit price for each chemical as a constant in daily cost calculations until a new price is manually entered into the system following contract updates. This approach has important implications for cost trend interpretation: step changes in calculated costs occurring on dates coinciding with known contract updates indicate procurement pricing effects rather than operational efficiency changes, while smooth cost trends between price updates reflect the combined effects of efficiency variations and throughput changes that can be further decomposed through reference to the energy consumption and treated volume displays. The one-time entry of supplier pricing from procurement documentation represents a manual data input requirement distinct from the automated sensor-based data acquisition supporting most other KPIs, introducing potential for data entry errors or delays in updating prices following contract changes. The decision to present chemical unit costs disaggregated by species rather than as an aggregate chemical cost reflects the diverse cost structures and pricing volatilities associated with different reagents. The presentation of energy consumption in absolute terms (kWh/day) in Chart 2 rather

than normalized specific consumption (kWh/m³) reflects the diagnostic purpose of this display: to reveal the consumption pattern enabling distinction between throughput-driven scaling and efficiency-driven variations when correlated with the treated volume display in Chart 3. If specific energy consumption were displayed instead, the relationship with throughput would be obscured by the normalization used, preventing visual assessment of whether energy increases reflect proportional scaling with load or disproportionate efficiency degradation.

5.3.3.3. Technical Specification

The Chemical Conditioning Process Costs indicator comprises total process cost calculation integrating chemical and energy cost components, with diagnostic decomposition enabled through presentation of constituent factors including unit costs, specific consumption rates, energy consumption, and treated volume. All cost calculations are expressed in € (euros). The primary indicator is the Total Unit Process Cost (UPC_{CC}) that represents the total operational expenditure per cubic meter of water treated in the chemical conditioning section, calculated as the sum of chemical costs, energy costs, and sludge management costs normalized by treated volume:

$$UPC_{CC} = \frac{C_{chem,total} + C_{energy} + C_{sludge}}{V_{treated,CC}}$$

Where C_{chem,total} represent the total chemical costs for all four reagents during aggregation period, C_{energy} stands for the electrical energy costs during aggregation period, the C_{sludge} is related to the sludge management costs (disposal or net of recovery revenues) during aggregation period, while the V_{treated,CC} represents the volume of water treated in chemical conditioning section during aggregation period (m³).

The total chemical cost is calculated as the sum of individual reagent costs:

$$C_{chem,total} = \sum_i M_i \times P_i$$

Where M_i is the mass consumed of chemical species i and P_i is the unit cost of chemical i (€/kg), with the summation performed over the four reagents (coagulant, polyelectrolyte, Na₂CO₃, NaOH).

The energy cost is calculated from measured electrical consumption coming from a specific meter and applicable electricity tariff:

$$C_{energy} = E_{CC} \times T_{elec}$$

Where E_{CC} is the electrical energy consumed in the chemical conditioning section (kWh) measured by dedicated section sub-meter, and T_{elec} is the electricity tariff (€/kWh) applicable during the period.

The sludge management cost is calculated from the blended average unit cost and estimated or measured sludge production attributed to this section:

$$C_{sludge} = M_{sludge,CC} \times P_{sludge}$$

Where $M_{sludge,CC}$ is the mass of dry sludge solids generated in the chemical conditioning section during the period (tonnes dry solids), estimated from empirical correlations with coagulant dose or from direct measurement where section-specific sludge metering is available, and P_{sludge} is the net unit cost of sludge management from waste management contractor invoices accounting for disposal costs net of any recovery revenues.

Sub-indicator 1: Individual Chemical Unit Costs

It represents the cost for each chemical reagent represents the procurement price expressed in €/kg, obtained from supplier invoices and procurement contracts. These values are entered manually into the system when contracts are renewed, or pricing adjustments occur.

Sub-indicator 2: Chemical Conditioning Energy Consumption

It expresses the electrical energy consumed by the chemical conditioning section equipment is measured by a dedicated section sub-meter integrating consumption across all electrical loads within the section boundary.

Sub-indicator 3: Electricity Tariff

It represents the cost per unit energy consumed, expressed in €/kWh. Tariff structures vary depending on contractual arrangements (the type of tariff agreed)

Sub-indicator 4: Individual Chemical Costs

For each individual chemical is calculated from the product of mass consumed and applicable unit cost:

$$C_{chem,i} = M_i \times P_i$$

Sub-indicator 5: Specific Energy Consumption

It represents electrical energy consumed per unit volume treated, calculated as:

$$SEC_{CC} = \frac{E_{CC}}{V_{treated,CC}}$$

This metric is not displayed as a primary KPI but is calculated for diagnostic purposes and presented within a specific widget to enable decomposition of energy cost variations into consumption efficiency effects versus tariff pricing effects.

5.3.3.4. Visual Display and Dashboard Widget

The related widget employs a vertically stacked three-chart configuration designed to enable rapid visual decomposition of process cost variations into their constituent drivers through coordinated presentation of cost trends, consumption/pricing factors, and throughput scaling.

The top chart displays the unit costs (€/kg) for the four chemical reagents employed in the chemical conditioning section as a function of time. The visualization employs a multi-line format with each chemical species represented by a distinct color-coded line. The characteristic appearance of this chart differs fundamentally from typical process trend displays: rather than smooth continuous variations, the unit cost lines exhibit step-function behavior with flat step interrupted by discontinuous jumps when new procurement pricing takes effect. During periods between contract renewals or supplier price adjustments, the lines remain perfectly horizontal reflecting the constant unit costs used in daily cost calculations. When procurement personnel enter updated pricing following contract negotiations or market price adjustments, the lines jump vertically to the new price level, creating the distinctive staircase pattern. The vertical axis spans the range of observed unit costs for each chemical, typically requiring logarithmic scaling. Alternatively, the chart may employ separate sub-panels for each chemical to avoid scale compression that would render small price changes in low-cost chemicals imperceptible, though this sacrifices the ability to visually compare relative cost magnitudes across species.

The chart in the middle shows the energy consumption representing the daily electrical energy usage for the chemical conditioning section as a continuous trend line over the selected time horizon. The energy consumption is measured directly by the dedicated section sub-meter which integrates consumption across all electrical loads within the section. The trend line is displayed in gray to maintain visual distinction from the chemical-specific color coding employed in Charts 1 and 3. The vertical axis spans the range of observed daily consumption from minimum values during low-load operation to maximum values during peak operation. The presentation of energy consumption in absolute terms (kWh/day) rather than normalized specific consumption (kWh/m³) is deliberate: the absolute consumption format enables visual

correlation with throughput (Chart 3) to distinguish throughput-driven scaling from efficiency-driven variations.

The last chart, at the bottom of the visual widget includes a dual-axis configuration presenting two complementary metrics that complete the diagnostic triad: treated water volume ($V_{\text{treated,CC}}$) displayed as vertical bars on the primary vertical axis in m^3/day , and total unit process cost (UPC_{CC}) displayed as a continuous trend line on the secondary vertical axis in $\text{€}/\text{m}^3$. The treated volume bars are displayed in neutral gray for consistency across the KPI framework. The bars provide immediate visual indication of throughput variations over time, with seasonal patterns clearly visible as alternating high bars and low bars. A horizontal dashed reference line at the design capacity level provides context for assessing capacity utilization. Over the bars, the total unit cost trend line is displayed in bold dark blue to ensure visual prominence and distinction from the gray bars. This line represents the comprehensive economic performance metric integrating all cost components in $\text{€}/\text{m}^3$. The trend line's vertical position and temporal evolution provide the primary cost performance indicator, with variations requiring investigation through correlation with the upstream Charts 1 and 2.

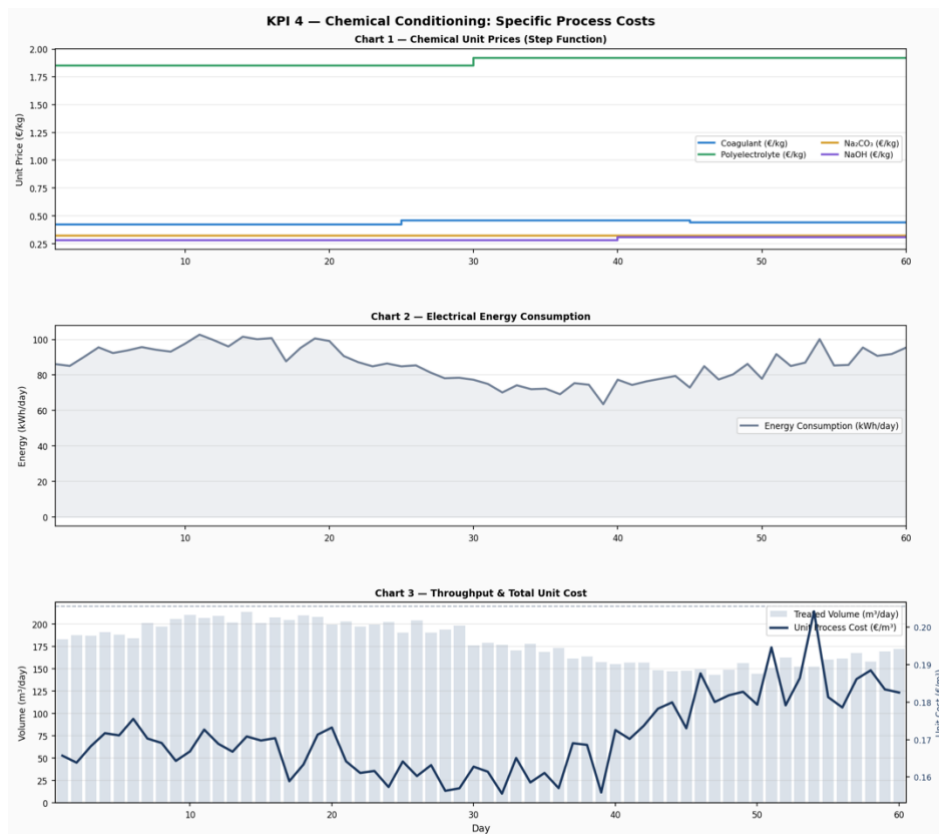
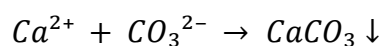


Figure 6: Conceptual dashboard mock-up for KPI 4 (AI-assisted design prototype; not based on operational data)

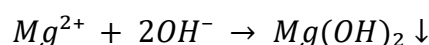
5.4. Crystallizer Section KPIs

5.4.1. Section Overview

The crystallizer section is a dedicated treatment stage designed to remove dissolved inorganic compounds mainly calcium, magnesium, and silica that tend to create blocks. If not removed, these substances would accumulate on the surfaces of downstream reverse osmosis membranes, causing a gradual loss of performance and potentially leading to premature system failure. To prevent this, the crystallizer operates as a controlled precipitation reactor in which supersaturation conditions are intentionally created so that the target ions form solid crystals on added seed particles. This controlled environment ensures that crystallization occurs where intended, rather than depositing on pipes, equipment, or membrane surfaces. The process, often referred to as pellet softening or crystallization-precipitation, directs crystal growth into solid particles that can be easily separated by gravity, thereby protecting the membrane system and ensuring long-term operational reliability. The fundamental chemical reactions governing crystallizer operation involve pH-driven precipitation of calcium and magnesium salts. Calcium removal occurs primarily as calcium carbonate (CaCO_3) when pH is elevated shifting the carbonate-bicarbonate equilibrium toward carbonate ion predominance according to the precipitation reaction:



while magnesium precipitates as hydroxide at elevated pH (typically >10) according to:



Silica removal mechanisms involve more complex adsorption and co-precipitation phenomena whereby dissolved silica incorporates into growing calcium carbonate and magnesium hydroxide crystals or precipitates as magnesium silicate compounds under alkaline conditions. The crystallizer operates as a fluidized bed reactor, where small seed particles are kept suspended by the upward flow of water. This design creates a large surface area for crystal growth and ensures that precipitation takes place on the seed material rather than on reactor walls or downstream equipment. As a result, unwanted deposits inside pipes and on membrane surfaces are minimized. Process efficiency depends mainly on how quickly and effectively crystals form and grow. This, in turn, is influenced by the level of supersaturation, the flow conditions inside the reactor, and the presence of substances that may slow down crystal formation. Temperature is also an important factor. Higher temperatures increase reaction rates and make crystal formation easier, especially when water composition or operating conditions reduce the natural tendency of minerals to precipitate. To maintain stable performance under unfavorable conditions such as low influent

temperature, high flow rates, or high concentrations of scaling ions, the system includes a thermal support step. When required, a boiler increases the process temperature to improve reaction rates and maintain the desired removal efficiency. Boiler activation therefore serves both as operational support and as an indicator that process conditions are less favorable for natural precipitation.

The performance of the crystallizer directly affects the scaling potential of the water entering the reverse osmosis section. If the crystallizer does not operate effectively, scaling may occur on the reverse osmosis (RO) membranes, leading to increased pressure drop, reduced water recovery, more frequent cleaning, and in severe cases, permanent membrane damage requiring costly replacement. The solid material discharged from the bottom of the crystallizer, after dewatering by centrifugation or filter press, consists mainly of calcium carbonate and magnesium hydroxide. Compared to conventional chemical sludge, it has a relatively high mineral purity. This makes beneficial reuse possible, for example as an agricultural soil amendment (if heavy metal content is sufficiently low), as a raw material for the cement industry, or as construction aggregate after proper processing. When agreements for material recovery are in place, sludge management costs may be reduced or offset by revenue from reuse. In some cases, this can lower the overall operating cost of the treatment system.

5.4.2. KPI 5: Crystallizer – Specific Process Costs

5.4.2.1. Context and Relevance

The crystallizer operating costs indicator provides economic visibility into a specialized treatment section characterized by a fundamentally different cost structure compared to the other sections, in which the consumption of the chemical substances is the dominant cost driver. Instead regarding the crystallizer, the cost structure includes energy consumption as the primary operational cost, maintenance costs arising from the abrasive nature of the circulating crystal slurry causing faster equipment degradation and sludge management costs for disposal or recovery of extracted crystal solids. Energy consumption deserves special attention because a boiler provides extra heat when the ambient temperature is not enough to reach the target crystallization rate. The boiler runs intermittently, switching on only when the process needs stronger heating due to low inlet temperature, high throughput that shortens the time the material stays in the system, or difficult inlet composition. Thus, the frequency and duration of boiler operation therefore serve as both a cost driver and a diagnostic indicator of process stress, with excessive boiler utilization signaling conditions leading to an investigation such as crystallizer performance degradation or persistent influent quality issues. The crystallizer fulfills the critical function of controlled precipitation and removal of scaling-prone dissolved species (calcium, magnesium,

silica) protecting downstream reverse osmosis membranes from irreversible damage. The economic significance extends beyond direct operating costs to encompass the protective value provided to high-capital-value membrane assets, creating interdependencies with membrane performance indicators that must be considered when evaluating crystallizer cost optimization opportunities.

5.4.2.2. Design Rationale

The formulation of this indicator as a composite cost metric including the energy consumption and the total unitary cost in the section.

Chart 1 presents energy consumption with boiler operating hours as contextual information. The boiler, operating intermittently only when thermal enhancement is necessary, serves as an indicator of process intensification requirements: frequent or prolonged boiler operation signals that ambient temperature crystallization is insufficient, warranting investigation of underlying causes. The presentation of energy consumption in absolute terms (kWh/day) with boiler hours as background bars enables visual correlation between total energy costs and the proportion attributable to thermal enhancement versus baseline recirculation requirements. While Chart 2 integrates all cost components (energy, maintenance, sludge management) into the total unit operating cost (€/m³) alongside treated volume, enabling throughput-normalized cost assessment. Sludge management costs follow the methodology established in KPI 4, with the crystallizer's predominantly calcium carbonate sludge composition potentially enabling recovery as industrial feedstock rather than disposal, creating opportunities for zero-cost removal or revenue generation that would reduce the total unit cost when such arrangements are active.

5.4.2.3. Technical Specification

Primary Indicator: Total Unit Process Cost (UPC_CRYs):

$$UPC_{CRYs} = \frac{C_{energy,CRYs} + C_{maint,CRYs} + C_{sludge,CRYs}}{V_{treated,CRYs}}$$

Where $C_{energy,CRYs}$ represents the cost of electrical energy consumed in the crystallization section during the aggregation period, $C_{maint,CRYs}$ corresponds to the amortized maintenance costs allocated to the same section, and $C_{sludge,CRYs}$ indicates the net sludge management cost, calculated as disposal expenses minus any revenues from material recovery. Finally, $V_{treated,CRYs}$ represents the volume of water treated in the crystallization section, expressed in cubic meters, used to normalize total costs on a unit basis. In which each term is calculated as follow:

$$\text{Energy cost: } C_{energy,CRYs} = (E_{elec,CRYs} \times T_{elec}) + (E_{thermal,CRYs} \times T_{fuel})$$

Assuming that the section is powered by electrical energy for equipment such as pumps and mixers, and by thermal energy for the boiler system, the overall energy demand includes both electrical and thermal contributions. If the boiler were also electric, the second term would become zero. While the related Energy Consumption (E_{CRYS}) is calculated as: Total energy = electrical energy (from sub-meter EM-CRYS) + thermal energy (from boiler fuel consumption or the related meter).

The sub-indicator tracks the Boiler Operating Hours (H_{boiler}) computed as the cumulative hours of boiler operation during aggregation period, from control system binary ON/OFF signal integrated over time. Regarding the Sludge Management Cost ($C_{\text{sludge,CRYS}}$) following the methodology presented for KPI 4, the net unit cost comes from contractor invoices accounting for disposal costs minus recovery revenues, multiplied by estimated daily sludge production. Especially, for the crystallizer sludge (whose predominantly sludge is CaCO_3) may enable recovery as cement feedstock or industrial calcium compound, potentially achieving zero-cost removal or revenue generation.

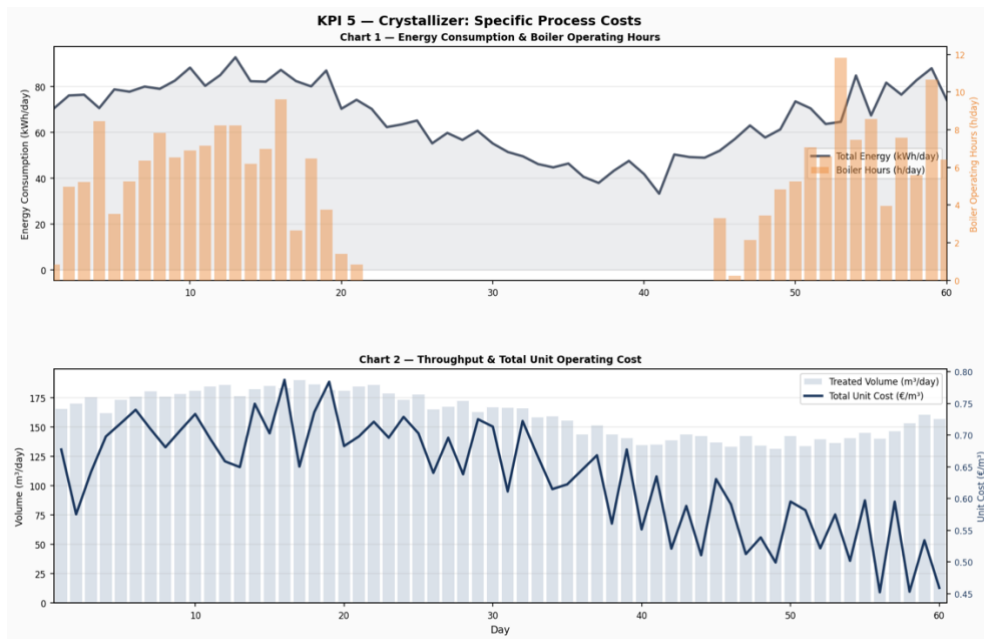


Figure 7: Conceptual dashboard mock-up for KPI 5 (AI-assisted design prototype; not based on operational data)

5.4.2.4. Visual Display and Dashboard Widget

This KPI's widget employs a vertically stacked two-chart configuration designed to provide focused diagnostic visibility into crystallizer operational efficiency and economic performance while minimizing visual complexity given the composite nature of the cost metric and the specialized operational characteristics of this section. The first chart on top of the visual widget represent the Energy Consumption and

Boiler Operating Hours employing a dual-axis configuration presenting electrical and thermal energy consumption as a continuous trend line on the primary vertical axis (left side, units: kWh/day) and boiler operating hours as vertical bars on the secondary axis (right side, units: hours/day). The energy consumption trend line is displayed in dark gray and represents the total energy consumed by the crystallizer section during each daily aggregation period. The trend shows a typical pattern that includes a baseline component from the continuous operation of the recirculation pump, which increases slightly with throughput, and a variable component from the intermittent operation of the boiler, which turns on only when additional heat is needed to support the crystallization process. As background bars, the boiler operating hours are displayed as semi-transparent vertical bars in orange, with bar height representing the cumulative hours of boiler operation during the daily period. The bars provide immediate visual indication of when thermal enhancement was employed: zero-height bars indicate periods of ambient temperature operation, while visible bars indicate boiler activation with height proportional to intensity of thermal enhancement deployment. The dual-representation format enables rapid diagnostic correlation: energy consumption increases coinciding with appearance of orange bars immediately identify thermal enhancement as the driver, while energy increases without corresponding bar activation indicate electrical consumption increases potentially from intensified recirculation, additional equipment activation, or electrical system issues. On the other side, frequent or tall orange bars without proportional energy increase would indicate anomalous conditions leading to investigation, such as boiler firing without heat delivery to process or data quality issues. The chart at the bottom represents the Throughput and Total Unit Operating Cost panel presenting treated water volume as vertical bars (gray, primary axis, m³/day) and total unit operating cost as a continuous trend line. The treated volume bars provide throughput context enabling interpretation of cost trends through the fundamental relationship that unit costs at constant operational efficiency should remain stable across throughput variations, while absolute costs scale proportionally with volume. Deviations from this expected pattern signal efficiency changes or cost structure changes requiring investigation through correlation with Chart 1 energy patterns and reference to maintenance event logs. The total unit operating cost trend line integrates all three cost components into the comprehensive economic performance metric. The cost calculation methodology ensures that episodic variations are smoothed through amortization and rolling averages, producing an interpretable trend reflecting underlying economic performance rather than effects caused by the timing of individual cash payment. Remaining variability in the unit cost trend derives primarily from:

- Energy efficiency variations: Reflected in Chart 1, driven by throughput-dependent load distribution, boiler activation frequency, or equipment performance changes

- Maintenance intensity changes: Gradual trends as equipment approaches end-of-service-life requiring more frequent interventions, or step reductions following major maintenance establishing extended service life
- Sludge cost variations: Monthly step changes when updated unit costs from contractor invoices are entered, particularly significant if recovery arrangements change from disposal to recovery

The two-chart configuration, while simpler than the three-chart structure employed for chemical conditioning, provides targeted diagnostic capability aligned with the crystallizer section's distinct operational characteristics: the energy/boiler chart addresses the operational efficiency and process intensification dimension unique to this section, while the cost/throughput chart provides the comprehensive economic assessment common across all section-level cost indicators.

5.5. Neutralization Section KPIs

5.5.1. Section Overview

The neutralization section covers the essential function of restoring the pH of chemically treated water to neutral range compatible with both biological treatment requirements and discharge regulations following the alkaline conditioning imposed by the upstream crystallizer. The crystallizer discharge pH, typically maintained at 9-10.5 to drive calcium carbonate and magnesium hydroxide precipitation, substantially exceeds the optimal pH range for the subsequent biological treatment section and the regulatory discharge limits specified in Legislative Decree 152/06, necessitating acidification through controlled chemical addition. The neutralization process includes three chemical reagents serving complementary pH adjustment and buffering functions:

- Sulfuric acid (H_2SO_4) provides the primary acidification capability for reducing pH from the alkaline crystallizer effluent to neutral range, selected for its cost-effectiveness, availability, and acceptable environmental impact of sulfate ions in the discharge stream;
- Sodium hydroxide (NaOH) provides pH adjustment in the opposite direction, employed when the crystallizer effluent pH falls below target range due to process variations or when fine-tuning is required following acidification;
- Sodium carbonate (Na_2CO_3) supplies buffering capacity when the water lacks sufficient natural alkalinity to resist pH fluctuations, ensuring stable pH control through the neutralization process and downstream biological treatment.

The section comprises three sequential neutralization basins designed to achieve progressive pH adjustment through multi-stage neutralization rather than trying to complete pH correction in a single vessel. This staged approach provides several operational advantages: the distribution of acid addition across multiple contact zones reduces the risk of localized over-acidification and pH undershoot, the sequential arrangement allows observation of intermediate pH values providing early indication of control issues before final effluent pH is affected, and the extended total hydraulic retention time (sum of three basin volumes divided by flow rate) provides residence time for complete acid-base reaction equilibration and dissolved carbon dioxide degassing from carbonate neutralization reactions.

Each basin is equipped with pH measurement instrumentation providing continuous monitoring of the neutralization progression, with the three pH values serving both process control functions and diagnostic purposes. The pH control strategy includes controls organized in different steps with feedforward compensation. The final basin pH measurement provides the primary feedback signal comparing actual pH against the setpoint target and adjusting acid dosing rates to minimize deviation. The intermediate basin pH measurements provide anticipatory information enabling early detection of pH trends before they fully manifest in the final effluent, allowing dosing adjustments in advance. Feedforward signals based on influent flow rate and crystallizer effluent pH (when available from upstream instrumentation) provide anticipatory dosing rate adjustments compensating for known disturbances before pH deviations occur, improving control performance relative to real feedback approaches that respond only after deviations develop. The neutralization section exhibits operational challenges characteristic of pH control systems: the highly nonlinear relationship between acid addition rate and resulting pH change, measurement lag from transport delay between dosing point and pH sensor location plus electrode response time creating potential for control instability, and influent variability from crystallizer performance variations requiring adaptive dosing strategies. These challenges justify the staged basin configuration and sophisticated control architecture and motivate the pH monitoring included in the following indicator providing visibility into control performance across all three neutralization stages.

5.5.2. KPI 6: Neutralization – Specific Chemical Consumption

5.5.2.1. Context and Relevance

The neutralization chemical consumption indicator measures how much reagent is used to control pH in the neutralization process. It tracks three chemicals with different roles: sulfuric acid (H_2SO_4) lowers pH when the water is too alkaline, sodium hydroxide (NaOH) raises pH if it falls too low or needs fine adjustment, and sodium carbonate (Na_2CO_3) provides buffering to help the water resist sudden pH changes.

Monitoring chemical use provides more than cost information. Patterns in consumption reveal how the neutralization process is performing. For example, high sulfuric acid use indicates that the water entering neutralization is very alkaline, while rising sodium carbonate use may signal that the water lacks natural buffering capacity. Sodium hydroxide is normally used very little; if it is needed regularly, it may indicate that pH swings are occurring, that acid dosing is too high, or that the system requires adjustment. This indicator is useful to different groups within the plant. Operators can track consumption trends to identify unusual dosing patterns and ensure pH is being maintained correctly. Procurement staff use the data to plan inventory, set reorder levels, and forecast annual chemical needs. Engineers can analyze patterns to adjust dosing strategies, optimize control settings, and respond to seasonal or operational changes in water chemistry. Management can use the information to understand chemical costs as part of overall plant performance. The value of the indicator goes beyond individual chemical costs. How chemicals are used reflects the quality of the water entering neutralization and the stability of the process. Proper pH control supports downstream biological treatment, while inadequate dosing or poor buffering can create pH swings that stress the system and reduce treatment efficiency. By tracking consumption in a structured way, the KPI provides insight into both operational performance and the effectiveness of chemical management, helping guide decisions to maintain stable and efficient treatment.

5.5.2.2. Design Rationale

KPI 6 for the neutralization section measures how much chemical is used to control pH and provides insight into how effectively the neutralization process is operating. The indicator tracks three reagents, each with a different role: sulfuric acid lowers pH when water is too alkaline, sodium hydroxide raises pH if correction is needed in the opposite direction, and sodium carbonate adds buffering capacity to help the water resist sudden pH changes. The three chemicals behave differently over time. Sulfuric acid is used continuously as the main neutralizing agent, while sodium carbonate is applied only when natural buffering is insufficient, and sodium hydroxide is rarely needed under normal conditions. This variability means the visualization needs to distinguish between periods of no use that are normal and periods where unexpected dosing may indicate a problem. Another key design aspect is integrating pH measurements into the consumption visualization. In neutralization, the final pH of the water is the main measure of whether the process is effective, and chemical dosing affects pH in a nonlinear way. Near the natural buffering range, large changes in acid dose produce small pH changes, while outside this range, even small dosing changes can create big pH swings. Including pH data alongside chemical use allows operators to understand whether changes in consumption are appropriate responses to water conditions or signs of overdosing or control issues. The indicator shows pH from all three neutralization basins rather than only the final effluent. This provides early

diagnostic insight: the first basin receives most of the acid and shows the largest pH drop, the second provides intermediate adjustment, and the third fine-tunes to the target range. Patterns across the basins reveal control quality, such as whether dosing is properly staged, whether influent water conditions are challenging, or whether pH oscillations indicate instability. Displaying pH together with consumption allows operators to see not just how much chemical is used, but whether it is being used effectively. Inventory management is also incorporated into the KPI. Sulfuric acid, as the main reagent, has conservative thresholds to ensure supply is always available. Sodium hydroxide and sodium carbonate have standard thresholds, as their use is intermittent and a temporary shortage would not immediately affect operations. For intermittently used chemicals, the calculation of days of supply takes into account whether the reagent is actively being dosed or not, so that inventory adequacy is interpreted correctly even when consumption is uneven. Overall, KPI 6 combines chemical consumption, pH outcome, and inventory information in a single, visually integrated widget. This design helps operators quickly assess whether chemical dosing is adequate, whether pH is under control, and whether supply levels are sufficient, supporting efficient and safe operation of the neutralization process.

5.5.2.3. Technical Specification

The indicators presented for the neutralization section follow the methodological framework established for chemical conditioning, in which specific consumption of each reagent is calculated through the ratio of consumed mass to treated volume, supplemented by storage inventory monitoring enabling both consumption verification through mass balance reconciliation and supply chain management through days-of-supply tracking. The specific consumption for each chemical species i is calculated as:

$$SCC_i = (M_i / V_{treated, NEUT}) \times 1000$$

Where M_i represents the mass of chemical i consumed during the aggregation period (kg), $V_{treated, NEUT}$ is the volume of water treated in the neutralization section (m^3), and the factor 1000 converts units from kg/m^3 to g/m^3 for conventional expression, in which the mass consumed is determined through dual-measurement verification for liquid chemicals (H_2SO_4 , $NaOH$) combining dosing pump flowmeter totalizers (primary measurement) with storage tank level drawdown (secondary verification), while solid chemicals (Na_2CO_3) employ tank level measurement. The secondary measurement for all chemicals follows the mass balance formulation:

$$M_i = (L_0 - L_1) \times A_{tank} \times \rho_i + M_{delivered}$$

Where L_0 and L_1 represent the tank levels measured at the beginning and end of the aggregation period, respectively, and A_{tank} is the cross-sectional area of the tank, used to convert the change in level into a change in volume. The parameter ρ_i refers to the density of the chemical either the solution density for liquids or the bulk density

for solid sodium carbonate needed to convert volume into mass. Finally, $M_{\text{delivered}}$ represents the total mass of chemical received from the supplier during the same period.

Sub-indicator 1: Specific Sulfuric Acid Consumption

The specific consumption of sulfuric acid (H_2SO_4 , liquid form) is calculated as the mass of sulfuric acid consumed per unit volume of water treated in the neutralization section over the aggregation period. Dual-measurement verification combines dosing pump flowmeter totalizers (primary measurement) with storage tank level drawdown (secondary verification). Sulfuric acid consumption exhibits continuous patterns directly coupled to the residual alkalinity of the crystallizer effluent, with consumption rates scaling approximately with the product of treated volume and the alkalinity difference between crystallizer effluent pH and the neutralization target pH. Under stable upstream conditions, specific consumption should remain approximately constant; deviations indicate changes in crystallizer effluent alkalinity or modifications to the neutralization pH setpoint.

Sub-indicator 2: Specific Sodium Hydroxide Consumption

The specific consumption of sodium hydroxide (NaOH , liquid form) is calculated identically to sulfuric acid consumption, employing the same dual-measurement verification approach. Under normal operating conditions, sodium hydroxide consumption should be minimal or zero, as the dominant pH correction direction in neutralization is downward from the alkaline crystallizer effluent. Sustained NaOH consumption serves as a diagnostic indicator: it may signal crystallizer underperformance producing insufficiently alkaline effluent, acid overdosing causing pH to undershoot requiring corrective upward adjustment, or pH control system instabilities producing oscillations that necessitate dosing in both directions. The alarm logic for this sub-indicator is configured to trigger investigation when consumption exceeds a threshold duration rather than a magnitude threshold, reflecting the diagnostic significance of sustained rather than transient NaOH usage.

Sub-indicator 3: Specific Sodium Carbonate Consumption

The specific consumption of sodium carbonate (Na_2CO_3 , solid powder form) is calculated from storage tank level drawdown, as this reagent is not delivered through metering pumps but rather batch-fed to process streams or dissolution tanks. Sodium carbonate consumption reflects the alkalinity supplementation requirement of the treated water for sustaining adequate buffering capacity through the neutralization process and downstream biological treatment. Consumption exhibits intermittent patterns, with extended periods of zero consumption when natural alkalinity is sufficient and activation when influent water chemistry changes or upstream treatment modifications reduce carbonate buffering capacity. Increasing sodium carbonate consumption at stable throughput and stable coagulant usage in the upstream conditioning section signals an influent alkalinity deficit requiring

investigation of upstream conditions or adjustment of crystallizer lime dosing which affects the alkalinity balance.

Sub-indicator 4: Chemical Storage Inventory

The chemical storage tank inventory levels are monitored continuously for all three reagents to support supply chain management and provide independent consumption verification through mass balance reconciliation. Inventory is expressed as absolute volume (m³) and as days of supply at current consumption rate:

$$I_{chemical} = L_{current} \times A_{tank}$$

$$Days_{supply} = (I_{chemical} \times \rho_{chemical}) / M_{chemical,daily}$$

Where $M_{chemical,daily}$ represents the rolling 7-day average daily consumption for the respective chemical, providing a smoothed estimate of consumption rate less sensitive to day-to-day variations than single-day consumption values. Inventory management thresholds are differentiated according to operational criticality: sulfuric acid employs a reorder point, reflecting its role as the primary neutralizing agent without which the section cannot function; sodium hydroxide and sodium carbonate employ standard thresholds of reorder.

Sub-indicator 5: Water Treated in Neutralization Section

The water volume treated in the neutralization section is measured at the section inlet using flowmeters consistent with plant-level methodology but reported independently to enable section-specific normalization. Under normal operation, $V_{treated,NEUT}$ is equivalent to the crystallizer outlet flow; however, it is measured independently to account for potential bypass flows, recirculation streams, or operational modes in which the neutralization section processes water that has not passed through the crystallizer.

5.5.2.4. Visual Display and Dashboard Widget

This KPI widget adopts a vertically stacked three-chart configuration designed to provide an integrated view of chemical consumption in the neutralization section, inventory status, and pH control performance through a coordinated representation of economic, efficiency, and process-control metrics.

The upper chart employs a dual-axis layout that combines economic information with throughput data. Daily chemical costs are displayed as a stacked area chart in which the total height represents overall expenditure, while the three colored layers distinguish the reagents used: sulfuric acid, which typically accounts for the majority of total cost, sodium hydroxide, and sodium carbonate, both characterized by more intermittent contributions. On the same chart, semi-transparent vertical bars in the background indicate the daily treated volume, allowing immediate correlation between cost variations and throughput changes.

The middle chart follows the dual-axis structure and displays the specific consumption of the three reagents as continuous lines on the primary axis, while daily tank inventories appear in the background as vertical bars referenced to the secondary axis. Specific consumption of sulfuric acid, sodium hydroxide, and sodium carbonate is represented using the same color scheme as in the first chart, ensuring visual consistency. The consumption trends reflect the typical behavior of neutralization chemistry: sulfuric acid shows a continuous pattern linked to the residual alkalinity from the crystallization section and to variations in precipitation performance, whereas sodium hydroxide and sodium carbonate exhibit episodic patterns, activated only when pH elevation or alkalinity supplementation is required, and therefore appearing as intermittent peaks or plateaus. The semi-transparent inventory bars, rendered in lighter shades of the corresponding consumption lines, allow simultaneous assessment of reagent availability. Horizontal dashed lines indicate dynamic reorder and critical-level thresholds, calculated from the rolling seven-day average consumption, providing immediate insight into supply risks and procurement needs. The integrated representation of consumption and inventory supports verification of measurement consistency, monitoring of supply security, and correlation of efficiency variations with inventory trends.

The bottom chart adopts a configuration specifically tailored to diagnostic analysis of pH control, displaying pH values from the three neutralization basins. The three pH trend lines illustrate the progression of neutralization through the sequential basins. Under stable operating conditions, the first basin exhibits the highest pH values reflecting the interaction between the alkaline crystallizer effluent and the acid dosing; the second basin shows intermediate values, while the third maintains the pH within the target range of 6.8–7.2, indicating effective final control before biological treatment. The vertical spacing between the lines provides diagnostic insight: wide separation suggests more challenging influent conditions or more aggressive dosing, whereas narrow separation indicates a more stable process or conservative dosing. Colored horizontal bands define reference ranges for control assessment: the green band marks the optimal range, the yellow band indicates acceptable but improvable control, the orange band signals conditions that may stress the biological treatment, and red dashed lines denote regulatory limits beyond which violations occur.

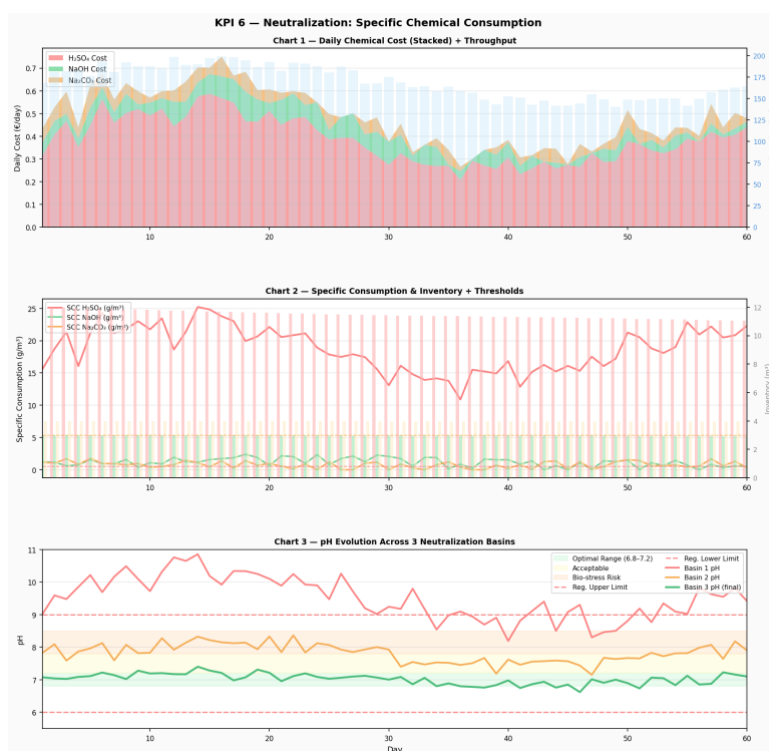


Figure 8: Conceptual dashboard mock-up for KPI 6 (AI-assisted design prototype; not based on operational data)

5.5.3. KPI 7: Neutralization – Specific Process Costs

5.5.3.1. Context and Relevance

The neutralization process cost indicator provides a comprehensive view of the economic impact of pH control operations. Its purpose is to translate chemical consumption and energy use into financial terms, allowing the neutralization section to be evaluated not only from a technical perspective but also from a cost perspective. While monitoring chemical quantities is essential to assess dosing efficiency, cost monitoring introduces an additional dimension: the economic consequences of operational choices. Variations in chemical prices, changes in energy tariffs, and shifts in process conditions can all influence total operating costs, even when physical consumption remains stable. For this reason, tracking costs separately from mass-based consumption is necessary to fully understand the section's contribution to overall plant expenditure. In the neutralization section, chemical reagents represent the main cost component. Sulfuric acid, used continuously for pH reduction, accounts for the largest share of expenditure. Energy costs are present but typically limited to mixing and dosing equipment. Unlike other treatment stages, neutralization does not produce sludge as a direct output, which simplifies the cost structure and concentrates the analysis on chemical and energy inputs. The relevance of this KPI also lies in its sensitivity to changes in incoming water characteristics. The amount of acid or

buffering agent required depends on the alkalinity and composition of the water entering the section. As a result, cost variations may reflect shifts in upstream water quality rather than inefficiencies within neutralization itself. Monitoring costs over time therefore supports a more informed interpretation of operational trends. This indicator is particularly useful for management and financial planning purposes. It supports budgeting, supplier evaluation, and cost control activities, while also providing operations personnel with visibility into the economic impact of dosing strategies. By linking process activity to financial performance, the KPI contributes to a balanced assessment of both technical effectiveness and economic sustainability.

5.5.3.2. Design Rationale

KPI 7 for the neutralization section follows the same general structure used for other cost indicators in the plant. Costs are expressed per unit of treated water (€/m³) in order to allow fair comparison over time, and the visualization uses a coordinated multi-chart layout so that related information can be read together. The overall design makes it possible to understand whether cost changes are linked to variations in treated volume, changes in chemical use, differences in energy consumption, or shifts in purchase prices. The main difference in the neutralization section is that its cost structure is simpler. The process generates no solid waste requiring disposal, so costs are limited to chemicals and energy. This reduces the number of cost drivers and makes interpretation more direct. When costs change, the reason can usually be tracked to one of four factors: variation in treated volume, changes in how much chemical is used, differences in chemical prices, or changes in energy use. Because the number of influencing factors is limited, identifying the cause of a cost variation is generally more straightforward than in more complex treatment stages. Although the cost structure is simpler, the visualization maintains the same three-part layout used in the overall framework to ensure consistency and ease of interpretation. However, the content is adapted to reflect the specific characteristics of neutralization. In particular, pH monitoring is integrated into the cost view because pH control quality is closely linked to cost efficiency. Including pH information in the cost indicator serves a different purpose than in the consumption indicator. In the consumption view, pH data help determine whether chemical dosing is technically effective. In the cost view, pH data help determine whether higher or lower spending is associated with better or worse pH control. For example, if costs increase but pH stability does not improve, the additional expense may not be justified and may require investigation. On the other hand, if higher costs are associated with more stable pH control, the increase may reflect a necessary and effective adjustment. Linking cost and pH performance in the same visual context supports this type of evaluation.

Energy use in the neutralization section is relatively simple compared to other processes. It mainly includes mixing equipment and dosing pumps. Energy

consumption tends to follow treated volume, with a small constant component due to equipment that runs continuously. For this reason, energy is displayed in a way that allows comparison with throughput, making it easier to identify unexpected deviations from normal operating patterns. Finally, costs are expressed primarily as unit cost (€/m³) rather than total cost. This approach removes the effect of seasonal variations in treated volume and makes it possible to compare efficiency across different periods. Absolute cost values are still available for budgeting and financial planning, but the main visual focus is on unit cost, as this provides a clearer measure of operational efficiency.

5.5.3.3. Technical Specification

The technical specification for the KPI focuses on the total unit process cost (UPC_NEUT), defined as the sum of total chemical expenditure and electrical energy consumption divided by the treated volume in the neutralization section as per the equation below:

$$UPC_{NEUT} = \frac{C_{chem,total} + C_{energy}}{V_{treated,NEUT}}$$

The chemical cost component includes the combined expenses for sulfuric acid, sodium hydroxide, and sodium carbonate, while the energy component corresponds to the electrical consumption measured by the section sub-meter EM-NEUT. The treated volume represents the daily flow processed in the neutralization stage. The calculation relies on several sub-indicators: manually updated unit prices for the three reagents based on supplier invoices.

Sub-indicator 1: Individual Chemical Unit Costs

The procurement price for each chemical reagent expressed in €/kg, obtained from supplier invoices and procurement contracts. These values are entered manually into the system when contracts are renewed or pricing adjustments occur, producing step-function behavior in the cost trend between updates. Sulfuric acid pricing typically reflects industrial commodity market trends with moderate volatility, while sodium hydroxide and sodium carbonate may exhibit different price dynamics depending on regional supply conditions and contractual arrangements.

Sub-indicator 2: Neutralization Energy Consumption

The electrical energy consumed by the neutralization section equipment is measured by a dedicated section sub-meter (EM-NEUT) integrating consumption across all electrical loads within the section boundary. The energy load comprises mixing equipment operating continuously within active basins and chemical dosing pumps whose consumption scales with dosing rate. The total energy consumption exhibits a linear-plus-constant relationship with throughput: a baseline component from

continuous mixing operations and a flow-proportional component from dosing pump activity.

Sub-indicator 3: Electricity Tariff

The cost per unit energy consumed, expressed in €/kWh. Tariff structures vary depending on contractual arrangements and may include time-of-day pricing components where applicable. The tariff value is entered manually into the system when contractual updates occur, consistent with the approach applied across all sections of the treatment plant.

Sub-indicator 4: Individual Chemical Costs

The cost for each individual chemical is calculated from the product of mass consumed and applicable unit cost: $C_{chem,i} = M_i \times P_i$. The individual chemical costs provide granularity for identifying which reagent is driving observed total chemical cost variations. Under normal conditions, sulfuric acid dominates total chemical cost, with NaOH and Na_2CO_3 contributing only during episodes requiring upward pH correction or alkalinity supplementation.

Sub-indicator 5: Specific Energy Consumption

It represents electrical energy consumed per unit volume treated, calculated as: $SEC_{NEUT} = E_{NEUT} / V_{treated,NEUT}$. This metric is not displayed as a primary KPI but is calculated for diagnostic purposes and available within the widget interface to enable decomposition of energy cost variations into consumption efficiency effects versus tariff pricing effects. Under stable conditions, SEC_{NEUT} should remain approximately constant with slight throughput dependence from the fixed mixing energy component.

Sub-indicator 6: pH Monitoring Across Neutralization Basins

The pH values measured continuously in each of the three sequential neutralization basins using standard glass electrode systems with reference junctions. While pH is not an economic sub-indicator, it is included within the KPI 7 visualization as process outcome context essential for interpreting cost efficiency, as described in the Design Rationale. The three pH measurements provide the progressive neutralization profile enabling assessment of dosing distribution quality and control stability.

5.5.3.4. Visual Display and Dashboard Widget

The visual representation of the KPI is structured into three coordinated charts. The first chart displays the unit prices of sulfuric acid, sodium hydroxide, and sodium carbonate as step-function trend lines, reflecting the episodic nature of procurement-driven price updates. The second chart presents the daily electrical energy consumption of the neutralization section as a continuous gray trend line

corresponding to the operation of mixing equipment and dosing pumps. The third chart, which constitutes the main diagnostic component, is divided into two sub-panels. The upper portion illustrates the pH evolution across the three sequential neutralization basins through three trend lines, each corresponding to one basin. The lower sub-panel of the third chart integrates treated volume and total unit cost through a dual-axis configuration, combining gray bars for daily volume with a dark blue line representing the unit cost. This integration allows operators to correlate cost fluctuations with hydraulic load and to identify whether cost anomalies arise from operational inefficiencies, chemical price changes, or variations in energy consumption. The combined diagnostic capability of the pH monitoring and cost analysis supports real-time operational decision-making. Suddenly deviations in pH trends leads to verification of dosing pump calibration, assessment of influent chemistry variations originating from the crystallizer, or adjustments to control algorithms. The multi-basin visualization enables intervention in advance by revealing early signs of instability before they affect the final effluent. The correlation with cost indicators further enhances diagnostic depth, as excessive pH oscillations often correspond to inefficient dosing strategies that increase chemical consumption through repeated overcorrection. Interactive features such as tooltips provide precise numerical values for pH, treated volume, and cost breakdowns, while alert indicators highlight excursions beyond acceptable or regulatory limits, ensuring timely corrective action.

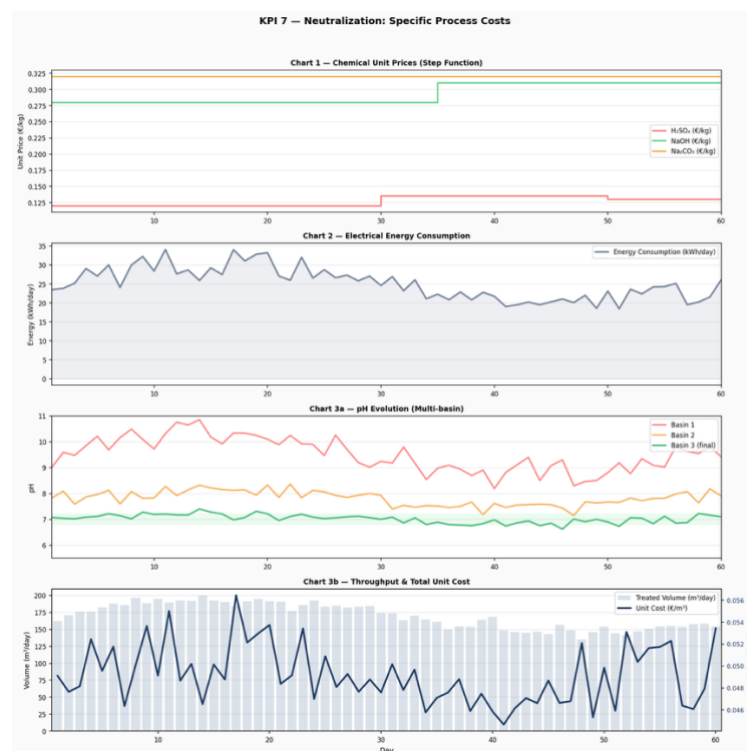


Figure 9: Conceptual dashboard mock-up for KPI 7 (AI-assisted design prototype; not based on operational data)

5.6. Biological Treatment Section KPIs

5.6.1. Section Overview

The biological treatment section employs aerobic and anoxic microbial processes to remove dissolved organic matter and nitrogen compounds from the chemically and physically conditioned water. This section is essential for achieving discharge compliance with biochemical oxygen demand ($\text{BOD}_5 \leq 25 \text{ mg/L}$), chemical oxygen demand ($\text{COD} \leq 125 \text{ mg/L}$) specified in Legislative Decree 152/06.

The biological treatment configuration adopts a process that integrates sequential anoxic and aerobic zones to achieve simultaneous organic matter oxidation and nitrogen removal through coupled nitrification-denitrification reactions. The process operates through two spatially separated zones serving distinct biochemical functions. The anoxic zone provides an oxygen-free environment where facultative heterotrophic bacteria reduce nitrate (NO_3^-) to nitrogen gas (N_2) using organic carbon as electron donor, a process termed denitrification. The aerobic zone maintains dissolved oxygen concentrations of 1.5-3.0 mg/L enabling aerobic processes: autotrophic nitrifying bacteria oxidize ammonia (NH_4^+) to nitrate through the two-step nitrification pathway, while heterotrophic bacteria simultaneously oxidize remaining organic matter. An internal recirculation loop transfers nitrate-rich mixed liquor from the aerobic to the anoxic zone at ratios of 3-4 times the inlet flow, supplying the nitrate electron acceptor required for denitrification while the influent provides the organic carbon electron donor. Following the biological oxidation processes, the treated water advances to a secondary clarifier where gravitational settling separates the biomass from the clarified water. The settled biomass is split into two streams: return activated sludge (RAS) recirculated to the anoxic zone to maintain the required microbial population concentration in the bioreactors, and waste activated sludge (WAS) withdrawn from the system to control the solids retention time and prevent excessive biomass accumulation. The clarified water leaving the secondary clarifier, while substantially reduced in organic matter and nitrogen compounds, still contains residual suspended solids and colloidal substances that require removal before advancing to the reverse osmosis stage. Following biological treatment, membrane filtration removes the remaining suspended solids before the reverse osmosis stage. Because this step plays a key role in protecting RO membranes and requires specific operational procedures, including backwashing and chemical cleaning, it is discussed separately with dedicated performance indicators.

5.6.2. Membrane Filtration: Sub-section Overview

The membrane filtration stage, located immediately downstream of biological treatment, provides complete removal of suspended solids, bacteria, and colloidal

particles that would otherwise cause rapid fouling of the reverse osmosis membranes. The system uses ultrafiltration (UF) or microfiltration (MF) with hollow-fiber membranes operating in outside-in mode. In this configuration, feed water flows from the outside of the fibers toward the inner channel, while the filtered water (permeate) is collected inside the fiber lumen. The system operates in cycles. During the filtration phase water passes through the membranes at design fluxes and particles are retained on the membrane surface. This is followed by a short backwash phase, during which permeate is pumped in the reverse direction to remove the accumulated solids layer. Regular backwashing is essential to maintain stable operation. Without periodic removal of the cake layer, hydraulic resistance would continuously increase, leading either to a drop in flux at constant transmembrane pressure or to an increase in transmembrane pressure at constant flux until operational limits are reached. The backwash stream, enriched with suspended solids, is sent to sludge handling. The performance of the biological treatment stage has a direct impact on membrane operation. Stable biological conditions that produce well-settling floc reduce the solids load reaching the membranes and therefore limit fouling and backwash frequency. In contrast, process disturbances such as sludge bulking or the formation of very fine, poorly aggregated floc led to higher carryover of suspended solids, accelerating fouling and potentially increasing the need for chemical cleaning. Biological performance also affects biofouling risk. Incomplete removal of dissolved organic matter can promote bacterial growth on membrane surfaces, while insufficient nitrification may allow ammonia to pass through, providing nutrients that support biological activity. Effective upstream treatment therefore reduces both particulate fouling and biological growth on the membranes. The permeate produced by membrane filtration, although largely free of suspended matter, still contains dissolved salts and low-molecular-weight organic compounds. Final removal of these dissolved species is achieved in the downstream reverse osmosis (RO) stage, which operates through a different separation mechanism based on selective diffusion across a semi-permeable membrane. The energy consumption in biological treatment is dominated by aeration, which typically represents 60-70% of section energy and constitutes the single largest energy consumer in the entire treatment plant. The aeration system must simultaneously satisfy biochemical oxygen demand from organic oxidation and nitrification while providing mixing energy to maintain solids suspension, creating inherent trade-offs between oxygen transfer efficiency.

5.6.3. KPI 8: Biological Treatment – Specific Chemical Characteristics

5.6.3.1. Context and Relevance

The integrated monitoring of hydraulic and chemical parameters in the biological treatment section is essential to ensure stable nitrification–denitrification performance and to prevent deterioration of effluent quality. Because biological reactions are

directly influenced by hydraulic conditions, parameters such as reactor water level and treated flowrate must be monitored together with chemical indicators. Reactor water level determines the effective reaction volume and therefore the hydraulic retention time (HRT). Any reduction in HRT, caused by low water level or increased flowrate, reduces the contact time between biomass and substrate and may compromise ammonia removal efficiency. Ammonium concentration is both the substrate for nitrification and a direct indicator of system performance. Elevated effluent ammonium may signal insufficient oxygen supply, inadequate retention time, or inhibition of nitrifying bacteria. Nitrate concentration provides confirmation of nitrification completeness and allows verification of nitrogen mass balance. Monitoring both parameters enables early detection of process instability. pH is critical because nitrification generates acidity. A progressive pH decrease may inhibit nitrifying bacteria, particularly below 6.5, and can lead to a decline in treatment efficiency if alkalinity is insufficient. Treated flowrate determines organic and nitrogen loading to the reactors and influences the food-to-microorganism ratio. Excessive loading may lead to substrate accumulation, while insufficient loading can result in biomass loss or reduced activity. Parallel monitoring of Train A and Train B is necessary due to the redundant configuration of the system. Comparative analysis allows rapid identification of operational imbalances and provides early warning of equipment or process anomalies.

5.6.3.2. Design Rationale

The development of KPI 8 required addressing a specific characteristic of biological treatment systems that differentiates them from upstream physio-chemical processes: biological performance cannot be meaningfully described through a single efficiency indicator. In contrast to chemical conditioning or neutralization, where a normalized consumption value or a cost per cubic meter can provide a concise measure of performance, biological treatment must be evaluated through the combined interpretation of several interrelated parameters. Each variable, when considered individually, offers limited explanatory value; only their joint analysis allows a reliable assessment of process stability.

The selection of the six monitored parameters reflects an effort to identify the minimum set of variables necessary to evaluate the correct functioning of the nitrification–denitrification process. Hydraulic retention time, derived from reactor level and flow rate, determines the contact time between biomass and substrate and represents a key operational condition influencing biological conversion. Dissolved oxygen regulates the metabolic pathway of the microbial community; insufficient oxygen levels reduce nitrification efficiency and may lead to incomplete oxidation. Ammonium concentration indicates the fraction of substrate not yet converted, while nitrate concentration represents the oxidation product, allowing verification of process

consistency through the expected stoichiometric relationship between ammonium removal and nitrate formation. Finally, pH reflects the acid–base balance within the reactor and acts as an early indicator of reduced buffering capacity, often preceding visible deterioration in effluent quality.

During the design phase, alternative composite indicators were considered, including nitrification efficiency (fractional ammonium removal) and volumetric nitrification rate. However, these indicators rely on influent ammonium measurements that are not continuously available. Their use as primary dashboard metrics would therefore introduce discontinuities and potentially misleading trends. For this reason, the dashboard prioritizes directly measured parameters, while derived performance indicators remain accessible for periods in which complete data are available. The decision to organize the six parameters into a hierarchical three-panel structure, rather than presenting them within a single multi-axis chart, reflects principles of effective information presentation. A single chart containing all parameters for both treatment trains would generate twelve concurrent trend lines, exceeding the threshold for rapid visual interpretation and increasing the risk of ambiguity. The adopted structure provides progressive detail: the first panel offers a plant-level overview (e.g., total throughput and reactor levels), enabling immediate assessment of overall system status, while the subsequent panels present train-specific information for diagnostic analysis when deviations occur. This arrangement reduces cognitive load during routine monitoring while preserving full analytical capability when required.

Within the train-specific panels, a dual-axis configuration is used to account for differences in measurement scale. Concentrations (dissolved oxygen, ammonium, nitrate) are expressed in mg/L and typically span a wider numerical range, whereas pH is dimensionless and varies within a narrow interval. Displaying all variables on a single axis would either compress pH variations or distort concentration trends. The dual-axis format maintains appropriate visual resolution for each parameter while preserving temporal comparability. An alternative design involving separate trend charts for each parameter was evaluated but not adopted. Although this approach would simplify individual visualization, it would limit the ability to identify temporal correlations among variables, which represent the primary diagnostic value of the KPI. For example, the simultaneous occurrence of a decrease in dissolved oxygen, an increase in ammonium, and a reduction in pH provides immediate evidence of aeration deficiency or hydraulic stress. Such relationships are more readily identifiable when parameters are displayed together. Finally, the parallel visualization of Train A and Train B serves a diagnostic purpose beyond redundancy control. Because both trains typically receive comparable influent conditions, their simultaneous display allows rapid identification of localized versus system-wide disturbances. If only one train shows performance degradation, the cause is likely associated with equipment or operational conditions specific to that unit. Conversely, simultaneous deviation in

both trains suggests an external or plant-wide factor. This comparative perspective enhances diagnostic reliability and supports timely operational decision-making.

5.6.3.3. Technical Specification

The integrated monitoring system tracks six primary parameters across both biological treatment trains, with each parameter defined through specific measurement principles and operational ranges:

Sub-indicator 1: Water Level

Water level in each train is measured using a level- transducers, with the measured height referenced to the bottom elevation of the reactor basin. The active volume at any instant is calculated as the product of water level and the cross-sectional area of the reactor, assuming constant geometry of the basin. Operational constraints typically define minimum and maximum permissible levels, where the minimum is set by the requirement to maintain adequate hydraulic retention time and the maximum is set by the need for freeboard to contain foam or floating solids without overflow. The instantaneous hydraulic retention time for each train follows directly from the ratio of active volume to influent flowrate, making this a derived rather than directly measured parameter.

Sub-indicator 2: Treated Flowrate

Treated flowrate is measured using dosing sensor of pumps within the sections. The total plant flowrate is obtained by summing the individual train flowrates, while the distribution between trains provides immediate indication of balance or imbalance in the hydraulic loading. From these flowrate measurements and the corresponding water levels, the instantaneous hydraulic retention time can be calculated for each train independently, allowing detection of situations where nominally parallel trains are operating at significantly different retention times due to level differences or flow maldistribution.

Sub-indicator 3: Dissolved Oxygen

Dissolved oxygen is measured continuously using on optical sensors based on fluorescence quenching. The operational range for aerobic nitrification is typically maintained between 1.5 and 3.0 mg/L, representing a compromise between ensuring adequate oxygen availability for the biological reactions and avoiding excessive energy consumption for aeration.

Sub-indicator 4: Ammonium Concentration

Ammonium concentration is measured either continuously using ion-selective electrodes or through discrete sampling with colorimetric analysis using the Nessler methods. The measurement provides direct indication of nitrification performance, with the removal efficiency calculated as the fractional reduction between influent and effluent concentrations.

Sub-indicator 5: Nitrate Concentration

Nitrate concentration is measured using either UV absorption spectrophotometry, with absorbance measured at 220 nanometers and corrected for organic interference at 275 nanometers. The nitrate measurement provides complementary information to the ammonium measurement because it represents the oxidation product rather than the residual substrate.

Sub-indicator 6: pH

pH is measured using standard glass electrode systems with reference junctions. The operational range is typically maintained between 6.8 and 7.8, with the lower limit set by inhibition of nitrifying bacteria below pH 6.5 and the upper limit set by the shift of ammonia speciation toward toxic free ammonia above pH 8.

5.6.3.4. Visual Display and Dashboard Widget

The visual presentation of these parameters is organized in a three-panel hierarchical structure that provides progressive details. This organization allows operators to quickly assess overall system status and then focus on detailed trends within individual treatment trains as needed.

The first panel presents plant-level overview information combining hydraulic loading and reactor levels. This panel employs a dual-axis time series in which the primary vertical axis displays the total treated water in the section as a continuous trendline. This line is rendered in black with moderate thickness to ensure clear visibility and uses either linear or cubic spline interpolation to smooth minor fluctuations while preserving significant trends. The secondary vertical axis, positioned on the right side of the same graph, displays water level for both treatment trains using a grouped bar chart format. Each time point shows two adjacent bars representing Train A (in blue color) and Train B (in orange color) water levels respectively, in a transparent color. The transparency allows visual detection of overlapping values while the color distinction enables immediate identification of which train exhibits higher or lower levels at any given time. This combined presentation of flowrate and water level in a single panel serves a specific diagnostic purpose. Since hydraulic retention time depends on the ratio of volume to flowrate, simultaneous visualization of both parameters allows immediate assessment of

whether changes in water level are responsive to flowrate variations or indicate other issues such as valve malfunctions or unintended drainage. For example, if flowrate increases while water levels remain constant, this suggests that the effluent control system is responding appropriately to maintain constant volume. Conversely, if water levels decline while flowrate remains steady, this indicates a loss of volume that requires investigation.

The panel includes horizontal reference lines at critical elevations. A red dashed line marks the minimum permissible water level, below which hydraulic retention time becomes insufficient for complete biological treatment. A green dashed line marks the design water level, representing normal operating conditions. These reference lines provide immediate visual context for assessing whether current levels fall within acceptable ranges. The visualization incorporates conditional formatting such that when water level in either train falls below the minimum, the corresponding bar changes from its standard color to red, providing an unmistakable alert condition. Similarly, if water level exceeds the maximum permissible value, the bar changes to yellow, indicating potential overflow risk.

The widget's second and third panels display trends for Train A and Train B, using an identical layout for direct comparison. Multiple parameters are plotted on a dual-axis time series, allowing correlations across variables to be observed simultaneously. The left axis shows key concentrations: dissolved oxygen, ammonium and nitrate. The right axis shows pH. By presenting these parameters together, the widget enables rapid assessment of process stability, highlighting deviations or anomalies and supporting monitoring and operational decision-making. This stable baseline pattern allows immediate recognition of abnormal conditions.

In the event of hydraulic overload in Train A, the first observable change is an increased flowrate, potentially lowering water levels in that train. Dissolved oxygen may drop as aeration struggles to meet higher demand, ammonium rises due to incomplete nitrification, and nitrate may plateau or decrease. pH can shift slightly depending on the balance between reduced nitrification and accumulation of organic acids. Critically, simultaneous observation of panel three showing Train B allows immediate determination that the performance degradation is specific to Train A rather than a plant-wide phenomenon affecting both trains equally. If Train B parameters remain stable while Train A parameters deviate, this confirms that the root cause is specific to Train A, such as a malfunctioning valve or local equipment failure. If both trains show similar deviations, this suggests a plant-wide cause such as increased influent strength or temperature change affecting biological kinetics throughout the system.

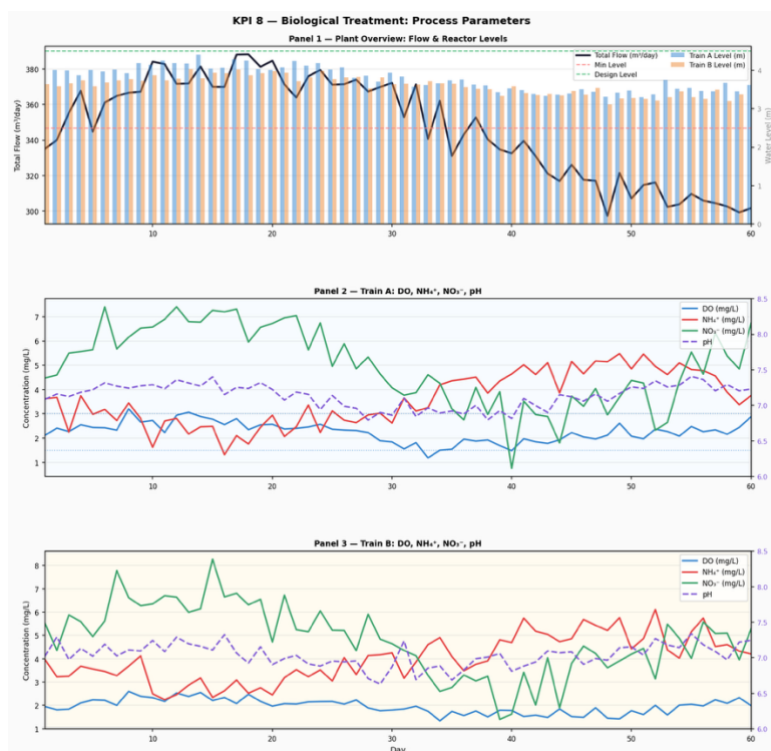


Figure 10: Conceptual dashboard mock-up for KPI 8 (AI-assisted design prototype; not based on operational data)

5.6.4. KPI 9: Biological Treatment – Specific Chemical Consumption

5.6.4.1. Context and Relevance

The biological treatment section utilizes three chemical reagents whose consumption patterns are governed by microbial process requirements rather than physicochemical treatment objectives, distinguishing them fundamentally from upstream chemical conditioning stages. Phosphoric acid is dosed to correct phosphorus deficiency in the influent produced water, maintaining the nutrient stoichiometry required for heterotrophic biomass metabolism; its consumption scales primarily with biomass inventory expressed as mixed liquor suspended solids concentration and with solids retention time, which increases during colder periods due to temperature-dependent reductions in biological kinetic rates, thereby raising the standing biomass and its associated phosphorus demand. Nutrient solutions provide essential trace elements that sustain enzymatic pathways critical for substrate oxidation and nitrification; dosing is typically intermittent and responsive, triggered by performance deterioration indicators such as declining nitrification efficiency or rising effluent ammonia concentrations rather than maintained at a fixed continuous rate. Polyelectrolyte is applied reactively to restore sludge settleability when the sludge volume index exceeds operational thresholds, addressing filamentous bulking or dispersed growth conditions that compromise secondary clarifier performance; its

consumption is therefore episodic and strongly correlated with settling quality rather than with hydraulic or organic loading.

The seasonal dimension represents a unifying driver across all three reagents: lower temperatures simultaneously increase solids retention time, elevate biomass concentration, reduce biological reaction rates, and may destabilize floc structure, producing concurrent increases in phosphoric acid demand, potential nutrient solution interventions, and polymer usage events. Specific chemical consumption indicators for this section provide diagnostic value by linking reagent utilization intensity to process state variables, enabling differentiation between demand increases driven by planned biomass management strategies and those signaling developing process instabilities such as nutrient limitation, nitrification inhibition, or sludge settling deterioration. Their interpretation requires concurrent evaluation of biological performance metrics including mixed liquor suspended solids, solids retention time, sludge volume index, dissolved oxygen profiles, and effluent nutrient concentrations to establish whether consumption variations reflect controlled operational adjustments or corrective responses to emerging process deviations.

5.6.4.2. Design Rationale

KPI 9 for the biological treatment section adopts the methodological framework established for chemical conditioning in Section 5.3.2, including specific consumption normalization per unit volume treated, dual-measurement verification, and inventory monitoring based on days-of-supply. Calculation procedures, visualization architectures, and diagnostic decomposition strategies follow established specifications, with the present section addressing only adaptations required by the intrinsic characteristics of biological processes. Full technical specifications are documented in system configuration materials.

Biological treatment exhibits strong temperature dependence, particularly for nitrification kinetics, which leads to seasonal variations in phosphorus demand independent of throughput. To prevent misinterpretation of expected winter increases in phosphoric acid consumption as inefficiencies, temperature data are integrated into KPI 9 visualization to contextualize stoichiometric variations. In addition, certain reagents, such as nutrient solutions and polyelectrolytes, display intermittent or episodic consumption patterns in which zero usage represents normal operation; alarm logic is therefore adjusted to distinguish between inactive periods and abnormal dosing during active events. Inventory management thresholds are differentiated according to process criticality and failure timescales, reflecting the rapid impact of phosphorus deficiency compared to slower degradation associated with other additives. The interpretation of biological chemical consumption further requires integration with performance indicators, as consumption trends alone are insufficient to diagnose process conditions. For this reason, KPI 9 incorporates contextual

visualization of key biological parameters, such as sludge settleability and effluent ammonia, enabling distinction between appropriate reactive dosing and underlying process deterioration. Detailed calculation procedures, instrumentation references, alarm thresholds, and visualization specifications follow the documentation standards established for the conditioning section, with parameter substitution reflecting the biological process configuration, and are formalized in system configuration and operator documentation.

5.6.4.3. Technical Specification

The Specific Chemical Consumption indicator for the biological treatment section includes consumption monitoring for three distinct chemical reagents, each measured through instrumentation appropriate to its physical form and dosing characteristics. No composite aggregation across chemical species is performed; each reagent consumption is tracked separately to preserve functional and diagnostic distinctions between these chemically and operationally distinct treatment inputs. The specific consumption for each chemical species i is calculated as the mass consumed per unit volume of water treated in the biological treatment section over the aggregation period:

$$SCC_i = (M_i / V_{treated,BIO}) \times 1000$$

Where M_i indicates the total mass of chemical i used during the selected aggregation period, expressed in kilograms, and $V_{treated,BIO}$ represents the total volume of water treated in the biological section over the same period, expressed in cubic meters. The multiplication factor 1000 is applied to convert the result from kilograms per cubic meter (kg/m^3) to grams per cubic meter (g/m^3), which is the standard unit commonly used to report specific chemical consumption. The mass of each substance is determined through measurement approaches consistent with those established for chemical conditioning. For liquid chemicals (phosphoric acid, nutrient solution), the primary measurement employs totalizing flowmeters integrated within the dosing pumps, which accumulate volumetric dose delivered and convert to mass through the known density of the solution. The secondary measurement employs level transmitters on the storage tank, calculating mass consumption from inventory drawdown over the measurement period accounting for any deliveries received:

$$M_i = (L_0 - L_1) \times A_{tank} \times \rho_i + M_{delivered}$$

Where L_0 and L_1 represent the tank levels measured at the beginning and at the end of the aggregation period, respectively, and A_{tank} is the cross-sectional area of the tank, used to calculate the change in stored volume based on the level variation. The parameter ρ_i represents the density of the chemical solution, which is needed to convert volume into mass. Finally, $M_{delivered}$ refers to the total mass of chemical supplied and added to the tank during the same period.

For polyelectrolyte, which may be prepared from solid powder in dissolution tanks prior to dosing, the consumption measurement relies on dissolution batch records combined with prepared solution tank level monitoring, providing an indirect but operationally verified mass balance approach.

Sub-indicator 1: Specific Phosphoric Acid Consumption

The specific consumption of phosphoric acid (H_3PO_4 , liquid form) is calculated as the mass of phosphoric acid consumed per unit volume of water treated in the biological treatment section over the aggregation period. Dual-measurement verification combines dosing pump flowmeter totalizers (primary measurement) with storage tank level drawdown (secondary verification). Phosphoric acid consumption exhibits continuous patterns with seasonal modulation driven by temperature-dependent solids retention time variations and corresponding biomass inventory changes. Under stable operating conditions, consumption scales approximately with the product of mixed liquor suspended solids concentration and treated volume, reflecting the stoichiometric phosphorus requirement of the active biomass.

Sub-indicator 2: Specific Nutrient Solution Consumption

The specific consumption of nutrient solution (liquid form) is calculated identically to phosphoric acid consumption, employing the same dual-measurement verification approach. Nutrient solution consumption exhibits intermittent patterns, with extended periods of zero consumption during stable biological conditions and activation triggered by performance deterioration indicators such as declining nitrification efficiency or elevated effluent ammonia concentration. The alarm logic distinguishes between inactive periods representing normal operation and abnormal non-dosing during states where active supplementation would be required, using state-dependent threshold criteria as described in the Design Rationale.

Sub-indicator 3: Specific Polyelectrolyte Consumption

The specific consumption of polyelectrolyte is calculated from prepared solution dosing records and dissolution batch tracking. Consumption is episodic and correlated with sludge settling quality deterioration events, appearing as discrete consumption peaks against a baseline of zero usage during periods of normal settleability. The consumption rate during active dosing episodes is monitored to verify that dosing intensity is appropriate for the severity of the settling problem, with reference to sludge volume index values and secondary clarifier blanket depth observations when available.

Sub-indicator 4: Chemical Storage Inventory

The chemical storage tank inventory levels are monitored continuously for all three reagents to support supply chain management and provide independent consumption

verification through mass balance reconciliation. Inventory is expressed as absolute volume (m³) and as days of supply at current consumption rate:

$$I_{chemical} = L_{current} \times A_{tank}$$

$$Days_{supply} = (I_{chemical} \times \rho_{chemical}) / M_{chemical,daily}$$

Where $M_{chemical,daily}$ represents the rolling 7-day average daily consumption for the respective chemical, providing a smoothed estimate of consumption rate less sensitive to day-to-day variations than single-day consumption values. Inventory management thresholds are differentiated according to process criticality: phosphoric acid employs a reorder point of 14 days of supply and a critical low threshold of 7 days, reflecting the rapid consequences of phosphorus deficiency on activated sludge performance; nutrient solution and polyelectrolyte employ standard thresholds of 7 days (reorder) and 3 days (critical), with additional consideration of active versus inactive dosing status in threshold interpretation.

Sub-indicator 5: Water Treated in Biological Treatment Section

The water volume treated in the biological treatment section is measured at the section inlet using flowmeters consistent with plant-level methodology but reported independently to enable section-specific normalization. This volume provides the normalization denominator for all specific consumption calculations. Under normal operation, $V_{treated,BIO}$ may differ from $V_{treated,CC}$ due to intermediate recirculation streams, bypass flows, or backwash water returns from the downstream membrane filtration stage.

5.6.4.4. Visual Display and Dashboard Widget

This KPI is structured as an integrated three-chart widget designed to interpret reagent consumption in relation to biological process performance and operational conditions. The layout follows the vertically stacked configuration with a shared time axis adopted throughout the KPI framework, while incorporating contextual elements specific to biological treatment that are not required in upstream physico-chemical sections.

The first chart presents total daily chemical expenditure expressed in monetary terms and displayed as a stacked area graph. Total cost is divided into contributions from phosphoric acid, polyelectrolyte, and nutrient solution, each represented by a distinct color layer. The daily treated volume is superimposed to provide operational context. Under normal conditions, phosphoric acid represents the main and continuous cost component, with gradual seasonal increases during colder periods due to temperature-related process demand. Polyelectrolyte appears as intermittent peaks, typically associated with temporary deterioration in sludge settleability, while nutrient solution is used only episodically in response to influent deficiencies.

Prolonged periods with no expenditure for these latter chemicals are generally consistent with stable biological operation.

The second chart combines specific consumption trends with storage inventory levels and includes a temperature overlay. Specific consumption for each chemical is represented as a time-series trend, while inventory levels are displayed as bar indicators referenced against predefined days-of-supply thresholds reflecting different levels of process criticality. Temperature is included because biological reaction rates are influenced by seasonal variations. In stable conditions, phosphoric acid consumption tends to increase as temperature decreases, whereas nutrient and polyelectrolyte consumption remain negligible except during specific operational events. This integrated view supports differentiation between expected seasonal variability and anomalous consumption patterns, while also assisting in procurement planning.

The third chart introduces direct process performance context. The upper panel displays treated volume within the biological section together with effluent ammonium concentration in relation to the regulatory limit. This representation allows normalization of chemical usage across different operating periods and provides an immediate link between reagent consumption and treatment effectiveness.

By presenting cost, specific consumption, inventory status, temperature, and effluent performance in a coordinated structure, the widget transforms chemical monitoring into a diagnostic support tool. The visual correlation across the three charts facilitates the distinction between normal biological variability, such as seasonal fluctuations, and abnormal conditions requiring corrective action, including persistent sludge bulking, nutrient imbalance, or broader process disturbances. The inclusion of temperature and effluent quality data enhances interpretative depth and addresses the inherent complexity of biological systems, where similar consumption patterns may correspond to different underlying process conditions.

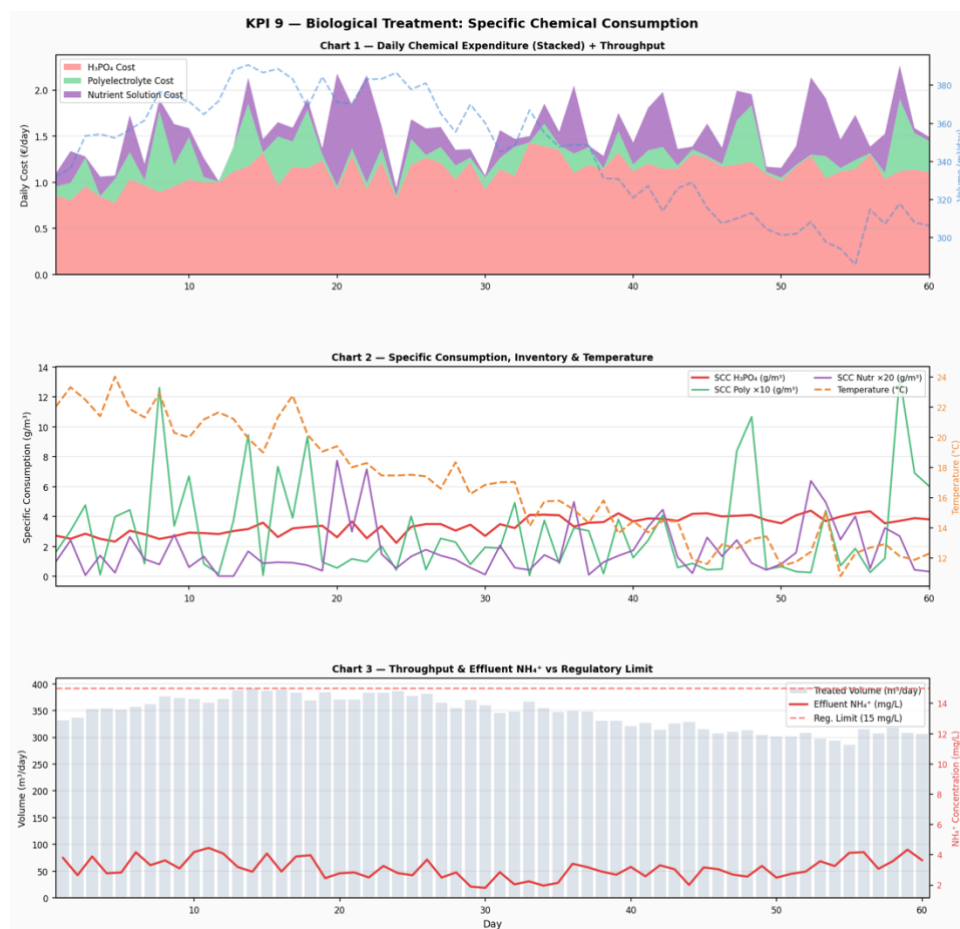


Figure 11: Conceptual dashboard mock-up for KPI 9 (AI-assisted design prototype; not based on operational data)

5.6.5. KPI 10: Biological Treatment – Specific Process Costs

5.6.5.1. Context and Relevance

The biological treatment section is evaluated through two economic performance indicators: specific chemical consumption, which quantifies reagent utilization intensity and specific process costs, which integrate chemical, energy, and sludge management expenditures into a comprehensive economic assessment. Chemical usage in this section differs fundamentally from upstream chemical conditioning and others, as it supports microbial stability rather than physicochemical particle removal. Phosphoric acid is applied to maintain balanced nutrient ratios required for activated sludge processes, particularly where industrial produced water is phosphorus-deficient, with demand influenced by biomass inventory and temperature-dependent kinetics that increase solids retention time during colder periods. Nutrient solutions supply essential trace elements necessary for enzymatic activity and are dosed intermittently in response to performance deterioration rather than continuously. Polyelectrolytes are used reactively to improve sludge settleability and control bulking

phenomena when settling indicators exceed acceptable thresholds. The cost structure in biological treatment is characterized by energy dominance, as aeration for dissolved oxygen control represents the majority of operating expenditures, substantially exceeding the relative contribution of chemicals. Seasonal temperature reductions further increase costs due to decreased oxygen transfer efficiency and slower biological reaction rates, which require extended biomass retention and higher aeration demand. Sludge disposal constitutes a significant secondary cost component, as waste activated sludge has high organic content, limited recovery potential, and elevated handling requirements. In contrast, reagent costs account for a comparatively minor share of total expenses, shifting optimization priorities toward aeration efficiency and process control rather than chemical minimization. These indicators provide operational and strategic value by supporting monitoring of biological stability, procurement planning for specialized reagents, and correlation of consumption trends with performance metrics such as mixed liquor suspended solids, sludge settleability, and nitrification efficiency. Their interpretation requires integrated analysis with process performance data, as variations in ammonia concentration, polymer demand, or energy expenditure may reflect nutrient limitation, sludge settling deterioration, or temperature-driven operational adjustments rather than isolated inefficiencies.

5.6.5.2. Design Rationale

KPI 10 for the biological treatment section adopts the methodological framework established for chemical conditioning in Section 5.3.3, including the three-component cost structure integrating chemicals, energy, and sludge management. Cost decomposition logic, attribution of variations to throughput, efficiency, or pricing effects, and visualization architecture are maintained to ensure methodological consistency and cross-section comparability. The present section addresses only adaptations required by the intrinsic characteristics of biological processes. Full technical specifications are documented in system configuration materials. Although biological treatment presents an inverted cost structure relative to conditioning, characterized by energy dominance and comparatively minor chemical expenditure, the visualization architecture of KPI 10 remains unchanged to preserve analytical coherence. Operational emphasis shifts toward aeration efficiency and sludge management rather than reagent optimization, reflecting the dominant contribution of dissolved oxygen control to total operating expenditure and the significant secondary role of waste activated sludge disposal costs. Seasonal temperature reductions further increase costs due to decreased oxygen transfer efficiency and slower biological reaction rates, which require extended biomass retention and higher aeration demand. KPI 10 enables structured diagnostic decomposition of expenditure variations, distinguishing throughput-driven changes, temperature-related seasonal effects, efficiency degradation, procurement impacts, and genuine process deterioration. By correlating costs, consumption, throughput, and biological performance context

within a unified framework, the indicator supports proactive operational optimization and informed cost management. Detailed calculation procedures, instrumentation references, alarm thresholds, and visualization specifications follow the documentation standards established for the conditioning section, with parameter substitution reflecting the biological process configuration, and are formalized in system configuration and operator documentation.

5.6.5.3. Technical Specification

The Biological Treatment Process Costs indicator comprises total process cost calculation integrating chemical, energy, and sludge management cost components, with diagnostic decomposition enabled through presentation of constituent factors including unit costs, consumption rates, energy consumption, and treated volume. All cost calculations are expressed in € (euros). The primary indicator is the Total Unit Process Cost (UPC_BIO) representing the total operational expenditure per cubic meter of water treated in the biological treatment section:

$$UPC_{BIO} = (C_{chem,total} + C_{energy} + C_{sludge}) / V_{treated,BIO}$$

Where $C_{chem,total}$ represents the total cost of all chemical reagents used in the biological treatment section during the aggregation period, expressed in euros, and C_{energy} corresponds to the electrical energy costs incurred over the same period. The term C_{sludge} indicates the cost associated with sludge management, specifically the disposal of waste activated sludge generated during treatment. Finally, $V_{treated,BIO}$ represents the volume of water treated in the biological treatment section during the aggregation period, expressed in cubic meters, and is used to normalize total costs on a unit basis.

The total chemical cost is calculated as the sum of individual reagent costs:

$$C_{chem,total} = \sum (M_i \times P_i)$$

Where M_i is the mass consumed of chemical species i and P_i is the unit cost of chemical i (€/kg), with the summation performed over the three reagents (phosphoric acid, nutrient solution, polyelectrolyte).

The energy cost is calculated from measured electrical consumption and applicable electricity tariff:

$$C_{energy} = E_{BIO} \times T_{elec}$$

Where E_{BIO} is the electrical energy consumed in the biological treatment section (kWh) measured by a dedicated section sub-meter (EM-BIO), integrating consumption across all electrical loads within the section boundary including aeration blowers, return and waste activated sludge pumps, internal recirculation pumps, and mixing systems. T_{elec} is the electricity tariff (€/kWh) applicable during the period, consistent with the tariff structure applied across all sections of the treatment plant.

The sludge management cost is calculated from the blended average unit cost and waste activated sludge production:

$$C_{sludge} = M_{sludge,BIO} \times P_{sludge}$$

Where $M_{sludge,BIO}$ is the mass of dry sludge solids generated through waste activated sludge withdrawal during the period (tonnes dry solids), estimated from WAS flow measurement combined with sludge concentration analysis or from direct measurement where section-specific sludge metering is available, and P_{sludge} is the net unit cost of sludge management (€/tonne dry solids) from waste management contractor invoices. Unlike the crystallizer section where sludge recovery arrangements may generate revenue offsets, biological waste activated sludge typically incurs disposal costs only, with the net sludge cost therefore equal to the gross disposal cost.

Sub-indicator 1: Individual Chemical Unit Costs

The procurement price for each chemical reagent expressed in €/kg, obtained from supplier invoices and procurement contracts. These values are entered manually into the system when contracts are renewed or pricing adjustments occur, producing step-function behavior in the cost trend between updates. Phosphoric acid pricing may reflect broader commodity market trends for phosphate chemicals, whereas polyelectrolyte often exhibits greater price volatility due to specialty chemical market dynamics and polymer-specific formulation costs.

Sub-indicator 2: Biological Treatment Energy Consumption

The electrical energy consumed by the biological treatment section equipment is measured by a dedicated section sub-meter (EM-BIO) integrating consumption across all electrical loads within the section boundary. Aeration blowers constitute the dominant component, typically representing 60–70% of total section energy consumption, with return and waste activated sludge pumps, internal recirculation pumps, and mixing systems accounting for the remainder. The energy measurement includes both flow-proportional loads and fixed loads that operate regardless of throughput within the active treatment trains.

Sub-indicator 3: Electricity Tariff

The cost per unit energy consumed, expressed in €/kWh. Tariff structures vary depending on contractual arrangements and may include time-of-day pricing components where applicable. The tariff value is entered manually into the system when contractual updates occur, consistent with the approach applied across all sections of the treatment plant.

Sub-indicator 4: Individual Chemical Costs

The cost for each individual chemical is calculated from the product of mass consumed and applicable unit cost: $C_{chem,i} = M_i \times P_i$. The mass consumed values are obtained from the specific chemical consumption monitoring established in KPI 9, ensuring consistency between the physical consumption indicator and its economic translation.

The individual chemical costs provide granularity for identifying which reagent is driving observed total chemical cost variations.

Sub-indicator 5: Specific Energy Consumption

It represents electrical energy consumed per unit volume treated, calculated as: $SEC_BIO = E_BIO / V_treated,BIO$. This metric is not displayed as a primary KPI but is calculated for diagnostic purposes and available within the widget interface to enable decomposition of energy cost variations into consumption efficiency effects versus tariff pricing effects. Under stable biological conditions and constant temperature, SEC_BIO should remain approximately constant across throughput variations, with deviations indicating either process efficiency changes or the influence of fixed energy loads at reduced throughput.

Sub-indicator 6: Sludge Management Cost

The sludge management cost attributed to the biological treatment section is calculated from the product of estimated waste activated sludge dry solids production and the blended average unit disposal cost. Sludge production is estimated from WAS flow measurement combined with periodic total suspended solids analysis of the waste sludge stream, or from mass balance calculations incorporating influent loading, effluent quality, and biomass inventory changes. The unit disposal cost (€/tonne dry solids) is obtained from waste management contractor invoices, entered manually into the system on a periodic basis (typically monthly following receipt of invoices), reflecting the blended average disposal cost accounting for actual disposal volumes and invoiced amounts during the billing period.

5.6.5.4. Visual Display and Dashboard Widget

KPI 10, Specific Process Costs, is structured as a three-chart widget that breaks down total biological treatment expenditure into its principal economic drivers while preserving methodological consistency with the chemical conditioning framework. The first chart presents unit procurement costs for phosphoric acid, polyelectrolyte, and nutrient solution as step-function trend lines. Prices remain constant between contract renewals and change discretely when updated supplier agreements are implemented. This representation enables clear identification of procurement-driven cost variations, distinguishing them from operational inefficiencies. Phosphoric acid pricing may reflect broader commodity market trends, whereas polyelectrolyte often exhibits greater volatility due to specialty chemical market dynamics. Step changes observed in this chart provide explanatory context for unit cost variations displayed elsewhere in the widget. The second chart displays daily electrical energy consumption measured by a dedicated sub-meter for the biological section, aggregating aeration blowers, return and waste activated sludge pumping and mixing systems. Aeration constitutes the dominant share of this consumption, and energy use

typically correlates with treated volume. Seasonal patterns are evident, as winter operation requires increased energy input due to reduced oxygen transfer efficiency and slower biological kinetics, often resulting in substantially higher consumption at equivalent throughput. Progressive baseline increases in energy demand, independent of loading or temperature, may indicate declining aeration efficiency, such as diffuser fouling, and therefore serve as an early signal for maintenance intervention. The third chart integrates treated volume and total unit process cost in a dual-axis format, enabling simultaneous visualization of throughput and normalized expenditure per unit volume. Stable unit costs across variable throughput indicate consistent operational efficiency, whereas cost increases during low-load conditions may reveal the influence of fixed energy components. Seasonal cost elevations aligned with temperature reductions generally reflect expected biological and aeration responses, while discrete unit cost shifts coinciding with procurement price updates are attributable to contractual changes rather than performance degradation. Conversely, gradual cost escalation under stable throughput and pricing conditions suggests declining process efficiency and warrants correlation with energy trends and biological performance indicators. The diagnostic workflow inherent in this structure begins with identification of anomalies in total unit cost, followed by systematic verification of procurement pricing and energy consumption patterns, and, where necessary, cross-referencing with biological performance metrics. This structured decomposition enables targeted investigation of cost deviations, differentiating procurement effects, operational inefficiencies, and genuine process deterioration. The widget maintains visual and analytical coherence with the established conditioning framework while integrating the biological-specific context necessary for accurate interpretation of cost dynamics in activated sludge systems.

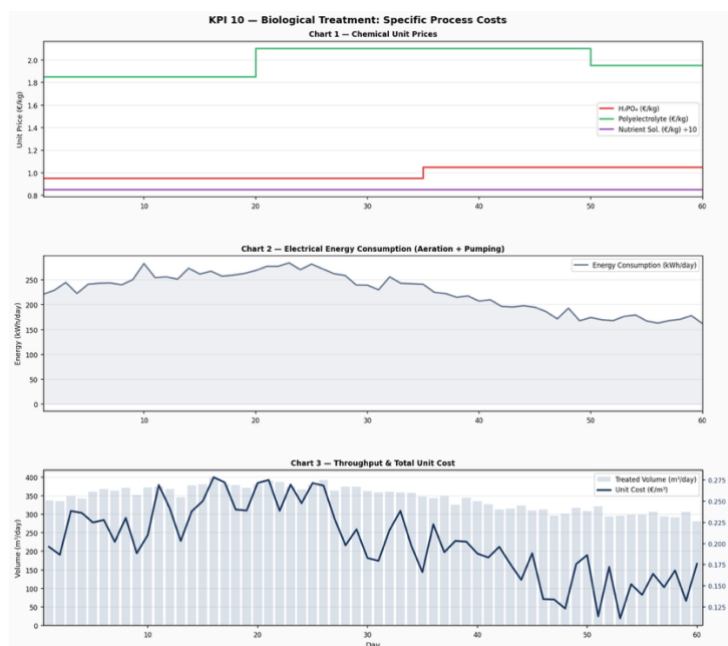


Figure 12: Conceptual dashboard mock-up for KPI 10 (AI-assisted design prototype; not based on operational data)

5.7. Reverse Osmosis Section KPIs

5.7.1. Section Overview

The reverse osmosis (RO) stage constitutes the final treatment barrier and is designed to remove dissolved salts and residual contaminants from the pretreated water. It operates through semi-permeable membranes that allow water to pass while retaining dissolved ionic species under applied pressure. The effectiveness and reliability of this stage depend critically on upstream ultrafiltration, which removes suspended solids and colloidal matter, thereby preventing particulate fouling of the RO membranes. Unlike ultrafiltration membranes, RO membranes are highly sensitive to solids due to their dense structure and narrow flow channels and therefore require essentially particle-free feed water. Although suspended solids are removed upstream, dissolved scaling compounds remain in solution and may concentrate during RO operation as water permeates and salts accumulate in the reject stream. Scaling risk is partially mitigated upstream through controlled precipitation processes, while within the RO section it is managed through continuous dosing of antiscalant to inhibit mineral precipitation. Additional chemical conditioning includes the use of biocide to control biological growth and sodium bisulfite ($NaHSO_3$) to remove residual oxidants that could damage the membranes. These chemicals are essential to preserve membrane integrity and sustain stable long-term performance.

Energy consumption in the RO stage is primarily associated with high-pressure pumping and represents a major operational cost component, despite the relatively smaller treated volume compared to earlier process stages. Actual energy demand exceeds the theoretical minimum required for salt separation due to practical inefficiencies and hydraulic losses inherent in real systems. Consequently, energy optimization is a central consideration in RO operation. Membrane replacement constitutes a significant lifecycle cost, as membrane elements have finite service lives that depend on feed water quality and operating conditions. Performance monitoring is therefore essential and typically includes tracking permeate flow, salt rejection efficiency, and integrity indicators. These parameters enable early detection of fouling, chemical degradation, or mechanical damage, allowing planned maintenance and replacement before water quality is compromised.

5.7.2. KPI 11: Reverse Osmosis: Specific Chemical Consumptions

5.7.2.1. Context and Relevance

Monitoring chemical consumption in the reverse osmosis stage is essential for both economic and technical reasons. As discussed in the process overview, chemical costs represent the dominant operational cost component of the RO system, significantly exceeding energy costs and accounting for a large share of total lifecycle expenditure. For this reason, tracking chemical usage is necessary to support budget control, cost forecasting, and identification of possible efficiency improvements. In addition to cost control, chemical consumption is also an important indicator of process performance. The RO system requires continuous dosing of three main chemicals: antiscalant to prevent mineral scaling on membrane surfaces, biocide to control biological growth, and sodium bisulfite (NaHSO_3) to remove residual oxidants that could damage the membranes. Each chemical plays a specific protective role. Changes in consumption levels may therefore indicate changes in operating conditions or emerging problems. Under stable operating conditions, chemical dosing should remain relatively constant when related to the amount of water produced. For this reason, consumption is typically evaluated using a specific consumption indicator, expressed as mass of chemical per volume of permeate produced (e.g., kg/m^3). An increase in specific chemical consumption may suggest deterioration in feed water quality, reduced effectiveness of upstream treatment, or the beginning of membrane fouling. For example, increasing antiscalant consumption may indicate higher scaling risk, while higher biocide use may reflect increased biological activity in the system. Chemical monitoring is also linked to inventory management. Storage tanks have limited capacity, and delays in chemical supply could force system shutdown if protective dosing cannot be maintained. At the same time, excessive stock increases tied-up capital and storage risks. Monitoring consumption trends therefore supports both operational continuity and financial efficiency. Overall, the KPI for chemical

consumption provides a practical tool for controlling operating costs, maintaining membrane protection, and evaluating the stability of the RO process.

5.7.2.2. Design Rationale

The design of KPI 11 follows the general methodological approach already introduced for chemical conditioning. The same overall logic is maintained in order to ensure consistency across all sections of the plant and allow meaningful comparison between KPIs. Specific consumption is normalized, storage levels are monitored in relation to expected days of supply, and the visual structure remains aligned with the framework adopted throughout the thesis. However, the RO section presents operational characteristics that require specific adaptations in the design logic of the visual widget. The most relevant design choice concerns how chemical consumption is related to plant output. In upstream sections, consumption is linked to the total volume of water entering the treatment stage, since this volume represents the reference for contaminant removal. In the RO section, instead, the incoming flow is divided into two streams: permeate (the treated product water) and concentrate (the reject stream). For this reason, using the total inlet volume as the only reference would not fully reflect the economic purpose of chemical dosing.

Chemicals in the RO system are primarily used to protect membrane performance and ensure stable production of permeate. Therefore, consumption is related to permeate production, which represents the actual product of the process. This choice makes the indicator more meaningful from an operational and economic perspective, since it expresses chemical use per unit of product water. The inlet flow remains available as a secondary reference, but permeate production is considered the most representative basis for performance evaluation.

Another important design consideration concerns the different roles of the chemicals used in the RO section. Unlike upstream processes, where chemicals often have similar dosing patterns, RO chemicals serve distinct protective functions and may show different usage trends over time. Some are dosed continuously, others intermittently depending on operating conditions. For this reason, the visualization keeps the consumption of each chemical clearly distinguishable rather than combining them into a single aggregated value. This approach supports clearer interpretation and aligns with the general philosophy adopted throughout the KPI framework.

A further adaptation relates to the need to interpret chemical consumption together with membrane performance. In upstream sections, consumption can often be assessed mainly in relation to cost and treated volume. In the RO section, however, chemical dosing serves a preventive function: it protects membranes from scaling, fouling, or chemical damage. As a result, lower consumption does not automatically

indicate improved efficiency. A reduction in dosing could, in some cases, anticipate membrane performance deterioration. Conversely, increased dosing may represent an appropriate response to changing feed conditions. For this reason, the visual design integrates chemical consumption with contextual information on membrane performance. This combined perspective allows the user to distinguish between genuine efficiency improvements and situations in which membrane protection may be insufficient. The objective is not simply to report consumption values, but to support informed interpretation of their operational meaning.

The overall structure of the widget remains consistent with the vertically organized format used throughout the thesis, ensuring visual coherence and comparability. At the same time, the content is adapted to reflect the specific nature of the RO process, where product quality and membrane condition play a central role in interpreting chemical usage. In this way, KPI 11 maintains methodological continuity with the rest of the framework while addressing the particular interpretative challenges of reverse osmosis systems.

5.7.2.3. Technical Specification

The Specific Chemical Consumption indicator for the reverse osmosis section includes consumption monitoring for three distinct chemical reagents employed for membrane protection, each measured through instrumentation appropriate to its physical form and dosing characteristics. No composite aggregation across chemical species is performed; each reagent consumption is tracked separately to preserve functional and diagnostic distinctions. The specific consumption for each chemical species i is calculated as the mass consumed per unit volume of permeate produced over the aggregation period:

$$SCC_i = (M_i / V_{permeate}) \times 1000$$

Where M_i represents the total mass of chemical species i consumed during the selected aggregation period, expressed in kilograms, and $V_{permeate}$ denotes the total volume of permeate produced by the reverse osmosis section over the same period, expressed in cubic meters. The multiplication factor 1000 is applied to convert the resulting value from kilograms per cubic meter (kg/m^3) to grams per cubic meter (g/m^3), which is the unit conventionally used to express specific chemical consumption. The mass of each substance is determined through dual-measurement verification combining dosing pump flowmeter totalizers (primary measurement) with storage tank level drawdown (secondary verification), following the methodology established in Section 5.3.2.3:

$$M_i = (L_0 - L_1) \times A_{tank} \times \rho_i + M_{delivered}$$

Where L_0 and L_1 represent the tank levels measured at the beginning and at the end of the aggregation period, respectively, and A_{tank} indicates the cross-sectional area of

the tank, which is used to determine the change in stored volume based on the variation in level. The parameter ρ_i corresponds to the density of the chemical solution, required to convert the calculated volume into mass. Finally, $M_{\text{delivered}}$ refers to the total mass of chemical supplied and added to the tank during the same period.

Sub-indicator 1: Specific Antiscalant Consumption

The specific consumption of antiscalant (liquid form) is calculated as the mass of antiscalant consumed per unit volume of permeate produced over the aggregation period. Dual-measurement verification combines dosing pump flowmeter totalizers (primary measurement) with storage tank level drawdown (secondary verification). Antiscalant consumption exhibits continuous patterns proportional to feed flow, modulated by feed water scaling potential which depends on the concentrations of calcium, magnesium, silica, and other scaling precursors remaining after upstream crystallizer treatment. Under stable feed water quality and constant recovery ratio, specific antiscalant consumption should remain approximately constant; deviations indicate changes in feed water scaling potential (linked to crystallizer performance variations) or changes in the RO recovery ratio affecting concentration polarization at the membrane surface.

Sub-indicator 2: Specific Biocide Consumption

The specific consumption of biocide (liquid form) is calculated identically to antiscalant consumption, employing the same dual-measurement verification approach. Biocide consumption patterns depend on the dosing strategy employed: continuous low-dose operation produces smooth trend lines proportional to feed flow, while intermittent shock dosing protocols produce periodic consumption peaks at intervals determined by the biofouling management schedule. The alarm logic accommodates both dosing strategies, distinguishing between expected periodic peaks during shock dosing and unexpected consumption increases that may indicate elevated biological fouling risk requiring investigation of upstream biological treatment performance.

Sub-indicator 3: Specific Sodium Bisulfite Consumption

The specific consumption of sodium bisulfite (NaHSO_3 , liquid form) is calculated using dual-measurement verification combining dosing pump flowmeters and storage tank level drawdown. Sodium bisulfite is dosed continuously to neutralize residual oxidants (primarily free chlorine or chloramine residuals) that would cause irreversible oxidative degradation of polyamide RO membranes. Consumption is proportional to the oxidant residual concentration in the RO feed water, which depends on upstream disinfection practices and the residence time between disinfection point and the RO feed. Increasing specific consumption at stable feed flow may indicate elevated upstream oxidant dosing or reduced oxidant decay rate along the pre-treatment train.

Sub-indicator 4: Chemical Storage Inventory

The chemical storage tank inventory levels are monitored continuously for all three reagents to support supply chain management and provide independent consumption verification through mass balance reconciliation. Inventory is expressed as absolute volume (m³) and as days of supply at current consumption rate:

$$I_{chemical} = L_{current} \times A_{tank}$$

$$Days_{supply} = (I_{chemical} \times \rho_{chemical}) / M_{chemical, daily}$$

Where $M_{chemical, daily}$ represents the rolling 7-day average daily consumption for the respective chemical. Inventory management for RO chemicals carries heightened operational criticality compared to upstream sections: interruption of antiscalant dosing risks irreversible membrane scaling damage within hours under high-recovery operating conditions, interruption of sodium bisulfite dosing exposes membranes to oxidant damage with similarly rapid and irreversible consequences, and interruption of biocide dosing allows biological fouling to initiate, although consequences develop over days rather than hours. These criticality profiles justify conservative inventory thresholds: antiscalant and sodium bisulfite employ a reorder point of 14 days of supply and a critical low threshold of 7 days, reflecting the rapid and irreversible consequences of dosing interruption; biocide employs standard thresholds of 7 days (reorder) and 3 days (critical), consistent with its slower failure timescale.

Sub-indicator 5: Permeate Production Volume

The volume of permeate produced by the RO section is measured using dedicated permeate flowmeters downstream of the membrane modules. This volume serves as the normalization denominator for all specific consumption calculations and represents the product water output of the RO system. The distinction between permeate volume and feed volume is governed by the water recovery ratio: $V_{permeate} = R \times V_{feed, RO}$, where R is the fractional recovery typically ranging from 0.70 to 0.85 depending on feed water quality and operational strategy. Permeate volume is reported independently alongside feed volume to enable monitoring of recovery ratio variations that directly affect both chemical consumption intensity and energy efficiency.

Sub-indicator 6: Total Chemical Cost

The total chemical cost for the RO section is calculated as the sum of individual reagent costs: $C_{chem, RO} = \sum (M_i \times P_i)$, where M_i is the mass consumed of chemical species i and P_i is the unit cost of chemical i (€/kg), with the summation performed over the three reagents (antiscalant, biocide, sodium bisulfite). Unit costs are obtained from supplier invoices and procurement contracts, entered manually into the system when contracts are renewed or pricing adjustments occur.

5.7.2.4. Visual Display and Dashboard Widget

The widget is organized as a vertically stacked set of three coordinated charts sharing the same time axis. This structure allows the user to read cost, consumption, and performance information in an integrated way, making it easier to understand how changes in chemical use relate to overall RO operation. The layout follows the general visual approach adopted throughout the KPIs framework, while introducing elements that reflect the specific protective role of chemicals in reverse osmosis.

The first chart provides an overview of total daily chemical cost in the RO section. The total expenditure is visually broken down into its main components, so that variations in overall cost can be quickly linked to the reagent responsible. Permeate production is shown in the background to provide context. This combined view allows the reader to distinguish between cost changes driven simply by higher or lower production volumes and cost changes resulting from variations in dosing strategy or operating conditions.

The second chart focuses on how much of each chemical is used in relation to permeate production, together with information on available stock. Consumption trends are displayed over time so that gradual shifts or sudden changes can be easily identified. Inventory levels are shown alongside consumption in order to provide immediate awareness of supply status. This integrated view supports two key objectives: verifying that measured consumption is consistent with storage variations and ensuring that stock levels remain adequate in relation to current usage rates.

Keeping the three chemicals visually distinct is important because they serve different protective functions. Antiscalant use is mainly linked to scaling risk, biocide reflects biological fouling control, and sodium bisulfite is related to upstream oxidant removal. Presenting them separately allows the user to understand which operational factor may be influencing chemical demand, without merging all effects into a single aggregated value.

The third chart introduces process performance context. It combines information on permeate production with an indicator of membrane condition. This connection is essential in the RO section because chemical dosing has a preventive purpose: it is intended to protect membranes rather than directly improve an immediate output parameter. For this reason, changes in consumption cannot be evaluated independently from membrane behaviour. A reduction in chemical use does not automatically indicate improved efficiency if membrane performance deteriorates at the same time. Conversely, an increase in dosing may represent an appropriate response to changing feed conditions if membrane performance remains stable.

By presenting cost, specific consumption, inventory status, production level, and membrane performance in a coordinated structure, the widget supports a clear and structured interpretation process. The vertically stacked format allows the user to move from a general overview to more detailed operational context without losing temporal alignment between variables. The inclusion of membrane performance information represents the distinctive element of the RO chemical consumption widget compared to upstream sections. In reverse osmosis, chemicals serve primarily a protective function, and their adequacy can only be assessed by observing their effect on membrane condition. For this reason, the visual design does not simply report consumption data, but places them within a broader operational context that supports informed decision-making and timely identification of potential risks.

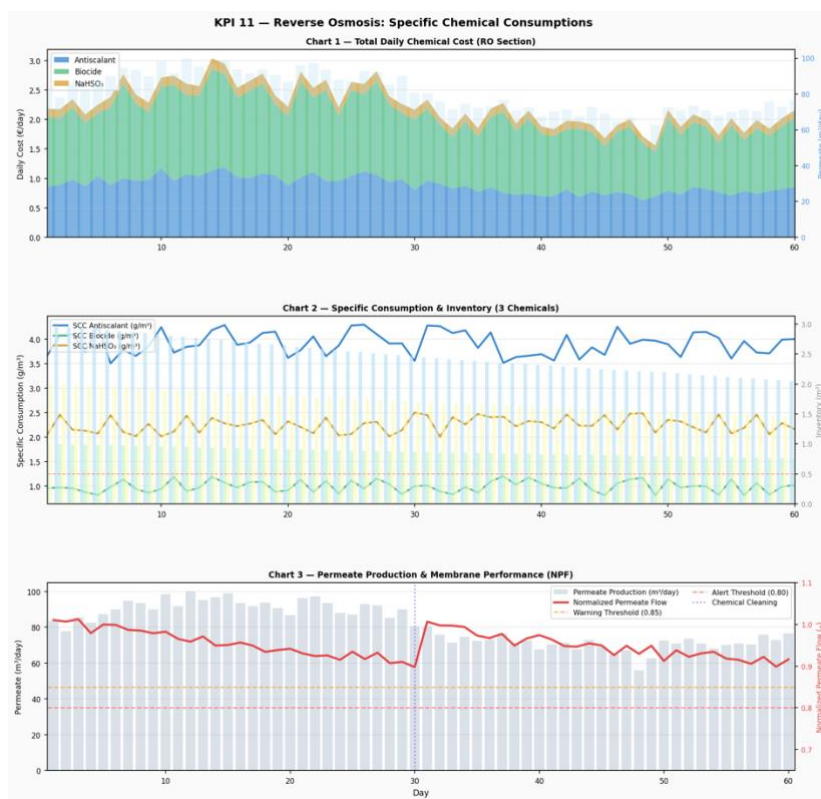


Figure 13: Conceptual dashboard mock-up for KPI 11 (AI-assisted design prototype; not based on operational data)

5.8. Summary: Complete KPI Dashboard

This chapter has presented eleven key performance indicators organized across the water treatment facility's functional sections, each supported by dedicated visualization widgets designed to transform raw measurement data into actionable operational intelligence. The complete dashboard integrates these individual widgets within a unified monitoring environment, enabling operators and managers to assess

plant performance at multiple hierarchical levels while maintaining visibility into the cross-sectional dependencies that characterize multi-stage treatment processes.

5.8.1. Integrated Monitoring Architecture

The KPI dashboard establishes a comprehensive monitoring framework that spans the entire treatment train from initial chemical conditioning through final reverse osmosis polishing. This integrated architecture recognizes that treatment stages, while serving distinct functions, operate as coupled elements within a continuous process where upstream performance directly influences downstream operation. The dashboard design therefore moves beyond isolated section-level monitoring to provide a unified operational view that reveals both local process conditions and cross-stage interactions. The monitoring system addresses three fundamental operational requirements that apply across all treatment stages: process performance verification ensures each section achieves its intended treatment objectives under current conditions, early fault detection identifies developing problems before they cause treatment failures or equipment damage, and resource optimization identifies opportunities to reduce energy consumption, chemical usage, and maintenance costs while maintaining treatment effectiveness. The complete dashboard architecture integrates eleven primary indicators distributed across six operational levels: plant-level strategic oversight (2 KPIs), chemical conditioning (2 KPIs), crystallizer (1 KPI), neutralization (2 KPIs), biological treatment (3 KPIs), and reverse osmosis (1 KPI). This multi-level structure accommodates diverse stakeholder needs, from high-level management oversight to detailed operational troubleshooting.

5.8.2. Visual Design Consistency and Alert Hierarchies

The dashboard employs consistent visual design conventions across all widgets to minimize cognitive load and enable rapid pattern recognition. Color coding follows industrial HMI standards: green for normal operation within targets, yellow for caution approaching limits, orange for significant deviations requiring attention, and red for alarm conditions violating operational or regulatory thresholds. Trend line colors maintain consistency across related widgets: treated volume appears as gray bars throughout all section displays, chemical costs employ consistent species-specific colors preserved across different sections, and energy consumption displays uniformly as dark gray lines. This color consistency enables operators to quickly identify specific metrics across multiple widgets without repeatedly consulting legends. Reference lines employing dashed patterns indicate critical thresholds: regulatory limits appear as red dashed horizontals, design capacity as green dashed lines, and inventory reorder points as orange dashed lines. The uniform use of dashed patterns distinguishes static reference values from dynamic measured trends. Alert prioritization follows a three-level hierarchy:

- Level 1 alerts (regulatory violations, critical failures) trigger modal notifications requiring acknowledgment;
- Level 2 alerts (significant degradation, approaching supply depletion) activate flashing widget borders and populate a persistent alert banner;
- Level 3 alerts (minor deviations, informational warnings) employ color changes within affected widgets without interrupting workflow.

5.8.3. Operational Benefits and Decision Support

The integrated dashboard provides tangible operational benefits that extend well beyond simple data visualization. Its structure transforms raw process data into decision-support information, enabling faster interpretation, improved cost control, and more reliable plant management. A primary advantage lies in the automatic normalization of consumption indicators. By expressing chemical usage as specific consumption (mass per volume of water produced), the system eliminates distortions caused by fluctuations in production throughput. Changes in operating capacity can otherwise generate apparent variations in chemical use that do not reflect real efficiency shifts. Normalization ensures that performance evaluation is based on comparable metrics, thereby converting raw operational data into actionable information that requires limited expert interpretation. The integration of inventory management with real-time consumption monitoring further introduces a predictive logistics function. By continuously estimating depletion time based on current stock levels and recent usage trends, the system provides early warning of supply requirements. This capability reduces the risk of unexpected chemical shortages that would force emergency shutdowns or urgent deliveries at premium cost. At the same time, it supports more efficient working capital management by avoiding excessive stock accumulation and long storage periods that may compromise chemical stability. Another important benefit is comparative validation through the parallel visualization of Biological Treatment Trains A and B. Under stable conditions, the two trains should exhibit similar performance profiles, thereby providing mutual confirmation of instrumentation reliability and process stability. In addition, this configuration enables structured optimization trials: one train may operate under modified parameters while the other serves as a reference, allowing direct assessment of performance differences. Such controlled comparison enhances operational learning and reduces the risk associated with process adjustments. Finally, the coordinated presentation of chemical consumption, cost indicators, production throughput, and key process parameters within unified widgets accelerates root cause analysis. When deviations occur, operators can more rapidly determine whether the underlying cause is related to procurement price fluctuations, operational inefficiencies, or changes in production scale. This structured diagnostic approach reduces response time and directs corrective actions toward the actual limiting factor, thereby improving both economic and technical performance.

5.8.4. Strategic Value for Plant Management

Beyond immediate operational benefits, the integrated dashboard delivers strategic value by providing enhanced visibility into efficiency trends and cost drivers. One key advantage lies in the detection of gradual performance degradation. Historical trending of chemical consumption, production throughput, and process parameters allows operators to identify declines in efficiency that are not apparent in day-to-day observations but become clear when plotted over weeks or months. This capability supports a shift from reactive maintenance, triggered by failures, to predictive maintenance based on observed degradation trends, thereby reducing unplanned downtime and extending the service life of critical equipment. The dashboard also facilitates economic quantification of operational decisions. By tracking both chemical and energy costs, management can assess the financial impact of process optimization initiatives. For example, improvements in pretreatment that reduce downstream chemical consumption can be directly evaluated to determine whether the resulting cost savings justify associated capital and operating expenditures. Integrated monitoring further supports the prioritization of optimization interventions through systematic root cause analysis. Rather than addressing isolated issues within individual sections, the system enables identification of where performance limitations originate and where corrective actions will yield the greatest overall benefit. For instance, if data indicate that instability in neutralization pH is causing biological treatment inefficiency and increased scaling in the RO stage, the most effective intervention may be improved alkalinity control upstream, rather than simply increasing chemical dosing downstream. Finally, the use of specific consumption metrics provides a foundation for benchmarking. Normalizing chemical use to water production allows comparison against industry standards or peer facilities, helping to determine whether current performance aligns with best practices or whether there is significant potential for improvement. This benchmarking capability supports both operational excellence and informed strategic decision-making.

5.8.5. Implementability Roadmap

The implementation of the dashboard, which follows the design phase, is associated inherently risks associated with system integration, data reliability, and operational adoption. To manage these risks and ensure controlled deployment, the implementation is structured into multiple sequential phases, each delivering incremental value while maintaining operational stability:

- *Phase 1 – Foundation:* Deploy plant-level KPIs to establish strategic oversight and ensure mandatory compliance monitoring. This phase provides essential operational visibility and supports regulatory

reporting requirements, forming the baseline for subsequent enhancements.

- *Phase 2 – Economic Visibility*: Introduce section-specific cost indicators granting management comprehensive insight into the drivers of operational expenditure and enabling informed economic decision-making.
- *Phase 3 – Operational Detail*: Implement indicators for chemical consumption and process parameters to support detailed operational optimization, performance monitoring, and diagnostic troubleshooting.
- *Phase 4 – Advanced Analytics*: Exploit the historical database to enable statistical process control, predictive modeling, and automated recommendation systems for optimization, providing the foundation for data-driven decision support.

The standardized widget architecture and consistent data models allow new indicators to be incorporated without disrupting existing functionality, supporting a controlled and continuous evolution of the dashboard as operational requirements and analytical capabilities expand.

5.8.6. Conclusion

The integrated eleven-indicator dashboard, covering chemical conditioning, crystallizer, neutralization, biological treatment, and reverse osmosis, provides a comprehensive monitoring framework for operational, economic, and strategic oversight. It transforms raw process data into actionable intelligence through clear visualizations, performance metrics, and cross-sectional integration, revealing interactions not visible when sections are monitored separately. The hierarchical panel design serves both management, for high-level status monitoring, and operational staff, for detailed diagnostics. Color coding, reference lines, and synchronized time axes simplify interpretation and enable rapid identification of deviations or emerging issues. By combining process performance with economic and inventory data, the dashboard supports optimized treatment effectiveness, cost control, and supply continuity. More than a visualization tool, the dashboard functions as a decision support system, enhancing operator effectiveness, accelerating problem diagnosis, guiding optimization, and providing management with insight for strategic planning. In an environment of increasing efficiency demands, regulatory requirements, and cost pressures, this integrated monitoring capability is essential for achieving operational excellence in gas storage-integrated water treatment operations.

6 Conclusion and Further Developments

6.1. Summary of Objectives and Contributions

This thesis addressed the design of a comprehensive KPIs framework for a water treatment facility integrated within a gas storage operation. The central objective was to translate the broad operational requirement of monitoring and optimizing plant performance into a set of indicators capable of serving multiple stakeholder groups, from plant operators requiring real-time process diagnostics to senior management requiring strategic economic oversight and compliance officers requiring continuous regulatory verification. The work originated from a clearly defined industrial need: the water treatment facility, despite being equipped with extensive sensor infrastructure and process instrumentation, lacked a formalized performance measurement system capable of converting the available operational data into structured, actionable information for decision-making. Operational measurements were recorded and stored, but not systematically aggregated, normalized, or presented in formats aligned with the distinct requirements of different stakeholder groups. The objective of this thesis was therefore practical in nature: to carry out the complete design phase of a KPI framework that bridges the gap between raw data availability and operational intelligence, producing implementation-ready indicator specifications. The existing literature on water treatment performance measurement and industrial KPI design, reviewed in Chapter 3, provided methodological foundations and reference frameworks that informed the design choices, but the core contribution of this work lies in the application of these principles to the specific operational, regulatory, and economic context of a gas storage-integrated treatment plant, resulting in a tailored set of indicators ready for deployment. The methodological approach adopted to address this problem combined two complementary perspectives, integrated through an iterative design process. The top-down perspective proceeded from organizational requirements to indicator specifications: structured interviews with key stakeholders, including plant managers, operations engineers, compliance officers, and procurement personnel, identified the performance questions that indicators needed to answer, the decision-making contexts in which they would be used, and the temporal and spatial granularity required for each stakeholder group. The bottom-up perspective proceeded from physical measurement capabilities to feasible indicator formulations: a systematic field-based analysis of the installed instrumentation catalogued the sensors, flowmeters, level transmitters, and analytical instruments available at each process section, establishing the measurement boundary conditions within which any indicator must operate. The

intersection of these two perspectives, what is needed from an organizational standpoint and what is measurable from an instrumentation standpoint, defined the feasible indicator space from which the final eleven KPIs were selected and specified. The resulting framework comprises nine indicators organized across five functional macro-areas (chemical conditioning, crystallization, neutralisation, biological treatment, and reverse osmosis) plus two plant-level indicators providing aggregate strategic oversight. Each indicator was developed through a rigorous four-part specification structure encompassing operational context and relevance, design rationale documenting the reasoning behind formulation choices, detailed technical specifications including mathematical formulations and measurement references, and visual display design for dashboard integration. This consistent structure ensures that each indicator is not only technically sound but also traceable in its design logic, reproducible in its calculation, and interpretable by its intended audience. A distinctive feature of the framework is the explicit treatment of seasonal load variability inherent in gas storage operations, a characteristic largely absent from the conventional water treatment performance measurement literature. The gas extraction-injection cycle imposes order-of-magnitude variations in water production rates across the annual cycle, necessitating careful normalization strategies. The adoption of specific consumption metrics (mass per unit volume treated, energy per unit volume treated, cost per unit volume treated) throughout the framework addresses this challenge systematically, enabling meaningful performance comparison across periods of dramatically different throughput and distinguishing genuine efficiency variations from throughput-driven matters. Another contribution of this work is the way the widget is designed to break down and analyze problems to make diagnosis easier. Rather than presenting isolated numerical values, each section-level cost indicator is structured as a coordinated multi-chart visualization enabling operators to decompose observed cost variations into their constituent drivers: throughput effects, specific consumption (efficiency) effects, and procurement pricing effects. This diagnostic capability transforms the dashboard from a passive data display into an active analytical instrument supporting root cause investigation and targeted corrective action.

6.2. Limitations and Current Criticalities

While the framework provides a comprehensive design-phase output ready for implementation, several limitations and criticalities must be acknowledged to provide an honest assessment of its current maturity and to guide the subsequent implementation process.

6.2.1. Data Heterogeneity and Measurement Granularity

A fundamental assumption underlying the unified dashboard presentation is that all input measurements are available at compatible temporal resolutions and with comparable reliability. In practice, this assumption does not hold uniformly across the indicator set. The instrumentation analysis revealed substantial heterogeneity in measurement characteristics: electromagnetic flowmeters provide continuous high-frequency signals, level transmitters operate at similar frequencies, and analytical sensors for pH, dissolved oxygen, and conductivity deliver readings at intervals ranging from seconds to minutes. However, certain critical inputs operate on fundamentally different timescales. Chemical unit prices are updated manually following procurement contract renewals, typically quarterly or semi-annually, introducing step-function discontinuities in cost calculations that are qualitatively different from the smooth variations characterizing sensor-based measurements. These heterogeneities have practical implications for indicator interpretation. A daily unit process cost value combines sensor-derived measurements updated in real time with price parameters that may reflect procurement conditions from several months earlier and maintenance cost estimates based on historical averages. The resulting composite metric, while mathematically well-defined, carries an implicit uncertainty that is neither quantified nor communicated to the dashboard user. This limitation does not invalidate the indicators but requires awareness during interpretation: short-term cost fluctuations reflect primarily consumption and throughput variations at constant prices, while price-driven effects appear only as discrete step changes coinciding with manual parameter updates.

6.2.2. Absence of Formal Uncertainty Quantification

The technical specifications developed in Chapter 5 define calculation algorithms, input measurements, and expected value ranges, but do not include formal propagation of measurement uncertainty through the indicator calculation chain. Each sensor carries an intrinsic measurement uncertainty specified by the manufacturer (typically expressed as a percentage of full scale or of reading), and when multiple measurements are combined through arithmetic operations, these individual uncertainties propagate to the calculated indicator value according to well-established statistical principles. For example, the treatment efficiency indicator involves the ratio of two volume measurements, each derived from numerical integration of flow signals over time; the propagated uncertainty of the efficiency value depends on the individual flowmeter accuracies, the correlation structure between the measurements, and the integration methodology employed. The decision to exclude formal uncertainty analysis from the current design phase reflects a pragmatic prioritization: establishing the indicator architecture, calculation logic, and visualization framework constituted the primary deliverable, with uncertainty quantification identified as a subsequent refinement step requiring detailed sensor calibration data and statistical

analysis that falls outside the scope of the present work. However, this omission means that the current framework cannot formally distinguish between genuine performance variations and measurement noise, particularly for indicators involving ratios or differences of similarly scaled quantities where relative uncertainties may be amplified.

6.2.3. Scalability and Transferability of the Approach

The methodology adopted in this work, combining top-down stakeholder analysis with bottom-up instrumentation mapping, is conceptually general and not inherently specific to the particular facility studied. However, the degree to which the resulting indicator set is directly transferable to other water treatment plants or industrial process facilities requires careful qualification. The methodological approach is scalable and transferable. The systematic process of identifying stakeholder requirements, cataloguing available instrumentation, defining the feasible indicator space at the intersection of needs and capabilities, and specifying indicators through the four-part structure (context, rationale, specification, visualization) constitutes a replicable design methodology applicable to any process facility where performance monitoring is required. The principles of normalization for throughput variability, diagnostic cost decomposition, and hierarchical indicator architecture are domain-independent and can be instantiated in different operational contexts. The specific indicator formulations, however, are tightly linked to the particular process configuration, instrumentation layout, regulatory environment, and operational characteristics of the studied facility. A water treatment plant with different process stages would require different section-level indicators reflecting its distinct unit operations and associated cost drivers. Similarly, facilities operating under different regulatory frameworks would require adaptation of the compliance indicator to reflect applicable discharge standards and monitored parameters. The seasonal variability normalization, while conceptually transferable to any facility with time-varying throughput, would require recalibration of expected ranges and alarm thresholds to reflect the specific variability patterns of the target application. The scalability challenge also extends to the complexity of the stakeholder analysis. The present work benefited from a relatively well-defined stakeholder structure with identifiable roles and information needs. Larger organizations with more complex governance structures, or multi-site operations requiring cross-facility benchmarking, would introduce additional requirements for indicator standardization, data harmonisation, and hierarchical aggregation that are not addressed in the current framework.

6.2.4. Validation Gap

The most significant limitation of the current work is the inherent absence of empirical validation. The framework has been designed and specified but not yet implemented and operated with real process data over a sustained period. Consequently, several

critical aspects remain unverified. The expected value ranges specified for each indicator are based on design calculations, literature references, and engineering judgement, but have not been confirmed against actual operational data from the specific facility. The alarm thresholds and reference lines incorporated into the dashboard visualizations are preliminary estimates that may require adjustment once real performance baselines are established. The diagnostic decomposition logic embedded in the multi-chart widget configurations has not been tested against actual operational scenarios to verify that cost variation patterns can be correctly attributed to their constituent drivers in practice. The visual display designs, while informed by human-machine interface principles and operator workflow considerations, have not been subjected to usability testing with actual plant operators to verify that the intended information hierarchy and rapid-assessment capabilities are achieved in real operational conditions. This validation gap is an expected characteristic of a design-phase deliverable and does not represent a methodological shortcoming; rather, it defines the boundary between the completed design work and the subsequent implementation and commissioning activities necessary to bring the framework into operational use.

6.2.5. Manual Data Entry Dependencies

Several indicators rely on manually entered parameters that cannot be acquired automatically from the installed sensor infrastructure. Chemical unit prices require periodic manual input following procurement contract updates. Sludge disposal costs depend on manual entry of contractor invoice data. Electricity tariff rates must be updated when contractual pricing changes. Maintenance cost amortization requires manual input of actual maintenance expenditure data. These manual dependencies introduce risks of data entry errors, delayed updates creating temporal mismatches between actual and recorded values, and inconsistent update practices across different parameters or operational shifts. While each individual manual input is straightforward, the aggregate burden of maintaining all manually entered parameters across all section-level cost indicators is non-negligible and represents an ongoing operational requirement that must be considered in the implementation planning.

6.3. Recommendations for Future Development

Based on the work completed and the limitations identified, the following recommendations are proposed for the subsequent phases of framework development and deployment.

6.3.1. Phased Implementation and Operational Validation

The implementation requires a dedicated validation period during which calculated indicator values are cross-referenced against independent measurements, operator observations, and historical records. Phase 1 deployment of plant-level KPIs should include a parallel operation period of no less than three months during which the automated indicator calculations are compared against manual calculations performed by operations staff using the same underlying data. Discrepancies identified during this parallel period should be systematically investigated and resolved before proceeding to subsequent phases. This validation process serves the dual purpose of verifying calculation correctness and building operator confidence in the automated system, both of which are essential for successful adoption. Following implementation, a baseline characterization campaign is recommended to capture a complete seasonal cycle and establish statistically robust expected value ranges for each indicator. These empirically-derived baselines should replace the preliminary design-phase estimates currently specified and should form the basis for calibrated alarm thresholds reflecting actual process variability rather than theoretical assumptions.

6.3.2. Uncertainty Propagation and Data Quality Framework

A formal measurement uncertainty analysis should be conducted as part of the implementation process, quantifying the propagated uncertainty for each indicator based on documented sensor accuracies, calibration records, and the specific calculation algorithms employed. This analysis would enable the dashboard to present indicator values with associated confidence intervals, allowing operators and managers to distinguish statistically significant performance changes from measurement noise. The uncertainty framework should incorporate sensor health monitoring, flagging indicators whose reliability is degraded by sensor drift, calibration expiry, or instrument malfunction, and should define procedures for handling missing data and measurement gaps without generating misleading indicator values.

6.3.3. Progressive Automation of Manual Inputs

The manual data entry dependencies identified in Section 6.2.5 should be progressively reduced through integration with enterprise resource planning and procurement management systems. Chemical unit prices could be automatically imported from the procurement database when new purchase orders are registered. Electricity tariff schedules could be imported from energy management systems or utility company portals providing machine-readable pricing data. Each integration reduces the risk of data entry errors and delays while decreasing the operational burden on plant staff, although the feasibility and cost-effectiveness of each integration must be evaluated against the current IT infrastructure.

6.3.4. Advanced Analytics and Predictive Capabilities

Once a sufficient historical database has been accumulated through sustained operation, the framework should be extended with statistical process control and predictive analytics capabilities. Statistical process control charts applied to specific consumption trends and efficiency indicators would enable automated detection of statistically significant process shifts, distinguishing genuine performance changes from random variation with quantified confidence levels. Predictive models correlating upstream process conditions with downstream performance could enable anticipatory operational adjustments, for instance predicting membrane fouling rates based on crystallizer performance trends and antiscalant consumption patterns or forecasting chemical inventory depletion based on seasonal throughput projections and historical consumption profiles. Machine learning approaches could further enhance the diagnostic capabilities by identifying complex multivariate patterns in the cross-sectional indicator data that are not apparent through the pairwise visual correlation analysis currently supported by the dashboard design. However, the adoption of such approaches should be guided by the principle that model transparency and interpretability must be preserved.

6.3.5. Operator Training and Continuous Improvement

The effectiveness of the KPI framework depends not only on the technical quality of the indicators and visualizations but also on the ability of operators and managers to interpret and act upon the information provided. A structured training programme should accompany the implementation process, covering the theoretical basis for each indicator, the diagnostic decomposition methodology and the interpretation of typical and atypical patterns in the dashboard displays. Feedback mechanisms should be established to capture operator experience with the dashboard during routine use, identifying visualization elements that are unclear or unhelpful, information gaps that impede decision-making, and opportunities for refinement based on practical operational experience. The framework should be treated as a living system subject to continuous improvement rather than a static deliverable. As operational experience accumulates, indicator formulations may require refinement, alarm thresholds recalibration, and visualization layouts adaptation to reflect evolving operational practices and stakeholder needs. The modular architecture of the dashboard, with standardized widget structures and consistent data models, supports this evolutionary approach by enabling modification and extension of individual indicators without disrupting the overall framework integrity.

6.4. Concluding Remarks

This thesis has delivered a design-phase specification for a KPIs framework tailored to the operational, economic, and regulatory monitoring requirements of a gas storage-

integrated water treatment facility. The hybrid top-down and bottom-up methodology ensured that the resulting indicators are both organizationally meaningful and technically feasible, grounded simultaneously in stakeholder needs and instrumentation realities. The framework addresses a documented gap in the water treatment performance measurement literature regarding facilities characterized by extreme seasonal throughput variability, and provides a replicable methodological template applicable, with appropriate adaptation, to analogous industrial process monitoring contexts. The transition from design to operational deployment represents the critical next phase, where the theoretical soundness of the framework will be tested against the complexities of real process data, actual operator workflows, and the inevitable discrepancies between design assumptions and operational reality. The recommendations provided in this chapter are intended to guide this transition, managing the inherent risks of system integration while preserving the systematic, multi-stakeholder, and diagnostically oriented character that distinguishes this framework from ad hoc monitoring approaches. Ultimately, the value of a performance measurement system lies not in the elegance of its design but in its capacity to improve the decisions made by the people who use it. The framework presented in this thesis provides the architectural foundation for such improvement; its realization depends on the rigor and commitment with which the subsequent implementation, validation, and continuous improvement phases are executed.

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