D2.2 – TECHNOLOGIES AND PRACTICES EVALUATION FRAMEWORK

WP2 – INDUSTRIAL WATER SAVING, RECOVERY, TREATMENT AND RE-USE TECHNOLOGIES AND PRACTICES

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ABSTRACT	Deliverable 2.2 has been created through the works of Task 2.2 under Work Package 2 in the AquaSPICE project. This report provides the framework for the evaluation of industrial practices related to water in the AquaSPICE process industries. It gives an overview of relevant water utilizing processes and defines a first set of relative metrics (indicators), which may be used by the industries to benchmark/measure their current water utilizing and reuse practices as well as monitoring any progress made towards achieving circular economy. The water treatment technologies applied and tested within the AquaSPICE project shall optimize the industrial water practices regarding sustainability and water-efficiency goals. Thus, for evaluation of the innovative technologies applied, key performance indicators (KPIs) have been defined/proposed, highlighting various evaluation criteria. Therefore, depending on local constraints, KPIs can be weighted according to the specific importance of evaluation criteria.			

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ABBREVIATIONS/ACRONYMS

AGS	Aerobic Granular Sludge
BACF	Biologically Activated Carbon Filtration
BFW	Boiler Feed Water
BWRO	Brackish Water Reverse Osmosis
CAPEX	Capital Expenditure
CoC	Cycles of Concentration
COD	Chemical Oxygen Demand
CS	Case Study
CTBD	Cooling Tower Blow Down
CTMU	Cooling Tower Make-Up
EC	Electrical Conductivity
EDI	Electrodeionisation
EDR	Electrodialysis Reversal
EN	European Norm
EU	European Union
GAC	Granular Activated Carbon
GHG	Greenhouse Gas
IEX	Ion Exchange
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LCIA	Life Cycle Impact Assessment
MBR	Membrane Bioreactor
MF	Microfiltration
OPEX	Operational Expenditure
RO	Reverse Osmosis
RWTH	Rheinisch-Westfaelische Technische Hochschule Aachen
SDG	Sustainable Development Goal
SEC	Specific Energy Consumption
SotA	State-of-the-Art

SWRO	Seawater Reverse Osmosis
TDS	Total Dissolved Solids
UF	Ultrafiltration
UV	Ultraviolet

1. Executive summary

Deliverable 2.2 has been created through the works of Task 2.2 under Work Package 2 in the AquaSPICE project. This report provides the framework for the evaluation of industrial practices related to water in the AquaSPICE's process industries. It gives an overview of relevant water utilizing processes and defines a first set of relative metrics (indicators), which may be used by the industries to benchmark/measure their current water utilizing and reuse practices as well as monitoring any progress made towards achieving circular economy.

The water treatment technologies applied and tested within the AquaSPICE project shall optimize the industrial water practices regarding sustainability and water efficiency goals. Thus, for evaluation of the innovative technologies applied, key performance indicators (KPIs) have been defined/proposed, highlighting various evaluation criteria: (1) water usage, (2) water quality, (3) general process operations, (4) chemical consumption, (5) energy consumption, (6) environmental impacts and (7) economics. If possible, benchmarks were given for correct classification of obtained values. Hence, depending on local constraints, KPIs can be weighted according to the specific importance of evaluation criteria.

A detailed monitoring and operation protocol for each CS to be reported in Deliverable 2.3 will be derived by assessing the defined indicators and KPIs. Deliverable 2.2 serves as the framework for evaluation of the pilot trials, facilitating comparison between CSs in similar manufacturing sectors to ultimately introduce technologies for water efficiency on a large scale.

Due to the non-availability of the SynDi plant in CS#4, this CS is considered as void case and no work related to this CS is reported in this deliverable.

2. Introduction

Sufficient supply of water is essential for the industrial sector [1]. However, water resources are affected by overexploitation, pollution and climate change, leading to increased business risks [2]. The United Nations' 2030 Agenda, fixing the sustainable development goals (SDGs) to safeguard our planet, highlighted the fundamental role of sustainability issues. Companies around the world thus need to integrate environmental, social, and economic dimensions within their strategies [3].

The European manufacturing, mining, and quarrying as well as construction industries are key pillars of the European society. However, these industries also account for about 18 % of total freshwater abstraction in Europe [4] – thus contributing to and simultaneously suffering from water stress. European industrial sites situated in Southern Europe are affected most, but water stress also increasingly occurs in the other regions of Europe. Depending on the region and season, the water stress varies, as illustrated in Figure 2.1. The water exploitation index (WEI+), indicated for different river basins in Figure 2.1, is a measure of water stress. It measures level of water scarcity by comparing water use with the renewable freshwater resource available. A WEI+ of above 20 % implies that a river basin is under stress, and a WEI+ of more than 40 % indicates severe stress and clearly unsustainable resource use [5].

Most industries involved in the AquaSPICE project (as indicated in Figure 2.1) are situated in water-scarce areas, and are aiming to facilitate water circularity, thus decreasing water supply risk. Involved industry partners mainly originate from the chemical sector (DOW Terneuzen (NL) and DOW Böhlen (DE), BASF Antwerpen (BE), Rosignano SOLVAY (IT) and Tupraş (TR)), but also the food sector (meat production, AGRICOLA (RO)) is represented. All sectors are highly depending on water for their production.

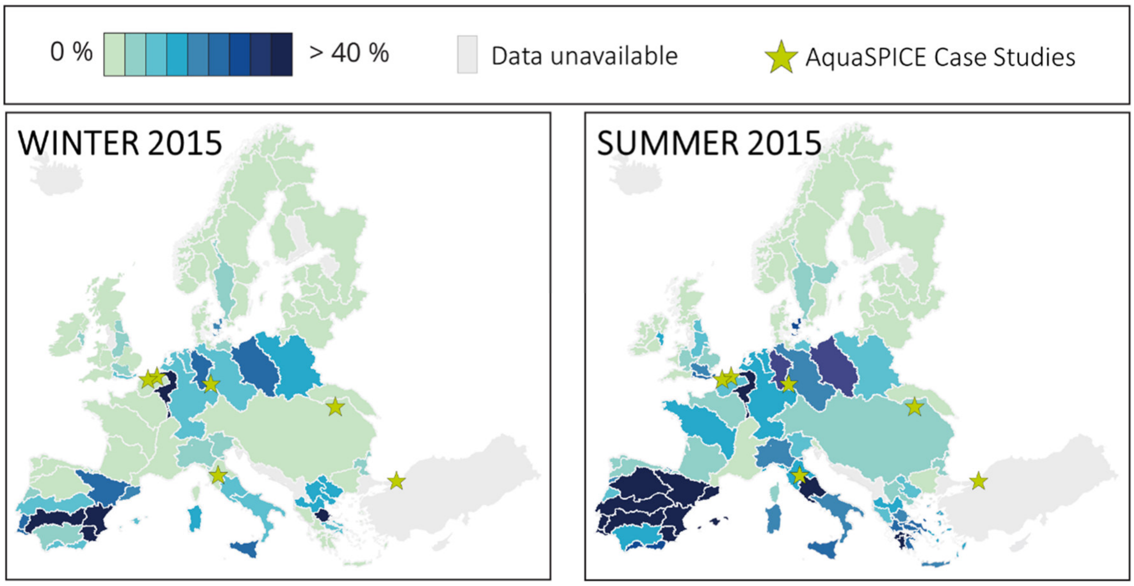

Figure 2.1: Water Exploitation Index by River Basin in 2015, adapted from [4]

To enhance water-efficiency and possibly circularity at the industrial sites, the standard ISO 46001 - Water efficiency management systems — Requirements with Guidance for use [6] provides guidance. The first step is the **analysis of water use** within the industries/organizations. Thus, activities and processes of significant water use will be defined, and possible improvements of water efficiency can be identified. Taking a holistic approach, water efficiency objectives and plans to achieve those shall then be defined. [6]

Abstracted water in the chemical industries is mainly required for cooling purposes, steam generation (boiler feed water) and process water [7]. In food production, water is similarly used for cooling, but also for cleaning, sanitation and other manufacturing purposes [8].

To identify and evaluate the current industrial practices regarding water usage, a first set of **global** key performance indicators (KPIs) were defined within this work. These KPIs serve as a first basis to analyse and benchmark the current water management practices applied in the participating industries. Because typically water treatment technologies need to be applied to improve a site's water efficiency, KPIs were also defined on a **technological** level regarding different topics/aspects. Thus, depending on an industrial site's local constraints and givens, different aspects of certain technology (trains) can be weighted accordingly when planning for implementation.

While this deliverable describes a methodology to evaluate water treatment technologies and practices, based on the two types of KPIs (global/technological) relevant for the AquaSPICE Case Studies (CSs), detailed monitoring and operation protocols will be presented at the end of Task 2.2 in Deliverable 2.3, together with technical specifications and operational concepts for each CS.

The methods and prospects of digitalization (monitoring, real-time control and data-driven solutions) can be further applied to use the defined KPIs as objective functions for problem optimizations.

3. Key Performance Indicator Definition for Benchmarking and Evaluation

To increase sustainability and water-efficiency while simultaneously decreasing business risks, indicators need to be developed to benchmark current industrial water management practices and monitor progress or changes. Such indicators should enable managers and operators to identify possibilities quickly and simply for optimization/improvements.

The values of a defined KPI can be obtained by measurements and/or theoretical calculations/assumptions (if no measurement exists). Reference values, aiming to contextualize obtained measurements/calculations will be given (by consultation of experts in the particular field and literature review) within this work, where available.

KPIs and incorporated values need to be defined clearly. If the definitions are not standardized, it is hard to gain acceptance for proposed KPIs [9]. Oftentimes, indicators and certain values are defined differently in different industries or industrial sites (e.g. total dissolved solids (TDS) concentration in freshwater – definitions range from a maximum TDS concentration between 1000 [10] to 3000 [11, 12] parts per million (ppm)). Thus, there is a clear need to standardize certain definitions to gain valuable output as was already indicated in Deliverable 1.1 of the AquaSPICE project. [13]

According to Almström *et al.* [9], the main purposes of the defined KPIs are to

1. Report,
2. Control and
3. Improve.

This approach, including the usage of the KPIs/indicators for benchmarking and evaluation, will also be adopted in this work. A detailed description of other existing frameworks and the definition process of a holistic Business Performance Measurement System can be found in the literature [9, 14].

Obviously, not all defined indicators will be "key", but KPI has become a commonly accepted term and thus will be used throughout this work. Further, it must be considered that some KPIs are interdependent (e.g. energy consumption per m^3 of treated water in a Reverse Osmosis (RO) process increases with an increasing water recovery [15]).

KPIs meant for the optimization of water consumption in the steel making processes have recently been defined by Branca *et al.* [16]. According to the European Steel Association EUROFER [17] (as cited by Branca *et al.* [16]), KPIs should represent the following characteristics: Representativeness, Comparability, Simplicity, Reliability, Quantifiable, Sensitive to changes, Cost Efficiency. Eurofer, more precisely the *EUROFER Sustainability for Steel Construction Products Committee*, certifies and awards steel companies with the EUROFER Sustainability for Steel Construction Products MARK. According to the authors' knowledge, such a certification system does not yet exist within the chemical industry nor the food processing industry (as represented industries in AquaSPICE).

A first set of global key performance indicators (KPIs) and indicators are defined within this work to identify and evaluate the current industrial practices regarding water usage. These indicators and KPIs serve as a basis to analyse and benchmark the current water management practices but need to be further developed for actual application throughout the AquaSPICE project, to gain broader acceptance. Eventually, they should suggest (also when compared to other industrial sites) possible room for improvement in water efficiency at specific industrial sites (i.e. chemical). All given KPIs are in a relative unit to enable comparability between the sites and minimize confidentiality concerns. Indicators are differentiated from KPIs as they do not imply performance metrics, but rather analyse current water usage practices.

Typically, water treatment technologies need to be implemented and/or optimized to close water loops and/or increase water efficiency and sustainability. To simplify decision making and encourage consideration of multiple evaluation criteria, KPIs were also defined on the technological level. The technological KPIs are structured according to the following topics: (1) water usage, (2) water quality, (3) general process operations, (4) chemical consumption, (5) energy consumption, (6) environmental impacts and (7) economics (see Figure 3.1).

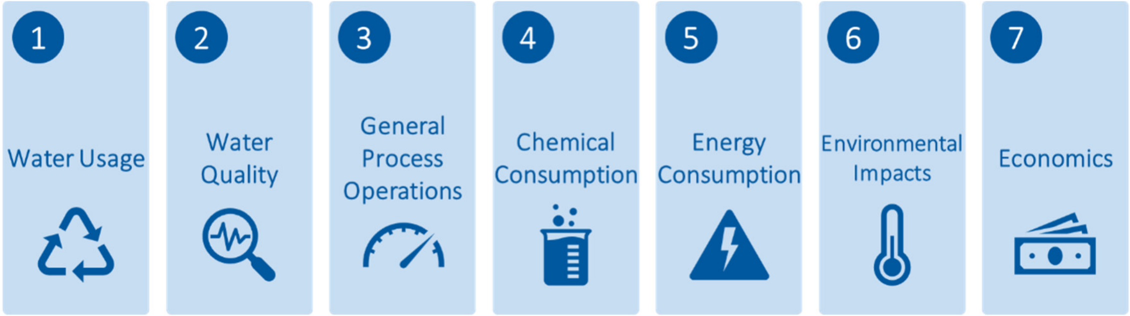

Figure 3.1: Structure of technological KPIs

Due to the complexity of water networks and water treatment processes, which are usually process chains instead of singular processes, the KPIs should be used with caution to compare between different case studies. However, serving as benchmarks, they can accelerate decision making for technology implementation/optimization. Further, using the different topics, one technology (train) can be compared to another, while considering the given aspects and taking local constraints and differences into account.

4. Global indicators and KPIs on Water Usage in the Process Industries

The industrial sector highly depends on water. According to Ellis *et al.* [18], the major industrial uses for water are cooling, process and boiler feed water. In their works, Ellis *et al.* [18] cite a study conducted in 1998 by Bowman in the US state Texas. According to Bowman’s publication, the chemical and petroleum refining industries use more than 50 % of their water intake for cooling purposes, around 10 to 30 % for process water and 10 to 30 % for boiler feed water. The food processing industries are quoted to require more than 50 % for process water, around 30 % for cooling purposes and less than 10 % for boiler feed water. (Only chemical and food processing industries will be considered in this work because these are the represented industries in the AquaSPICE CSs.)

Unfortunately, according to the authors’ knowledge, none such study exists with more recent values for European (manufacturing) industries, which demonstrates a clear lack of a transparent and broad industrial water use analysis. Further, the above stated publication(s) do not give clear indication on the definition of “water intake”. Is water intake referred to all water (incl. brackish and sea water) or just freshwater intake?

To get a better understanding of the current industrial practices in the chemical industries involved in AquaSPICE, the indicators on water usage as shown in Table 4-1 were chosen. Here it is referred to the term “indicators”, because these rather benchmark the industrial practices, but do not necessarily give indications on performances related to water usage.

Initially, a more elaborate set of indicators was proposed (similar to the indicators/KPIs proposed by Branca *et al.* [16], including cost, additive and further consumption metrics of water treatment), but was found to be impractical to measure throughout the AquaSPICE CSs. Amongst the reasons for dropping many parameters were the complexity of industrials sites, unavailability of data, and outsourcing of water treatment capacities by certain companies. For the elaborate set of KPIs, refer to the publication of Branca *et al.* [16].

Table 4-1: Global indicators defined for the global industrial site(s)

ID	Indicator Name	Unit	Calculation/Evaluation (All to be multiplied with 100%)
A-1	Freshwater Intake Share	%	$\frac{Total\ Annual\ Freshwater\ Intake}{Total\ Annual\ Water\ Intake}$
A-2	Water Intake Share used for Once-Through Cooling Systems	%	$\frac{\begin{array}{c}Total\ Annual\ Water\ Intake\\ for\ Once\ Through\ Cooling\end{array}}{Total\ Annual\ Water\ Intake}$
A-3	Discharged Water Share	%	$\frac{\begin{array}{c}Total\ Annual\ Discharged\ Water\\ -Water\ Discharge\ due\ to\ Precipitation\ on\ Site\end{array}}{Total\ Annual\ Water\ Intake}$
A-3.1	Percentage of Discharged Water (treated)	%	$\frac{\begin{array}{c}Total\ Annual\ Discharged\ Water\\ (treated\ for\ Discharge)\end{array}}{Total\ Annual\ Discharged\ Water}$
A-3.2	Percentage of Discharged Water (not requiring treatment to be discharged)	%	$\frac{\begin{array}{c}Total\ Annual\ Discharged\ Water\\ (not\ requiring\ treatment\ prior\ to\ Discharge)\end{array}}{Total\ Annual\ Discharged\ Water}$
A-4	Real and Apparent Water Losses Share (further information on definition in Table 4-3)	%	$\frac{\begin{array}{c}(Total\ Annual\ Water\ Intake\\ -Total\ Annual\ Water\ Remaining\ in\ Product\\ -Total\ Annual\ Discharged\ Water\\ (incl.\ Discharge\ due\ to\ Precipitation\ on\ Site\\ and\ incl.\ Discharge\ of\ Produced\ Water)\\ -Annual\ Water\ Evaporation\\ (incl.\ Water\ Used\ for\ and\\ Evaporated\ through\ Firefighting)\\ -Annual\ Water\ lost\ through\ Steam\ Traps)\end{array}}{Total\ Annual\ Water\ Intake}$
A-5	Water Intake Share of Open Recirculating Cooling Systems	%	$\frac{\begin{array}{c}Total\ Annual\ Water\ Intake\\ used\ for\ Open\ Recirculating\ Cooling\ System\end{array}}{Total\ Annual\ Water\ Intake}$

ID	Indicator Name	Unit	Calculation/Evaluation (All to be multiplied with 100%)
A-6	Water Intake Share of “fresh” Boiler Feed Make-Up	%	$\frac{\mathit{Total\ Annual\ Boiler\ Feed\ Make\ Up\ Water}}{\mathit{Total\ Annual\ Water\ Intake}}$
A-7	Water Intake Share of Process Water(s)	%	$\frac{\substack{\mathit{Total\ Annual\ Water\ Intake} \\ \mathit{used\ as\ Process\ Water}}}{\mathit{Total\ Annual\ Water\ Intake}}$

The frequency of measurement/assessment of the given indicators is suggested to be annual (as shown in the column “Calculation/Evaluation”) to enable comparisons over the years. Comparability and simplicity of indicators are facilitated by using relative units. Table 4-2 gives a summary of shared values of global indicators by the AquaSPICE CSs.

Table 4-2: Shared values (rounded to full number) of global indicators by AquaSPICE CSs

ID	CS1 (Terneuzen, NL)	CS1 (Böhlen, GER)	CS2 (IT)	CS3 (BE)	CS4 (SI)	CS5 (RO)	CS6 (TR)
A-1	3 %	100 %	No values shared	Not applicable	Not reported	100 %	31 %
A-2	97 %	0 %				Not available	Not available
A-3	99 %	39 %					
A-3.1	2 %	62 %				80 %	
A-3.2	98 %	38 %				Not available	
A-4	< 1 %	2 %					
A-5	1 %	68 %				10 %	21 %
A-6	2 %	17 %				Not available	Not available
A-7	1 %	6 %		< 1 %		60 % (estimate)	

Indicator A-1 gives an indication of freshwater intensity of a particular industrial site. The “Total Annual Water Intake” includes all water being introduced to an industrial site’s water balance: fresh, brackish and seawater intake as well as recycled water streams from other industrial sites, domestic wastewater effluent and rainwater/precipitation used for the industrial processes. Freshwater hereby shall be defined as water naturally occurring with a TDS concentration lower than 1000 mg/L. Freshwater is either directly extracted from the industry or indirectly extracted by an external water provider. As freshwater is valuable not only in terms of industrial use but also for other stakeholders in the regions (drinking water), A-1 is an indicator which should be minimized. A lot of industries already receive treated municipal wastewater as valuable water source (e.g. Solvay (represented by CS2), Tüpraş (CS6) and DOW (CS1)), which offers additional water besides freshwater. However, depending on local conditions, freshwater might be the only water source available. CS1 in Terneuzen and Böhlen, CS2 and CS5 aim to significantly reduce their freshwater intake by implementation of the AquaSPICE technologies [20]. In the author's survey, some of the AquaSPICE participating industrial sites share the value of A-1. Depending on regional circumstances, A-1 at the chemical industrial sites reported as 100 %, 31 % and 3 %. The represented food processing industry reports 100 % Freshwater Intake Share.

Indicator A-2 measures the share of water used within the industrial site for once-through cooling systems. The water consumed for once-through cooling systems oftentimes makes up the biggest water use at industrial sites (if once-through cooling is applied). For better understanding of the different cooling systems, refer to Section 4.1 below. The AquaSPICE participating chemical industries report a value of 97 % (CS1 Terneuzen) and 0 % (CS1 Böhlen).

The discharged water share (indicator A-3), together with its sub-indicators A-3.1 and A-3.2, suggests the fate of water used. A-3.1 indicates the discharged water being polluted "slightly" and discharged back into the environment without requiring treatment (e.g. cooling, i.e. once-through cooling). A-3.2 implies polluted water requiring treatment before being released to the environment. A-3.1 and A-3.2 should always sum up to 100 %. The chemical industries participating in AquaSPICE report 99 %, 43 % and 39 % for A-3. A-3.1 is reported as 2 % and 62 % for the chemical industries. The represented food processing industry reports 80 %. A-3.2 is reported as 98 % and 38 % by the chemical industries.

A-4, "Real and Apparent Water Losses Share" should give an indication of e.g. water lost through leakage(s), erroneous data, unauthorized consumption and/or insufficient monitoring of complex water systems. The IWA [21] gives standard terminologies for setting up water balances for water utilities. Adapting this approach, the term *Water Losses* shall be defined including apparent and real losses. Table 4-3 further explains the structure of *Water Losses.* No reported values can be shared yet.

Table 4-3: Standard terminology for water utilities' water losses according to the IWA [21] adapted to be applied to process industrial sites

Water Losses Q_L	Apparent Losses Q_{AL}	Unauthorized Consumption
		Meter Inaccuracies and Data Handling Errors
	Real Losses Q_{RL}	Leakages on transmission and distribution mains
		Leakages and overflows at storage tanks
		Leakages on connections
		Water losses through drift (mainly cooling towers)
	Controlled Losses Q_{CL}	Water losses through evaporation (mainly cooling towers)
		Water losses through steam traps (steam systems)
		Water losses in product

Water lost through steam traps and evaporation should be minimized (see section 4.2), however steam traps and evaporation are essential for a well-functioning steam/cooling system. Thus, water lost through steam traps and evaporation in cooling towers shall not be considered as (real and/or apparent) water losses, but controlled water losses.

Water balances which cannot be closed are an indication for (apparent and/or real) water losses and should trigger further investigations. Such investigations require the involvement of production experts, site managers, the correct usage of data etc. and can be costly. However, investigations can pay off (Figure 4.1).

As an example, CS1 hopes to reduce water losses by 5 % by improving condensate return management through improved digitalization [20].

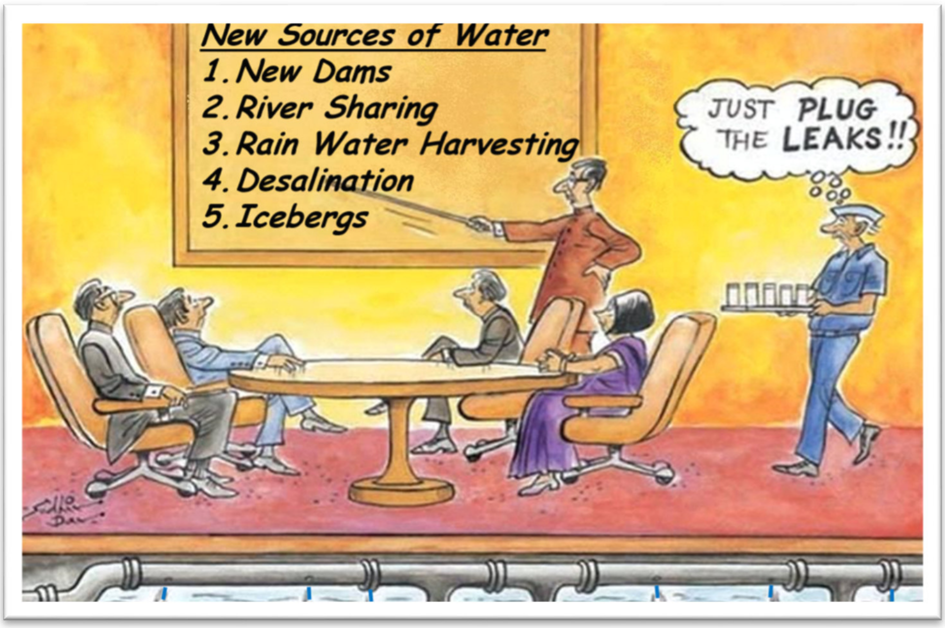

Figure 4.1: ("New") Sources of Water [22]

Indicators A-5, A-6 and A-7 further show the share of the water intake used for cooling (open-recirculating cooling), steam production and the processes at the industrial sites. The chemical industries participating in AquaSPICE report A-5 as 1 %, 68 % and 22 % (only 3 sites shared values). Agricola, the participating food processing industry reports A-5 as approximately 10 %. A-6 is reported as 2 %, 17 % from the chemical industries. Agricola indicates that the required measurements are not obtained at the site. A-7 is reported as 1 % and 6 % from two chemical industries. Agricola reports an estimated value of 60 %.

The collection of the above mentioned indicators/values requires a sophisticated analysis of the water use at industrial sites and thus checks off the first step according to the ISO. Additionally, the indicators can give hints where reuse and water-efficiency enhancement will have the biggest impact.

As most water is used for cooling purposes, steam production and within processes (process water), the following sections further dive into these specific topics. KPIs are defined in the following for the water usage in these systems.

4.1. Water Usage for Cooling Purposes

Water for cooling is needed in many industries. As established before, cooling processes are the most water-intensive processes in the chemical and other industries and therefore present a big opportunity for water savings. As elaborated in a publication by Guerras and Martín [23], the efficiency of wet cooling towers and their broad application in various industries show that even under scarce water availability these cooling systems are competitive and offer critical global energy-efficiency when compared to dry cooling [24, 25].

Types of industrial cooling systems include: direct/indirect once-through cooling systems, direct/indirect open recirculating cooling systems, closed circuit wet/dry air cooling systems, and open recirculating/closed circuiting hybrid cooling systems [26].

In once-through systems, the water is passed through a heat exchange equipment and then being discharged back to the environment at elevated temperatures [27]. Usually, once-through systems are only employed where water is available in large volume and at low cost with suitable low temperature. Usual sources of once-through cooling water are wells, rivers, lakes (e.g. brackish/sea water at coastal locations) where the only cost involved in usage is that of pumping [28]. Water usage here is much higher compared to other systems (average water use of 86 m^3/h/MW$_{th}$ [29]). Thus, this kind of cooling system cannot be considered water-efficient, and thus will not be considered for water-efficiency enhancement.

The ISO 22449 [26] has defined five types of industrial cooling systems which can make use of reclaimed water, as presented in Table 4-4. ISO 22449 also excluded once-through cooling systems but did not offer a direct explanation. The authors assume that due to the low water-efficiency of once-through cooling systems, reclaimed water will not play a role for these systems due to low price/performance ratio. For further information on cooling systems, definitions and more, it is referred to the BREF document on Industrial Cooling Systems [29] and the works by Hill *et al.* [30].

Table 4-4: Wet industrial cooling systems which can use reclaimed water (adapted from [26])

Cooling System	**Cooling Process**	**Water Make-Up Requirements**	**Water Contamination**	**Average Water Use [m^3/h/MWth]**
(1) Direct open recirculating cooling water system	Water that is recirculated is in direct contact with the object to be cooled.	Controlled water losses due to evaporation, and blowdown. Real water loss through drift. 1-5 % of make-up water compared to circulating water flow.	Recirculated water contains large amounts of impurities. High concentrations of suspended solids and oils	2
(2) Indirect open recirculating cooling water system	Water that is recirculated is only indirectly in contact with the object to be cooled.		Continuously increasing salt/nutrient concentration. No direct contamination, besides conditioning chemicals.	2

Cooling System	Cooling Process	Water Make-Up Requirements	Water Contamination	Average Water Use [m^3/h/MWth]
(3) Open recirculating hybrid cooling system	Similar to a direct open recirculating cooling process with prior heat removal through air current (dry cooling).	Controlled water losses due to evaporation and blowdown. Real water loss through drift. 20 % less make-up water required than for a wet cooling tower	See direct/indirect open recirculating cooling water system.	0.5
(4) Closed circuit cooling water system	Water is circulated in a closed circuit without contact to the environment. (Primary circuit)	Make-up water in primary circuit is only needed if system has leakages or is drained for maintenance. (Real water losses)	Increasing concentration due to evaporation and drift. No direct contamination (except conditioning chemicals).	Variable
(5) Closed circuit hybrid cooling system	Similar to a closed-circuit cooling process with a wet and a dry cooling phase.	Controlled water losses due to evaporation and blowdown. Real water loss through drift. 20 % less make-up water required than for a wet cooling tower.		1.5

As shown in Table 4-4, cooling systems differ in characteristics, water qualities and make-up requirements. To fully assess and optimize an industrial site's water-efficiency, the cooling systems used need to be reconsidered and checked for optimization potential (e.g. drift reduction and specific cooling tower design). Within the AquaSPICE project, the focus will be laid solely on the water used and overall water usage in the cooling systems, not on the cooling systems themselves, as changing the entire systems would require further investments beyond the scope of this project. Within the AquaSPICE CSs which consider cooling systems, focus is laid on cooling water for/from open recirculating cooling systems. Thus, in the following, this type of cooling systems will be considered for evaluation/assessment (see Table 4-4, systems (1), (2), and (3) and Figure 4.2).

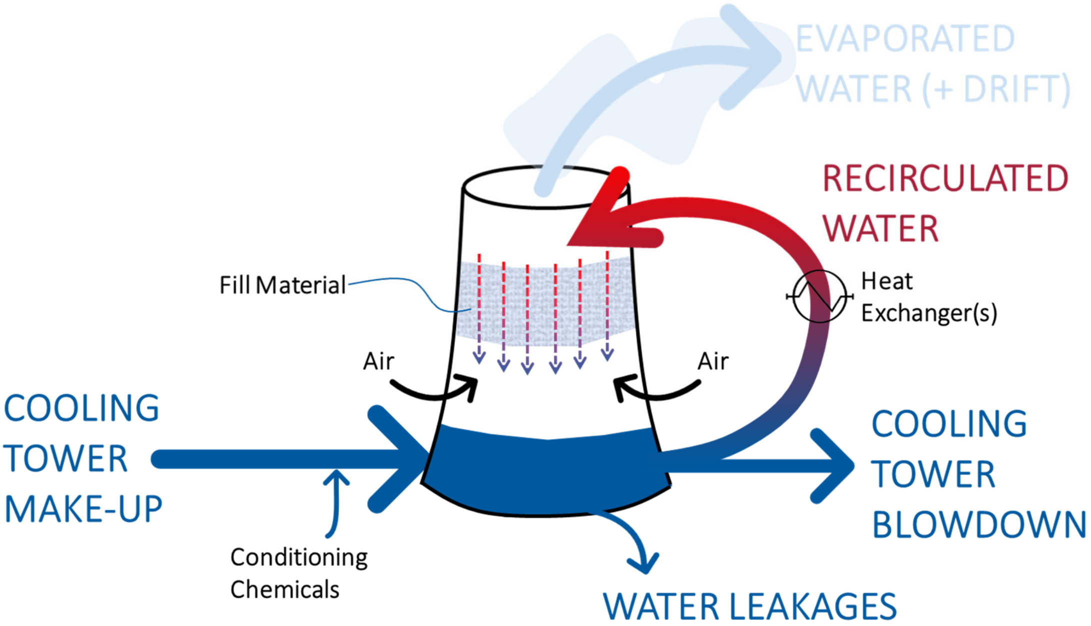

Figure 4.2: Schematic of a common type of design of open recirculating cooling tower (adapted from [31]) and respective water flows (in capital letters)

Figure 4.2 illustrates the water flows in a typical open recirculating cooling system. Water is lost from the cooling system during operation mainly due to evaporation or other occurrences such as drift or leakages, however also apparent water losses might be significant (see Table 4-3). As water is reused/-circulated, the salt concentration increases due to continuous evaporation. Hence, discharging water as blowdown (CTBD) is the preferred option to maintain adequate concentrations. Make-up water (CTMU) is needed to maintain the cooling system's water balance [31, 32].

The main challenges in the operation of open recirculating cooling systems are corrosion, scaling and biofouling. For prevention of these phenomena, cooling water is treated accordingly and/or conditioning chemicals are dosed to the cooling water. Besides, key water quality parameters are monitored. For further explanation, refer to Chapter 1.2.3 ff. in the works by Pinel [31].

Table 4-5 defines the global KPIs to be applied for the open recirculating cooling systems in the AquaSPICE case studies. C-1, the Cycles of Concentration (CoC), is a well-known parameter in the field of cooling tower operations [29]. Increasing the CoC (C-1) will decrease the amount of necessary CTMU and thus shall be maximized for increased water-efficiency. However, it might also lead to an increased demand for anti-fouling/conditioning chemicals to allow for higher salt concentrations and/or more sophisticated treatment of CTMU or recirculating water. Under specific conditions of certain discharge permits, increased concentrations of relevant (possibly harmful) compounds in the CTBD must be considered, thus limiting the use of chemicals. For reports on new methods with low chemical demand it is referred to recent research done by Pinel *et al.* [33], but also former reports by Cunningham [34] and Alfano and Sherren [35] as cited in the BREF document [29]. In AquaSPICE CS3, the effect of increasing the CoC (KPI C-1) is evaluated in order to save significant amounts of water [20]. Some participating chemical industries shared the values for KPI C-1: The highest value reported by one industrial site was 5, one site reported values between 2 to 4.3, while another reported C-1 to be between 2.7 to 3.8.

Table 4-5: Defined global KPIs for Cooling System(s) (only open recirculating cooling systems)

ID	KPI Name	Unit	Calculation/Evaluation
C-1	Cycles of Concentration	-	$\frac{TDS_{Cooling\ Tower\ Blowdown}}{TDS_{Cooling\ Tower\ Make-Up}}$
C-2	Blow Down Water Cooling System (Share)	%	$\frac{Total\ Annual\ CTBD}{Total\ Annual\ CTMU} \cdot 100\ \%$
C-3	Real and Apparent Water Losses Share Cooling System	%	$\frac{Total\ Annual\ CTMU - Total\ Annual\ Evaporated\ Water - Total\ Annual\ CTBD}{Total\ Annual\ CTMU} \cdot 100\ \%$
C-4	Recycled Blowdown Share	%	$\frac{Total\ Annual\ Recycled\ CTBD\ (in\ other\ processes\ or\ in\ cooling\ towers\ as\ CTMU)}{Total\ Annual\ CTBD} \cdot 100\ \%$

The KPI C-2 should be $\approx \frac{100\ \%}{KPI\ C-1}$. Strong deviation indicates water leakages in the system. Thus, it is recommended to perform both calculations. As can be taken from the dependency of C-1 and C-2, C-2 should be minimized to improve water efficiency. However, similar challenges apply as mentioned above. C-2 was shared by three chemical industries: 20 %, 20 % and 46 %.

KPI C-3 refers to real and apparent water losses occurring in the cooling system that are unwanted (e.g. drift, leakages, metering inaccuracies, see Table 4-3). Usually, the evaporated water is not measured. Within ISO 22449, the calculation (estimation) of the evaporation rate is given by the following formula [26], using the rule of thumb that for each 10 °F the circulated water needs to be cooled, one percent of the cooling water is evaporated:

$$\begin{aligned} Evaporated\ Water \left[\frac{m^3}{h}\right] \\ &= Recirculated\ Water\ Flow\ Rate \left[\frac{m^3}{h}\right] \\ &\cdot (Warm\ Water\ Temperature\ [°F] \\ &- (Desired)\ Cool\ Water\ Temperature\ [°F]) \cdot \frac{0.01}{10\ °F} \end{aligned}$$

Differences in temperature/humidity should theoretically be considered but an estimate serves for a first assessment. C-3 should be minimized. No values of participating industries can be shared.

KPI C-4 measures the share of recycled CTBD in relation to the total CTBD generated. Depending on the obtained water quality during reclamation, the water can also be used in other processes (process integration). Within AquaSPICE CS1 in both Terneuzen and Böhlen, CTBD is treated and thus shall be reused to increase KPI C-4 [20]. Two chemical industrial sites report a value of 0 %. Table 4-6 summarizes the shared values of Cooling System(s) KPIs from the AquaSPICE CSs.

Table 4-6: Shared values (rounded to full number) of Cooling System(s) KPIs by AquaSPICE CSs

ID	CS1 (Terneuzen, NL)	CS1 (Böhlen, GER)	CS2 (IT)	CS3 (BE)	CS4 (SI)	CS5 (RO)	CS6 (TR)
C-1	5	2 to 4	No values shared	Not applicable	Not reported	No measurements available yet	3 to 4
C-2	20 %	20 %					46 %
C-3	Approx. 1 %	Not available					No measurements available
C-4	Not available	0 %					Not available

4.2. Water Usage for the Steam System

For heating processes, water/steam is the most used fluid due to its high heat capacity. For steam generation, high amounts of water are required. The water used in the boiler must be recharged through the addition of make-up water to compensate for steam, condensate, and other water losses as well as blowdown (see Figure 4.3). The water being fed into the boiler (here to be defined as boiler feed water) consists of make-up water and the condensate return (treated) of the steam generated before. The amount of boiler feed make-up water required is thus defined by the amount of condensate captured, the given, pre-set blowdown water and further controlled/real/apparent water losses (e.g. condensate not returned, steam traps, …) occurring in the steam system [36].

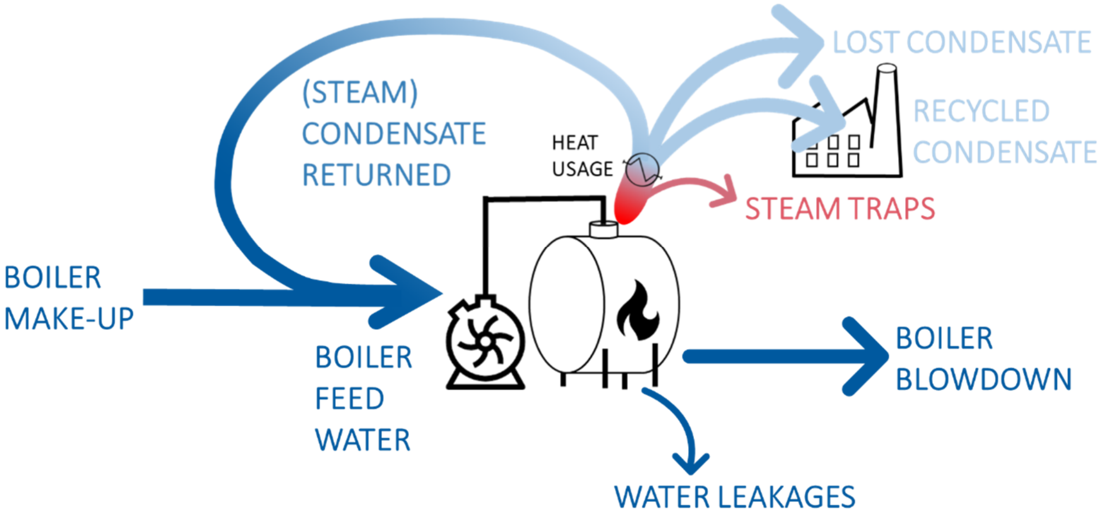

Figure 4.3: Simplified schematic of steam system water flows

Depending on the type of boiler, especially its boiler pressure, the required feed water quality is determined. For further information on required water qualities, refer to EN 12953-10 [37].

Increasing the amount of return condensate and minimizing boiler blowdown and other water losses can significantly decrease the required water make-up in the boilers. Besides, the energy saving potential might be considerable as well, as indicated in previous works by Wright *et al.* [36], U.S. DOE OIT [38] and Kocabaş and Savaş [39]. As cited by Wright *et al.* [36], the US Georgia Tech Industrial Energy Extension Services developed a series of Steam Tip fact sheets, of which ten were adapted by the U.S. DOE OIT:

1. Inspect and Repair Steam Traps
2. Insulate Steam Distribution and Condensate Return Lines
3. Use Feedwater Economizers for Waste Heat Recovery
4. Improve Your Boiler's Combustion Efficiency
5. Quantify and Eliminate Steam Leaks
6. Clean Boiler Fire-side Heat Transfer Surfaces
7. Clean Boiler Water-side Heat Transfer Surfaces
8. Return Condensate to the Boiler
9. Minimize Boiler Blowdown
10. Recover Heat from Boiler Blowdown

Four of these (1., 5., 8., and 9.) can be directly linked to water efficiency. Thus, to quantify the given tips and highlight improvement potential in water usage, the following KPIs were defined in the AquaSPICE project. All KPIs are given in a relative unit to enable comparability between the different sites and decrease confidentiality concerns.

Table 4-7: Defined global KPIs for the Steam System(s)

ID	KPI Name	Unit	Calculation/Evaluation (All to be multiplied with 100 %)
S-1	Condensate Return Share of Boiler Feed Water	%	$\frac{\text{Total Annual Return Condensate}}{\text{Total Annual Boiler Feed Make Up Water} + \text{Total Annual Return Condensate}}$
S-2	Blowdown Share of Boiler Feed Water	%	$\frac{\text{Total Annual Blowdown from Steam System}}{\text{Total Annual Boiler Feed Make Up Water} + \text{Total Annual Return Condensate}}$
S-3	Real/Apparent and Controlled Water Losses and Condensate Loss in Steam System (as share of Boiler Feed Water)	%	$\frac{\text{Total Annual Boiler Feed Make Up Water} - \text{Total Annual Boiler Blowdown from Steam System} - \text{Total Annual Recycled Condensate (for/in other Processes)}}{\text{Total Annual Boiler Make Up Water} + \text{Total Annual Return Condensate}}$
S-4	Recycled Water Share from Steam System	%	$\frac{\text{Total Annual Return Condensate} + \text{Total Annual Recycled Condensate (for/in other Processes)} + \text{Total Annual Recycled Blowdown}}{\text{Total Annual Boiler Make} - \text{Up Water} + \text{Total Annual Return Condensate}}$

Due to confidentiality issues, most measured parameters cannot be shared publicly within this document. However, previous studies have shown that e.g. KPI S-2, the Share of Blowdown in Boiler Feed Water (Blowdown Rate), typically ranges between 4 to 8 % [38]. The higher the boiler feed water purity, the lower the blowdown can be. As previously mentioned, DIN EN 12953-10 gives further information on typical water qualities required. Besides, extensive operating practices have been developed by the American Society for Mechanical Engineers [40].

KPI S-1 gives an indication of how much of the water fed to the industrial boilers is reused in the boiler unit itself. Oftentimes the condensate produced in the steam systems is still of very good quality and thus can be reused with rather low effort. Additionally, energy recovery from condensate streams might be possible. Thus, the value of S-1 should be maximized. One chemical industry participating in the AquaSPICE project reports S-1 as 65 %.

The "Blowdown Share of Boiler Feed Water", KPI S-2, quantifies the amount of blowdown on the total water fed to the boilers (boiler feed water). As mentioned above, according to literature this value should be around 4 to 8 % and should be minimized. Further, the heat of the blowdown should be recovered wherever possible. One participating chemical industrial site reports S-2 to be 8 %.

KPI S-3 illustrates the amount of controlled, real and apparent water losses after having been used within the steam system. It takes both Boiler Make-Up Water and Return Condensate into account, because both water streams are highly valuable and purified water streams need to be considered. This percentage should be reduced to a minimum.

With KPI S-4, process integration shall be considered. The value the "Recycled Water Share Steam System" (S-4) measures the efforts to increase water-circularity not only by returning the condensate back to the boilers but including possible reuse scenarios for/in other processes (process integrations). Within both AquaSPICE CS1 and CS3, the amount of reused water originating from the steam system(s) shall be increased by the implementation of the AquaSPICE solutions/technologies [20].

In conclusion, when adequate water treatment capacities for condensate return water and/or even blowdown water exist, the steam generation process can be operated with little freshwater requirements. Thus, if feasible and implementable, applying water efficiency measures to boiler feed water can result in high water and even energy savings.

Table 4-8: Shared values (rounded to full number) of Steam System(s) KPIs by AquaSPICE CSs

ID	CS1 (Terneuzen, NL)	CS1 (Böhlen, GER)	CS2 (IT)	CS3 (BE)	CS4 (SI)	CS5 (RO)	CS6 (TR)
S-1	Not for disclosure	Not for disclosure	No values shared	65 %	Not reported	No measure-ments available yet	Not for disclosure
S-2				8 %			
S-3				2 %			
S-4				Not applicable			

4.3. Other Water Usage

Besides cooling and steam generation, process water is another large share of water in the (chemical) industries. Process water comprises activities such as dilution, dissolution, washing, and rinsing. Although some portions of water are consumed in manufacturing (e.g. through evaporation or water as a constituent in the final product), most of the water needed is returned after application(s) (also referred to as return-flow water) [41].

Thus, there is great potential for efficiency enhancement for process water in the (chemical) industries. Wash water is needed in most production processes for equipment and plant cleaning [42]. Due to the high-quality requirements, the grade of the water for washing purposes needs to be considered. Depending on equipment to be cleaned, it might be required to use water above potable water standards, e.g. purified water [41]. The effluent produced during washing processes may be composed of different pollutants due to the variety of products being produced in the industries [42]. It is, therefore, necessary to assess the inflowing and outflowing water qualities specifically for each case. Equipment washing can be carried out either in open-loop or closed-loop configuration. Open-loop systems use wash water only once before discharging the effluent, whereas closed-loop systems collect the water for possible treatment and reuse. [43]

In the food processing industry, besides cooling and water for steam production, (process) water in different qualities and relatively high quantities is required as product itself (bottled water) but also for product washing, fluming and starting-up, rinsing, cleaning and disinfecting the processing equipment and facilities [44].

Due to the specific nature of process water streams at each site and their usage in both chemical and food processing industries, just one KPI is defined here in order to allow for some comparison between the CSs. Any additional KPI would be site-specific and outside the scope of the work.

KPI P-1 measures the water-efficiency effort of reusing/recycling process waters at the industrial sites. The “Total Annual Recycled Process Water” includes any kind of water reuse (also e.g. cooling and steam production) and thus considers process integration throughout the industrial site(s). Only water which is possibly recycled should be considered, thus the total annual process water loss is deducted from the sum in the denominator.

AquaSPICE CS2 aims to increase the amount of reclaimed/reused water by treating wastewater generated during the peroxide and peracetic acid production, thus increasing KPI P-1, additionally resulting in a decrease of the total freshwater intake at the site [20]. Measured values by industries could not be shared/collected throughout all CSs.

Table 4-9: Defined global KPI for Process Water Recycling

ID	KPI Name	Unit	Calculation/Evaluation
P-1	Recycled Share Process Water	%	$\frac{Total\ Annual\ Recycled\ Process\ Water}{\begin{gathered}Total\ Annual\ Process\ Water\ Intake\\ +\ Total\ Annual\ Recycled\ Process\ Water\\ (Reused\ as\ Process\ Water)\\ -\ Total\ Annual\ Process\ Water\ Loss\ (all)\\ (e.g.\ Evaporation, in\ Product, \dots)\end{gathered}} \cdot 100\ \%$

5. Technological indicators and KPIs for Water Treatment in the Process Industries

The KPIs used for the assessment of the water treatment technologies will be based on the seven topics as presented in Figure 3.1.

Within the AquaSPICE case studies, a variety of technologies and technology trains are planned to be tested and assessed for different treatment applications (based on initially planned technologies in AquaSPICE Deliverable 2.1 [20]):

- Physico-chemical processes:
    - Coagulation/Flocculation (CS1),
    - Granular Activated Carbon (GAC) (CS1, CS2),
    - Ion Exchange (IEX) (CS1, CS2, CS3, CS5),
    - Heterogeneous Fenton Process (CS2),
    - Ultraviolet (UV)/Chemical Disinfection (CS2)
- Membrane-based processes:
    - Microfiltration (MF) (CS1),
    - Ultrafiltration (UF) (CS1, CS6),
    - Reverse Osmosis (RO) (CS1, CS3, CS6),
    - Electrodialysis Reversal (EDR) (CS1, in CS3 Electrodialysis with bipolar Membranes (EDBM) is used; including acid/base recovery),
    - Electrodeionisation (EDI) (CS3)
- Biological processes:
    - Biologically Activated Carbon Filtration (BACF) (CS1),
    - Membrane Bioreactor (MBR) (CS2, CS5),
    - Aerobic Granules (AGS) (CS6)

While some KPIs are applied to all treatment processes and the overall treatment train, others need to be specifically defined for one type of technology only. In the following tables presenting the defined KPIs, T in the column “ID” refers to technology and can be interchanged depending on the treatment (train) that is looked at. The authors would like to highlight here that, when evaluating technologies, the whole picture must always be considered. On the one hand, optimising one process might have a negative impact on following stages. On the other hand, process integrations within certain treatment technology steps, such as reusing RO concentrate for filter backwashing or IEX resin regeneration might significantly improve performance of the overall process chain.

5.1. Water Usage

In terms of water usage, similar KPIs can be defined for most treatment technologies and trains. Measurement intervals should be long-term (possibly throughout the whole trial/testing phase, to include backwashing water use etc.).

The recovery rate [%] (T-1.1, Table 5-1), defined as the percentage of feedwater emerging from the system as product/treated water [45] not including treated water used for e.g. backwashing, plays a major role when comparing different treatment technologies. In particular in water-scarce areas or when feedwater is only available at high costs, the water recovery rate should be increased (while considering effects on e.g. achieved water quality, energy demand, cleaning intervals etc.). It is a delicate parameter representing a trade-off between capital and operational costs in (membrane) treatment systems [46, 47].

Obviously, the recovery rate highly differs for the same treatment technology operating under different conditions: While Sea Water Reverse Osmosis (SWRO) systems are typically operated at recovery rates of 35 to 50 %, standard Brackish Water Reverse Osmosis (BWRO) systems are within the range of 50 to 85 % [47]. Optimized RO systems (low-pressure) for pure water production with appropriate pre-treatment (i.e. softening) may exceed recovery rates of 90 % [12]. The wide range of this KPI for the RO treatment technology highlights its complexity and importance.

Electrodialysis Reversal (EDR) is typically operated at water recoveries around 85 to 90 % [48]. Ultrafiltration (UF) and Microfiltration (MF) are operated with 85 to 98 % water recovery [49]. Electrodeionisation (EDI) is specified to operate at 88 to 95 % recovery rate [50].

The recovery rate can and should also be measured in non-membrane-based processes such as IEX (expected recovery rates > 95 %). However, when the specific water treatment involves a significant amount of total suspended solids (TSS) producing sludge, such as biological processes, coagulation/flocculation, and backwashing water required in filtration system (resulting in produced sludge), the measurement of the specific sludge production [kg/m³] (T-1.2, Table 5-1) offers more value. The sludge production will also offer information on possibly relevant waste disposal costs. The recovery rate can be measured indirectly from the produced sludge if the specific water content of the produced sludge is determined. When doing so with literature values [51–54] and assuming remaining (sludge) water contents after mechanical drainage of 90 to 75 % [55], recovery rates of around 95 % can be approximated, depending on total suspended solids (TSS) to be removed, biomass production and other influencing factors.

A technology, where the measurement of neither T-1.1 nor T-1.2 make sense is UV/Chemical Disinfection (CS2) as typically no sludge or wastewater is produced.

Table 5-1: Defined technological KPIs related to the topic Water Usage

ID	KPI Name	Unit	Calculation/Evaluation
T-1.1	Recovery Rate	%	$\frac{Treated\ Water\ Volume\ by\ Process\ [m^3]}{Feedwater\ Volume\ to\ Process\ [m^3]} \cdot 100\ \%$
T-1.2	Sludge Production	kg/m³	$\frac{Amount\ of\ Sludge\ Produced\ by\ Process\ [kg]}{Feedwater\ Volume\ to\ Process\ [m^3]}$

What needs to be kept in mind when looking at the technologies is that combinations thereof often perform better on particular tasks than individual processes (e.g. pre-treatment before RO processes is the State-of-the-Art (SotA)). Besides, process integration (e.g. using RO concentrate as backwash for GAC filter) might significantly save water. Thus, as mentioned above, when evaluating the technologies, the whole technological train should be considered.

5.2. Water Quality

The different technologies and technology trains highly vary in terms of the quality of water they produce and require. Besides, depending on the point of use of the treated water, the requirements highly differ as well. It is referred to European Norm (EN) 12953 [37] (Boiler Feed Water Quality Requirements), ISO 22449 [26] (Cooling Water Quality Requirements for Reclaimed Water), and the EU Regulation 2020/741 [56] (Irrigation Water Quality Requirements for Reclaimed Water) for different water quality requirements depending on the point-of-use. Further explanations on other specific regulations are to be found in AquaSPICE D1.1 [13].

Thus, depending on the goals for water (re)use, different parameters (e.g. pH, Electrical Conductivity (EC), Total Organic Carbon (TOC), specific metals (e.g. Fe, Mg and Ca), specific salts (NaCl, $CaSO_4$, nutrients) need to be monitored. Thus, within the AquaSPICE Case Studies, relevant parameters are analyzed and applied technologies are evaluated according to given KPIs in Table 5-3. If applicable, elimination/modification rates of relevant parameters (KPI T-2.1, Table 5-3) should be normalized to e.g. reference temperatures (or other reference points) to enable valid comparison between technology trains and/or technologies. Normalization may also be applied to allow comparison of actual process performance of one applied technology to a given reference performance while taking into account influences of operating parameters, temperature changes and change in feed water conditions [57]. If, for example, an RO process is operated at different temperatures, the pressure difference between inlet (feed) and outlet (concentrate) changes (if all other conditions remain the same) only due to changed viscosities of water at different temperatures. In order to neither over- nor underestimate the temperature effects, the normalized pressure difference needs to be considered.

Table 5-2 below gives an overview of water quality parameters, which should be tested according to EN 12953 (Norm for BFW), ISO 22449 (Norm for Water Reuse in Cooling Towers) and EU Regulation 2020/741 (European Union Regulation on Water Reclamation for Irrigation).

Table 5-2: Relevant testing parameters according to EN 12953 [37] (BFW), ISO 22449 [26] (CTW) and EU Regulation 2020/741 [56] (Irrigation)

Parameter	Relevant Point-of-Use	Unit	Reference Norm(s)/ Regulation
Electrical Conductivity (EC)	All	µS/cm	EN 12953, ISO 22449
pH	All	-	EN 12953, ISO 22449
Hardness (as Ca and Mg)	BFW, CTW	mmol/L or mg/L as $CaCO_3$	EN 12953, ISO 22449
Total Alkalinity	BFW, CTW	mmol/L or mg/L as $CaCO_3$	EN 12953, ISO 22449
Iron (Fe)	BFW, CTW	mg/L	EN 12953, ISO 22449
Cupper (Cu)	BFW	mg/L	EN 12953
Silica (SiO_2)	BFW, (CTW – only if specific risk of chemical instability is identified or conditioning requires measurement)	mg/L	EN 12953, ISO 22449
Oxygen (O_2)	BFW	mg/L	EN 12953
Oil/Grease	BFW	mg/L	EN 12953
Organics	BFW, CTW	mg/L	EN 12953
Phosphate (PO_4^{3-})	BFW, CTW	mg/L	EN 12953, ISO 22449
Potassium (K), depending on conditioning	BFW	mg/L	EN 12953
BOD_5	CTW, Irrigation	mg/L	ISO 22449, EU 2020/741
COD	CTW	mg/L	ISO 22449
TSS	CTW, Irrigation	mg/L	ISO 22449, EU 2020/741
TDS	CTW	mg/L	ISO 22449
Residual Chlorine	CTW	mg/L	ISO 22449

Parameter	Relevant Point-of-Use	Unit	Reference Norm(s)/ Regulation
Chloride	CTW	mg/L	ISO 22449
Fecal Coliform	CTW	CFU/100 mL	ISO 22449
NH_3-N	CTW	mg/L	ISO 22449
Heterotrophic Plate Count (If necessary, e.g. reclaimed water from municipal waste water treatment plants)	CTW	CFU/mL	ISO 22449
Mn (if specific risk of chemical instability is identified [26])	CTW	mg/L	ISO 22449
E. coli	Irrigation	CFU/100 mL	EU 2020/741
Turbidity (only for Reclaimed water quality class A [56])	Irrigation	NTU	EU 2020/741
Legionella	Irrigation (if there is risk of aerosolization), CTW	CFU/L	ISO 22449, EU 2020/741
Further Parameters if conditioning requires them	BFW, CTW	-	EN 12953, ISO 22449

The frequency of measurements (online, hourly, daily, weekly and so on) is determined according to the specific needs and resources of the CSs. The EU Regulation 2020/741 [56] indicates minimum required measuring intervals.

It must also be considered that specific water treatment technologies require specific water qualities to function properly/reliably. For instance, certain membrane types can only be operated under specific conditions. A good example is EDI, where the feedwater requirements are high (Hardness < 1 parts per million (ppm); Silica < 1 ppm; Heavy Metals < 10 parts per billion (ppb); Chlorine < 20 ppb; TOC < 500 ppb as C) [48].

Table 5-3 gives the proposed general KPIs related to the topic of Water Quality. Depending on where the water shall be used further and the technologies applied, parameters shall be selected, and frequency of measurement determined by the CSs.

Table 5-3: Defined technological KPIs related to the topic of Water Quality, where Parameter XY is a generic representation of the parameters to be selected by the respective CS

ID	KPI Name	Unit	Calculation/Evaluation
T-2.1	(Normalized) Modification of Parameter XY	%	Monitoring (Online or Sample(s)) in Feed and Effluent
T-2.2	Influent Concentration of Parameter XY	e.g. mg/L	Monitoring (Online or Sample(s))
T-2.3	Effluent Concentration of Parameter XY	e.g. mg/L	Monitoring (Online or Sample(s))

5.3. General Process Operation

Due to significant differences between the technologies in terms of process operations (completely different concepts), general KPIs and/or Indicators cannot be defined here, but need to be based specifically on the water treatment technology. The only KPI applicable to all technologies is related to reliability, which is also part of process efficiency. In terms of safety and simplicity, the reliability of processes shall be measured as T-3.1 (Table 5-4). All further Process Operational KPIs and Indicators defined can be found in the Annex.

Table 5-4: Defined KPIs and Indicators related to Process Operations

ID	KPI/ Indicator Name	Unit	Calculation/Evaluation
T-3.1	Process Reliability	%	$\frac{Total\ Days\ of\ Operation - Total\ Days\ of\ Major\ Operational\ Failure}{Total\ Days\ of\ Operation} \cdot 100\ \%$
See Annex (Chapter 8) for specific Process Operational KPIs and Indicators.			

5.4. Chemical Consumption

Most of the technologies applied in the AquaSPICE Case Studies require additives for process operation. For some technologies, adding chemicals is the essence of the process, such as coagulation/flocculation. Other technologies require additives for process stability or optimization (e.g. antiscalants in RO processes). Besides, cleaning of process equipment (membranes, filters) often involves chemicals for better cleaning effects.

Chemicals are not just relevant to the process operations themselves, they also pose possible harm for the environment/staff, involve costs for purchasing as well as sludge disposal, and lead to greenhouse gas (GHG) emissions. Thus, chemical/additives shall be monitored within the AquaSPICE Case Study technology evaluations, as defined in Table 5-5.

Table 5-5: Defined technological KPIs related to the topic of Chemical Consumption

ID	KPI Name	Unit	Calculation/Evaluation
T-4.1	Addition of Chemical/Additive XY	mg/L	Measurement in relation to total water treated [L]
T-4.2	Addition of All Additives to Treatment	mg/L	Measurement in relation to total water treated [L]

5.5. Energy Consumption

The specific energy consumption (SEC) of water treatment processes is an important parameter for technology evaluation as it simultaneously implies operational costs and emission of GHGs. Table 5-6 gives references to benchmark values of energy requirements for the treatment technologies applied in the AquaSPICE CSs. Regarding energy requirements, it always needs to be defined and differentiated where and how the balance is drawn. While for some water treatment processes the production and therefore energy consumption of necessary ingredients (i.e. chemicals (H_2O_2 or $FeCl_3$)) is outsourced, for other processes the main additions to processes are produced on-site (e.g. O_3).

Table 5-6: Energy Requirements for different treatment technologies as references

Technology	Energy Requirements
Coagulation/Flocculation	Fast Mixing ca. 0.4 kWh/m³ [58], Slow Mixing ca. 0.0008 kWh/m³ (of water to be treated) [58] – thus, depending on mixing applied, values can be used for an estimate. Additionally, pumping requirements (highly dependent on set-up) and sludge dewatering (0.5 to 1.6 kWh/(m³ sludge) or 20 to 65 kWh/Mg TS of sludge [59]) need to be considered.
GAC/BACF	Pumping requirements for treatment mode and backwashing (e.g. 0.04 kWh/m³ [60]) need to be taken into account. Further, sludge dewatering of produced backwash water (0.5 to 1.6 kWh/(m³ sludge) or 20 to 65 kWh/Mg TS of sludge [59]) should be considered.
IEX	Energy demand for pumping due to pressure loss throughout resin vessels (energy requirements should be comparable to GAC/BACF process (first approximation): 0.04 kWh/m³ [60]) and height to overcome need to be considered. (Additionally, energy requirements for waste disposal (high chemical loads: acids, bases) need to be considered.)
Fenton Process (heterogeneous)	Can be compared to GAC/BACF process, as operational principle is similar.
UV Disinfection	0.013 to 0.04 kWh/m³ water treated [61]
MF/UF	0.1 to 0.9 kWh per m³ permeate produced [48, 50]
SWRO	3 to 5 kWh per m³ permeate produced [48, 50]
BWRO	0.5 to 1 kWh per m³ permeate produced [48, 50]
RO (low pressure)	< 0.5 kWh per m³ permeate produced [48, 50]
EDR	0.5 to 1.8 kWh per m³ treated water produced [48, 50]
EDI	0.2 to 0.3 kWh per m³ treated water produced [48, 50]
MBR	0.21 kWh/m³ to 0.89 kWh/m³ (references after 2018), SEC highly dependent on TSS applied in operation, size of treatment plant, choice of membrane modules and operation of aeration. [62–68]
AGS	0.17 kWh/m³ [69] (includes influent pumping and aeration; low energy demand is attributed to lack of mixers, conventional recycle pumps, settlers and sludge return pumps as well as increased water depth of AGS tanks [69]), additionally sludge dewatering and possible energy generation and consumption through subsequent anaerobic digestion of sludge need to be considered.

The defined KPI in Table 5-7 considers the specific energy consumption based on the amount of treated water [m³]. It may be applied to specific technologies only or a set of technologies (technology trains). The value related to a specific treatment technology should be related to given benchmark values (Table 5-6) to assess process optimization potential related to the specific technology, if applicable.

Table 5-7: Defined technological KPI related to the topic of Energy Consumption

ID	KPI Name	Unit	Calculation/Evaluation
T-5.1	Energy Requirement for Treated Water	kWh/m^3	Measurement/Estimation based on the amount of treated water [m^3] including pumping requirements and any other energy requirements for water treatment (aeration, voltage application, UV lamps operation for UV disinfection, stirring/mixing, sludge dewatering/handling of produced waste)

5.6. Environmental Impact

The environmental impact of technologies to be applied shall be evaluated as well. Within the ISO 14044, Life Cycle Impact Assessment (LCIA) is defined as the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system" [70]. Thus, the purpose of the impact assessment phase is to interpret the life cycle emissions and resource consumption inventory in terms of indicators, to evaluate the impact on entities that we want to protect, e.g. Human Health, Natural Environment and Natural Resources [71]. Depending on the midpoint impact categories chosen (see Figure 1-1 in the *ILCD Handbook: Framework and requirements for LCIA models and indicators* [71] for more information), the measured indicators change. The selection of the most appropriate ones is case specific and will not be further elaborated here. Further work on (dynamic) life cycle assessments and thus relevant indicators will be conducted in the AquaSPICE Work Package 4. In previous studies related to the evaluation of water treatment processes [72, 73], the midpoint impact categories (*"Midpoints are considered to be links in the cause-effect chain (environmental mechanism) of an impact category, prior to the endpoints, at which characterization factors or indicators can be derived to reflect the relative importance of emissions or extractions" [74])* and thus functional units given in Table 5-8 were chosen and proposed. However, as these are case specific and possibly complex, the table shall be seen as a suggestion, not a final definition.

Table 5-8: Proposed midpoint impact categories/environmental KPIs (adapted from [72, 73])

ID	Midpoint impact category	Environmental KPI/Unit	Calculation/ Evaluation
T-5.1	Climate Change	$t_{CO2\text{-}eq}/m^3$	Measurement/Estimation based on the amount of treated water [m^3]
T-5.2	Freshwater Resource Depletion	m^3/m^3	
T-5.3	Eutrophication	$kg_{PO43\text{-}eq}/m^3$	
T-5.4	Human Toxicity	$kg_{1,4DCB\text{-}eq}/m^3$	
T-5.5	Acidification	$kg_{SO2\text{-},eq}/m^3$	
T-5.6	Aquatic Ecotoxicity	$kg_{1,4DCB\text{-}eq}/m^3$	
T-5.7	Terrestrial Ecotoxicity	$kg_{1,4DCB\text{-}eq}/m^3$	
T-5.8	Photochemical Ozone Formation	$kg_{O3\text{ formed-}eq}/m^3$	

ID	Midpoint impact category	Environmental KPI/Unit	Calculation/ Evaluation
T-5.9	Ionising Radiation	DALYs/m^3	
T-5.10	Ozone depletion	$kg_{CFC\text{-}11\text{-}eq}/m^3$	
T-5.11	Other resources depletion	Depends on chosen resource e.g. $kg_{antimony\text{-}eq}/m^3$	

5.7. Economics

As elaborated in the AquaSPICE D1.1, the costs associated with building a brand new or upgrading an existing system are one of the many important barriers to the enhancement of water efficiency in the European process industry. This covers the capital costs (CAPEX) and operational costs (OPEX) of the treatment facilities. An overview on the costs, using cost functions, of existing treatment technologies is highlighted in D1.1 [13]. Within the AquaSPICE project, estimates shall be conducted to evaluate the technologies and/or technology trains economically (T-7.1, Table 5-9).

Table 5-9: Defined technological KPI related to the topic of Economics

ID	KPI Name	Unit	Calculation/Evaluation
T-7.1	Costs for Treated Water	€/m^3	Measurement/Estimation of CAPEX and OPEX

The possible cost savings related to better water efficiency and water recycling are another parameter important to estimate (e.g. reduced overall water intake of an industrial site). But as this parameter is not applicable to a single technology (train), it is not included in the defined technological KPIs.

6. Conclusions

Deliverable 2.2 provides the framework for the evaluation of industrial practices related to water utilization in the process industries participating in the EU funded AquaSPICE project.

The relevant water utilizing processes, i.e. cooling system and steam system, require significant amounts of (fresh) water, making efficient water use essential for the industries. By measuring the indicators defined in D2.2 for water usage, industrial site's water practices are analysed and assessed. Potential opportunities for optimization can thus be identified and later implemented to increase water efficiency, but also save energy and other resources. Thus, the overall sustainability performance of industries can be improved to contribute to the UN's agenda 2030, the SDGs to safeguard our planet.

To improve water efficiency and close the water loops, appropriate water treatment technologies need to be applied. Within the AquaSPICE project, innovative technologies and technology trains are or will be piloted and assessed. D2.2 gives a framework, defining relevant indicators and key performance indicators (KPIs) for evaluation of the applied water treatment technologies. The different criteria for evaluation are (1) water usage, (2) water quality, (3) general process operations, (4) chemical consumption, (5) energy consumption, (6) environmental impacts and (7) economics. Defined/proposed KPIs can then be applied to the specific CS depending on local constraints and focus. A detailed monitoring and operation protocol for each CS to be reported in Deliverable 2.3 will be derived by assessing the defined indicators and KPIs. Thus, D2.2 serves as the framework for evaluation of the pilot trials, facilitating comparison between CSs in similar manufacturing sectors to ultimately introduce technologies for water efficiency on a large scale.

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8. Annex: Technological KPIs and Indicators related to Process Operation

All given KPIs and Indicators are based on the authors' knowledge and references. KPIs/Indicators might be very case-specific. For some CSs, the defined Indicators in Table 8-1 can also be KPIs. Thus, depending on objectives, CSs may change a given Indicator listed below to become a KPI. Completeness of parameters is not guaranteed.

Table 8-1: Proposed Technological KPIs related to Process Operation for Coagulation/Flocculation

Coagulation/Flocculation					
ID	**KPI**	**Indicator**	**Name**	**Unit**	**Comments**
COAG-3.2		✓	Water Flows (Feed, Sludge, Effluent)	m^3/h	Measurement
COAG-3.3		✓	Mixing Speed(s)	1/min or rpm	Measurement
COAG-3.4		✓	Mixing Time(s)	s	Measurement
COAG-3.5		✓	Settling Time(s)	min	Measurement
COAG-3.6		✓	Temperature	°C	Measurement
COAG-3.7	✓	✓	Sludge Volume Index (SVI)	mL/g	Measurement
COAG-3.8	✓	✓	Sludge Dewaterability e.g. Capillary Suction Time (CST)	s	Measurement

Table 8-2: Proposed Technological KPIs related to Process Operation for GAC and BACF

GAC and BACF					
ID	**KPI**	**Indicator**	**Name**	**Unit**	**Comments**
GAC/BACF-3.2		✓	Water Flows (Feed, (Sludge,) Effluent)	m^3/h	Measurement
GAC/BACF-3.3		✓	Pressure(s)	bar	Measurement
GAC/BACF-3.4	✓	✓	(Normalized) Pressure Drop	bar	Measurement and Calculation
GAC/BACF-3.5	✓	✓	GAC Replacement Per Year	%/a	Measurement and Calculation
GAC/BACF-3.6		✓	Temperature	°C	Measurement

GAC and BACF					
ID	**KPI**	**Indicator**	**Name**	**Unit**	**Comments**
GAC/BACF-3.7	✓	✓	Backwashings Per Year	1/a	Measurement and Calculation
GAC/BACF-3.8		✓	Empty Bed Contact Time (EBCT)	Min	Measurement and Calculation
GAC/BACF-3.9		✓	Filtration Velocity	m/h	Measurement and Calculation
GAC/BACF-3.10		✓	Bed Volumes operated	1/a	Measurement and Calculation
GAC/BACF-3.11		✓	GAC Specifications	Depending on parameter	Given by supplier (typically), e.g. effective size d_{10} [mm], uniformity coefficient U [-], porosity f [%], hardness *Moh* [-] [75]

Table 8-3: Proposed Technological KPIs related to Process Operation for IEX

IEX					
ID	**KPI**	**Indicator**	**Name**	**Unit**	**Comments**
IEX-3.2		✓	Water Flows (Feed, Effluent, Regeneration Flows)	m^3/h	Measurement
IEX-3.3		✓	Pressure(s)	bar	Measurement
IEX-3.4	✓	✓	(Normalized) Pressure Drop	bar	Measurement and Calculation
IEX-3.5	✓	✓	Resin Replacement Per Year	%/a	Measurement and Calculation
IEX-3.6		✓	Temperature	°C	Measurement
IEX-3.7	✓	✓	Backwashings Per Year	1/a	Measurement and Calculation (Backwashing ≠ Regeneration)
IEX-3.8		✓	Resin Specifications	Depending on parameter	Given by supplier (typically), e.g. resin capacity

IEX					
ID	**KPI**	**Indicator**	**Name**	**Unit**	**Comments**
IEX-3.9	✓	✓	Bed Volumes (till Regeneration)	BV	Measurement over a certain time period
IEX-3.10		✓	Regenerant Strength	meq/L	Measurement/Calculation
IEX-3.11		✓	Regeneration Time	min	Measurement
IEX-3.12		✓	Regeneration Flow Rate	BV/h	Measurement/Calculation
IEX-3.13		✓	Stochiometric Excess Factor for Regeneration	-	Excess capacity (meq/L) needed for regeneration divided by Theoretical Capacity to regenerate (meq/L)

Table 8-4: Proposed Technological KPIs related to Process Operation for Heterogeneous Fenton in GFH Filter Bed

Heterogeneous Fenton in GFH Filter Bed					
ID	**KPI**	**Indicator**	**Name**	**Unit**	**Comments**
GFH-3.2		✓	Water Flows (Feed, Effluent, Backwash Sludge)	m^3/h	Measurement
GFH-3.3		✓	Pressure(s)	bar	Measurement
GFH-3.4	✓	✓	(Normalized) Pressure Drop	bar	Measurement and Calculation
GFH-3.5	✓	✓	GFH Replacement Per Year	%/a	Measurement and Calculation GFH: Granular Ferric Hydroxide
GFH-3.6		✓	Temperature	°C	Measurement
GFH-3.7	✓	✓	Backwashings Per Year	1/a	Measurement and Calculation (Backwashing ≠ Regeneration)

Heterogeneous Fenton in GFH Filter Bed

ID	KPI	Indicator	Name	Unit	Comments
GFH-3.8		✓	GFH Specifications	Depending on parameter	Given by supplier (typically), e.g. effective size d_{10} [mm], uniformity coefficient U [-], porosity f [%], hardness *Moh* [-] (similar to GAC)

Table 8-5: Proposed Technological KPIs related to Process Operation for UV Disinfection

UV Disinfection

ID	KPI	Indicator	Name	Unit	Comments
UV-3.2		✓	Water Flows (Feed and/or Effluent)	m^3/h	Measurement
UV-3.3		✓	Pressure(s)	bar	Measurement (to detect fouling or similar)
UV-3.4	✓	✓	Normalized Pressure Drop	bar	Measurement and Calculation
UV-3.5		✓	UV intensity	mW/cm^2	Measurement
UV-3.6		✓	UV transmittance	%	Measurement
UV-3.7		✓	Operational UV dose	mJ/cm^2	Measurement
UV-3.8		✓	Lamp age	a	-
UV-3.9		✓	Contact time	s	Measurement/Estimation
UV-3.10		✓	Liquid level in UV reactor(s)	%	Measurement if lamps are not always covered by water

Table 8-6: Proposed Technological KPIs related to Process Operation for MF and UF

MF/UF					
ID	**KPI**	**Indicator**	**Name**	**Unit**	**Comments**
MF/UF-3.2		✓	Water Flows (Feed, Permeate (and Concentrate))	m^3/h	Measurement
MF/UF-3.3		✓	Temperature	°C	Measurement
MF/UF-3.4		✓	Pressure(s) (Feed, Permeate (and Concentrate))	bar	Measurement
MF/UF-3.5	✓	✓	Normalized Pressure Drop	bar	Measurement and Calculation (if applicable)
MF/UF-3.6		✓	Filtration time (till Backwash)	min	Measurement
MF/UF-3.7		✓	Flux	LMH	Measurement and Calculation
MF/UF-3.8		✓	Critical Flux	LMH	Measurement and Calculation
MF/UF-3.9		✓	Backwash Time	Min	Measurement
MF/UF-3.10	✓	✓	Amount of CIPs per year	1/a	CIP: Clean in Place
MF/UF-3.11		✓	Amount of CEBs per year	1/a	CEB: Chemically enhanced Backwash
MF/UF-3.12	✓	✓	Membrane Replacement per year	%/a	Measurement and Calculation

Table 8-7: Proposed Technological KPIs related to Process Operation for RO

RO					
ID	**KPI**	**Indicator**	**Name**	**Unit**	**Comments**
RO-3.2		✓	Water Flows (Feed, Permeate and Concentrate)	m^3/h	Measurement

RO					
ID	**KPI**	**Indicator**	**Name**	**Unit**	**Comments**
RO-3.3		✓	Temperature	°C	Measurement
RO-3.4		✓	Pressure(s) (Feed, Permeate and Concentrate)	bar	Measurement
RO-3.5	✓	✓	Normalized Pressure Drop (NPD)	bar	Measurement and Calculation (if applicable)
RO-3.6		✓	Flux	LMH	Measurement and Calculation
RO-3.7		✓	Crossflow Velocity	m/s	Measurement and Calculation
RO-3.8	✓	✓	Mass Transfer Coefficient (MTC)	m/(s Pa)	Measurement and Calculation, see Bisselink *et al.* [57]
RO-3.9		✓	Membrane Flushings per year	1/a	Measurement and Calculation
RO-3.10		✓	Amount of CIPs per year	1/a	CIP: Clean in Place
RO-3.11		✓	Transmembrane Pressure (TMP)	bar	Measurement and Calculation
RO-3.12	✓	✓	Membrane Replacement per year	%/a	Measurement and Calculation

Table 8-8: Proposed Technological KPIs related to Process Operation for EDR and EDI

EDR and EDI					
ID	**KPI**	**Indicator**	**Name**	**Unit**	**Comments**
ED-3.2		✓	Water Flows (Feed, Permeate, Concentrate, Electrolyte)	m^3/h	Measurement
ED-3.3		✓	Temperature	°C	Measurement
ED-3.4		✓	Pressure(s) (Feed, Permeate and Concentrate)	bar	Measurement

EDR and EDI					
ID	**KPI**	**Indicator**	**Name**	**Unit**	**Comments**
ED-3.5	✓	✓	Normalized Pressure Drop (NPD)	bar	Measurement and Calculation (if applicable)
ED-3.6	✓	✓	Normalized Current Efficiency (NCE)	-	Measurement and Calculation, see Bisselink *et al.* [57] for more information
ED-3.7	✓	✓	Normalized Membrane Resistance (NMR)	-	Measurement and Calculation, see Bisselink *et al.* [57] for more information
ED-3.8		✓	Applied (or resulting) Voltage	V	Measurement
ED-3.9		✓	Applied (or resulting) Current	A	Measurement
ED-3.10		✓	Crossflow Velocity along Membranes/ Hydraulic Stages	m/s	Measurement and Calculation
ED-3.11		✓	Stack Flushings per year	1/a	Measurement and Calculation
ED-3.12		✓	Amount of CIPs per year	1/a	CIP: Clean in Place
ED-3.13		✓	EDR Stack Specifications	-	Given by used stack: e.g. hydraulic and electrical stages
ED-3.14		✓	Membrane Replacement per year	%/a	Measurement and Calculation
EDR-3.15		✓	Polarity Reversal per day	/day	Measurement and Calculation

Table 8-9: Proposed Technological KPIs related to Process Operation for MBR

MBR					
ID	**KPI**	**Indicator**	**Name**	**Unit**	**Comments**
MBR-3.2		✓	Water Flows (Feed, Permeate (and Concentrate))	m^3/h	Measurement

MBR					
ID	**KPI**	**Indicator**	**Name**	**Unit**	**Comments**
MBR-3.3		✓	Temperature	°C	Measurement
MBR-3.4		✓	Pressure(s) (Feed, Permeate (and Concentrate))	bar	Measurement if necessary
MBR-3.5	✓	✓	Conversion Rates (TOC/COD, Total Nitrogen (TN), Total Phosphorus (TP))	e.g. $kg_{COD}/(m^3day)$	Measurement and Calculation
MBR-3.6		✓	Filtration time (till Backwash, if applicable)	min	Measurement
MBR-3.7		✓	Flux	LMH	Measurement and Calculation
MBR-3.8		✓	Critical Flux	LMH	Measurement and Calculation
MBR-3.9		✓	Backwash Time	Min	Measurement
MBR-3.10		✓	Amount of CIPs per year	1/a	CIP: Clean in Place
MBR-3.11		✓	Amount of CEBs per year	1/a	CEB: Chemically enhanced Backwash
MBR-3.12	✓	✓	Membrane Replacement per year	%/a	Measurement and Calculation
MBR-3.13		✓	Transmembrane Pressure (TMP)	bar	Measurement and Calculation
MBR-3.14		✓	Specific Oxygen Uptake Rate (SOUR)	mg_{O2}/g_{VSS}	Measurement and Calculation
MBR-3.15		✓	Food to Mass Ratio (F/M)	-	Measurement and Calculation
MBR-3.16	✓	✓	Biomass Yield Coefficient	g_{VSS}/g_{COD}	Measurement and Calculation
MBR-3.17	✓	✓	Sludge Volume Index (SVI)	mL/g	Measurement and Calculation
MBR-3.18		✓	Sludge Age	d	Measurement and Calculation
MBR-3.19	✓	✓	Sludge Dewaterability e.g. Capillary Suction Time (CST)	s	Measurement

Table 8-10: Proposed Technological KPIs related to Process Operation for AGS

AGS					
ID	**KPI**	**Indicator**	**Name**	**Unit**	**Comments**
AGS-3.2		✓	Water Flows (Feed, Permeate (and Concentrate))	m^3/h	Measurement
AGS-3.3		✓	Temperature	°C	Measurement
AGS-3.4		✓	Pressure(s) (if applicable)	bar	Measurement if necessary
AGS-3.5	✓	✓	Conversion Rates (TOC/COD, Total Nitrogen (TN), Total Phosphorus (TP))	e.g. kg$_{COD}$/(m^{3}day)	Measurement and Calculation
AGS-3.6	✓	✓	Specific Oxygen Uptake Rate (SOUR)	mg$_{O2}$/g$_{VSS}$	Measurement and Calculation
AGS-3.7		✓	Food to Mass Ratio (F/M)	-	Measurement and Calculation
AGS-3.8	✓	✓	Biomass Yield Coefficient	g$_{VSS}$/g$_{COD}$	Measurement and Calculation
AGS-3.9	✓	✓	Sludge Volume Index (SVI)	mL/g	Measurement and Calculation
AGS-3.10		✓	Sludge Age	d	Measurement and Calculation
AGS-3.11	✓	✓	Sludge Dewaterability e.g. Capillary Suction Time (CST)	s	Measurement