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Sustainability and Strategic Assessment of Water and Energy Integration Systems: Case Studies of the Process Industry in Portugal

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Abstract: The most recent sustainability policies of each region of the world conjointly define that economic activities shall follow the principles of natural resource use minimisation, as well as eco-efficiency and circular economy promotion, in addition to the specific objectives defined in each policy. Most recently, a group of researchers has proposed innovative conceptual systems designated Water and Energy Integration Systems (WEIS) for issues related to water and energy use (two prominent categories of natural resources). These are based on engineering projects encompassing a multitude of processes and technologies. In this work, an assessment based on the determination of several sustainability and strategic-aims-related indicators is performed for two WEIS case studies set in the Portuguese process industry (in this case, a ceramic plant). Such an assessment serves as an expansion of previously performed studies on the economic and environmental viability associated with the installation of this type of system with the ultimate goal of proving the effective compliance of water- and energy-use-reduction-related results with sustainability and strategic aims (namely, the ones associated with the most recent policies and aspects associated with the social, economic, and environmental pillars of sustainability). The results for the overall assessment proved that the conceptualised WEIS are robust in terms of eco-efficiency, circular economy potential, and strategic objective achievement potential (with a 6.46% and 4.00% improvement for the aggregated eco-efficiency indicator having been obtained for, respectively, case studies 1 and 2, a null water discharge for both case studies, and a level of 8.58% and 6.69% of recirculated heat over total energy consumption, respectively). The obtained results prove the sustainability promotion effectiveness of the WEIS as conceptual systems. The overall set of indicators defined in this work are part of a methodology that may be used and adapted for further studies considering the innovative WEIS approach, with the specific results obtained in this work presented with the aim of their being used for comparison.

Keywords: Water and Energy Integration Systems; eco-efficiency; circular economy; sustainability; process industry

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1. Introduction

The overall production process within a factory entails significant quantities of external natural resources for its functioning [1,2]. Two of the most important of these resources are water and energy [3]. While energy is used in diverse forms (such as fuels and electricity) [4], the use of water is not generally significantly differentiated (a water stream may contain several dissolved contaminants in different quantities, although this represents a characterisation of a single resource rather than a differentiation within a single category of a resource) [5]. The operational improvement of production processes occurs not only through the increase in production capacity but also through the reduction of the total use of external resources for the same exact end [6].

Several approaches have been taken to reduce the use of water and energy in process industries. For water efficiency improvement, the installation of wastewater treatment units coupled with water recirculation have been proposed for several case studies as a set of measures that allow the overall decrease in freshwater consumption and also the reduction of contaminant discharges [7]. For energy efficiency improvement, various measures, such as waste heat recovery [8], thermal energy storage [9–11], and high-efficiency electric motor installation [12], have been proposed. Advanced categories of measures include energy recovery from water and wastewater [13,14], in which specific discharges of water systems are used to bring benefits at the level of energy use.

With the aim of more effectively analysing improvements in water and energy use in end-use sectors from a holistic perspective, the concept of the water–energy nexus has been introduced [15]. This concept deals with all of the potential interdependencies between the use of water and energy resources, for which their exploitation must be performed so as to bring an overall compromise between economic viability, environmental burden reduction, and social stability so as to promote the sustainable character of physical systems [16]. A specific application of the water–energy nexus has most recently been proposed by the definition of the concept of Water and Energy Integration Systems (WEIS) [17,18]. These are systems that encompass a set of combustion-based processes and a set of water-using processes, as well as the installation of several types of technologies, which, from a holistic perspective, bring benefits at the level of the reduction of overall water and energy inputs and gas and solid contaminant discharges.

A conjoint effort led by researchers in Portugal (namely, from ISQ—Instituto de Soldadura e Qualidade e Instituto Superior Técnico) has been dedicated to the study of the potential to install the mentioned types of systems and improvement measures in the context of the development of engineering projects for single industrial plants [17], assisted by the use of simulation and optimisation tools—namely, the specialised Modelica- and Python-languages-based ThermWatt [18]. Although these models have been successful with respect to the estimation of the economic and environmental impact reduction potential associated with WEIS, a systemisation of the compliance of this type of complex engineering project with the specific sustainability and strategic aims may be developed, with the ultimate purpose of assisting the end-use sector stakeholders in the selection of the most favourable projects (thus facilitating the commissioning of these projects as well as the technology readiness levels associated with some technologies). To this end, the aforementioned research effort is set to be completed through the performance of a sustainability and strategic assessment that will include an estimation of several eco-efficiency and circular economy character promotion indicators and also a comparison of the results with the aims delineated in sustainability policies. This work performs the described assessment for two different case studies set within the Portuguese process industries (namely, the ceramic industry).

2. Background

The sustainability and strategic assessment performed in this work is based on the general concept of sustainability and the finding of a compromise between the social, environmental, and economic aspects associated with newly commissioned industrial plants. The adequacy of the general concept of sustainability in relation to the specific objectives of this work is presented in Figure 1.

Based on Figure 1, the economic and environmental viability associated with the conceptualised WEIS is set to be reinforced through the determination of several eco-efficiency and circular economy promotion indicators. On the other hand, the promotion of the social aspect associated with the new plants (which is potentially associated with the mitigation of social impacts) will be assessed through the determination of specific indicators to be compared with the specific aims pointed out in the sustainability policies of Portugal. The aim is to assess the adequacy of the results obtained in the context of the case studies in relation to the specific policy objectives and whether the promotion of social-stability-related aspects included in the same policies is also secured. A direct correlation is assumed between the verification of the compliance, the strategic aims, and the social-related aspects (which are not directly determined).

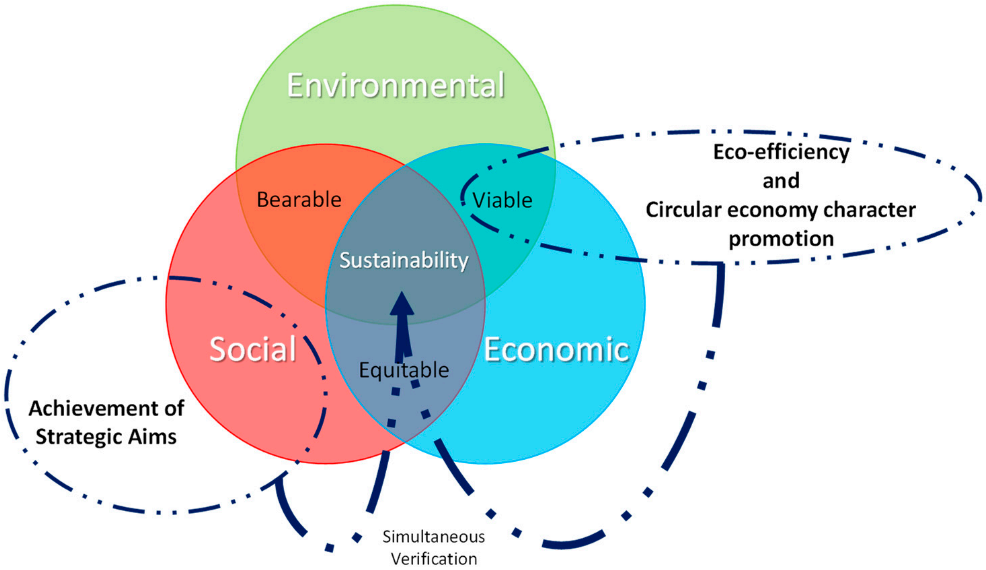

Figure 1. Context of the general objectives of this work within the three dimensions of sustainability.

The handling of the proposed study is based on a general framework related to three aspects:

- Sustainability policies of the European Union and Portugal;
- The most recent social issues related to the energy crisis and water scarcity;
- The adequacy of the circular economy concept.

2.1. Review of Current Research and Knowledge Gap

The assessment of viability associated with the implementation of WEIS is primarily based on the analysis of the potential benefits, including energy savings, water savings, GHG emission reduction, and wastewater pollutant reduction. These benefits may all be translated to economic-based values by means of monetary-based unitary factors (such as water and energy unitary costs and the costs associated with pollutant emissions). In the context of the benefits related to water and energy use reduction, a set of indicators have been defined by several authors who have exploited the paradigms associated with water and energy efficiency. These indicators may be implemented to express the eco-efficiency and circular economy character of systems similar to WEIS, either by establishing a ratio between production-related parameters and an environmental-burden-related parameter or by implying the performance of recirculation of material and energy streams. In the context of the aforementioned conceptual systems, these indicators may be used to compare a case study with an implemented WEIS with:

- The baseline case within a plant (in which improvement measures have yet to be implemented);
- Other systems (conceptualised and implemented for similar case studies).

In Table 1, several indicators that have been exploited by authors within the paradigms of water and energy efficiency are characterised.

Table 1. Characterisation of assessment indicators.

Indicator	Characterisation	Refs.
Related to Water Use		
Specific water consumption (m^3 water/ton material)	It is the ratio between water consumption and the produced ceramic material of a process or across the overall plant. It is (commonly) implemented to assess the potential of several measures to reduce water use.	[19,20]
Economic value per dissipated water (EUR/kg dissipated water)	It is the ratio between the economic value associated with ceramic production and the amount of dissipated water.	[21]
Wastewater Circonomics Index	It is an aggregated indicator that measures the circularity character of a water system. It is determined by the product of three sub-indicators: a wastewater reuse indicator (which measures the part of product mass relative to reusability), a composite wastewater re-use indicator (a value-weighted indicator measuring the equivalent shadow prices of eliminated externalities), and a wastewater recycle indicator (measures the ratio of the quantity of wastewater that is effectively used by economic activities). Up to 50% water recirculation in the ceramic industry overall is regarded as a benchmark.	[22]
Specific water consumption (m^3 water/ton material)	It is the ratio between water consumption and the produced ceramic material of a process or across the overall plant. It is (commonly) implemented to assess the potential of several measures to reduce water use.	[19,20]
Related to Energy Use		
Specific electric energy consumption (MWh_{el}/ton material)	It is (commonly) used to assess the general energy efficiency associated with the overall use of electric energy in a ceramic plant.	[23–26]
Specific thermal energy consumption (MWh_{th}/ton material)	It is (commonly) used to assess the overall energy efficiency associated with the fuel consumption of thermal processes.	
Produced material emission intensity (ton GHG/ton material)	It is the ratio between GHG emissions (CO_{2eq} and NO_X) and the produced material related to an overall plant or a process. Considering that combustion-related emissions are highly superior to process emissions for all ceramic thermal processes, it may be used to evaluate the emission intensity reduction potential associated with several measures.	[23,26]
Energy carbon footprint (ton CO_{2eq}/TJ)	It is the ratio between CO_{2eq} emissions and energy consumption (thermal and electric) in a plant from an overall perspective.	[27,28]
Thermal efficiency	It consists of the ratio between the useful thermal energy output and the thermal energy input in a ceramic thermal process.	[29]
Aggregated		
Waste Heat Performance Ratio (kg water/kg waste heat stream or GJ-produced vapour/GJ waste heat)	It is the ratio between the produced treated water and the used amount of a waste heat stream. In the context of heat-driven water treatment, it may be determined by comparing the material quantities (the ratio between the mass flow rate of produced treated water and the waste heat stream) and the energy quantities (the ratio between the produced vapour and the supplied thermal energy).	[30,31]
Energy water footprint (m^3 water/TJ)	It is the ratio of water consumption and energy consumption (thermal and electric) in a plant from an overall perspective.	[28,32]

The set of indicators explored in Table 1 is effectively adequate for the assessment of projects related to heat-recovery-based energy efficiency improvement and the improvement of the operation of water systems in terms of water use and hot/cold utilities consumption. These are effective from the standalone perspective of each of the aforementioned aspects. Nonetheless, the establishment of these indicators (in the current form in which they are presented) is associated with limitations at the level of:

- The evaluation of the water–energy nexus promotion potential (the association between several energy-use-related parameters and water-use-related parameters);
- The capacity to perform an overall systemisation of the compliance of engineering projects with specific economic and environmental impact reduction aims (namely, the ones defined in the most recent sustainability policies);
- The analysis of the system based on the ratio between the levels of recirculation associated with different streams (for instance, the ratio between the quantities of treated water and water savings and the ratio between recirculated heat and total energy input).

The identified limitations are set to be overcome through the application of a methodological framework that is set to be established in the present work. While a part of the indicators is set to be maintained in terms of formulation, others are set to be re-formulated by reason of convenience related to the adequacy of the indicators for the specific paradigm of the WEIS.

2.2. Framework of Sustainability Policies

The driving force for the framework of WEIS has been the specific aims that are enunciated in the main sustainability policies of the European Union and, particularly, the policies of Portugal. The sustainability promotion policy that served as the conceptual origin of the WEIS is the EU Strategy for Energy System Integration, including, primarily, its first and third pillars (Energy Efficiency and Circular Economy Nexus and Alternative, Low-Carbon Fuels). As this strategy applied the previous principles included in the European Green Deal and the 2050 long-term strategy, the achievement of the aims of the Energy System Integration strategy through the framework of WEIS also serves the same purpose in relation to those policies. Nonetheless, this set of policies has only been framed on a conceptual basis up until this point.

Requirements for conjointly promoting low-carbon and circular economies and the improvement of water efficiency are addressed in the Roadmap for Carbon Neutrality 2050 (RNC2050) [33] and the *Programa Nacional para o Uso Eficiente da Água* (PNUEA) [34], which have been proposed as guiding instruments in Portugal. These two strategies are based on the delineation of specific objectives for all the end-use sectors, with RNC2050 containing specific guides for a set of subsectors of the whole industrial sector.

2.3. Framework for Studying the Social Issues of the Energy Crisis and Water Scarcity

The development of the present work emerged during a period of time marked by severe social issues related to the decrease in the availability of several natural resources and an economic crisis provoked by the COVID-19 pandemic and the Russia–Ukraine War [35]. In the context of the areas of actuation inherent to this work, including the ones related to energy and water management, an analysis of the impact of the ongoing global energy crisis and water scarcity on the actual, obtained results is relevant.

The current energy crisis is essentially based on gradually rising energy prices (which are particularly severe in the case of natural gas), which is directly related to existing cuts in the energy source supply provoked by the war and the economic rebound phenomenon that emerged in the follow-up to the pandemic. These gradually rising energy prices have been creating significant inflation rise, which, in turn, has been provoking an augmentation of economic discomfort across society in general [36]. Simultaneously, several regions of the world have been facing the depletion of water resources availability, an issue that was particularly prevalent in Europe in the years 2022 and 2023 [37]. While, for the former issue, the promotion of energy efficiency improvement measures allied to renewable energy and alternative fuel integration have been regarded as keys to solving it, for the latter, the promotion of improved water management techniques in end-use sectors has been similarly identified as a solving method. The concept of WEIS (as introduced in previous works by the authors [17]) promotes the reduction of the consumption of both energy and water while simultaneously approaching the development of methods for the solving of the two aforementioned issues.

2.4. Framework of the Circular Economy Concept

The potential for the promotion of the circular economy character associated with the framework of the WEIS is derived from the inherent attribute of these as essentially closed-loop systems. The installation of WEIS is based on the promotion of certain practices, such as recycling, reuse, and by-pass of to-be-valorised energy and water streams. These phenomena have been conjointly referred to in this work as recirculation.

The difference between standard energy and water efficiency improvement measures and WEIS implementation is based on the characteristic of the latter as using recirculation for the achievement of purposes related to decarbonisation, and, in a further step, eco-efficiency. Therefore, the conceptual aim of the WEIS may be enunciated as the promotion of both low-carbon and circular economies in an optimised manner while bearing in mind the objective of the maximisation of eco-efficiency.

From a social perspective, the concept of the circular economy has been facing critiques in terms of it being vague and metaphorical in nature [38]. The establishment of the relationship between the findings obtained for the study of WEIS and the specific features of the circular economy concept is relevant so as to further establish a relationship with the aims of the most recent sustainability policies.

2.5. Framework of Social-Related Benefits Promotion

The social-related benefits that are assumed to be promoted are based on the following aspects (which are prominently delineated in RNC2050 [33]):

- **Promotion of a socially fair and efficient energy transition**: the conceptualised WEIS installations do not require additional investment in land except that which is already used for plants to be installed, and it requires investment costs that are assumed to be allocated from the industrial stakeholders, with the existence of government incentives;
- **Reinforcement of the competitiveness of the regional and industrial economies**: payback periods of less than the most favourable and acceptable limit of 3 years [39] and a maximum acceptable limit of 5 years [40] are significant in that a considerable margin of total savings can be allocated to the promotion of other benefits. The limits to which the commissioned installations are considered to be economically viable are nevertheless not surpassed;
- **Promotion of the creation of work positions**: this may be regarded as one of the aforementioned benefits;
- **Improvement of air quality and overall human health**: while the improvement of air quality is secured by the reduction of waste gas emissions (as evidenced by the final simulation results obtained for the case studies), the improvement of human health may be secured through the combination of this benefit with the improvement of the quality of discharge water (which may be evidenced by the null level of the discharge water obtained for the case studies), as well as the relative increase in water availability.

Assurance of the existence of these benefits (in addition to proof of the economic and environmental viability characters associated with the conceptualised installations) is a necessary and sufficient condition to ensure the sustainability promotion character of the conceptualised WEIS installations.

3. Methodology and Process Industry Cases

This work is based on a new methodology based on the previously established WEIS concept in which a set of indicators mirroring the sustainability character of industrial installations is defined and a set of two case studies is used based on the implementation of the established indicators.

3.1. Definition of Assessment Indicators

The post-processing procedure performed through the assessment of results from computational models developed in previous work by the authors [18,41,42] consists, in general, of calculating indicators related to sustainability promotion (set to assess the economic viability and environmental impact reduction potential associated with the conceptualised WEIS). In this work, two other sets of indicators are calculated: one related to the eco-efficiency promotion and another related to circular economy character promotion (related to the passage from open-loop to closed-loop systems). These last not only serve to reinforce the viability of the proposed WEIS but also to prove the self-sufficiency of these in terms of exploitation of energy and water resources and the production of economic value. In the sequence of Tables 2 and 3, these sets of indicators are characterised by being defined with the exact units that are set to be used in the upcoming analysis.

Table 2. Definition of eco-efficiency promotion indicators.

Indicator	Definition	Calculation Formula	
	Energy-use-related indicators		
Specific Fuel Consumption (GJ/ton)	It consists of the ratio between the total consumption of a fuel, such as natural gas (FC), and the total quantity of produced material (Prod) in a plant, by assessing the dependency of the production process on the use of a determinate fuel.	$\text{SFC}(\text{GJ}/\text{ton}) = \frac{\text{FC (GJ/year)}}{\text{Prod (ton/year)}}$	(1)
Specific Electricity Consumption (MWh/ton)	It consists of the ratio between the total consumption of electricity (ElecC) and the total quantity of produced material (Prod) in a plant by assessing the dependency of the production process on the use of electric energy.	$\text{SElecC}(\text{MWh}/\text{ton}) = \frac{\text{ElecC (MWh/year)}}{\text{Prod (ton/year)}}$	(2)
	Water-system-related indicators		
Specific Water Consumption (m^3/ton)	It consists of the ratio between the total consumption of freshwater (FW) and the total quantity of produced material (Prod) in a plant by assessing the dependency of the production process on the use of water resources.	$\text{SFW}(\text{m}^3/\text{ton}) = \frac{\text{FW }(\text{m}^3/\text{year})}{\text{Prod (ton/year)}}$	(3)
Water energy footprint (MJ/m^3)	It consists of the ratio between the energy consumed in the water system (namely, the one corresponding to the consumption of hot and cold utilities) (EWS) and freshwater consumption (FW) by assessing the dependency of the production process on the use of water resources.	$\text{WEF}(\text{MJ}/\text{m}^3) = \frac{\text{EWS (MJ/year)}}{\text{FW }(\text{m}^3/\text{year})}$	(4)
	GHG-emissions-related indicators		
Produced material emission intensity (ton $CO_{2,eq}$/ton material)	It consists of the ratio between total equivalent carbon dioxide emissions in the plant ($CO_{2,eq}$) and the quantity of produced material (Prod) by assessing the footprint of greenhouse gas emissions on the production process.	$\text{GHGI}(\text{ton CO}_{2,eq}/\text{ton Prod}) = \frac{\text{CO}_{2,eq}\ (\text{ton CO}_{2,eq}/\text{year})}{\text{Prod (ton Prod/year)}}$	(5)
Energy carbon footprint (ton $CO_{2,eq}$/TJ)	It consists of the ratio between total equivalent carbon dioxide emissions in the plant ($CO_{2,eq}$) and total energy consumption (EC) by assessing the average emission factor associated with the energy mix of the plant.	$\text{EGHGF}(\text{ton CO}_{2,eq}/\text{TJ}) = \frac{\text{CO}_{2,eq}\ (\text{ton CO}_{2,eq}/\text{year})}{\text{EC (TJ/year)}}$	(6)

Table 2. *Cont.*

Indicator	Definition	Calculation Formula	
	Aggregated eco-efficiency indicators		
Aggregated eco-efficiency indicator (EUR/kg $CO_{2,eq}$)	It consists of the ratio between the revenue associated with produced material sales (Revenue) and total equivalent carbon dioxide emissions ($CO_{2,eq}$) by assessing the increase in production value in relation to the generated environmental burden.	$\text{EcoEff}\left(\text{EUR/kg } CO_{2,eq}\right) = \frac{\text{Revenue (EUR/year)}}{CO_{2,eq}\ \left(\text{kg } CO_{2,eq}\text{/year}\right)}$	(7)
Material productivity (EUR/kg material)	It consists of the ratio between the revenue associated with produced material sales (Revenue) and the quantity of produced material (Prod) by assessing the increase in production value in relation to the quantity of produced material in a plant.	$\text{PMP(EUR/kg Prod)} = \frac{\text{Revenue (EUR/year)}}{\text{Prod (kg Prod/year)}}$	(8)

Table 3. Definitions of circular economy promotion indicators.

Indicator	Definition	Calculation Formula	
	Energy-use-related indicators		
Waste Heat to Total Energy Ratio	It consists of the ratio between waste heat and heat losses (WH) and total energy consumption in the plant (EC).	$\text{WHE} = \frac{\text{WH (TJ/year)}}{\text{EC (TJ/year)}}$	(9)
Recirculated Heat to Baseline Total Energy Ratio	It consists of the ratio between recirculated heat (RH) and total energy consumption in the plant in the baseline scenario ($EC_{Baseline}$).	$\text{RHEB} = \frac{\text{RH (TJ/year)}}{EC_{Baseline}\ \text{(TJ/year)}}$	(10)
Waste Heat to Fuel Used in Combustion-Based Processes Ratio	It consists of the ratio between waste heat from combustion-based processes (WH_{TP}) and respective fuel consumption (FC_{TP}).	$\text{WHFTP} = \frac{WH_{TP}\ \text{(TJ/year)}}{FC_{TP}\ \text{(TJ/year)}}$	(11)
Recirculated Heat to Baseline Fuel Used in Combustion-Based Processes Ratio	It consists of the ratio of recirculated heat in-between combustion-based processes (RH_{TP}) and respective fuel consumption (FC_{TP}).	$\text{RHFTP} = \frac{RH_{TP}\ \text{(TJ/year)}}{FC_{TP}\ \text{(TJ/year)}}$	(12)
	Water-use-related indicators		
Discharge Water to Freshwater Ratio	It consists of the ratio between discharge water from the water system (DW) and freshwater (FW).	$\text{DWFW} = \frac{\text{DW}\ \left(m^3\text{/year}\right)}{\text{FW}\ \left(m^3\text{/year}\right)}$	(13)
Treated Water to Wastewater Ratio	It consists of the ratio between output treated water from wastewater treatment (TW) and input wastewater (WW).	$\text{TWWW} = \frac{\text{TW}\ \left(m^3\text{/year}\right)}{\text{WW}\ \left(m^3\text{/year}\right)}$	(14)
Recirculated to Produced Treated Water Ratio	It consists of the ratio between recirculated treated water (RTW) and the total produced treated water from wastewater treatment (TW).	$\text{RTWTW} = \frac{\text{RTW}\ \left(m^3\text{/year}\right)}{\text{TW}\ \left(m^3\text{/year}\right)}$	(15)
Recirculated Treated Water to Water Savings	It consists of the ratio between recirculated treated water (RTW) and the difference between freshwater consumption in the baseline ($FW_{Baseline}$) and improved scenarios (FW_{WEIS}).	$\text{RTWWSav} = \frac{\text{RTW}\ \left(m^3\text{/year}\right)}{\left(FW_{Baseline} - FW_{WEIS}\right)\ \left(m^3\text{/year}\right)}$	(16)

Table 3. *Cont.*

Indicator	Definition	Calculation Formula
Indicators related to energy input in the water system		
Energy in Water System in the Improved Scenario over the Baseline Scenario	It consists of the ratio between the energy input in the water system standalone (namely, hot and cold utilities and recirculated heat from combustion-based processes) in the improved scenario (EWS_{WEIS}) and the baseline scenario ($EWS_{Baseline}$).	$EWSR = \frac{EWS_{WEIS}\ (MJ/year)}{EWS_{Baseline}\ (MJ/year)}$ (17)
Withdrawn Energy from the Water System in the Improved Scenario over Energy in the Water System in the Baseline Scenario	It consists of the ratio between the energy withdrawn from the water system in the improved scenario (namely, the difference between total energy input in the water system standalone in the baseline scenario and the total energy input in the improved scenario) (wEWS) and the total energy input in the baseline scenario ($EWS_{Baseline}$).	$wEWEWS = \frac{wEWS\ (MJ/year)}{EWS_{Baseline}\ (MJ/year)}$ (18)

In Table 4, the formulas used to determine the most basic indicators of economic savings, and equivalent carbon dioxide emissions are defined. In both of the calculation formulas, the index i represents a certain energy source in which the WEIS is conceptualised to reduce the emission level (for instance, fuel or electricity). Furthermore, the Price and EF designate the unitary price and the emission factor that is associated with each energy and water utility, respectively. With respect to the revenue associated with improved scenarios, two sets of results are defined for monetary-based indicators:

- One is designated as **Beginning-of-Life,** corresponding to a scenario at the point in time of the acquisition of the required technology and machinery for the commissioning of the WEIS (in which the total investment cost is considered a negative parcel for the determination of the improved scenario revenue);
- Another is designated as **End-of-Life,** corresponding to a scenario in the immediate point in time following the return on investment (in which the total investment cost is not already considered as a parcel).

Table 4. Definition of primary calculation formulas.

Aspect	Calculation Formula	
$Sav\ (EUR/year) =$	$\left(FW_{Baseline} - FW_{Improved}\right)\ (m^3/year)\cdot Price_W\ (EUR/m^3) + \sum_{i=1} (EC_{i,Baseline} - EC_{i,WEIS})\ (J/year)\cdot Price_{EC,i}\ (EUR/J)$	(19)
$CO_{2,eq}\ (kg\ CO_{2,eq}/year) =$	$\sum_{i=1} EC_i\ (J/year)\cdot EF_{ES,i}\ (kgCO_{2,eq}/J) + Other\ Emissions(kg\ CO_{2,eq}/year)$	(20)
Energy Consumption in the Water-System-Related Indicators		
Beginning-of-Life	$Revenue_{WEIS} = (Revenue_{Baseline} + Sav) - CAPEX$	(21)
End-of-Life	$Revenue_{WEIS} = (Revenue_{Baseline} + Sav)$	(22)

The values obtained for the aforementioned sub-scenarios thus constitute the minimum and maximum values that can be obtained for the indicators in question.

3.2. Characterisation of Case Studies

The case studies used in this work are set within the ceramic industry of Portugal, including two sanitaryware plants installed in the same industrial site.

The plant of case study 1 comprises:

- Two tunnel kilns (kilns 1 and 2);
- One intermittent kiln;
- Four water-using lines, which, in turn, comprise:
    - Four water-using processes, with each installed to remove a specific unidentified salt contaminant;
    - Four heaters, which are hot water boilers using natural gas (as a hot utility);
    - One cooler, which is a heat exchanger in which a refrigeration organic fluid (cold utility) stream withdraws enthalpy from the water stream (electricity is used to produce the refrigeration stream through its path to the cooling tower).

The plant of case study 2 comprises:

- Two tunnel kilns (kilns 1 and 2);
- Two intermittent kilns (kilns 3 and 4);
- Three water-using lines, which, in turn, comprise:
    - Three water-using processes, with each one installed to remove a set of three unidentified salt contaminants;
    - Three heaters, which are hot water boilers using natural gas (as a hot utility);
    - Three coolers, which are are heat exchangers in which refrigeration organic fluid (cold utility) streams withdraw enthalpy from the water stream (electricity is used to produce the refrigeration streams through its passage in a cooling tower).

The characterisation of the industrial site and each case study plant in terms of energy consumption is performed in the sequence of Tables 5–7.

Table 5. General characterisation of the industrial site.

Parcel	Baseline Scenario	Improved Scenario	
		Case Study 1	Case Study 2
Energy Consumption (TJ)			
Natural Gas	304.10	277.34	280.02
Electricity	67.45	62.04	65.54
Liquid petroleum gas	0.45	0.45	0.45
Diesel fuel	3.27	3.27	3.27
Total	375.26	343.09	349.27
Other Indicators			
Production (Mg)	35.43	35.43	35.43
Revenue (EUR M)	26.52	27.38	27.16
$CO_{2,eq}$ Emissions (kton CO_{2eq})	28.56	26.14	26.80

The WEIS proposed for plant in case study 1, in general, comprises the following procedures:

- Direct hot air recirculation between the two kilns as part of pre-heated combustion air (to produce natural gas savings);
- Hot air and exhaust gas mixing (from both kilns) and further recirculation to an Organic Rankine cycle (ORC) (to produce additional electricity);
- Hot air mixing (from both kilns) and further recirculation to a multi-effect distillation unit (to produce treated water);
- Water stream recirculation within the water system.

Table 6. Characterisation of case study 1.

Natural Gas Consumption in Combustion-Based Thermal Processes				
Process			**Energy Consumption (TJ)**	
Kiln 1			69.34	
Kiln 2			36.52	
Annual Energy and Water Consumption in Water-Using Lines				
Water-Using Line	**Water Consumption (Baseline Scenario) (dam^3)**	**Water Consumption (Improved Scenario) (dam^3)**	**Hot Utility Consumption (TJ)**	**Cold Utility Consumption (TJ)**
Line 1	3.72		1.37	
Line 2	3.73		1.43	
Line 3	2.86		1.04	
Line 4	0.46		0.18	
Discharge Line				4.52
Total	10.77	8.22	4.01	4.52
Results of Economic and Environmental Impact Reduction Assessment				
Payback period associated with the installation of the WEIS (years)				1.80
TotalCO$_{2,eq}$Emissions reductionassociated with the installation of the WEIS (kton CO$_{2,eq}$/year)				2.42

Table 7. Characterisation of case study 2.

Natural Gas Consumption in Combustion-Based Thermal Processes				
Process			**Energy Consumption (TJ)**	
Kiln 1			44.99	
Kiln 2			42.38	
Kiln 3			4.34	
Kiln 4			16.26	
Annual Energy and Water Consumption in Water-Using Lines				
Water-Using Line	**Water Consumption (Baseline Scenario) (dam^3)**	**Water Consumption (Improved Scenario) (dam^3)**	**Hot Utility Consumption (TJ)**	**Cold Utility Consumption (TJ)**
Line 1	2.44		0.98	0.66
Line 2	3.80		1.41	1.04
Line 3	0.49		0.26	0.13
Total	6.73	4.14	2.65	2.65
Results of Economic and Environmental Impact Reduction Assessment				
Payback period associated with the installation of the WEIS (years)				2.83
TotalCO$_{2,eq}$Emissions reductionassociated with the installation of the WEIS (kton CO$_{2,eq}$/year)				1.76

The WEIS proposed for the plant in case study 2, in general, comprises the following procedures:

- Direct hot air recirculation between the two tunnel kilns as part of pre-heated combustion air (to produce natural gas savings);
- Hot air mixing (from kilns 1 and 2), further recirculation to phase change material (thermal energy storage heat exchanger (enthalpy charge phase)), and further pre-heating of an air stream (enthalpy discharge phase) that is then divided in four to be fed as part of pre-heated combustion air to each one of the four kilns;
- Hot air and exhaust gas mixing (from both tunnel kilns) and further recirculation to an Organic Rankine cycle (ORC) (to produce additional electricity);
- Hot air mixing (from kilns 1 and 2) and further recirculation to a multi-effect distillation unit (to produce treated water);

- Water stream recirculation within the water system.

In the context of this work, the two characterised case studies set within the Portuguese ceramic sector were selected by attending to the following reasons:

- The representativeness of the ceramic sector within the overall process industry in terms of energy and water use. This sector presents reasonable levels of energy and water use and associated waste streams, and the order of magnitude of the quantity of each resource to be valorised is compatible so as to permit significant savings for each one (for instance, waste heat may be recirculated to cause either significant fuel and electricity savings or to produce a significant level of treated water to be recirculated);
- Both case studies are comparable in terms of the existing energy- and water-using processes (these are based on the same categories of processes) and in terms of the order of magnitude of energy and water consumption;
- Significant availability of data associated with the baseline scenario. The numerical data associated with each parameter of interest characterising the case study are highly discerned (in opposition to similar process industry case studies that are either set in different sectors or in different countries).

In the sequence of Figures 2–4, the flowsheet of case study 1's WEIS using the capabilities of the ThermWatt computational tool (manufactured by ISQ—Instituto de Soldadura e Qualidade, Oeiras, Lisbon, Portugal) (baseline scenario and the described optimised scenario, respectively) is presented. In the sequence of Figures 5–7, the flowsheet of case study 2's WEIS using the capabilities of the ThermWatt computational tool (baseline scenario and the described optimised scenario, respectively) is presented.

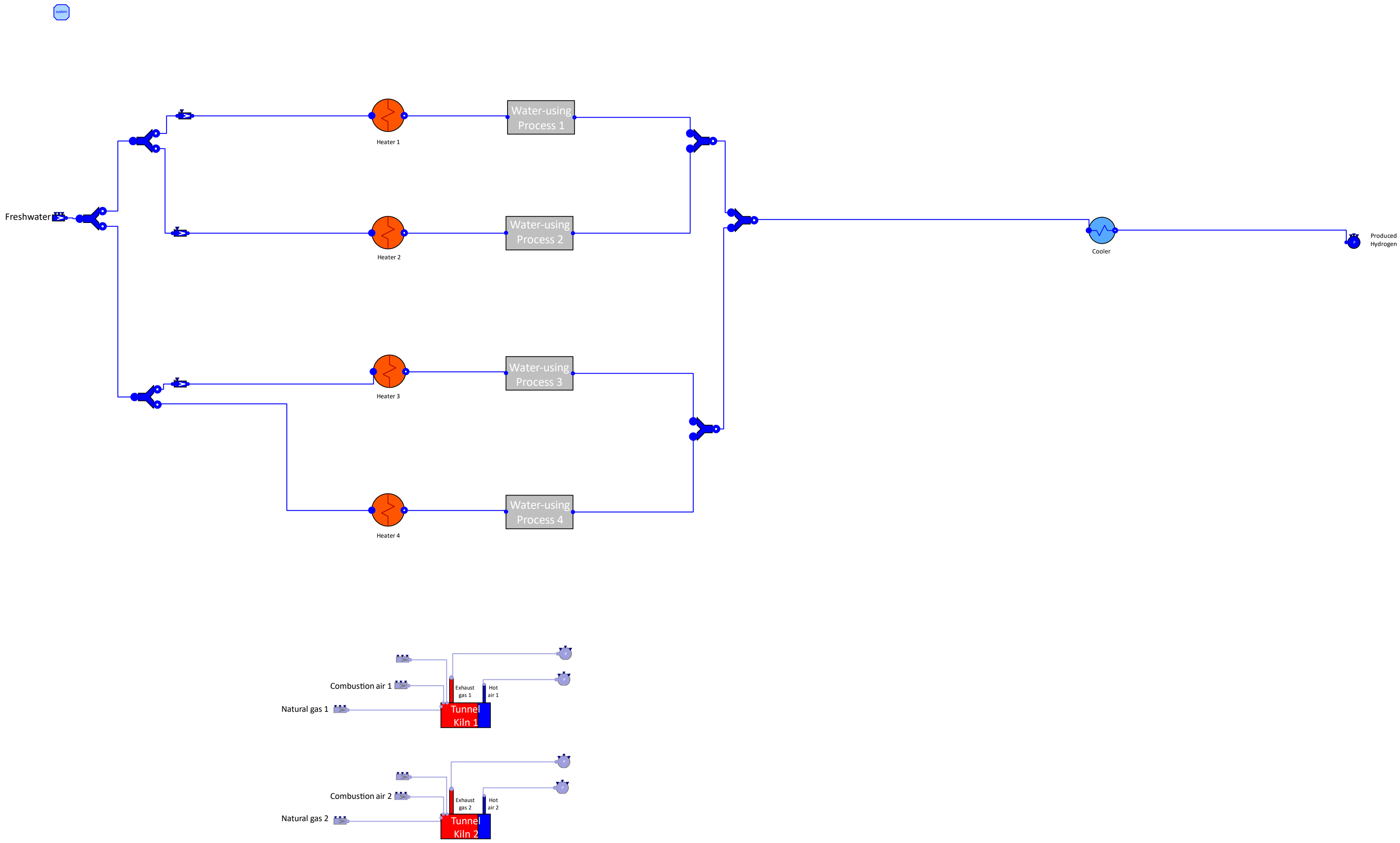

Figure 2. Flowsheet of the case study 1 baseline scenario using the ThermWatt Modelica library capabilities.

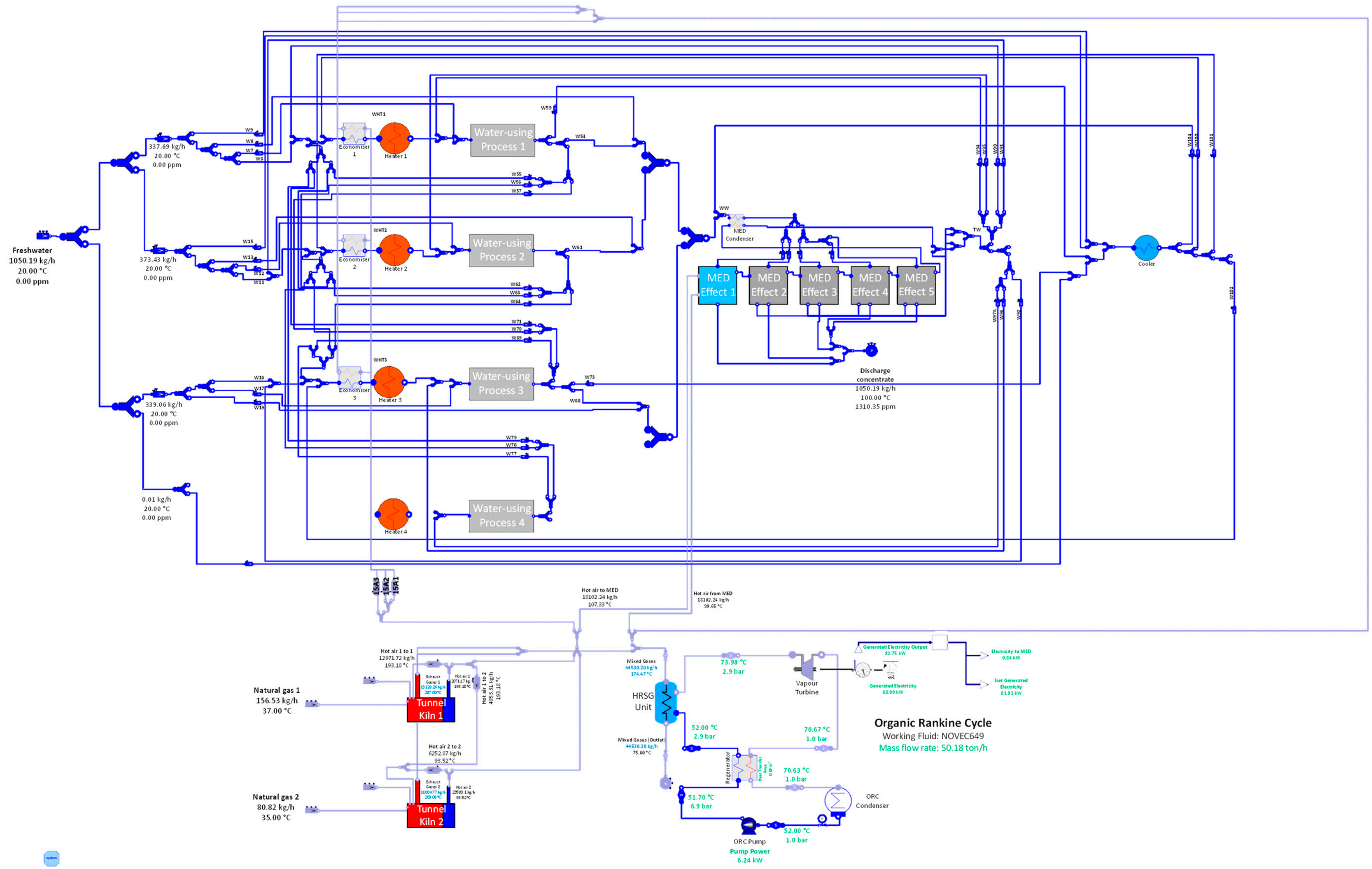

Figure 3. Flowsheet of the case study 1 final configuration using the ThermWatt Modelica library capabilities.

Hot air to Econ. 1 (15A1)
1393.94 kg/h
In.: 102.16 °C
Out.: 38.39 °C

Hot air to Econ. 2 (15A2)
1594.64 kg/h
In.: 102.16 °C
Out.: 38.16 °C

Hot air to Econ. 3 (15A3)
1459.68 kg/h
In.: 102.16 °C
Out.: 37.43 °C

Economiser 1
30.00 m^2

Economiser 2
40.00 m^2

Economiser 3
40.00 m^2

Effect 1 Heat Transfer Area
19.82 m^2

WP1
556.48 kg/h
95.00 °C
In: 146.73 ppm
Out: 1000.00 ppm

WP2
565.20 kg/h
95.03 °C
In: 155.84 ppm
Out: 1000.00 ppm

WP3
416.96 kg/h
95.08 °C
In: 123.58 ppm
Out: 1000.00 ppm

WP4
58.81 kg/h
99.98 °C
In: 0.00 ppm
Out: 998.65 ppm

W61
521.08 kg/h
95.03 °C
1000.00 ppm

W62
0.23 kg/h
95.03 °C
1000.00 ppm

W63
42.87 kg/h
95.03 °C
1000.00 ppm

W64
1.01 kg/h
95.03 °C
1000.00 ppm

WW
1386.41 kg/h
94.44 °C
992.57 ppm

TW
336.22 kg/h
99.98 °C
0.00 ppm

W90
0.01 kg/h
99.98 °C
0.00 ppm

W91
1.17 kg/h
99.98 °C
0.00 ppm

W92
20.63 kg/h
99.98 °C
0.00 ppm

W94
146.14 kg/h
99.98 °C
0.00 ppm

W6
328.27 kg/h
20.00 °C
0.00 ppm

W7
9.01 kg/h
20.00 °C
0.00 ppm

W8
9.01 kg/h
20.00 °C
0.00 ppm

W9
0.01 kg/h
20.00 °C
0.00 ppm

WHT1
409.95 kg/h
In Econ. 1: 38.06 °C
Out Heater 1: 91.14 °C
199.17 ppm

WHT2
457.89 kg/h
In Econ. 2: 38.04 °C
Out Heater 2: 92.60 °C
192.35 ppm

WHT3
401.98 kg/h
In Econ. 3: 37.29 °C
Out Heater 3: 94.82 °C
128.18 ppm

W68
302.36 kg/h
95.08 °C
1000.00 ppm

W69
0.34 kg/h
95.08 °C
1000.00 ppm

W70
0.82 kg/h
95.08 °C
1000.00 ppm

W71
0.55 kg/h
95.08 °C
1000.00 ppm

W95
102.53 kg/h
99.98 °C
0.00 ppm

W96
6.94 kg/h
99.98 °C
0.00 ppm

W97A
58.81 kg/h
99.98 °C
0.00 ppm

W97
244.36 kg/h
94.99 °C
999.90 ppm

W98
244.36 kg/h
94.99 °C
999.90 ppm

W100
79.61 kg/h
94.99 °C
999.90 ppm

W101
18.50 kg/h
94.99 °C
999.90 ppm

W102
127.76 kg/h
94.99 °C
999.90 ppm

W104
127.76 kg/h
94.99 °C
999.90 ppm

W11
368.61 kg/h
20.00 °C
0.00 ppm

W13
0.03 kg/h
20.00 °C
0.00 ppm

W12
4.77 kg/h
20.00 °C
0.00 ppm

W14
0.01 kg/h
20.00 °C
0.00 ppm

W54
424.91 kg/h
95.00 °C
1000.00 ppm

W55
0.07 kg/h
95.00 °C
1000.00 ppm

W59
131.45 kg/h
95.00 °C
1000.00 ppm

W56
0.02 kg/h
95.00 °C
1000.00 ppm

W57
0.03 kg/h
95.00 °C
1000.00 ppm

W76
1.42 kg/h
99.98 °C
998.65 ppm

W77
25.90 kg/h
99.98 °C
998.65 ppm

W78
31.49 kg/h
99.98 °C
998.65 ppm

W16
329.78 kg/h
20.00 °C
0.00 ppm

W18
1.24 kg/h
20.00 °C
0.00 ppm

W17
8.04 kg/h
20.00 °C
0.00 ppm

Figure 4. Values associated with the flowsheet of the case study 1 final configuration using the ThermWatt Modelica library capabilities.

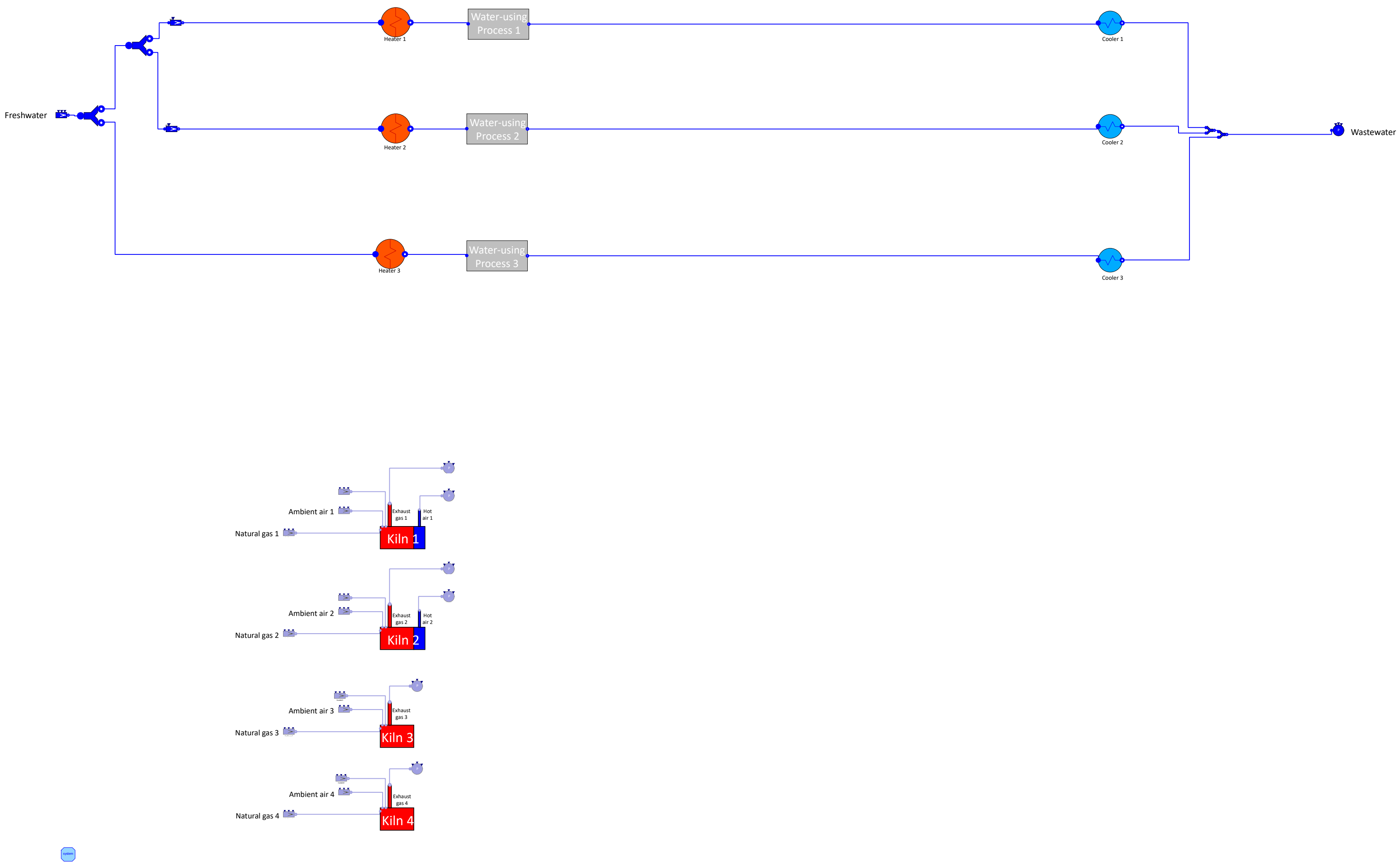

Figure 5. Flowsheet of the case study 2 baseline scenario using the ThermWatt Modelica library capabilities.

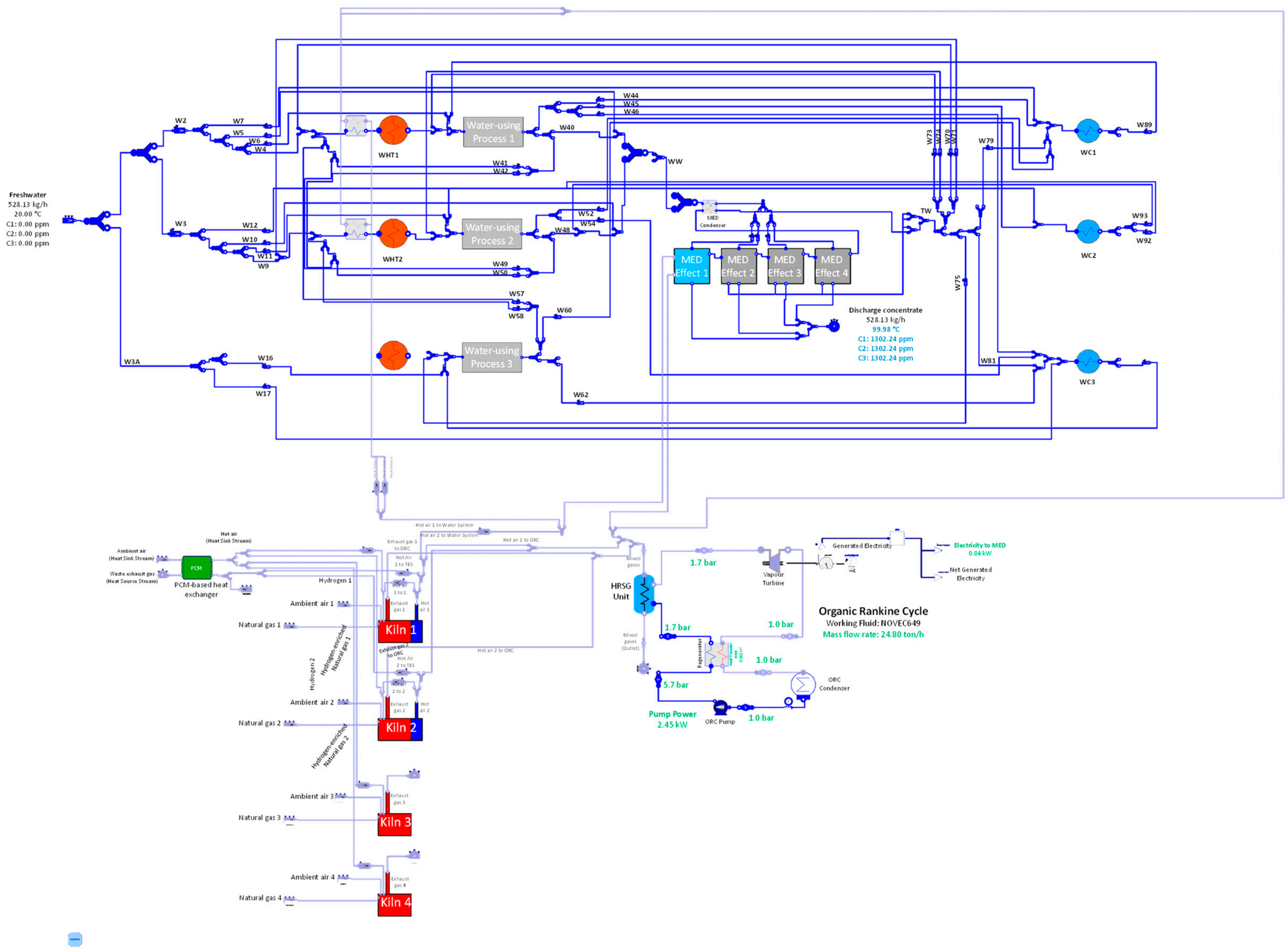

Figure 6. Flowsheet of the case study 2 final configuration using the ThermWatt Modelica library capabilities.

Economiser 1
1.17 m^2

Economiser 2
13.15 m^2

Effect 1 Heat Transfer Area
13.89 m^2

W4
27.44 kg/h
20.00 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W5
47.91 kg/h
20.00 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W6
0.83 kg/h
20.00 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W7
8.43 kg/h
20.00 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W9
378.74 kg/h
20.00 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W10
35.05 kg/h
20.00 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W16
1.63 kg/h
20.00 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W11
3.40 kg/h
20.00 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W12
23.06 kg/h
20.00 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W17
1.63 kg/h
20.00 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W69
2.07 kg/h
99.98 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W70
136.69 kg/h
99.98 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W71
1.05 kg/h
99.98 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W73
73.81 kg/h
99.98 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W74
1.07 kg/h
99.98 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W75
47.67 kg/h
99.98 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W2
84.61 kg/h
20.00 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W3
440.26 kg/h
20.00 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W3A
3.27 kg/h
20.00 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

TW
790.49 kg/h
85.71 °C
C1: 870.74 ppm
C2: 870.74 ppm
C3: 870.74 ppm

WW
262.36 kg/h
99.98 °C
C1: 0.00 ppm
C2: 0.00 ppm
C3: 0.00 ppm

W89
25.43 kg/h
70.27 °C
C1: 627.30 ppm
C2: 627.30 ppm
C3: 627.30 ppm

W92
8.35 kg/h
65.50 °C
C1: 606.61 ppm
C2: 606.61 ppm
C3: 606.61 ppm

W93
50.26 kg/h
65.50 °C
C1: 606.61 ppm
C2: 606.61 ppm
C3: 606.61 ppm

WC1
25.43 kg/h
In: 71.64 °C Out: 70.27 °C
C1: 627.30 ppm
C2: 627.30 ppm
C3: 627.30 ppm

WC2
58.62 kg/h
In: 67.07 °C Out: 65.50 °C
C1: 606.61 ppm
C2: 606.61 ppm
C3: 606.61 ppm

WC3
10.87 kg/h
In: 85.00 °C Out: 84.35 °C
C1: 718.02 ppm
C2: 718.02 ppm
C3: 718.02 ppm

WP1
301.40 kg/h
95.01 °C
C1 In: 173.47 ppm C1 Out: 1000.00 ppm
C2 In: 173.47 ppm C2 Out: 1000.00 ppm
C3 In: 173.47 ppm C3 Out: 1000.00 ppm

WP2
472.90 kg/h
95.03 °C
C1 In: 177.94 ppm C1 Out: 1000.00 ppm
C2 In: 177.94 ppm C2 Out: 1000.00 ppm
C3 In: 177.94 ppm C3 Out: 1000.00 ppm

WP3
60.17 kg/h
95.10 °C
C1 In: 129.67 ppm C1 Out: 958.64 ppm
C2 In: 129.67 ppm C2 Out: 958.64 ppm
C3 In: 129.67 ppm C3 Out: 958.64 ppm

WHT1
201.33 kg/h
In Econ. 1: 88.74 °C Out Heater 1: 96.60 °C
C1: 180.44 ppm
C2: 165.22 ppm
C3: 158.81 ppm

WHT2
460.08 kg/h
In Econ. 2: 36.47 °C Out Heater 2: 96.08 °C
C1: 171.88 ppm
C2: 171.88 ppm
C3: 171.88 ppm

Air1
6400.00 kg/h
111.47 °C

AirMED
4238.82 kg/h
111.47 °C

AirHT1
336.33 kg/h
In Econ. 1: 111.47 °C Out Heater 1: 92.23 °C

AirHT2
1824.86 kg/h
In Econ. 1:111.47 °C Out Heater 1: 50.06 °C

W40
250.45 kg/h
95.01 °C
C1: 1000.00 ppm
C2: 1000.00 ppm
C3: 1000.00 ppm

W41
3.15 kg/h
95.01 °C
C1: 1000.00 ppm
C2: 1000.00 ppm
C3: 1000.00 ppm

W42
8.20 kg/h
95.01 °C
C1: 1000.00 ppm
C2: 1000.00 ppm
C3: 1000.00 ppm

W44
2.38 kg/h
95.01 °C
C1: 1000.00 ppm
C2: 1000.00 ppm
C3: 1000.00 ppm

W45
35.56 kg/h
95.01 °C
C1: 1000.00 ppm
C2: 1000.00 ppm
C3: 1000.00 ppm

W46
1.66 kg/h
95.01 °C
C1: 1000.00 ppm
C2: 1000.00 ppm
C3: 1000.00 ppm

W48
406.81 kg/h
95.03 °C
C1: 1000.00 ppm
C2: 1000.00 ppm
C3: 1000.00 ppm

W49
12.88 kg/h
95.03 °C
C1: 1000.00 ppm
C2: 1000.00 ppm
C3: 1000.00 ppm

W50
42.86 kg/h
95.03 °C
C1: 1000.00 ppm
C2: 1000.00 ppm
C3: 1000.00 ppm

W52
5.61 kg/h
95.03 °C
C1: 1000.00 ppm
C2: 1000.00 ppm
C3: 1000.00 ppm

W54
4.75 kg/h
95.03 °C
C1: 1000.00 ppm
C2: 1000.00 ppm
C3: 1000.00 ppm

W57
21.18 kg/h
95.10 °C
C1: 958.64 ppm
C2: 958.64 ppm
C3: 958.64 ppm

W58
29.23 kg/h
95.10 °C
C1: 958.64 ppm
C2: 958.64 ppm
C3: 958.64 ppm

W60
8.31 kg/h
95.10 °C
C1: 958.64 ppm
C2: 958.64 ppm
C3: 958.64 ppm

W62
1.46 kg/h
95.10 °C
C1: 958.64 ppm
C2: 958.64 ppm
C3: 958.64 ppm

Figure 7. Values associated with the flowsheet of the case study 2 final configuration using the ThermWatt Modelica library capabilities.

4. Results and Discussion

In this section, the results of the previously defined sustainability assessment indicators, as well as the benchmark values for several sustainability-policy-related indicators associated with each case study, are presented and further discussed.

4.1. Assessment of Sustainability Aims Achievement

The application of the computational models of WEIS presented in Figures 3 and 5 converged in the obtention of results for economic and environmental impact, which are briefly presented in Tables 5 and 6. The obtained results mirror the effective viability associated with the conceptualised WEIS in comparison with the benchmark values for the European ceramic industry (2–3 years payback time and 0.775 kton $CO_{2,eq}$/year reduction [39,43]). This economic and environmental viability shall be reinforced through the determination of the following indicators:

- Eco-efficiency promotion (indicators that express the potentially improved economic value to environmental burden ratio);
- Circular economy promotion (indicators that express the capacity of the projects for improving the performance of recycling and reuse).

4.1.1. Eco-Efficiency Promotion Indicators

The assessment of eco-efficiency promotion in relation to the analysed installations may be performed through the analysis of indicators that either express the increase in the economic value associated with the project or the decrease in the environmental burden. The effective analysis of the improved eco-efficiency of the analysed installations must be performed according to the integrated analysis of all of the proposed indicators rather than the analysis of single indicators that express achieved benefits in terms of only one of the dimensions of sustainability. Such a procedure is performed to ensure that eco-efficiency promotion with respect to the proposed projects is effective. In Table 8, the proposed indicators for the eco-efficiency promotion characterisation determined for case studies 1 and 2 are, respectively, presented. For the proposed further analysis, the determination of indicators is performed for both the baseline and improved scenarios.

Table 8. Determination of eco-efficiency indicators.

Indicator	Baseline Scenario	Improved Scenarios			
		Case Study 1		Case Study 2	
		Beginning-of-Life	End-of-Life	Beginning-of-Life	End-of-Life
Energy-use-related indicators					
Specific Natural Gas Consumption (GJ/ton)	8.58	7.83		7.90	
Specific Electricity Consumption (MWh/ton)	0.53	0.49		0.51	
Water-system-related indicators					
Specific Water Consumption (m^3/ton)	0.30	0.23		0.12	
Water energy footprint (MJ/m^3)	660.38	9.88		1.01	
GHG-emissions-related indicators					
Produced material emission intensity (ton $CO_{2,eq}$/ton material)	0.81	0.75		0.76	
Energy carbon footprint (ton $CO_{2,eq}$/TJ)	76.11	77.94		76.72	

Table 8. *Cont.*

Indicator	Baseline Scenario	Improved Scenarios			
		Case Study 1		Case Study 2	
		Beginning-of-Life	End-of-Life	Beginning-of-Life	End-of-Life
Aggregated eco-efficiency indicators					
Aggregated eco-efficiency indicator (EUR/kg $CO_{2,eq}$)	0.75	0.75	0.80 (6.46% promotion)	0.73	0.78 (4.00% promotion)
Produced material productivity (EUR/kg material)	0.93	1.00	1.06	0.97	1.04

The analysis of the results of the indicator determination presented in Table 8 will be performed by analysing each of the categories in which the mentioned indicators were divided:

- The energy-use-related indicators are formulated to express the energy consumption in relation to total material production (which is the same value for both the baseline and improved scenarios); thus, it is based on a measure of the productivity of the plant in relation to energy costs;
- The water-system-related indicators are formulated to express water use in relation to total material production and the energy dependence of the water system;
- The GHG-emissions-related indicators shall express not only the environmental footprint but also the level of pollutant emissions against the total use of one of the resources in question (for instance, the level of total GHG emissions in relation to the total energy consumption);
- The aggregated eco-efficiency indicators shall be based on the relationship between the total achieved benefits in terms of increased economic value (achieved through the reduction of energy and water costs) and the reduced environmental burden (achieved through the reduction of pollutant emissions).

The results obtained for the proposed indicators for the case studies express, overall, the effective promotion of eco-efficiency achieved through the implementation of the WEIS project. In Table 9, the interpretation of the obtained results for the indicators is presented.

Taking into account the verifications presented in Table 9, it is possible to confirm that in both case studies, a reasonable level of eco-efficiency promotion related to the economic and environmental burden reduction benefits (generated by the decrease in energy- and water-related costs) is achieved. Nevertheless, it has been identified that the WEIS project shall be accompanied by the implementation of further measures, including, in particular, energy efficiency improvement measures, with the aim of being on par with benchmark values identified for the industrial sector.

Table 9. Interpretation of the results obtained for eco-efficiency promotion indicators.

Category	Interpretation
Energy-use-related	• It is possible to verify that a considerable decrease may be achieved through the implementation of the proposed project, with this reduction being significant in the case of natural gas use; • In comparison to benchmark values obtained for the European industry, the achieved levels of specific energy consumption are still above the average levels obtained for selected ceramic industry companies (6.09 GJ/ton in comparison to the obtained 7.83 GJ/ton and 7.90 GJ/ton for case study 1 and case study 2 in relation to natural gas, respectively, and 0.19 MWh/ton in comparison to the obtained 0.49 MWh/ton and 0.51 MWh/ton for electricity, respectively [44]); • Nonetheless, it may be affirmed that the project is effective for the approximation of the energy use levels to the average of the European industry, with such effective approximation being potentially achieved through the implementation of complementary energy efficiency improvement measures to the ones considered in the project of the WEIS.

Table 9. *Cont.*

Category	Interpretation
Water-system-related	• It is possible to verify relative improvements for both of the analysed indicators between the baseline and improved scenarios of case studies 1 and 2; • In comparison to benchmark values obtained for the European industry, the obtained levels of specific water consumption are comparable to the ones obtained for both the wet and dry routes of ceramic tile production (0.47–0.59 m^3/ton and 0.12–0.16 m^3/ton, respectively [45]), although the potential association of the water recirculation procedure with the conceptualised system falls short in comparison to the substitution from wet to dry routes in the referred subsector of the ceramic industry (which is associated with about 74% water savings); • In relation to the water–energy footprint, the relative decrease between the baseline and the improved scenarios for both case studies signifies a decrease in the energy dependence of the water system, in which a lesser total energy input is required for the operation of the water system considering the respective freshwater consumption levels. In light of these results, it is possible to affirm that the conjoined performance of water recirculation and hot air recirculation to the enthalpy-using units within the water system (in this case, economisers and the MED unit) generates an operational point in which the self-sufficiency of the water system in terms of enthalpy allocation increases.
GHG-emissions-related	• In relation to the produced materials' GHG emissions intensity, it is possible to verify considerable improvements for both case studies. Nevertheless, the emission intensity estimated for the improved scenarios is still higher than benchmark values (0.329, 0.338, and 0.263 (in two different plants) ton $CO_{2,eq}$/ton material for the production of four different tile products, respectively [43]); • In relation to the energy carbon footprint indicator, it is possible to verify an increase between the baseline and improved scenarios for both case studies 1 and 2. Such an increase may be interpreted in light of the relative decreases in the use of each of the energy sources in question and the emission factor associated with each energy source; the relative decrease in natural gas consumption is higher for both cases compared to the electric energy consumption, although the tabled emission factor for natural gas is lower than the one for electricity (64.1 kg $CO_{2,eq}$/GJ and 0.47 kg $CO_{2,eq}$/kWh corresponding to 130.56 kg $CO_{2,eq}$/GJ, respectively). As such, the highest relative decrease in natural gas consumption allows for the representativeness of the electric energy consumption of the plant in the improved scenario to be higher, thus augmenting the ratio between the total $CO_{2,eq}$ emissions and the total energy consumption. In light of the implementation of the WEIS project, such an increase is not significant for the evaluation of the project in terms of economic and environmental viability, but it is indicative of the dislocation of the energy efficiency improvement project towards natural gas reduction.
Aggregated eco-efficiency	• It is possible to verify improvements between the baseline and the End-of-Life, improved scenarios for both case studies for the two indicators; • The identified increase in the aggregated eco-efficiency indicator may be attributed to both an increase in the economic value associated with the plant and the decrease in the energy-use-related environmental burden; • The increase in material productivity indicates that the generated economic savings through the implementation of the WEIS increases the economic value of production for the same level of produced ceramic material; • For case study 2, it is possible to verify that the aggregated eco-efficiency indicator is lower for the improved scenario in the defined Beginning-of-Life stage, which may be interpreted as the capacity of the conceptualised WEIS to create economic value in relation to the energy-use-related environmental burden only at a determinate point in the project's lifetime.

4.1.2. Circular Economy Potential Promotion Indicators

The circular economy character associated with the conceptualised WEIS is set to be assessed in this work primarily through the development of diagrams that detail the energy fluxes in the plants—specifically, through the flux from the total energy consumption in a plant (corresponding to the final energy received by the plant) to the useful energy and energy losses (in this case, the energy loss parcels of interest are the ones corresponding to waste heat streams). A set of indicators is also set to be determined. Because water consumption within the analysed case studies is not associated with such a complex division of different uses, the circular economy character associated with this resource is enforced through the determination of several indicators. In the sequences of Figures 8 and 9 and Figures 10 and 11, the Sankey diagrams that detail the energy fluxes for the baseline and improved scenarios for case studies 1 and 2 are presented, respectively. The determined values associated with circular-economy-related potential indicators for case study 1 and 2 are presented in Tables 10 and 11, respectively.

Table 10. Determination of circular-economy-promotion-related indicators relative to case study 1.

Indicator	Baseline Scenario	Improved Scenario
Energy-use-related indicators		
Waste Heat to Total Energy Ratio	27.34%	23.25%
Recirculated Heat to Baseline Total Energy Ratio		8.58%
Waste Heat to Natural Gas Used in Combustion-Based Processes Ratio	96.90%	96.05%
Recirculated Heat to Baseline Natural Gas Used in Combustion-Based Processes Ratio		38.76%
Water-use-related indicators		
Discharge Water to Freshwater Ratio	100.00%	0.00%
Treated Water to Wastewater Ratio		24.25%
Recirculated to Produced Treated Water Ratio		100.00%
Recirculated Treated Water to Water Savings		103.14%
Indicators related to energy input in the water system		
Energy in Water System in the Improved Scenario over the Baseline Scenario		34.15%
Withdrawn Energy from the Water System in the Improved Scenario over Energy in the Water System in the Baseline Scenario		66.36%

Table 11. Determination of circular-economy-promotion-related indicators relative to case study 2.

Indicator	Baseline Scenario	Improved Scenario
Energy-use-related indicators		
Waste Heat to Total Energy Ratio	23.26%	19.71%
Recirculated Heat to Baseline Total Energy Ratio		6.69%
Waste Heat to Natural Gas Used in Combustion-Based Processes Ratio	46.38%	45.55%
Recirculated Heat to Baseline Natural Gas Used in Combustion-Based Processes Ratio		16.91%
Water-use-related indicators		
Discharge Water to Freshwater Ratio	100.00%	0.00%
Treated Water to Wastewater Ratio		33.19%
Recirculated to Produced Treated Water Ratio		99.21%
Recirculated Treated Water to Water Savings		78.50%
Indicators related to energy input in the water system		
Energy in Water System in the Improved Scenario over the Baseline Scenario		22.82%
Withdrawn Energy from the Water System in the Improved Scenario over Energy in the Water System in the Baseline Scenario		77.29%

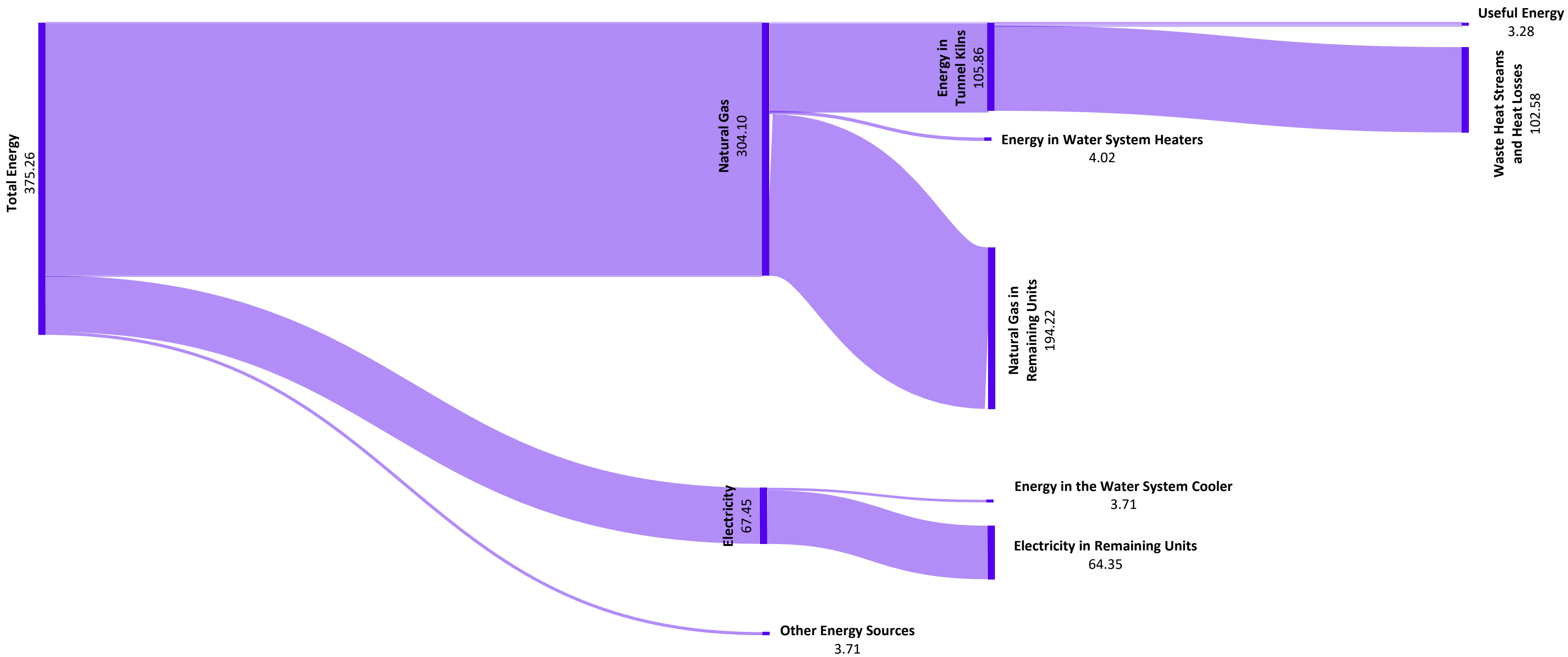

Figure 8. Sankey diagram for the plant energy balance in the case study 1 baseline scenario (energy consumption unit of TJ/year).

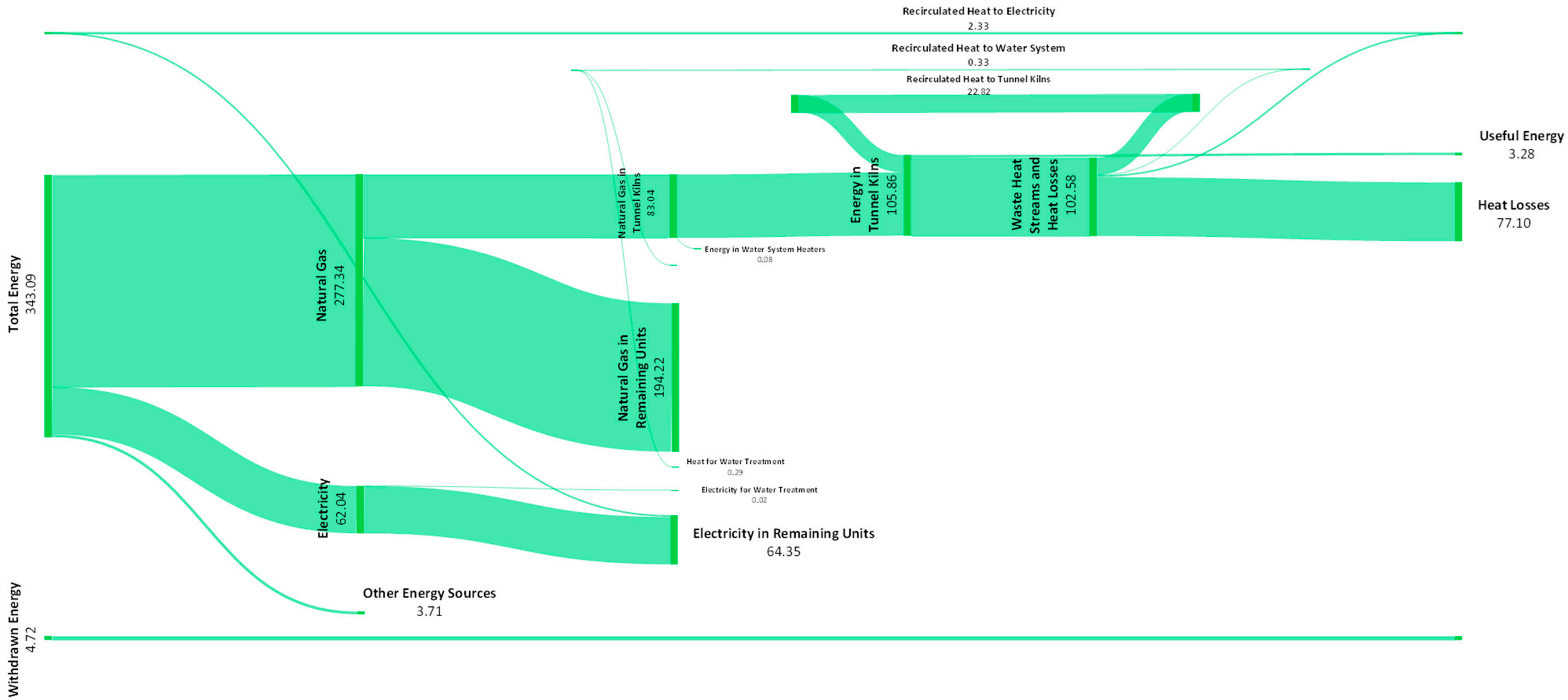

Figure 9. Sankey diagram for the plant energy balance in the case study 1 improved scenario (energy consumption unit of TJ/year).

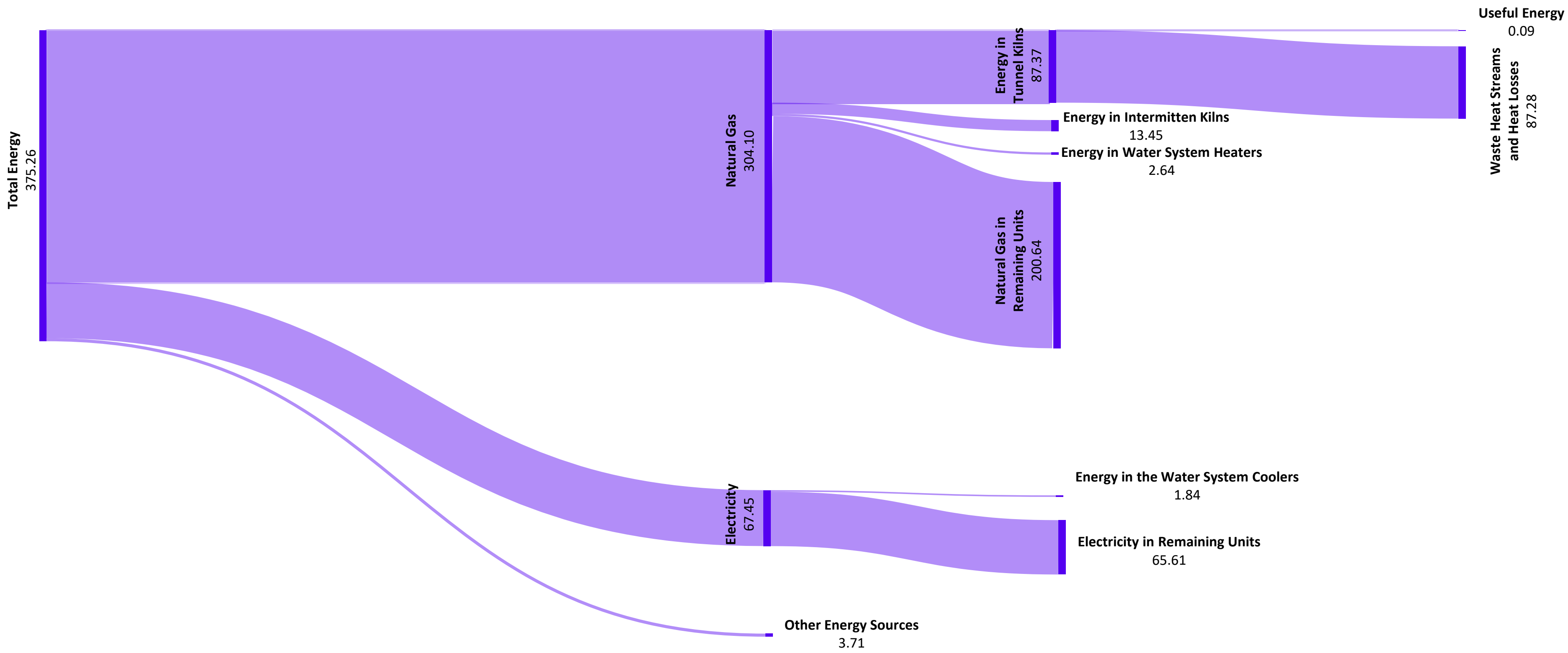

Figure 10. Sankey diagram for the plant energy balance in the case study 2 baseline scenario (energy consumption unit of TJ/year).

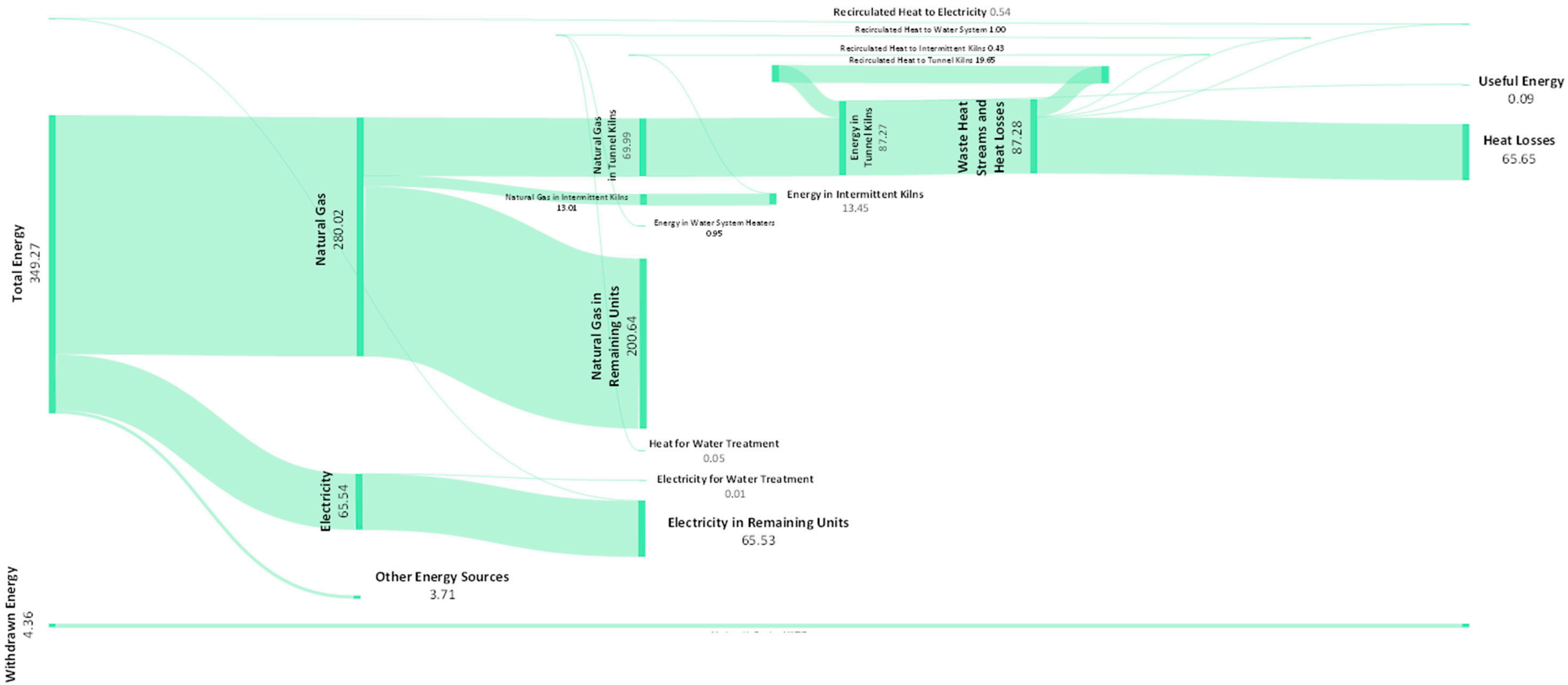

Figure 11. Sankey diagram for the plant energy balance in the case study 2 improved scenario (energy consumption unit of TJ/year).

The assessment of the circular economy character for the conceptualised plants encompassed by the results presented in Figures 6 and 7 may be determined by the comparison to the total resource comparison of the generated waste streams (waste heat and discharge water) or the recirculated streams. The indicators selected to be calculated and further presented in Tables 10 and 11 are generally from both categories, and this option of determination was selected so as to proceed with the circular-economy-related potential based on both benefits achieved through the implementation of closed-loop systems (recirculation promotion and waste reduction). In Table 12, the interpretation of the previously presented results and the effect of these results on circular economy promotion is presented.

Table 12. Interpretation of results obtained for the circular-economy-related potential promotion.

Category	Interpretation
Energy-use-related	• It is possible to observe that for both waste-reduction-type indicators (Waste Heat to Total Energy Ratio and Recirculated Heat to Natural Gas Used in Combustion-Based Processes Ratios), a considerable reduction occurs between the baseline and improved scenarios corresponding to case studies 1 and 2. Such a verification may be attributed to a superior capacity of the conceptualised WEIS to favour the reduction of the output of the energy-using units (waste heat) over the energy input (total energy and natural gas); • The recirculation-promotion-based indicators (Recirculated Heat to Baseline Total Energy and Recirculated Heat to Baseline Natural Gas Used in Combustion-Based Processes), in turn, shall give a measurement of the effectiveness of recirculated waste heat streams for the fulfilment of the energy requirements of the plants. As may be verified through the analysis of the sequence of Figures 2 and 3 and Tables 9 and 10, the recirculated heat streams correspond to a considerable part of the total energy and natural gas supply levels of the baseline scenario (which correspond to total energy requirements, either through energy input or energy recirculation), thus proving the effectiveness of waste heat recovery within the conceptualised system. Nonetheless, the total energy input (non-recirculated energy parcels) is still the most representative; • Considering that the existing to-be-valorised heat streams in the plants have been recirculated to the maximum point of valorisation (in which the whole enthalpy that is possible to be recovered has been withdrawn from these streams), the verifications identified for both indicator categories reinforce the aforementioned identified need to further implement alternative energy efficiency improvement measures within the industrial processes existing in the plant so as to effectively reduce the energy inputs.
Water-use-related	• It is possible to verify through the analysis of the sequence of values obtained for the indicators that water recirculation within the conceptualised water system has been extensively promoted; • For both cases, the ratio of discharge water to the inlet freshwater is null due to the null discharge water (the only outlet streams from the water systems are the concentrate streams from the MED units); • The values obtained for the ratio between the produced desalinated water and the inlet saline water in the MED units of both case studies are relatively low in comparison to the water saving requirements of the conceptualised system. Such an indicator may eventually be improved through the installation of a high number of effects for the MED unit, thus, in turn, promoting both water and enthalpy recirculation within the water system; • The recirculated to produced treated water ratio obtained for both case studies is relatively high, being 100% for case study 1 (which is akin to affirming that all of the produced desalinated water is effectively recirculated). It is important to note that the assessment of such an indicator is relevant so as to evaluate that the recirculation of treated water is not affected by another requirement, such as hot and cold utility minimisation, or the other recirculated streams within the water system, which may be considered secondary (as treated water shall be desirably recirculated owing to its extensively minimised salt concentration). Although treated water recirculation is not affected by the remaining requirements of case study 1, for case study 2, these requirements are preponderant, leading to the convergence of the developed optimisation model to a point in which a part of the total treated water quantity remains on the main water-using line; • The values obtained for recirculated treated water to the water savings ratio are significantly high, indicating that the recirculation of treated water is mostly significant for the production of water savings, although the recirculation of secondary water streams still has a considerable contribution in such savings.

Table 12. *Cont.*

Category	Interpretation
Related to energy input in the water system	• The Energy in Water System in the Improved Scenario over the Baseline Scenario indicator serves to assess the energy input related to the improved scenario (encompassing the input of hot and cold utilities proper and the enthalpy allocated from hot air to the economisers and to the MED unit) in relation to the hot and cold utilities input in the baseline scenarios. Such a comparison allows for assessing the potential of the valorisation of the recirculated streams to cause energy savings rather than to fulfil additional energy requirements (such as the ones related to wastewater treatment). For both case study 1 and 2, such an indicator is considerably low, which is significant for the total energy dependence of the water system (to both hot and cold utilities and recirculated heat from combustion-based processes) owing to water stream recirculation; • The previous sentence is supported by the significantly high value obtained for the Withdrawn Energy from the Water System in the Improved Scenario over Energy in the Water System in the Baseline Scenario indicator, which measures the energy that is not necessary to serve as an input on the water system of the improved scenario (in comparison to the baseline scenario) and that is not also necessary to be compensated by external energy sources (both hot and cold utilities and recirculated heat streams).

In conclusion, it is possible to confirm that the performance of the optimal point of stream recirculation achieved for the conceptualised systems (which minimises operational costs the most by respecting all of the operational constraints) effectively makes possible the reduction of waste streams and the promotion of the recirculation of water and energy to the maximum extent possible. Therefore, the same set of practices that have been associated with a potential to promote the eco-efficiency of the production processes (through the balanced reduction of both inputs of resources and outputs of wastes) of the analysed plants also have a similar potential to effectively promote the circular economy character associated with the whole industrial system.

4.2. Assessment of Strategic Aims

In addition to the determination of the aforementioned indicators (which, overall, enforce the sustainability promotion character that has been initially pointed out for the conceptualised systems), it is necessary to associate sustainability-promotion-related benefits to the specific aims of the existing policies. The aforementioned assessment procedure is interpreted as a method to achieve the contextualisation of the results of this work within the social dimension of the concept of sustainability, as, up until this point, the focus has been the economic and environmental aspects. From another perspective, and, in a sense, to finalise the assessment procedure, a framework of the results in relation to the most recent social issues related to energy and water, including the ongoing energy crisis and water scarcity (which was particularly aggravated in the summer of the most recent years of 2022 and 2023), is set to be performed.

4.2.1. Framework of Sustainability Policies Aims

The obtained results for the case studies shall reflect those specific aims so as to allow one to consider that the elaborated project is capable of achieving the strategic objectives delineated within the policies of the country in which the industrial sites are based. With respect to energy use and the promotion of low-carbon energy systems, the RNC2050 has proposed a detailed trajectorial strategy for the industrial sector, in which specific aims for the energy intensity within this end-use sector are proposed for future reference years. These energy intensity levels may be compared to ones determined for the baseline and improved scenarios of the plants. For water efficiency, the PNUEA has proposed a specific efficiency aim to be achieved for the industrial sector for the reference year of 2020 as an improvement of a previously attained objective referring to the year of 2009. The variation between these two levels may thus be compared with the variation obtained for freshwater consumption in the water systems. In Table 13, the energy intensity levels for the plant and the ones proposed in RNC2050 are presented. In Table 14, the water consumption and efficiency levels for the plant and the ones proposed in PNUEA are presented.

Table 13. Energy intensity levels for the plants and relative to RNC2050-specific objectives.

Energy Intensity Levels for the Case Study 1 Plant (MJ/EUR)		
Baseline Scenario	**Improved Scenario**	**Relative Reduction**
14.15	12.15	14.12%
Energy Intensity Levels for the Case Study 2 Plant (MJ/EUR)		
Baseline Scenario	**Improved Scenario**	**Relative Reduction**
14.15	12.56	11.20%
Energy Intensity Levels Within RNC2050 (MJ/EUR)		
2020 Reference Year	**2030 Reference Year**	**Relative Reduction**
96.27	75.47 | 65.78	21.60% | 31.67%

Table 14. Water consumption levels for the water system within the plants and relative to RNC2050-specific objectives.

Water Consumption Levels for the Water System Within the Case Study 1 Plant (dam^3/Year)		
Baseline Scenario	**Improved Scenario**	**Relative Variation**
10.78	8.22	23.71%
Water Consumption Levels for the Water System Within the Case Study 2 Plant (dam^3/year)		
Baseline Scenario	**Improved Scenario**	**Relative Variation**
6.73	4.14	38.57%
Water Efficiency Target Levels for the Industrial Sector (PNUEA)		
2009 Reference Year	**2020 Reference Year**	**Relative Variation (Water Input Levels)**
77.5%	85.0%	8.82%

As may be verified in Table 13, the energy intensity levels with respect to the baseline scenario for the plants are significantly inferior to the ones corresponding to the 2020 reference year. This may be attributed to the relativity low representativeness in terms of energy consumption of the ceramic industry in Portugal in relation to the other sectors. Nonetheless, such a comparison is relevant to evaluate the pairing of the objectives of the industrial stakeholders with the aims proposed at a country and sectorial level. As may be observed in Table 13, the reduction of energy intensity at the plant level is considerably inferior to the reduction obtained by comparing the levels for the reference years of 2020 and 2030. Such a prospect reinforces once more the need for the implementation of complementary energy efficiency improvement measures within the plants.

With respect to the levels of freshwater consumption in the plants, the benchmark comparison has been performed through the comparison of the freshwater input in each one of the water systems and the water efficiency target levels for the reference years of 2009 and 2020 mentioned in PNUEA (namely, the ones pointed out for industry in general). In this case, such a comparison is performed by comparing the relative water use reductions obtained for case studies 1 and 2 and the variation between the corresponding water input levels and the water efficiency levels of 77.5% and 85.0%, respectively (similarly to the relationship between useful energy and supplied energy, it is assumed that the useful quantity of water does not vary and that the total input of water is varied). As may be verified according to the analysis of the values presented in Table 14, the relative water reduction levels obtained for each case study are significantly higher than the corresponding value determined from the reference values present in PNUEA. Such a high difference may be attributed to the superior capacity of the WEIS related to stream recirculation, and thus the water- and energy-use-related benefits promoted by the implementation of these systems. In this case, this may be attributed to a significantly higher level of water recirculation within the conceptualised water system in comparison to other projected and existing systems. Such a recirculation of water streams not only allows for the minimal input of hot and cold utilities in the system but also for the total freshwater input to be decreased.

4.2.2. Framework for Studying the Impact of the Energy Crisis and Water Scarcity

With the aim of establishing a connection between the ongoing societal phenomena and the reality of the case studies considered in this work, it is necessary to perform a comparison of the determinate indicators calculated from the obtained results by considering the implications of the aforementioned issues. For the impact of the ongoing energy crisis, an analysis method was selected in which the total cost levels associated with natural gas and electricity for both the baseline and improved scenarios and considering the prices for the reference years of 2021 and 2022 are compared. For the assessment of the impact of water scarcity, a method was selected based on the determination of the water stress, which is calculated according to the ratio between freshwater consumption and water availability (this last is determined through an estimation based on the actual water availability in the region in which the case study plants are installed) [46]. The described analyses are, respectively, presented in the sequence of Tables 15 and 16.

Table 15. Determination of energy prices for the reference years of 2021 and 2022 and for the baseline and improved scenarios.

Year	Baseline Scenario (BS)	Improved Scenario (IS)	Relative Savings	Relative Difference Between BSs	Relative Difference between 2022 BS and 2021 IS
Case Study 1 Plant					
Natural-Gas-Associated costs					
2021	2.55	2.32	8.80%	64.62%	67.74%
2022	7.19	6.56			
Electricity-Associated costs					
2021	2.42	2.23	8.01%	11.31%	18.42%
2022	2.73	2.51			
Case Study 2 Plant					
Natural-Gas-Associated costs					
2021	2.55	2.34	7.92%	64.62%	67.42%
2022	7.19	6.63			
Electricity-Associated costs					
2021	2.42	2.36	2.83%	11.31%	13.82%
2022	2.73	2.66			

Table 16. Determination and comparison of water stress levels for the case study plants.

Baseline Scenario		Improved Scenario	
Water stress in relation to the water system within the case study 1 plant			
91.57%		69.86%	
Water stress in relation to the water system within the case study 2 plant			
57.19%		35.13%	
Benchmark water stress levels [46]			
Less than 10%	10–20%	20–40%	More than 40%

As may be observed through the analysis of the results presented in Table 15, the total energy-related costs obtained for the two reference years presented considerable deviations, which are much more significant in the case of natural gas, for which corresponding unitary price rise from 2021 to 2022 was about 183% for the case of the Portuguese industry. In Table 15, the obtained relative savings are presented to be compared with the relative difference between the 2021 and 2022 baseline scenarios and between the 2022 baseline scenario and the 2021 improved scenario. Based on the obtained relative savings, it is possible to verify that for natural gas, the obtained savings are much lower than the values obtained for the two mentioned relative differences, and this is verified for both case studies. For the case of electricity, such a disparity is not so high, although it is still considerable in case study 2. Taking into account the verified disparities, it may be affirmed that although the implemented energy efficiency improvement measures have been proven to be effective in the context of the overall promotion of eco-efficiency and the circular economy character associated with the production processes of the analysed plants, the obtained energy use reduction levels do not produce sufficient reduction at the level of operational costs to fully compensate for the rising energy prices. Therefore, it may be required to further propose and implement complementary improvement measures at the level of energy use with the aim of approximating the present energy-related costs to the ones that are estimated in the corresponding hypothetical 2021 scenarios. While for electricity this includes the implementation of additional measures related to the use of electricity (such as the ones related to the improvement of the operation of electric motors and involved systems), for natural gas, such approximations include more extensive and complex energy management projects, including the ones that involve the refurbishment of the plant operation to include alternative and potentially more economically viable fuels.

With respect to the assessment of the implications inherent to the water scarcity phenomenon, it is possible to verify through the analysis of the results presented in Table 16 that freshwater consumption within the water system of the plants is significantly higher in comparison to the estimated levels of average water availability for both case studies. In this respect, it may be affirmed that the analysed water systems are operating at a level that significantly surpasses the limit from which they generate local water stress, which may potentially be a cause of further unavailability of freshwater for local communities. Taking into account that the analysed water systems do not encompass all of the water-using units within the analysed plants, the implications of such observations are aggravated (particularly for case study 1, in which the baseline scenario corresponds to a 91.57% water stress). For case study 1, the improved water management achieved in the improved scenario is not even sufficient to alter the operation point from the water stress level, which is maintained at the severe scarcity level. For case study 2, it is possible, however, to generate an alteration from severe scarcity to significant scarcity. In light of these observations, it is possible to affirm that further water management techniques are required to be implemented to further diminish the risk of water stress levels of the analysed systems. Such techniques may include the diversification of feed water sources. Furthermore, it is possible to affirm that in the context of the geographical region in which the plants are installed, the overall use of water as a resource is much more representative.

5. Conclusions

This work presents an assessment of two process industry case studies in which a set of measures to improve the overall water and energy use have been previously implemented. Such joint measures comprise part of plant-level systems that encompass a set of combustion-based and water-using processes and all of the potential interdependencies between these, including through the sharing of to-be-valorised water and heat streams. This category of systems has been designated as Water and Energy Integration Systems (WEIS). As these types of systems have been analysed in previous work by the authors in terms of potential benefit analysis (assisted by the use of simulation and optimisation models) [17,18,47], in this work, the conceptualised systems have been analysed in terms of indicators related to sustainability (eco-efficiency and circular economy character promotion) and strategic aims.

With respect to the calculated eco-efficiency promotion indicators, it is possible to affirm that:

- A considerable eco-efficiency promotion is verified for both case studies by the aggregated analysis of the results obtained for all of the indicators;
- Additional improvement measures are necessary to ensure the case study plants are more proximate to the average levels of the sector (the ceramic industry), including, specifically, for the indicators of specific energy consumption, specific water consumption, and specific equivalent carbon dioxide emissions.

In relation to the calculated circular economy character promotion indicators, it is possible to affirm that:

- The stream recirculation practice encompassed by the conceptualisation of the WEIS has been successful in terms of circular economy character promotion;
- For all cases, the reduction of the system output (waste heat and discharge water) is favoured over the input (energy and freshwater entrances).

In relation to the calculated strategic-aims-related indicators, it is possible to affirm that:

- The conceptual aims encompassed by the relevant sustainability policies (RNC2050 and PNUEA) and the mitigation of the impacts brought about by the most recent social issues (energy crisis and water scarcity) have been addressed;
- Overall, with only the commissioning of the conceptualised WEIS for the specific water and energy use reduction levels, it is not possible to compare these levels to those required by sustainability policies and for the purpose of the full mitigation of the impacts of the aforementioned social issues.

5.1. Findings for Aggregated Indicators

The eco-efficiency and circular-economy-promotion-related potential associated with each case study may be prominently assessed through the analysis of most aggregated indicators. Although the assessment presented in this work is based on the integrated analysis of all defined indicators, these aggregated indicators are representative for the purpose of establishing a basis of comparison to be adopted for further case studies. In light of the obtained results in this work, it is possible to affirm that:

- A 6.46% and 4.00% improvement for the aggregated eco-efficiency indicator has been obtained for case studies 1 and 2, respectively, which is significant in that the economic value associated with the production processes of both plants is highly increased in relation to the decrease in environmental impact caused by the operation of energy- and water-using processes;
- A null water discharge for both case studies and levels of 8.58% and 6.69% of recirculated heat over total energy consumption have been obtained for case studies 1 and 2, respectively, which is proof of the effectiveness of circular economy promotion for both cases with respect to two inherent aspects of this concept, waste and recirculation of material/products, to the highest possible value.

5.2. Limitations of the Current Research and Future Work

The established methodological framework is associated with the following limitations:

- An inability to perform an exact allocation of estimated improvements associated with the social aspect of sustainability (a proposal of several indicators that are certainly improved in the current framework has been performed so as to prove that the social aspect is addressed and the overall sustainability promotion is secured, but it is performed through a direct calculation of each one of the indicators);
- The dependency of the defined strategic aims (related to sustainability policy benchmark values) on the current time period (these aims have been defined in the context of

the most recent policies, and, as such, the benchmark values must be updated in future work using the proposed methodology so as to secure the validity of obtained results).

Future work shall be based on:

- Application of the proposed methodology (indicator estimation and related analysis) for similar process industry case studies;
- Direct determination of indicators related to the social aspect of sustainability;
- Assuring that the comparison of strategic-aims-related results is performed based on benchmark values defined in the most recent sustainability policies (so as to ensure that all of the results are compared by taking into account the same basis and the update of these values according to the most recent socio-economic context).

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Nomenclature

CAPEX	Capital expenditure (EUR)
$CO_{2,eq}$	Annual equivalent carbon dioxide emissions (kg $CO_{2,eq}$/year)
DW	Annual discharge water quantity (m^3/year)
DWFW	Discharge Water to Freshwater Ratio
EcoEff	Aggregated eco-efficiency (EUR/kg $CO_{2,eq}$)
EC	Annual final energy consumption in a plant (J/year)
EF	Equivalent carbon dioxide emission factor (kg $CO_{2,eq}$/J)
EGHGF	Energy carbon footprint (kg $CO_{2,eq}$/J)
ElecC	Annual electric energy consumption (J/year)
EWS	Annual hot and cold utility consumption in a water system (J/year)
EWSR	Energy in Water System in the Improved Scenario over the Baseline Scenario
FC	Annual fuel consumption (J/year)
FW	Annual water consumption (m^3/year)
GHGI	Greenhouse gas emissions intensity (kg $CO_{2,eq}$/kg Prod)
PMP	Produced material productivity (EUR/kg Prod)
Price	Unitary price (EUR/m^3 and EUR/J)
Prod	Annual production of the material targeted to be produced in a plant (kg/year)
Red.$CO_{2,eq}$	Annual absolute reduction of equivalent carbon dioxide emissions (kg $CO_{2,eq}$/year)
Revenue	Annual revenue/sales turnover in a plant (kg Prod/year)
RH	Annual total quantity of recirculated heat in a plant (J/year)
RHEB	Recirculated Heat to Baseline Total Energy Ratio
RHFTP	Recirculated Heat to Baseline Fuel Used in Combustion-Based Processes Ratio
RTW	Annual quantity of recirculated treated water (m^3/year)
RTWTW	Recirculated to Produced Treated Water Ratio
RTWWSav	Recirculated Treated Water to Water Savings
Sav	Annual monetary savings (EUR/year)
SElecC	Specific electric energy consumption (J/kg Prod.)
SFC	Specific fuel consumption (J/kg Prod.)
SFW	Specific water consumption (m^3/kg Prod.)
TW	Annual treated water production (m^3/year)
TWWW	Treated Water to Wastewater Ratio

wEWS	Annual withdrawn quantity of consumed hot and cold utilities in a water system (J/year)
wEWEWS	Withdrawn Energy from Water System in the Improved Scenario over Energy in the Water System in the Baseline Scenario (J/year)
WEF	Water energy footprint (J/m$^{3)}$
WH	Annual total quantity of waste heat and heat losses in a plant (J/year)
WHE	Waste Heat to Total Energy Ratio
WHFTP	Waste Heat to Natural Gas Used in Combustion-based Processes Ratio
WW	Annual wastewater production (m^3/year)
Subscripts	
Baseline	Baseline case of a plant (a Water and Energy Integration System has yet to be implemented)
ES	Energy source
TP	Combustion-based process
W	Water
WEIS	Improved Case (a Water and Energy Integration System has been implemented)
Abbreviations	
EU	European Union
GHG	Greenhouse gases
MED	Multi-effect distillation
ORC	Organic Rankine Cycle
PNUEA	Programa Nacional para o Uso Eficiente da Água
RNC2050	Portugal Roadmap for Carbon Neutrality
TES	Thermal energy storage
WEIS	Water and Energy Integration Systems

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