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The Paradigm of Water and Energy Integration Systems (WEIS): Methodology and Performance Indicators

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ABSTRACT

This work approaches a detailed characterization of the aspects inherent to the innovative paradigm of Water and Energy Integration Systems (WEIS). These consists in conceptual physical systems which consider all potential energy-using and water-using processes in a site, all potential recirculation of material and energy streams between these and the integration of several categories of state-of-the-art technologies. The WEIS have the ultimate aim to promote the sustainability character associated to existing installations (through the reduction of energy and water input and contaminants output). The specific characteristics of WEIS are compared to existing similar process integration methodologies and a set of performance indicators are determined, having as a basis two previous case-studies approached for the Engineering project of WEIS. The performed analysis in this work revealed that the innovative paradigm is able to constitute Engineering projects with associated sustainability promotion potential, with the possibility to be modelled with existing computational tools and not being associated to impediments in terms of the maturity and availability of constituting technologies.

Keywords: Water and energy integration systems, water-energy nexus, energy recovery, sustainability, performance indicators

1. INTRODUCTION

The water-energy nexus has been introduced on the scope of the most relevant sustainability policies of each region of the world. This concept deals with all potential interdependencies between water and energy, and the full understanding of the inherent aspects is fundamental for the promotion of simultaneous water and energy use-related benefits [1–3].

The paradigm of Water and Energy Integration Systems (WEIS) was recently developed by a working group of researchers from both ISQ – Instituto de Soldadura e Qualidade and CERENA – Centro de Recursos Naturais e Ambiente [4]. It consists of physical systems encompassing a set of water and energy-using units in a site, and the water and energy recirculation between these units, with the goal of achieving economic and environmental benefits. In parallel to the development of this innovative paradigm, a digital twin-based computational tool has been developed by the authors for the virtual implementation of WEIS in the context of end-use sector case-studies, designated as ThermWatt [4–6].

The innovative WEIS paradigm was developed to expand the Total Site Integration (TSI) and Combined Water-Energy Integration (CWEI) concepts, and to attend to their limitations. The WEIS paradigm focus on energy-using and water-using processes as a whole (in opposition to a standalone focus on each process category), adapting conceptual elements from both TSI and CWEI and introducing new ones. These include technologies for energy recovery from water/ wastewater units (such as electrolysis) and the supply of thermal energy (direct waste heat) or electric energy (indirectly produced in thermodynamic cycles) to fulfill already existing energy requirements (hot utilities, in this case) and additional ones (wastewater treatment units).

In this work, it is performed a detailed description of the methodology inherent to the innovative paradigm of Water and Energy Integration Systems, subsisting on the definition of most generic superstructures which may be furtherly adapted to each end-use sector case-study in specific. The specific characteristics associated to the WEIS methodology is compared to the existing methodology and a set of performance indicators are determined to assess the viability of these systems in terms of the integration of these on real-life Engineering projects.

2. METHODOLOGY

In general, the conceptualization of Water and Energy Integration Systems (WEIS) passes by the simultaneous application of the principles of water recirculation and heat recovery. In this prospect, two different configurations have been primarily conceptualized:

- **Configuration 1**: Standard Configuration (combustion-based process in continuous operation);
- **Configuration 2**: Dynamic Configuration (combustion-based process in continuous and batch operation and implementing thermal energy storage).

The general description points associated to all superstructures may be extensively defined as follows:

- The WEIS encompasses M combustion-based processes and N water-using processes;
- Each combustion-based process encompasses the feeding of a fuel stream (primary energy source) and combustion air stream;
- Each combustion-based process encompasses a set of waste heat streams, which jointly constitute a potentially recirculated heat stream (to the same process or other processes);
- The set of all combustion-based processes and its inlet and outlet streams constitutes the designated thermal process system;
- The set of a combustion-based process and recirculated heat streams that are transported from the outlet to the inlet of processes constitute a thermal process sub-system;
- In the context of the superstructures furtherly represented, the recirculated heat stream directed to a combustion-based process's inlet may (direct heat recovery) or may not (indirect heat recovery) be mixed with the inlet ambient air stream (it depends whether the recirculated heat stream is air or an exhaust gas, as commonly verified and implemented);
- The recirculated heat stream at the outlet of a combustion-based process may be recirculated to the same combustion-based process or the other M – 1 combustion-based processes;
- In Configuration 2, another recirculated heat stream is transported to an energy storage system (TES) to heat up a heat sink stream, which is then split to be fed to each combustion-based processes;
- For each water-using process is installed a WWT unit for the treatment of the wastewater stream at the outlet of the water-using process, in addition to a heater and a cooler;
- The set of all water-using processes, WWT units, heater, cooler and inlet, outlet and recirculated streams constitutes the water system;
- The set of a water-using process, associated WWT unit, heater, cooler and respective inlet, outlet and recirculated streams (which do not recirculate to other N – 1 water-using processes) constitute a water sub-system;
- Each water sub-system is fed by a freshwater stream and a discharged water stream results as an outlet stream;
- At the outlet of the water-using process, WWT unit, heater and cooler results several recirculated streams (recycled, reused and by-passed):
    - From the water-using process to the WWT unit inlet, heater inlet, cooler inlet, the WS outlet, other N – 1 heaters and other N – 1 coolers;
    - From the WWT unit to WP inlet, heater inlet, cooler inlet, the WS outlet, other N – 1 heaters and other N – 1 coolers;
    - From the heater to WP inlet, WWT unit inlet and WS outlet;
    - From the cooler to WP inlet, WWT unit inlet and WS outlet;
    - For each WWT unit, a sludge stream is generated and then directed to the inlet of a wastewater-to-energy module (mixed with the discharged water stream);
    - The generated energy (in the form of fuel) in the wastewater-to-energy is directed to the inlet of each combustion-based process sub-system and a combustion chamber which is (by hypothesis) installed within the thermodynamic cycle;
    - In the context of the configuration furtherly represented, the additional fuel stream may be (directly) mixed with the primary fuel stream or be (indirectly) transported to each combustion chamber.
- In addition to the recirculation within the thermal process system, the recirculated heat may be directed to the water system (the stream is divided for each water sub-system, and in its turn for each heater and WWT unit), a thermodynamic cycle (for the production of additional electric energy) and the WtE unit (according to the specific energy input in this process). The generated electricity is directed to each WWT unit and the WtE unit.

The most generic superstructure-based formulation of both WEIS configurations is presented in the sequence of Figure 1 (presented for Configuration 2, Configuration 1 is only different in the aspect that does not consider the Thermal Energy Storage unit).

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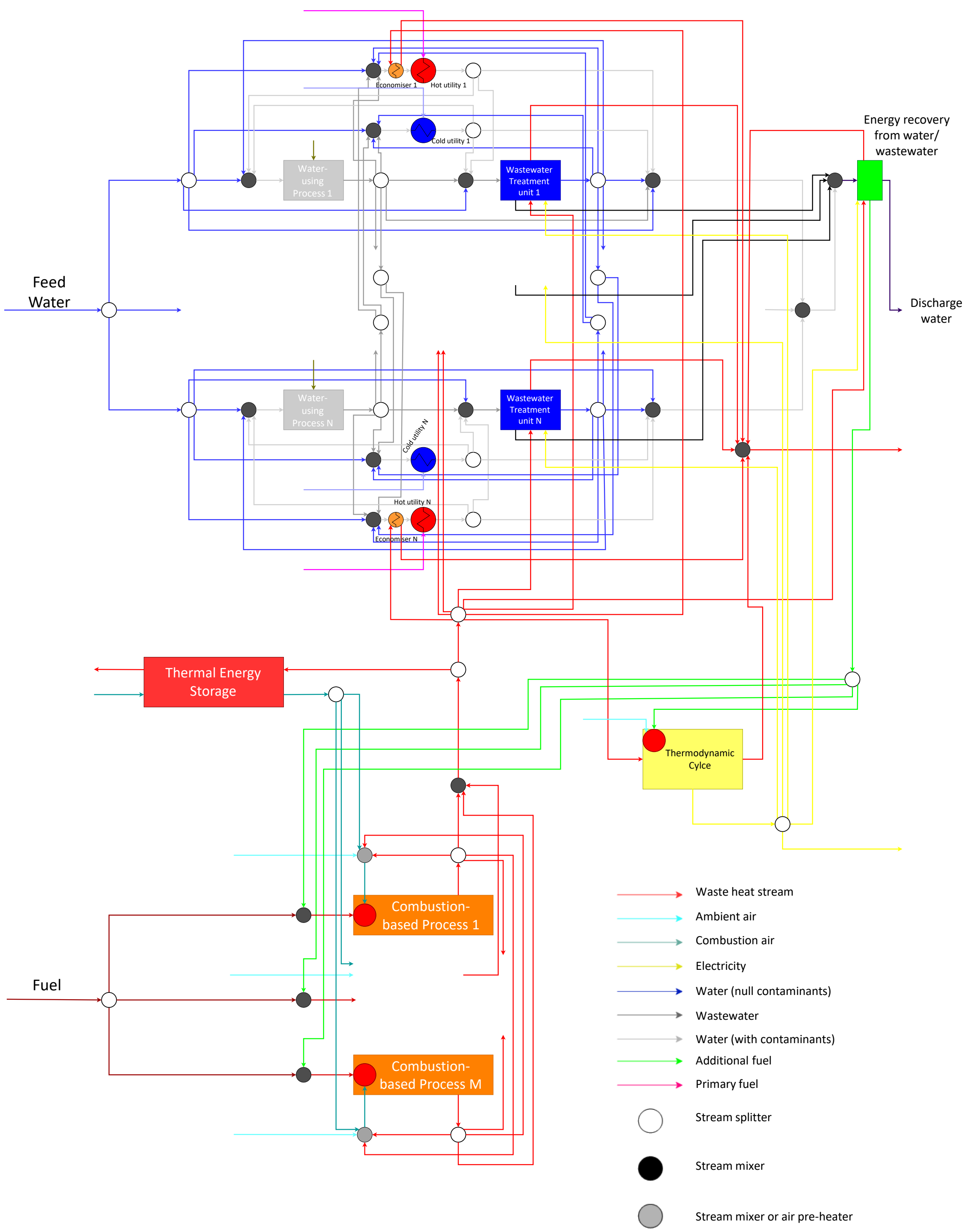

Figure 1: Generalized superstructure for WEIS Configuration 2 (Dynamic, transient state-based)

Table 1: Comparison between Methodologies

<table>
<tr><th>Existing Methodologies</th><th>Water and Energy Integration Systems (WEIS)</th></tr>
<tr><td>Combined Water and Energy Integration (CWEI) [7]
• The object of study is a water network constituted by a set of water-using processes and wastewater treatment units;
• It is based on the application of steady state-based optimisation methodologies for the assessment of the most favourable levels of water stream re-circulation in several points of the water network;
• Being based on the use of a resource as both an additional water and heat source, it only considers water streams for re-circulation.
Total Site Integration (TSI) [8]
• The object of study is a set of energy-using processes connected by a common utility system;
• It is based on the analysis of heat recovery between several processes through consumption and generation of utilities, in each the heating and cooling needs of each process are identified for the purpose of utility targeting;
• The supply of utilities with the aim to improve energy use may be performed through several measures (utility replacement, recirculated heat streams and renewable energy resources);
• For variable energy demand and supplies, it may involve the use of thermal energy storage units;
• It is itself an extension of the simpler heat integration methodologies (such as pinch analysis).</td><td>• The object of study is a set of water-using and combustion-based thermal pro-cesses within a plant;
• It is based on the assessment of all potential recirculation points, in which waste heat streams may be recirculated to all pro-cesses with thermal energy requirements (combustion-based processes and water system hot utilities), as well as for the purpose of electricity generation, and discharge water streams may be recirculated from one unit operation of one water-using line to the inlet of the others within the same line and to the inlet of all the processes within the other water-using lines;
• The practical method is based on the valorisation of output streams, rather than on the rationalization of input streams;
• In terms of technological integration, it over-all encompasses the same technologies as CWEI and TSI and in addition units for the energy recovery from water/ wastewater.</td></tr>
</table>

As may be evidenced by the analysis of Table 1:

- The innovative methodology may be considered a simultaneous expansion and combination of the CWEI and TSHI methodologies in conceptual terms. Such is attributed to it overall considering categories of processes that are not considered in CWEI (only approaching water-using processes and associated consumption of material and energy-related utilities) and TSI (only approaching energy-using processes and related utility system);
- While TSI does not only consider energy efficiency improvement but also on the adaptation/ substitution of energy inputs, the general concept of WEIS considers system-level improvements only through discharge stream recirculation (which would otherwise be classified as several types of wastes). The WEIS paradigm does not completely disregard the consideration of other energy inputs (such as renewable resources and alternative hot and cold utilities), it only focuses on waste stream valorisation.

3. PERFORMANCE INDICATORS

The overall assessment of the viability of the WEIS paradigm for practical implementation depends on the several aspects which may be analysed according to the determination of several performance indicators. In Table 2, it is presented the determination of several indicators according to each category of interest. The presented aspectual and numeric values have been gathered from the results associated to previous works by the authors, namely two cases (Cases 1 and 2) within a Portuguese ceramic industry plant [4–6]. The operation of the mentioned plant is associated to a 375.26 TJ/year energy consumption and a 10.77 dam^3/year water consumption. The WEIS Engineering projects include Organic Rankine cycle (ORC) units, multi-effect distillations (MED) units and a phase change material (PCM)-based heat exchanger unit (Case 2 only). The sustainability assessment has been performed considering the benchmark values of 2 – 3 year payback period and 0.722 kton $CO_{2,eq}$/year emissions reduction. An extensive description in respect to the characterization of the case-studies, developed simulation models (and final configurations), optimisation models and post-processing assessments is presented in the digital supplementary material (with information adapted from [4]).

In relation to the determined performance indicators presented in Table 2:

- The set of implemented simulation and optimisation modelling methodologies revealed to be suitable for the development of digital twins of set-to-be-implemented WEIS;
- The balanced combination of all capabilities associated to the Modelica and Python languages revealed to be effective for the development of a customised digital tool for WEIS;
- It is furtherly necessary to exploit the potential for the interface between Modelica-based simulation models and dynamic programming models, for a reason of achieving the highest possible integration associated to the digital tool;
- The determined sustainability assessment-based indicators revealed the sustainability promotion potential associated to WEIS-based case-studies;

Furthermore, in respect to the considered technology assessment-related indicators, it is possible to observe that the technologies considered for implementation in the context of the two approached WEIS with lowest technological maturity are in general associated to the lowest technology readiness (TRL) level of TRL5. Such is significant that the considered technologies have been at least validated in a relevant operational environment. In this prospect, it may be affirmed that overall technological maturity is not a particularly relevant factor which affects the potential implementation of WEIS in real-life taking as a basis the conditions associated to the two approached case-studies, since the considered technologies have been at least validated for similar operational conditions. Moreover, it further proves the technological development potential associated to the WEIS paradigm, in which the requirement for the Engineering projects of these types of systems and their further real-life implementation (itself caused by significant needs for water and energy efficiency improvement in end-use sectors) necessarily creates the necessity for the implementation of the referred technologies in a real-life perspective (and thus the increase of the maturity of these from a development phase to a deployment phase).

Table 2: Determination of performance indicators

Indicator	Case 1	Case 2
Computational Model-based		
Simulation Model (OpenModelica)	Completed	Completed
Steady state-based Optimisation Model (Python GEKKO package)	Completed	Completed (Water System)
Dynamic Optimisation Model (OpenModelica)	Not applicable	Completed (Combustion-based Processes System)
Application of OpenModelica Python (OMPython) API	Completed	Semi-completed (Not between simulation model and DP optimisation model)
Sustainability Assessment-based		
Energy Savings	8.57%	6.88%
Water Savings	23.71%	38.57%
Eco-efficiency promotion	6.46%	4.00%
Payback period	1 year and 10 months	2 years and 10 months
Emission reductions	2.42 kton $CO_{2,eq}$/year	1.76 kton $CO_{2,eq}$/year
Technology assessment-based		
Technology readiness level (associated to the considered technology with the less maturity)	TRL5 (Heat-driven water/ waster treatment technologies with less maturity [9])	TRL5 (Heat-driven water/ waster treatment technologies with less maturity [9]) TRL5-7 (Phase change material-based thermal energy storage [10])

4. CONCLUSIONS

This work approaches the fundamental aspects of the paradigm of Water and Energy Integration (WEIS) which has been created and approached in previous works by the authors, and which consists of an innovative methodology that compensates for conceptual gaps associated to similar methodologies. In this prospect, the innovative methodology (subsisting in two most generic superstructures for these types of physical systems), the comparison of this one with existing methodologies and a set of performance indicators have been presented and analysed.

In terms of the developed methodological framework and the determined performance indicators, the following affirmations may be performed:

- The WEIS methodology had already successfully expanded and complemented existing process integration methodologies;
- The WEIS methodology has still to be furtherly updated to include all potential categories of energy-using processes, in addition to combustion-based ones.
- The set of implemented modelling methodologies revealed to be suitable for the development of WEIS digital twins and the sustainability assessment procedure for two approached case-studies revealed the economic and environmental viability associated to the implementation of WEIS in real-life end-use sector sites (industrial plants);
- The implementation of WEIS in real-life is not substantially compromised by technological maturity of involved technologies, and it even has a potential to boost the TRL of less mature technologies;
- It is furtherly necessary to exploit the potential for a more automatic integration (co-simulation) of

simulation models and dynamic programming models.

Taking into account the aforementioned aspects, it is possible to affirm that the developed paradigm of Water and Energy Integration Systems is a relevant opportunity for end-use sectors, being able to constitute Engineering projects with associated sustainability promotion potential, possibility to be modelled with existing computational tools and not being associated to impediments in terms of the maturity and availability of constituting technologies.

DIGITAL SUPPLEMENTARY MATERIAL

Digital supplementary material is available at https://psecommunity.org/LAPSE:2025.0035.

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DEDICATION

The authors would like to dedicate this contribution to the memory of Professor Pedro Castro, who passed away during the review process. His guidance, knowledge and friendship will be greatly missed.

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