Non-renewable and renewable levelized exergy cost of water (LExCOW) with focus on its infrastructure and chemicals

***Javier Uche*[a]*, Alessandro Lima*[a]*, Nicolás Villanueva*[a]*, Alicia Valero*[a]**

[a] *Research Institute for Energy and Resource Efficiency of Aragón (ENERGAIA) – University of Zaragoza, Zaragoza, Spain, javiuche@unizar.es*

Abstract:

This study develops the concept of the levelized exergy cost of water (LExCOW), evaluating key global water technologies in the water cycle. It distinguishes the origin of the exergy (non-renewable and renewable) with focus on the infrastructure, but also the chemicals consumed to supply water in appropriate conditions. The data collection is based on an analysis of the state of the art of the scientific literature, in addition to the authors' previous work on various projects in Spain.

The technologies studied cover the entire water cycle. These include all those of desalination (MultiStage Flash, Multi Effect Distillation, Reverse Osmosis, Electrodialysis, Membrane Distillation), water supply (water transfer, reservoir or groundwaters), drinking water plant, drinking water network, water uses (industrial, irrigation, and urban), sanitation network, wastewater treatment plants, and finally water reuse, including rainwater harvesting.

Using this indicator, we studied the non-renewable resource use of these technologies in terms of exergy cost. The LExCOW results differ somewhat from those found in the authors' previous studies regarding LExCOE. In water technologies, the weight of civil engineering infrastructure is often significant compared to other materials, such as certain metals, and energy consumption is relevant relative to infrastructure only in some technologies, such as desalination.

The values obtained with LExCOW serve as an indicator of the future sustainability of certain technologies compared to others at the same stage of the water cycle, as well as a comparative reference between stages to identify where to focus efforts to improve the overall sustainability of the cycle.

Keywords:

Water; Exergy Cost; Infrastructure; Sustainability.

1. Introduction

The global water crisis represents one of the most significant challenges for the XXI century, driven by a combination of population growth, rapid urbanization, and the intensifying effects of climate change [1–6]. As freshwater scarcity becomes a systemic risk, the industrial and municipal response has been the implementation of increasingly complex technological solutions, ranging from large-scale desalination to advanced wastewater reclamation. However, the transition toward water security often comes at a high physical and environmental cost. Traditional metrics for assessing these systems, such as the Levelized Cost of Water (LCOW) in monetary terms [7] or carbon footprinting in environmental terms [8], often fail to capture the fundamental physical degradation – or irreversibility – inherent in these processes. To truly evaluate the sustainability of our water systems, we must look beyond economic or single-issue environmental indicators and turn toward the second law of thermodynamics.

The concept of exergy provides a rigorous physical basis for this evaluation. Unlike energy, which is conserved, exergy is consumed as it is used to drive processes, representing the "useful" part of energy that can perform work. Forty years ago, the introduction of the exergy cost concept by Valero et al. [9] provided a method to quantify the total exergy required to obtain a product, accounting for both the exergy contained within the product and the irreversibilities (exergy destruction) encountered throughout its life cycle. In the context of the water sector, this approach allows us to view 1 m³ of water not just as a volume, but as a product with a physical "history" of resource consumption.

In recent years, the scope of exergy analysis has expanded from simple process boundaries to a comprehensive "cradle-to-grave" or even "cradle-to-cradle" perspective. This has culminated in the "Thermodynamics of Sustainability" (ToS) framework, which introduces the concept of the "irreversibility backpack" (IB). This backpack sums all cumulative irreversibilities across five distinct scopes: direct process irreversibilities, energy supply footprints, supply chain and infrastructure impacts, natural resource scarcity (exergy replacement costs), and residues remediation costs. While much research has focused on the operational energy consumption of water technologies – particularly energy-intensive processes like desalination – the exergy cost of the physical infrastructure and the chemical reagents consumed during water treatment has often been neglected.

This study introduces the Levelized Exergy Cost of Water (LExCOW) as a novel indicator to address these gaps. Similar to the Levelized Exergy Cost of Energy (LExCOE) [10], the LExCOW incorporates temporal factors such as technology learning curves and performance degradation, ensuring that the physical costs of pre-operation (infrastructure), operation (energy and reagents), and post-operation phases are integrated into a single, time-normalized value. By distinguishing between non-renewable and renewable exergy origins, this indicator provides a clear picture of the long-term sustainability of various water technologies.

The objective of this research is to evaluate key global water technologies – including desalination (MSF, MED, RO, ED, MD), water intake (transfers, reservoirs, groundwater), potable treatment, distribution, and wastewater recovery – through the LExCOW lens. By analyzing a wide range of case studies from Spain, China, the US, and elsewhere, we aim to identify the stages of the water cycle where the greatest thermodynamic degradation occurs.

2. Methodology

2.1. Technologies and cases analysed

In the analysis of the water cycle, the most relevant technologies at each stage were considered, following the entire chain of processes and facilities. The inventories of materials involved in all cases are based on scientific literature or on original, previously published work. In all cases, the plants are of considerable size, representative of significant consumption and major cities. Pilot plants were excluded because their material and energy intensity did not accurately reflect the technology or process stage, despite the high level of detail available in those cases. If the energy consumed at the plant or stage came from different sources, both types were included. Regarding the reagents consumed in the plants, in some cases, they were selected from another study, particularly for plants with a substantial inventory of materials but limited inventories of these consumables. In the case of desalination technologies, when they are the only alternative resources, the MSF (multi-stage flash) and MED (multiple-effect distillation) technologies, widely used in the Persian Gulf, have been analyzed [11,12]. In the first case, the inclusion of nanofiltration membranes allows for higher production [13]. Anyway, a Chinese MED plant was used for this technique [14,15]. In addition, reverse osmosis (RO) has been used for seawater (SWRO) [14,16] and brackish water (BWRO) [17,18], and it is the dominant and most flexible technology. For brackish water, electrodialysis (ED) can be a competitive technique and can be integrated with photovoltaics to produce desalinated water without environmental impact [19,20]. For lower production and with solar input, membrane distillation (MD) is also an interesting option [20].

For surface water, five alternatives have been studied. The first is water transfer from other basins (WT), for which the infrastructure has been examined in two case studies in Spain [21,22] and China [15]. The second is the diversion of water from a canal (CWS) [23], and the third is reservoir retention (DWS) [24]. The fourth is pumping from a river (PWS) [25], and finally, groundwater extraction (GWS) is considered in a Mediterranean area [24] where it is used intensively for irrigation.

Water treatment for human consumption has been analyzed in two plants in the United States [23] and Spain [25], following a conventional coagulation-flocculation, filtration, and disinfection (WWTP) process. For the same two cities (Cincinnati and Zaragoza), where a detailed inventory of their water supply networks (WDNs) was previously available, they were selected for the study. Regarding water use itself, a distinction was made between industrial use of high-purity water (IWU) for the electronics industry [26], as well as the analysis of a 700-hectare irrigation infrastructure (IRU) in France supplied by a reservoir [27], and urban use in the city of Zaragoza (UWU) [25], which includes energy consumption for domestic hot water and washing machines.

The drainage system for collecting wastewater (SDN) was again inventoried in the two aforementioned cities [23,25]. However, the two wastewater treatment plants in Zaragoza were chosen as representative [25], one using activated sludge technology and the other using anaerobic digestion. Finally, regarding water regeneration, two case studies of rainwater harvesting (RW) were initially selected: one for a residential building incorporating ultraviolet (UV) [28] and another for a shopping center [29]. As for water regeneration (WR) technologies, the combined reverse osmosis (RO) and microfiltration (MF) technique [25] and the membrane bioreactor (MBR) were analyzed [30].

Table 1 summarizes the analyzed cases for the water cycle, including the type of process, the technology used, the plant or process capacity, and the reference used for the analysis.

Table 1. *Summary of analyzed case studies for the water cycle.*

Stage	Technology	Location	Capacity (m3/d)	Ref.

Desalination	MSF	Al-Taweelah B (Abu Dhabi)	45600	[11,12]
	MSF+NF	N.D.	6912	[11,13]
	MED	Tianjin (China)	100000	[14,15]
	SWRO	Akkar (Lebannon)	4500	[14,16]
	BWRO	Almería (Spain)	21000	[17,18]
	ED	Gran Canaria Island (Spain)	96	[19,20]
	MD	N.D. (extrap. from pilot plant)	5000	[31]
Intake	WT-1	Ebro-Segura (Spain)	4200000	[21]
	WT-2	Tajo-Segura (Spain)	2928000	[22]
	WT-3	South to North-Tianjin (China)	2790000	[15]
	CWS	Cincinnati (US)	545000	[23]
	DWS	Segura Basin (Spain)	1526400	[24]
	PWS	Zaragoza (Spain)	348174	[25]
	GWS	Segura Basin (Spain)	750685	[24]
Potable	DWTP-1	Cincinnati (US)	545000	[23]
	DWTP-2	Zaragoza (Spain)	169412	[25]
Distribution	WDN-1	Cincinnati (US)	545000	[23]
	WDN-2	Zaragoza (Spain)	325300	[25]
Use	IWU	Iran (Persian Gulf)	3483	[26]
	IRU	South France	40037	[27]
	UWU	Zaragoza (Spain)	109590	[25]
Drainage	SDN-1	Cincinnati (US)	545000	[23]
	SDN-2	Zaragoza (Spain)	568000	[25]
Depuration	WWTP-1	Zaragoza (Spain)	204560	[25]
	WWTP-2	Zaragoza (Spain)	40180	[25]
Recovery	HAR-UF	Forianópolis (Brazil)	1000	[28]
	HAR	Washington DC (US)	7.3	[29]
Reuse	WR-RO+MF	Gran Canaria Island (Spain)	6000	[25]
	MD-MBR	Atlanta City (US)	1.3	[30]

2.2. Disaggregation and calculation methods

A Thermodynamics of Sustainability approach was considered. The calculation method is explained in detail in the work presented by Lima *et al* in this same conference [32]. It considers the irreversibility backpack created by all upstream processes and products needed to obtain a product – in this case, 1 m^3 of water. All of streams are categorized in Natural Resources, Raw Materials, Products and Emissions.

In the Thermodynamics of Sustainability (ToS) framework, the exergy cost (ExCoW) is calculated as the total exergy input from natural resources required to obtain a specific unit of product output. This calculation is performed using a multi-layered approach that tracks physical costs across a system's entire life cycle.

The general exergy cost of a product is expressed mathematically by Eq. (1):

$$ExCoW = \sum_{r=1}^{22} B_r^{(nr)}, \qquad (1)$$

Where B represents the exergy of the natural resource requirements r (based on a 22-dimensional resource vector). This value is typically measured in MJ of exergy per m^3 of water (MJ/m^3).

To account for a system's entire lifetime, the framework uses a levelized exergy cost, which incorporates temporal factors such as technology learning curves, physical amortization rates (r), and performance degradation over time (t), as Eq. (2) shows:

$$LExCoW = \sum_{t}^{T} \frac{B_t}{(1+r)^t}, \qquad (2)$$

This ensures that the physical costs of pre-operation, operation, and post-operation phases are all integrated into a single value.

The framework expands the traditional definition of exergy cost through the "irreversibility backpack" (IB), which sums all cumulative irreversibilities associated with a product across five distinct scopes:

Scope 1: Exergy of the product plus direct process irreversibility.

Scope 2: Energy supply footprints (e.g., electricity and heat).

Scope 3: Supply chain footprints, including raw materials and infrastructure.

Scope 4: Natural resource scarcity creation (exergy replacement costs).

Scope 5: Residues remediation costs linked to the nine planetary boundaries.

The calculation relies on three integrated computational tools. The LCI Aggregator uses an adaptive Leontief solver (Eq. 3)

$$x = [I - A]^{-1} * e_j, \qquad (3)$$

to link technology matrices of the technosphere's supply chain with unit demand, mapping flows to 22-dimensional resource and 26-dimensional emission vectors. The Exergy Cost Evaluator tracks resource consumption and emissions across nine life-cycle stages, from extraction and manufacturing to maintenance and decommissioning. Meanwhile, the Total Exergy Calculator computes chemical exergy based on elemental composition, adjusting for local reference environments (temperature, pressure, and local chemical concentrations) rather than just global averages.

By combining these elements, the framework provides a "cradle-to-cradle" view of the physical cost, accounting for both the depletion of natural resources and the exergy required to abate environmental harm.

3. Results

As a preliminary result, two plants are analyzed and their material, exergy, energy and water footprints are shown.

3.1. Material and energy footprints

Table 2 shows the direct impacts of the construction of two analyzed technologies: a Drinking Water Plant (DWP) and a Wastewater Treatment Plant (WWTP), both in Zaragoza. The lifetime of these plants is 50 years, and their productions during lifetime are 3046 and 442 hm^3, respectively. The energy consumption (electricity and gasoil) from construction represents 4 % of the total lifetime construction for DWP and 10 % for WWTP, while the rest in energy consumption during operation, both in electricity and reagents.

Table 2. *Impacts during the construction of the plants.*

Plant	Earth excavated (m^3)	tkm	Gasoil used in construction (m^3)	Electricity used during construction (kWh)	Land use (ha)
DWP	50960	28429	3.26	15288	6.37
TTWP	15984	177107	1.02	4795	2.00

As Table 2 shows, the impacts and consumptions of the DWP are considerably larger than those of the WWTP, but the larger production capacity of the plant means it has a lower footprint per water m^3 produced, indicating scale economy and differences in processes.

3.2. LExCOW

Figure 1 shows the obtained LExCOW for both technologies, considering the whole lifetime. The WWTP has a considerable larger LExCOW per cubic meter. This mainly because of its important consumption in electricity which the process uses to keep oxygenated the pools, and also because of the use of energy-intensive reagents, like NaOH, NaClO or coagulants like polyelectrolites or $AlCl_3$. The direct electricity consumption of the WWTP is 0.47 kWh/m^3, which translated to exergy using LExCOE [33], means an exergy cost of 4.06 kJ/m^3, with the rest being the exergy cost of reagents.

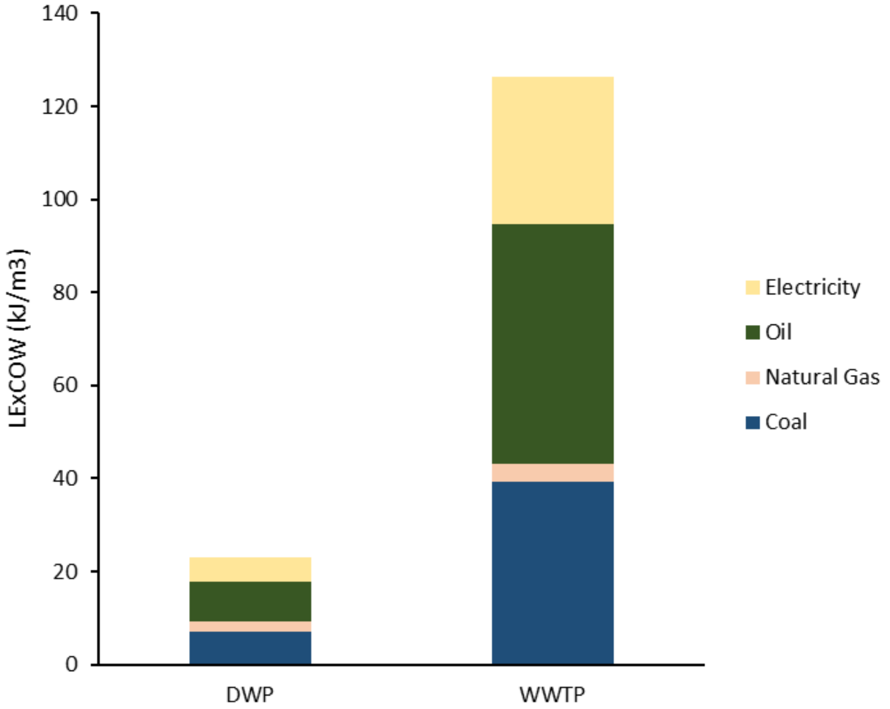

Figure 1. *LExCOW of two different technologies analyzed: Drinking Water Plant (DWP) and Wastewater Treatment Plant.*

In the case of the DWP, the direct electricity consumption is considerably lower, reaching 0.029 kWh/m^3, for a total exergy of 0.25 kJ/m^3. The total exergy consumption from electricity for this plant was 2.14 kJ/m^3, indicating that around 75 % of the exergy cost of electricity of the process comes from construction and reagents. Both the DWP and the WWTP results highlight the importance of considering the complete life-cycle of plants when analyzing water supply technologies.

Water footprints were also obtained for both plants. For the Drinking Water Plant, the water footprint reached 2.34 m^3/m^3, meaning a resource efficiency of less than 50 %. Similar was the case for the Wastewater Treatment Plant, with 2.03 m^3/m^3. This indicates that, to purify a m^3 of sewage water, an additional m^3 of water is needed. Even though this might seem contradictory, the water footprint of emitting sewage water directly to freshwater sources would probably be higher due to pollution (grey footprint).

4. Conclusions

The development and application of the Levelized Exergy Cost of Water (LExCOW) indicator provide a definitive thermodynamic framework for assessing the sustainability of the global water cycle. By moving beyond traditional mass or energy balances and adopting the "Thermodynamics of Sustainability" (ToS) perspective, this research has quantified the "irreversibility backpack" associated with providing clean water and managing wastewater. The findings offer a comprehensive view of the physical resources required to sustain our water infrastructure, highlighting the critical role of both operational energy and the materials embedded in civil engineering works.

The application of LExCOW across various technological stages reveals several critical insights into the thermodynamic efficiency of the water cycle. One of the primary contributions of this work is the disaggregation of exergy costs into renewable and non-renewable components. This distinction is vital for future-proofing water systems; as we transition away from fossil fuels, understanding which technologies rely heavily on non-renewable "exergy backpacks" – such as those found in mineral-intensive infrastructures or chemical reagents – is essential for true sustainability.

Furthermore, the "levelization" of exergy costs allows for a fair comparison between technologies with different lifespans and performance characteristics. By incorporating physical amortization and degradation over time, LExCOW ensures that the massive initial exergy investment in infrastructure is accurately reflected alongside ongoing operational costs. This is particularly relevant in the water sector, where large-scale civil engineering works (e.g., dams, water transfers, and networks) have lifespans reaching 50 years or more.

A central finding of this study is the significant weight of civil engineering infrastructure compared to other materials and energy consumption in specific stages. In many conventional water supply and distribution technologies, the materials used for construction – such as concrete and metals – represent a major portion of the total exergy cost. For technologies like desalination, however, the exergy destruction during operation (energy consumption) dominates the overall LExCOW.

The preliminary analysis comparing a Drinking Water Plant (DWP) and a Wastewater Treatment Plant (WWTP) in Zaragoza illustrates these differences vividly. Despite the DWP having a larger physical footprint and construction impact in terms of land use and earth excavated, its high production capacity results in a lower LExCOW per cubic meter of water compared to the WWTP. The WWTP exhibits a significantly higher LExCOW (reaching over 120 MJ/m³ in some metrics) due to the intensity of its operation. Specifically, the aeration processes required to oxygenate treatment pools consume substantial amounts of electricity, and the use of energy-intensive chemical reagents – such as NaOH, NaClO, and coagulants like $AlCl_3$ – adds a heavy thermodynamic burden that is often overlooked in simpler analyses.

While this study noted that chemical reagents are generally less significant than energy consumption when viewed across the entire water cycle due to their dilution, they represent a critical "hotspot" for exergy destruction in the depuration stage. The production of these chemicals involves high-exergy industrial processes, and their consumption in wastewater treatment contributes significantly to the overall non-renewable exergy cost of the cycle.

The analysis also highlights the importance of the "economy of scale" in thermodynamic terms. Larger plants, while having higher absolute impacts during construction, often achieve a lower LExCOW per unit of water because their massive production volumes dilute the fixed exergy costs of their infrastructure and construction energy.

The methodology established here—linking Leontief-based technology matrices with 22-dimensional resource vectors—provides a robust tool for researchers and policymakers. By tracking resource consumption across nine life-cycle stages and adjusting chemical exergy for local reference environments, the framework offers a level of precision that global averages cannot match.

The values obtained with LExCOW serve as a vital indicator for identifying where efforts should be focused to improve the sustainability of the water cycle. For instance, reducing the electricity consumption of WWTPs or finding lower-exergy alternatives for chemical reagents could yield significant reductions in the total LExCOW of urban water systems.

In conclusion, the LExCOW provides a scientifically rigorous "price tag" for water in terms of the planet's physical wealth. It shows that water sustainability is not just about volume or carbon, but about the wise management of the exergy invested in our infrastructure and the efficiency of the processes we use to clean and distribute this vital resource. Future research should continue to expand this database, incorporating more renewable energy scenarios and diverse geographical contexts to help build a truly sustainable, low-exergy-cost water future.

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