Energy Conversion and Management 284 (2023) 116960

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Comprehensive performance evaluation of water and power production technologies using water-exergy nexus analysis

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ARTICLE INFO

Keywords:
Desalination and wastewater treatment
Life cycle analysis
Power production
Renewable energy
Water-exergy nexus

ABSTRACT

Insight into less-known aspects of sustainable development has been deepened through the development of the nexus between water and energy in the last decades. However, the complex sustainability problem cannot be fully investigated owing to the intrinsic shortcomings of the physical concept of energy. This study considered the exergy concept as a substitute for energy to develop water-exergy nexus analysis (WExNa) as an efficient analytical framework. Accordingly, four evaluation criteria were proposed as quantitative tools of WExNa. Consequently, seven power and seven water production technologies were analyzed considering the model uncertainties in their life cycle. A big data bank, comprising 803 water and 812 power production plants, was labeled to facilitate consideration of the spatial, temporal, and environmental variety of technologies in a stochastic data-driven program. The results showed that wind, solar, and concentrating solar power plants used the least amount of water for exergy production during the entire life cycle, whereas only geothermal power technology could compete with non-renewable power in the operating stage by an exergy dissipation for product exergy index in the range of 0.2 – 3. Despite the significance of chemicals in water production, chemical exergy dissipation was negligible compared with electrical and thermal exergies. Water treatment facilities were generally superior to desalination technologies, considering all types of exergy for water. Although multi-stage flash and electrodialysis exhibited the best and worst operation metrics among the water technologies, they dissipated the most and least exergies for water production, respectively, with an acceptable confidence considering the entire life cycle. Moreover, the contrast between conventional operation indexes and the new WExNa variables entails potentially new horizons through the sustainable evaluation of engineering systems using the proposed analysis.

1. Introduction

Anthropogenic climate change cannot be mitigated without committing to sustainable development. Sustainable development goals constitute a consolidated multi-aspect platform that should be pursued as unity. The two intertwined pillars of the sustainable development paradigm are clean water and energy [1]. A concise investigation of sustainability indices has revealed the significance of a nexus between water and energy. Owing to 90 % of energy production being water-intensive, clean water supply has been jeopardized by increasing energy consumption [2]. The previous record of 52 billion m^3 of fresh water for global energy production [3] is expected to be broken because the world's power demand is forecasted to grow by 1.5 times by 2030 [4]. However, water collection, treatment, and distribution are energy-intensive processes. Wastewater treatment plants consumed 0.27, 0.8, and 3 % of the total domestic power generated in China, Europe, and the United States in 2019, respectively [5]. Energy and water can mutually intensify each other's consumption patterns in a non-sustainable loop. Hence, the nexus between water and energy has garnered the attention of environmental strategists.

Concerning the significance of the water-energy nexus (WEN) in providing a holistic insight into the performance of engineering systems, the literature was systematically reviewed using a computer program as elucidated in the **Supplementary materials** [6]. The text scatter plot of both runs of the program is shown in Fig. 1, where the vertical and

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https://doi.org/10.1016/j.enconman.2023.116960
Received 7 December 2022; Received in revised form 15 February 2023; Accepted 21 March 2023
Available online 30 March 2023

Nomenclature

Abbreviations
Activated sludge plant ASP
Amorphous silicon a-Si
Biochemical oxygen demand BOD
Cadmium telluride CdTe
Chemical Chem.
Circular fluidized bed CFB
Combined cycle CC
Combustion turbine CT
Concentrating solar power CSP
Construction Const.
Conventional Conv.
Copper indium gallium selenide CIGS
Crystalline silicon c-Si
Decommissioning DECOMG
Desalination Des.
Electrical Electr.
Electrodialysis ED
Enhanced geothermal systems EGS
Exergy dissipation for water production ExW
Gain-output ratio GOR
Greenhouse gas GHG
Integrated gasification combined cycle IGCC
Life cycle assessment LCA
Manufacturing Manu.
Material Mat.
Maximum Max.
Mechanical vapor compressor MVC
Median Med.
Membrane Mem.
Membrane bioreactor MBR
Minimum Min.
Mixed Liquor Suspended Solids MLSS
Mixed liquor suspended solids MLSS
Mono-crystalline silicon m-Si
Multiple effect distillation MED
Multi-stage flash distillation MSF
Poly-crystalline silicon p-Si
Preliminary Prelim.
Process Pro.
Pulverized coal PC
Reverse osmosis RO
Secondary Sec.
Sequencing batch reactor SBR
Solar photovoltaic PV
Subcritical SC
Supercritical SuC
Suspended solids SS
Thermal Ther.
Thermal vapor compressor TVC
Total dissolved solids TDS
Transportation Trans.
Treatment Treat.
Water-energy nexus WEN
Water-exergy nexus WExN
Water-exergy nexus analysis WExNa

Variables
Absolute temperature (K) T_o
Availability of the power plant Av
Capacity factor of the power plant CF
Chemical exergy (kJ/s) $ChEx$
Chemical exergy for water production (kWh/m^3) $CExW$
Coefficient of standard chemical exergy LS
Concentration of the i$^{\text{th}}$ chemical in a mixture (mg/L) C_i
Concentration of the referenced chemical in a mixture (mg/L) C_o
Electrical energy (kWh) E_{elec}
Electrical exergy for water production (kWh/m^3) $EExW$
Exergy dissipation for product exergy $ExEx$
Exergy dissipation for water (kWh/m3) ExW
Exergy efficiency η_{ex}
Fuel uncertainty factor FU
Gibbs free energy (kJ/mol) ΔG
Higher heating value of the fuel (MJ/kg) HHV
Ideal gas constant (m3·atm/K·mol) R
Input heat to the process (kWh/m^3) Q
Lifetime (years) Lt
Lower heating value of the fuel (MJ/kg) LHV
Mass flowrate (kg/s) $\dot{m}$
Mass of elements (kg) m_{ch,n_e}
Number of molecules of the considered element in the molecules of the reference species n_i
Number of moles of the element per unit of the compound n_e
Operating temperature (K) T_{actual}
Performance ratio PR
Quantity of water for fuel WFF
Quantity of water for power WFP
Recovery ratio RR
Resource variation factor RV
Specific chemical exergy (kJ/mol) b_{ch}
Standard chemical exergy of the reference element (kJ/mol) $b^o_{ch,r}$
Standard exergy of the fuel (MJ/kg) Ex^0_F
Standard normal free energy of reaction (kJ/mol) ΔG_r
Thermal energy (kWh) E_{th}
Thermal exergy for water production (kWh/m^3) $TExW$
Total exergy dissipation in desalination (kWh/m^3) ExW_{des}
Total exergy dissipation in wastewater treatment (kWh/m^3) ExW_{wt}
Total water for product exergy (L/MWh) W_{Ex}
Unit conversion factor UCF
Water consumption for product exergy $WCEx$
Water loss for water production WW
Water use for product exergy in the fuel cycle (L/MWh) W_F
Water use for product exergy in the power cycle (L/MWh) W_P
Water withdrawal for product exergy $WWEx$

horizontal axes represent the abundance of keywords in the titles of the WEN and tripartite nexus literature, respectively. An interactive file of the scatter plot is presented in the **Supplementary materials**. In the recent nexus literature, 1,004 publications belonged to WEN, and 2,909 studies included parties other than water and energy. WEN research has focused on investigating hydrologic and water management problems, whereas the tripartite nexus has handled sustainable assessment. Geographically, China and the United Kingdom were frequently repeated in the titles of publications. These two countries are among the highly studied case studies following the U.S. with the highest number of publications (Fig. 2 **(a)**). According to the map, WEN research suffers from an unequal geographical distribution of studies, which can be attributed to the restricted availability of open-access data in various nations. The cumulative number of WEN publications is shown in Fig. 2 **(b)**. Despite the increase in tripartite nexus studies in recent years, the growth rate of WEN studies without a third party has decreased. This implies the sufficient maturity of WEN studies, and the research has been further extended via the inclusion of other sustainability sectors.

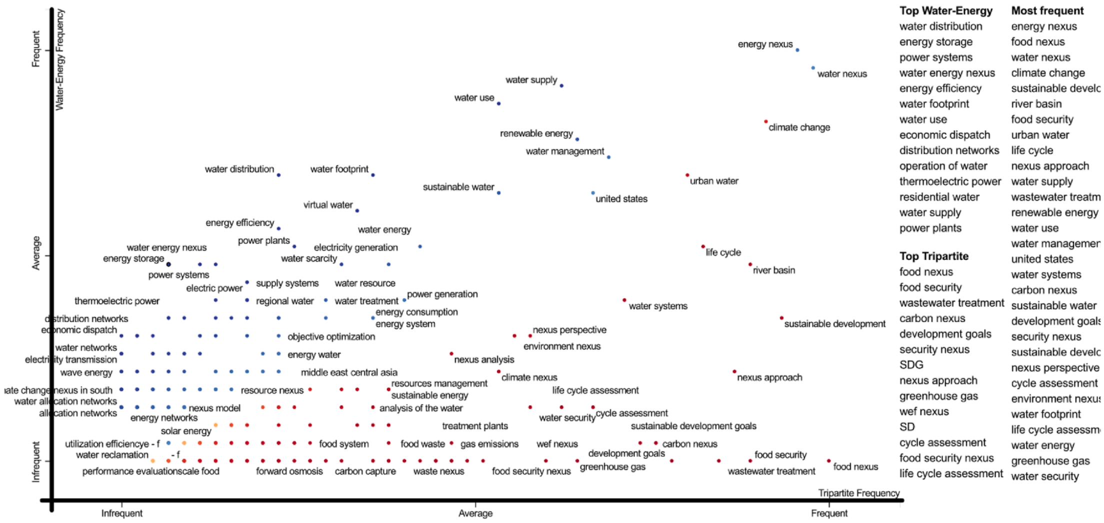


Fig. 1. The text scatter plot of the systematic search 6

Thus, a fundamental conceptual shift can usher in new solutions to unsolved problems.

WEN has been frequently addressed in system design [7], analysis [8], optimization [9], and monitoring [10]. Although mature WEN was proposed to obtain efficient solutions for sustainability problems, many aspects of the complex problem have not been investigated owing to the intrinsic restrictions of the energy concept. First, energy analytics consider quantities that ignore the quality. Thus, all forms of energy with similar values and units have been treated equally, neglecting their availability. Second, the irreversibility has not been considered in energy-oriented processes. However, trade between energy and other sectors involves considerable losses, such as substantial irreversibility. Third, sustainability discourse is associated with optimal pathways for decision making, but the energy concept provides insufficient information for optimization problems. Such bottlenecks in nexus studies can be obviated via substituting energy by the concept of exergy. The water-exergy nexus (WExN) terminology was first proposed in 2019 by Ifaei et al. [11] to compare the performance of two power-generation and power-cooling cogeneration systems with similar configurations. Later, this metric was used to design a utility-free multigeneration system for dry regions [12]. Owing to the successful application of the concept, four WExN-based evaluation criteria were proposed for the performance comparisons of a model-based low-water-consuming power plant with similar technologies in 2020 [13]. The criteria magnified the progress in saving water during power production in the optimal energy system; therefore, a many-objective optimization model was developed with WExN-based variables as its decision variables [14]. These initial steps highlighted significant progress in the sustainable evaluation results by substituting the traditional WEN with the water-exergy nexus analysis (WExNa) in model-based systems. However, WExNa has not been implemented in life cycle analysis of various technologies in global settings, yet.

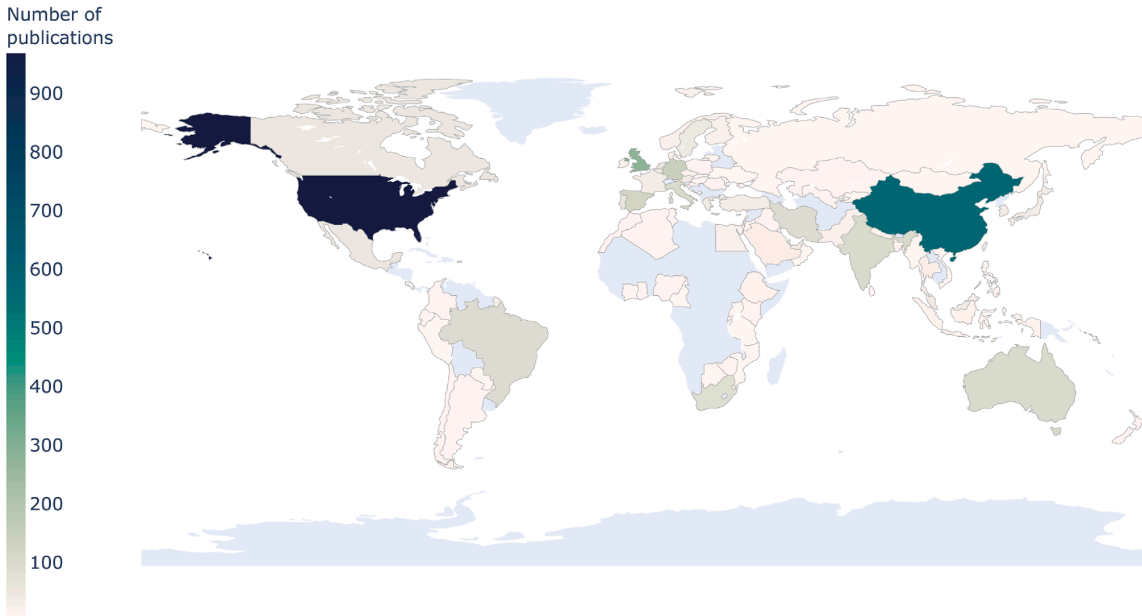
In addition to analyzing individual systems, the concept of WEN has been successfully addressed in data-driven studies to draw holistic conclusions over global management issues. A number of the distinguished studies of this category is summarized in Table 1. The WEN concept is employed in various sectors from inter-regional to global settings. However, a study considering both water and energy technologies is scarce. According to the table, most of the studies use deterministic models to avoid complicated calculations at the cost of unrealistic model simplification. The results of these models are not accurate because they neglect environmental fluctuations, operation dynamicity, and other modeling uncertainties in global scales. Moreover, most of the studies avoid life cycle of the technologies by focusing on operating stage to obtain performance coefficients. Finally, no studies have employed WExNa in evaluating the performance of engineering systems in a data-driven model.

This study contributes to sustainability research by developing the WExN concept, conducting a WExNa of engineering systems considering their life cycle, and evaluating power and water technologies considering this perspective. The novelties of this study are fourfold. First, a big data bank of seven water and seven power production technologies was provided. The big WExNa dataset was labeled in multiple stages and equipped with various features to consider the impacts of spatial dispersion, complexities of processes, and environmental conditions in a comprehensive mathematical model. Second, water production technologies were evaluated by considering thermal and chemical exergies in addition to electrical exergy during their life cycle. Hence, further details regarding the performance of the wastewater treatment and desalination processes were presented. Third, an innovative stochastic model was developed to evaluate technologies that consider the impacts of temporal changes, a variety of processes, and uncertain model parameters. WExNa was represented by an acceptable level of confidence to provide reliable results for probabilistic conclusions using a Monte Carlo simulation. Fourth, two evaluation indexes and five assessment variables were proposed to appraise engineering systems in the entire or part of their life cycle. The new WExNa criteria were calculated for 14 technologies to render a comparative evaluation of their performance using kernel density estimation.

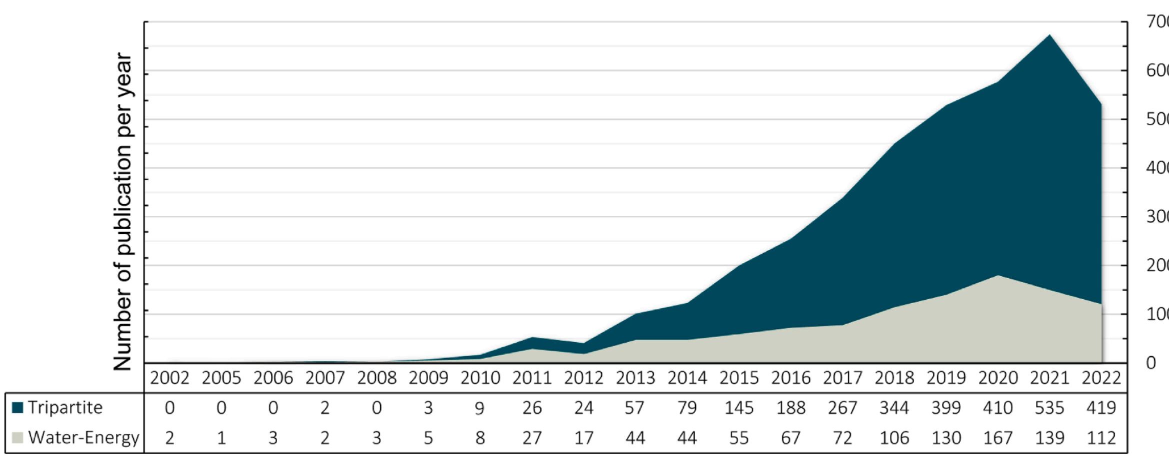
The remainder of this paper is organized as follows. Qualitative WExNa is briefly explained by elucidating various aspects of the new concept in Section 2.1. The goals and boundaries of life cycle analysis (LCA) are detailed in Section 2.2, and the evaluated water and power production technologies are reviewed in Section 2.3. Further, the raw data, basic WExN models, and mathematical program are provided in Section 2.4. The WExNa-based data are visualized, and the computed indexes are used to compare the operational performance of the technologies in Section 3.1. Finally, the results of the stochastic model are discussed in section 3.2, and compared to WEN-based models in section 3.3 to draw a conclusion on the WExNa-based performance of the conventional water and power production pathways.

2. Material and methods

The procedure of formulating the WExN in an analytical framework for evaluating the performance of water and power production technologies is elucidated after briefly highlighting its conceptual differences with WEN in this section.



(a)



(b)

Fig. 2. The results of the systematic survey considering (a) the geographical distribution and (b) the historical background of the studies

Table 1
Some of the distinguished data-driven sustainable management studies using water-energy nexus concept

Sector	Geographical scale	Model	Analytics	Third-parties	Ref.
Power	Global	Deterministic	Water life cycle and sensitivity analyses	NA	[15]
Electricity	Global	Deterministic	Scenario-based estimations models	NA	[16]
Renewable energy	Global	Deterministic	Life cycle and uncertainty analyses	NA	[17]
Electricity	Europe	Deterministic	Scenario-based estimations models	NA	[18]
Water resource	Karkheh river basin	Stochastic	TOPSIS/Entropy decision-making model	Food	[19]
Power	Global	Deterministic	Natural language data analysis	NA	[20]
Water treatment	Chile	Deterministic	Regression analysis	NA	[21]
Water industry	Australia	Deterministic	Scenario-based estimations models	NA	[22]
Freshwater production	Africa	Deterministic	Data mapping	NA	[23]
Power	Global	Deterministic	Compatibility and life cycle analyses	Carbon	[24]

2.1. Water-exergy nexus concept

In scientific terms, energy is deemed as *the potential for performing work or heat*. It has been classified into various forms to simplify the setting of thermodynamic laws, conversion principles, and conservation rules. From an industrial perspective, energy harnessing, conversion, transfer, and storage can be sectorized to study their relationships with other sectors [24]. In other words, energy is treated as a commodity to

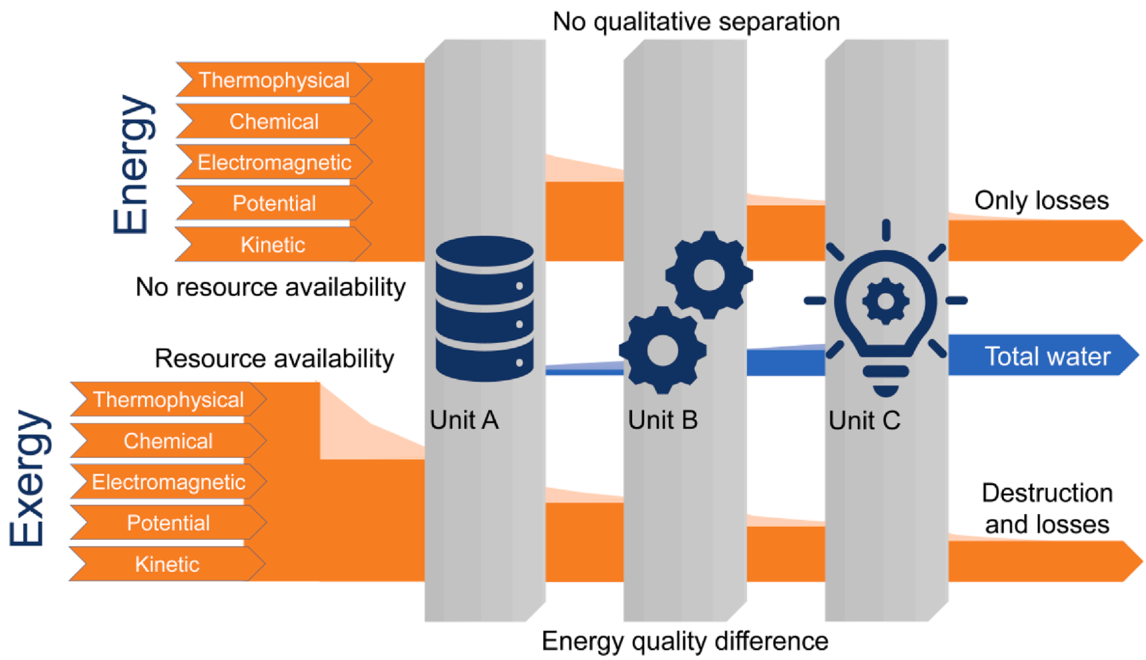


Fig. 3. A schematic comparison between the water-energy and water-exergy nexus analyses

be managed in sustainable analytics to facilitate modeling and reduce computation costs. In contrast to the First law-originated energy, an exergy analysis is derived from the Second Law of Thermodynamics. Exergy is defined as *the useful work potential of a given amount of energy at a specified state*. It represents an upper limit of work that a system delivers without violating any thermodynamic laws [25] and involves the irreversibility of processes while differentiating between losses and destruction. Hence, exergy represents the amount of energy as well as its availability and quality. Compromising on a given dead state, two engineering systems with identical energy efficiencies deliver various amounts of exergy when operating at different temperature levels or consume different chemicals [26]. This is shown in Fig. 3, which presents a schematic comparison of the WEN and WExN concepts. The availability level of various energy resources, quality and quantity of the converted energy in various processes, and generated entropy are considered in the exergy analysis, whereas the energy analysis considers only the quantity of energy. Considering water usage during the operation of a system, WExNa details the quantity of water for a useful amount of energy; thus, it can be proposed as an upgraded representation of the WEN with further details. WExNa ca

2.2. The criteria and boundaries of the analysis

Neglecting water quality, this study examined the quantity of water based on two metrics, water consumption and withdrawal. The former refers to *the amount of water leaving the boundaries of a system without recoverability*, for example, by evaporation in a wet cooling tower. The latter represents *the amount of water taken from the ground for use in energy sector*, for example, circulated water in once-through cooling systems [11]. Based on this perspective, the amount of water consumed cannot exceed that of withdrawn water for a particular technology. Exergy destruction is proportional to entropy generation; thus, any irreversibility results in the destruction of certain exergy. Irreversibility is caused by a wide range of processes such as chemical reactions, mixing procedures, friction, heat transfer in a finite temperature difference, unrestrained expansion, and non-quasi-equilibrium compression (or expansion) [27]. The product and fuel exergies are *the amounts of the output and supplied exergies of and into the boundaries of a system determined based on the desired functionality of a component*. Accordingly, the loss exergy is *the amount of the fuel exergy leaving the boundaries of a system neither as a product nor being destructed*. Hence, the exergy dissipation for product exergy (*ExEx*) is *the summation of the lost and destroyed exergies to obtain a particular amount of product exergy*, and water loss for water production (*WW*) is *the amount of used water to yield a given amount of water with known standards* [14]. These two indices vary according to the technologies, processes, and conditions under which the systems operate; thus, they are unique operating indexes.

The goal of the LCA in this study was aimed at obtaining the required water consumption (*WCEx*) and withdrawal for product exergy (*WWEx*) of power systems, and electrical (*EExW*), chemical (*CExW*), and thermal exergy (*TExW*) dissipation of water production technologies. The boundaries of WExNa for power and water production are shown in Fig. 4 **(a)** and **(b)**. The power production life cycle was divided into power and fuel cycles, with the power cycle classified into the upstream, operating, and downstream stages [28]. Further, the water consumed and withdrawn during the construction and manufacturing of power production facilities are labeled as *WCEx* and *WWEx* at the upstream stage, respectively. The water in the operating stage is primarily used for the cooling and maintaining power plants. The downstream stage encompasses the end-of-life and decommissioning processes of the power facilities. Certain power production technologies such as coal and gas power plants consume water-intensive fuels to produce electricity. Thus, the water required during fuel extraction, processing, transport, and end-of-life processes are separately calculated for these technologies in the fuel cycle [15]. The water production life cycle was divided into operating and non-operating stages. The former included pre, primary, secondary, and post treatment processes, whereas the non-operating stage included both upstream (construction) and downstream (decomposition) substages. In addition, the sewage cycle contained wastewater collection and conveyance substages. In the present life cycle analysis, the sewage cycle was neglected for model simplicity.

2.3. Analyzed technologies

Seven power- and seven water-production technologies each were studied to validate the new indices and variables. Four renewable and three fuel-based power technologies are considered, as follows:

Coal-fired power plants: Approximately 40 % of the global electricity

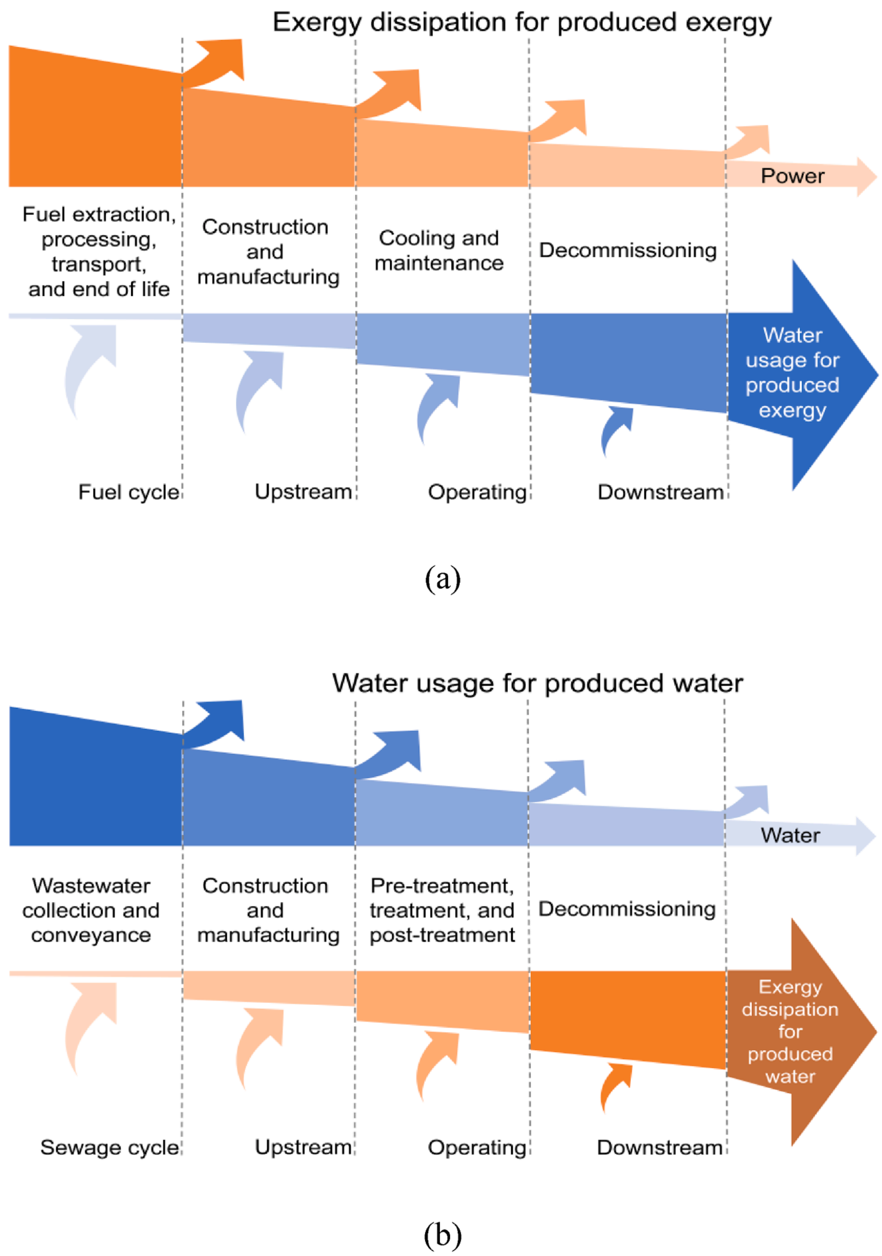


Fig. 4. Boundaries of water-exergy nexus analysis during (a) power and (b) water production

was produced through coal combustion in the last decade [29]. Here, subcritical (SC), supercritical (SuC), circular fluidized bed (CFB), pulverized coal (PC), and integrated gasification combined cycles (IGCC) were studied as coal subcategories [15]. Both fuel and plant stages were considered in the *WCEx* and *WWEx* calculations. The fuel cycle comprised extraction (surface or underground mining), processing, and transport (train or slurry) sub-cycles.

Natural gas power plants: It is anticipated to supply 24 % of global energy from gas, implying that natural gas will surpass the coal usage by 2040 provided there is no occurrence of a long-term global crisis [30]. Both shale and conventional gas technologies were considered in the fuel cycle with drilling, fracturing, processing, and transport subcycles. Gas-to-power conversion units include both a less-efficient combustion turbine (CT) and a highly efficient combined cycle (CC).

Nuclear power plants: Despite public safety concerns and disposal of hazardous waste, nuclear power plants are expected to supply 7 % of global energy under new energy policies by 2040 [30]. These inflexible power plants exhibit a more complex fuel cycle than previous technologies, comprising fuel conversion, enrichment (diffusion and centrifugal), fabrication, and end-of-life sub-cycles.

Solar photovoltaics (PVs): The electricity harnessed by solar PVs has exceeded 800 TWh in recent decades [31]. This considerable increase is forecasted to further increase by 2030 and aid in achieving sustainability goals. Various PV production technologies have been studied, including cadmium telluride (CdTe), copper indium gallium selenide (CIGS), mono-crystalline (m-Si), polycrystalline (p-Si), and amorphous silicon (a-Si) cells [15]. The flat and concentrated PVs were considered in the analysis.

Wind turbines: With over 800 GW installed capacity, the wind electricity has grown by six times in a decade, reaching over 1,300 TWh in 2019 [32]. In this study, both low- and high-efficiency offshore wind turbines were analyzed at various hub heights.

Concentrating solar power (CSP) plants: As of the end of 2016, the operating and planned capacities of CSP plants reached approximately 5,000 and 3,600 MW, respectively [33]. Parabolic trough concentrators, linear Fresnel reflectors, and solar towers are among the most commonly used CSP technologies. Herein, both the power towers and troughs were analyzed using wet, dry, and hybrid cooling facilities.

Geothermal plants: The total installed geothermal energy is approximately 10 GW, with 90 % of the energy prevalent in only eight countries in 2020 [34]. In contrast to weather-driven renewable energy systems, geothermal plants convert thermal to electrical exergy in a semi-stable pattern. They appeared in three configurations: binary, flash, and enhanced geothermal systems (EGS) in the analyses.

Three continuous, batch, and membrane wastewater treatment processes, as well as two membrane and two thermal desalination technologies, were studied as water production units, as follows:

Reverse osmosis (RO): Approximately 69 % of total installed capacity of desalination plants benefit from RO technology worldwide [35]. RO is the most popular desalination technology owing to continuous process improvements, including improvements in membrane materials and module design. RO technology was studied in both integrated and stand-alone configurations over a wide range of operating capacities.

Multi-stage flash distillation (MSF): The MSF technology accounts for 21 % of the global installed desalination capacity [36]. The production capacity of an MSF system is governed by the difference in the total operating temperature. Moreover, mature MSF systems exhibit high gain-output ratio values among desalination processes. Here, all conventional MSF configurations were included in the simulation procedure.

Multiple effect distillation (MED): Represents approximately 7 % of global capacity, several types of MED systems have been commercially operated with capacities of over 100,000 ton/day [37]. MED technology can be easily integrated with available facilities; therefore, both feed-forward and parallel-cross feed integrated, stand-alone, and combined MED systems were evaluated.

Electrodialysis (ED): ED is a well-known and useful method for managing hypersaline solutions. It requires low-pressure ranges, and exhibits increased efficiency for brackish water total dissolved solids (TDS) range of 2,000 to 15,000 mg/l [38].

Activated sludge process (ASP): ASP is used worldwide for municipal and industrial wastewater treatment. The daily excess sludge generation from a conventional ASP results in approximately 15 – 100 L/kg BOD_5 elimination, with water accounting for over 95 % of the total [39]. Considering the expelled excess sludge, ASP can be considered both as a treatment process and as a biomass source in water-energy nexus studies.

Sequencing batch reactor (SBR): This can facilitate saving more than 60 % of the operating costs of traditional ASPs along with achieving high effluent quality in a very short aeration period. Moreover, SBR has been preferred over the ASP in recent applications. More than 90 % of biochemical oxygen demand (BOD) may be removed via the SBR, whereas traditional procedures remove only 60 – 95 % of the BOD with a significant reduction in suspended solids (SS) content (less than 10 mg/L) [40].

Membrane bioreactor (MBR): MBR systems do not require activated sludge flocs in the bioreactor, which must be removed by settlement. Hence, the bacteria in the bioreactor (biomass) can operate at very high levels of mixed liquor suspended solids (MLSS); generally, at concentrations between 12,000 and 18,000 mg/l and as high as 22,000 mg/l. Thus, MBR is more efficient than other treatment processes in industrial applications.

2.4. The data, models, and program

The harmonized data by Meldrum et al. [15] were adopted to develop water consumption and withdrawal for exergy datasets with 415 and 397 data objects, respectively. Reliable data were obtained by monitoring a multitude of power production facilities worldwide, covering an extensive geographical distribution. If not stated in the references, water withdrawal was assumed equal to consumption. The water content in the fuel cycle was obtained using Eq. (1).

Table 2
The parameters to estimate water for product exergy [15,17,42–58]

Technology	Energy efficiency (%)	Lifetime (years)	Other parameters
Coal power plants	35.4 – 39.9	30	21.01 MMBtu/ton (LHV)
Gas power plants	33 – 51	30	1,031 Btu/scf (HHV)
Nuclear power plants	29.36 – 36	40	0.00433 kg UO_2/MWh
Geothermal plants	1 – 20	30	-
CSPs	15 – 20	30	2,400 kWh/m^2yr
Wind turbines	5 – 46	20	-
Solar PVs	6.3 – 13	30	1,700 kWh/m^2yr

Table 3
Lower and upper bounds of the uncertain parameters of power technologies [41,42,46,48–50,53–57,60–102]

Technology	Variation range			
	η_{ex}	$Av \times CF$	RV	FU
Coal power plants	0.218 – 0.53	0.6046 – 1	–	1 – 1.029
Gas power plants	0.17 – 0.7	0.3476 – 1	–	1 – 1.049
Nuclear power plants	0.2899 – 0.461	0.905 – 1	–	1 – 1.039
Geothermal plants	0.25 – 0.83	0.7838 – 1	–	–
CSPs	0.06 – 0.597	0.0448 – 1	0.8 – 1.2	–
Wind turbines	0.01 – 0.92	0.122 – 1	0.8 – 1.2	–
Solar PVs	0.0251 – 0.15	0.0448 – 1	0.8 – 1.2	–

$$W_F = \frac{WFF \times UCF \times LHV}{Ex_F^0 \times \eta_{ex} \times Lt} \tag{1}$$

where W_F is the consumed or withdrawn water for product exergy in the fuel cycle (L/MWh), WFF is the reported quantity of water for fuel, UCF is the conversion factor selected according to the units of the data source (further details in **Supplementary materials**), LHV is the lower heating value of the fuel (MJ/kg), Ex_F^0 is the standard exergy of the fuel (MJ/kg), η_{ex} is the exergy efficiency of the pertinent power plant, and Lt is the total lifetime to produce electrical exergy.

The water at the power cycle was estimated using Eq. (2).

$$W_P = \frac{WFP \times UCF}{Av \times CF \times \eta_{ex} \times Lt} \tag{2}$$

where W_P is the consumed or withdrawn water for product exergy in the operating or non-operating (upstream or downstream) stages (L/MWh), WFP is the reported quantity of water for the power production facility, Av is the availability of the power plant, which is the feasible time to produce energy over a certain period divided by the total time of the same, and CF is the capacity factor of the power plant, which is the amount of electricity produced over a period divided by that could have been produced if the plant ran at its full load over that period [41]. The model constants necessary to obtain W_F and W_P are summarized in Table 3. Appropriate parameters were selected to harmonize the data depending on the units, assumptions, and methods employed in the data sources. For instance, four different types of coal power plants exhibit different thermal efficiencies, which are covered in the given variation range of energy efficiency in Table 2. The details of the employed constants for each sub-technology and pertinent references are provided in the **Supplementary materials**.

Having obtained water at the fuel cycle and power facilities, the water for the product exergy was modeled considering the uncertain parameters, as expressed in Eq. (3).

$$W_{Ex} = FU \times W_F + RV \times W_P \tag{3}$$

Where W_{Ex} is the total consumed ($WCEx$) or withdrawn ($WWEx$) water for the product exergy, FU is the fuel uncertainty associated with the variation in the Ex_F^0/LHV ratio for different fuels [59], and RV is the

Table 4
Standard chemical exergy of chemical substances [166,167]

Substance/ Chemicals	Chemical formula	Molar mass (g/mol)	Standard chemical exergy (kJ/mol)	Chemical exergy (kJ/kg)
Calcium hydroxide	$Ca(OH)_2$	74.09	70.8	0.955594547
Carbon Dioxide	CO_2	44.01	19.48	0.442626676
Chlorine	Cl_2	70.906	123.6	1.743152907
Copper	Cu	63.546	134.2	2.111855978
Ethanal	$C2H4O_2$	44.05	907.2	20.59477866
Ferric Chloride	$FeCl_3$	162.2	228.1	1.406288533
Ferrous Sulfate	$FeSO_4$	151.908	170.9	1.12502304
High Density Polyethylene	$C2H_4$	6000000	1360.3	0.000226717
Lime	CaO	56.0774	127.36	2.271146665
Phosphoric Acid	$H3PO_4$	97.994	89.6	0.914341694
Polycarboxylic Acid	$C_6H_5NO_2$	123.11	3041.775	24.70778166
Polyphosphonate	NH_4PO_3	149.09	1339.895	8.987155409
Polypropylene Glycol	$C_3H_8O_2$	76.095	2171.94	28.54247979
Sodium hydrogen sulfite	$NaHSO_3$	104.061	1070.2	10.28435245
Sodium Hydroxide	NaOH	39.997	74.9	1.872640448
Sodium Hypochlorite	NaOCl	74.44	425.685	5.718498119
Sodium Sulphite	Na_2SO_3	126.043	287.5	2.280967606
Sulphuric Acid	H_2SO_4	98.079	163.4	1.666003936
borosilicate (g)c	SiO_2	179.93	2.2	0.012226977
Hydrochloric Acid	HCL	36.458	84.5	2.317735476
Polyamide	$C_{12}H_{20}N_2O_2$	111.14	7260.03	65.32328595
Polypropylene	C_3H_6	354.6	2002.7	5.647772138
Polyvinyl chloride	C_2H_3Cl	62.5	1256.975	20.1116
Polyvinyl fluoride	C_2H_3F	46.04	1169.875	25.40996959
Ammonia	NH_3	17.031	354.495	20.81469086
Chlorine dioxide	ClO_2	67.45	91.07	1.350185322
Methane	CH_4	16.04	831.2	51.82044888
Nitrate	NO_3	62.0449	6.315	0.101781129
Nitrous oxide	N_2O	44.013	2.705	0.061459114
Nitrile	$C_{14}H_{11}NO_2S$	41.053	7620.62	185.6288213
Chromium	Cr	51.996	584.7	11.24509578
Dinitrogen monoxide	N_2O	44.013	2.705	0.061459114
Nitrogen oxides	NO_2	46.0055	55.6	1.208551151
Nitrous oxide	N_2O	44.013	2.705	0.061459114
Potassium	K	39.102	366.6	9.375479515
PVC	C_2H_3Cl	62.5	1256.975	20.1116

resource variation that changes with the geographical location of weather-driven technologies. The variation ranges of the uncertain parameters of the stochastic model are presented in Table 3. Two types of uncertainties were assumed in the model: η_{ex} was assumed to have discrete values obtained from the literature, whereas $Av \times CF$, RV, and FU were assumed to vary following a uniform distribution within a given range. Further, RV and FU were considered for renewable technologies and fuels, respectively. All these parameters and their references are provided separately in the **Supplementary materials**.

Overall, 803 data objects were recorded to develop exergy dissipation for water production from several articles, reports, and reliable documents, as presented in the **Supplementary materials** [103–114,114–124,124–163]. Credible statistics were gathered by monitoring a multitude of water production sites worldwide, ensuring that they covered a wide geographical range of applications. The electrical and thermal exergies of each water technology were considered at the operating and non-operating stages; however, the chemical exergy calculations were only performed at the operation stage to simplify the computations. Consequently, the standard chemical exergy of the compounds for desalination and water treatment systems was estimated based on the standard free energies of formation, reaction, and concentration provided in the first, second, and third terms of Eq. (4), respectively [164,165].

$$CEx = \sum n_i \times (\Delta G_f + \sum n_e \times b^o_{ch,n_e}) + \frac{1}{n_i} \times (b^o_{ch,r} - \Delta G_r - \sum n_e \times b^o_{ch,ne}) + R \times T_o \times \sum_i n_i \times \ln(C_i/C_o) \quad (4)$$

where ΔG is the standard normal free energy of the compound, n_e and n_i are the number of moles of the element per unit of the compound and of molecules of the considered element in the molecule of the reference species, respectively, b^o_{ch,n_e} is the standard chemical exergy of the element (kJ/mol), summarized in Table 4, $b^o_{ch,r}$ is the standard chemical exergy of the reference element, ΔG_r is the standard normal free energy of reaction,R is the ideal gas constant, T_o is the absolute temperature, C_i is the concentration of the i^{th} chemical in the mixture, and C_o is the concentration of the reference chemical component in the mixture. It was assumed that the chemical exergies of all input streams (chemical compounds) at the operational stage of a technology would be completely dissipated.

The thermal exergy (TEx) of the streams is obtained using Eq. (5) [11]:

$$TEx = Q \times (1 - \frac{T_o}{T_{actual}}) \quad (5)$$

where Q is the heat input to the process (kWh/m^3), T_o is the temperature of the dead state (K), and T_{actual} is the process temperature (K). The variation range of the uncertain parameters of the stochastic model was determined according to the labels given to each data object, as shown in the **Supplementary materials**. The calculated quantities were assumed to vary between ±5% and ±25%, depending on the assigned label. The greatest variation occurred during the transportation stage, wherein the chemical exergy of the truck fuel varied with respect to the distance such that the excess sludge and other materials were carried.

The features of the new dataset comprised the calculated water consumption and withdrawal for exergy and electrical, thermal, and chemical exergy dissipation for water values. Each feature was assigned six labels and fed to a mathematical program to implement data-driven WExNa and subsequently visualize the results. The corresponding pseudocode is given in the **Appendix A.** The data labels included category, technology, cycle, and three labels of technology details and operation information. Thus, there were four categories of *WWEx*, *WCEx*, *EExW*, *CExW* and *TExW*, and 14 technologies, as described in the previous section. Operating, non-operating, and fuel cycles are cycle labels. Label 4 provides the details of the sub-cycles, such as upstream or downstream sub-cycles of a non-operating cycle (power technologies) or the classes of the exergy type (water technologies). Further, the details of the subcycles (or processes) and sub-technologies are provided in labels 5 and 6, respectively. Considering the labels of the dataset, a data tree was developed. Consequently, the uncertainties were implemented while tracing the power and water production pathways from the data leaves to the root. All possible combinations were considered when adding two sets with more than one member, and a Monte Carlo simulation was employed when dealing with continuous uncertain variables. For instance, the water for the cooling tower, open-loop cooling, and pond cooling alternatives were separately combined with water for coal data after considering a uniform distribution for FU to implement the model in Eq. for the *WCEx* category of coal power technology. Detailed results of the complex stochastic model are discussed in the subsequent section.

3. Results and discussion

Python and C^{++} were used to program and visualize the novel WExNa using labeled data features, and Excel spreadsheets were employed for life cycle analysis. Subsequently, the operation indices and life cycle WExNa variables were calculated considering the uncertainties

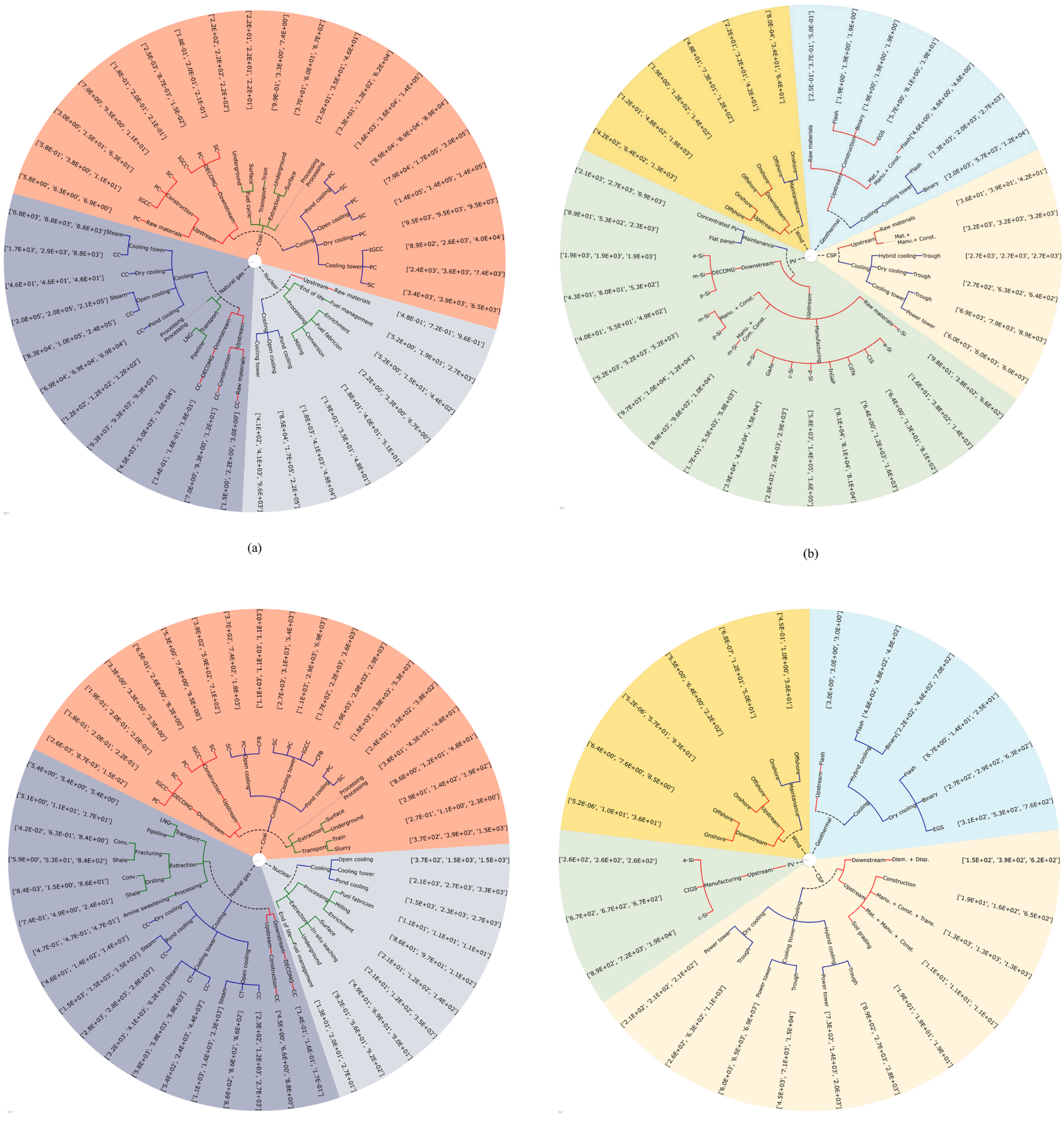
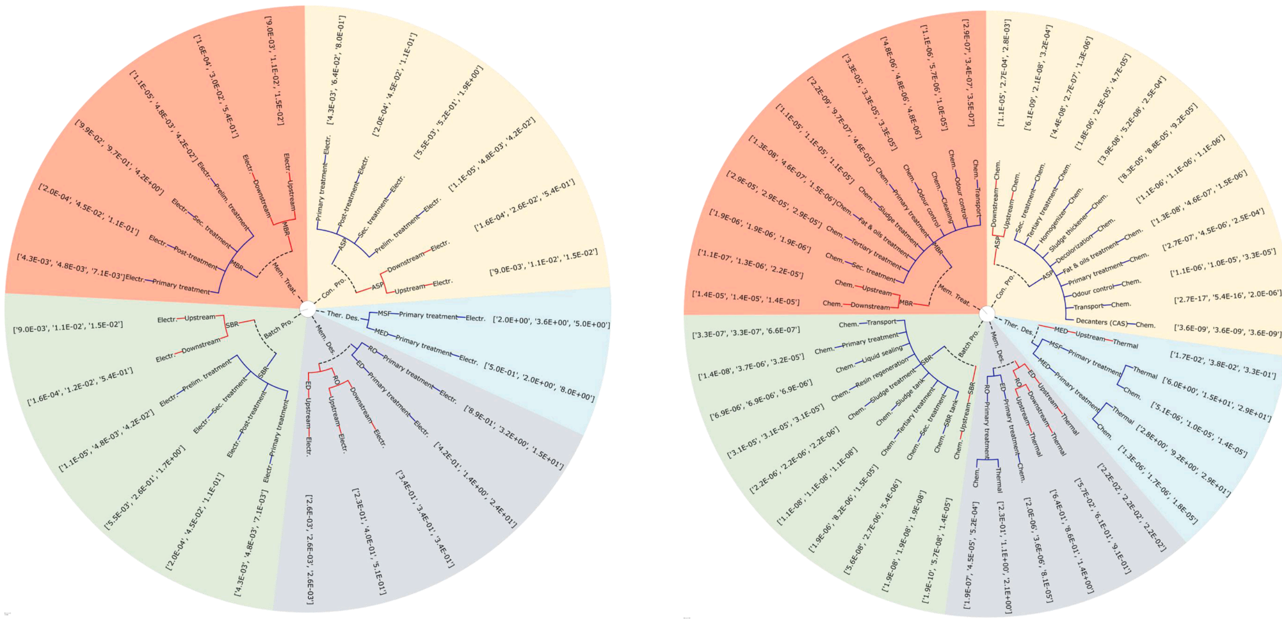


Fig. 5. Stats of power sector including *WWEx* of (a) non-renewable and (b) renewable technologies and *WCEx* for (c) non-renewable and (d) renewable technologies for each technology, and the results are discussed in this section.

3.1. Water-exergy nexus data and operation indexes

The *WWEx* and *WCEx* data trees are graphically illustrated in Fig. 5 . These technologies are separated by color to facilitate visual distinctions. For instance, solar PVs occupied the green area in the figures. Further, the operating, non-operating, and fuel cycles are indicated by blue, red, and green branches, respectively. In addition, labels 4 and 5 follow the cycles, and the minimum, median, and maximum records for each pathway were reported in brackets at the end of each branch. All numerical values of the data tress are individually discussed in the **Supplementary materials**. Moreover, considering the availability of data in the literature, the number of the calculated values varied between 1 and 24 for each leaf in the data tree.

The *WWEx* varied with a wide range from 0.79 L/GWh for maintenance of onshore wind turbines to 300.7 m^3/kWh for open loop cooling of PC plants. The highest median value of *WWEx* during the operating stages of the natural gas, coal, and nuclear plants equipped with open-loop cooling utilities of 179.4, 204, and 173.7 m^3/MWh, respectively. Hence, the *WWEx* was mainly governed by the types of cooling facilities rather than power production technologies. However, the decommissioning process of coal and gas plants resulted in negligible water withdrawal at the downstream stage of the power life cycle according to their median values. Thus, considering the fuel cycles, natural gas transport yielded the greatest *WWEx* both as liquid natural gas (9.3 m^3/



(a) (b)

Fig. 6. Exergy for water stats including (a) EExW and (b) CExW and TExW of water production technologies

MWh) and in pipelines (5 m^3/MWh). Whereas, nuclear fuel enrichment and management yielded the smallest *WWEx* (14.6 and 18.7 L/MWh, respectively). Among the renewable energy systems, the greatest and smallest quantities of *WWEx* correspond to the manufacturing processes at the upstream stages of solar PVs and geothermal plants, respectively. The manufacturing process of the p-si solar PVs withdrew 137 m^3/MWh, whereas the raw materials processing withdrew only 0.37 L/MWh of the produced exergy of the geothermal plants. This can be attributed to the low efficiency and availability of solar PVs compared to the high efficiency, availability, and capacity of geothermal plants. Thus, water withdrawal from renewable energy systems is mainly governed by the operation of the facilities rather than non-operating factors, such as the type of materials or manufacturing processes.

According to Fig. 5 **(b)**, the maximum and minimum values of *WCEx* were observed at the manufacturing stage of the c-si PVs (18.7 m^3/MWh) and maintenance of onshore wind turbines (0.0007 L/Wh), respectively. The low efficiency and availability of solar PVs (the small denominator in Eq.) resulted in high *WCEx* values of solar PVs, with the wind facilities consuming almost no water during the operation stage. In addition, trough and power towers, retrofitted by cooling towers, consumed 7.1 and 6.5 m^3/MWh water for product exergy exhibiting the dominance of evaporative losses during the operation of these renewable facilities. However, water consumption was negligible during the upstream stage of the renewable facilities. Considering the median amounts, the CT and steam power plants yielded the greatest *WCEx* values of 5.8 and 4.1 m^3/MWh when using cooling towers as their cold utilities among the non-renewable technologies. However, regardless of the technology type, *WCEx* was negligible while decommissioning gas and coal plants. Hence, most *WCEx* belonged to the operational stages of the technologies. Further, at the fuel cycle, the greatest and smallest *WCEx* values were observed in the slurry transport (395 L/MWh) and amine sweetening (0.47 L/MWh) processes of coal and gas cycles, respectively. Overall, the water consumption was mainly associated with the use of cooling towers during the operating stages of the life cycle.

The *EExW* of water production technologies is shown in Fig. 6 **(a)**. The five main technologies are shown in separate colors: membrane treatment (Mem. Treat., red) batch processes (Batch Pro., green), conventional treatment processes (Conv. Pro., yellow), thermal desalination (Ther. Des., blue), and membrane desalination (Mem. Des., gray). The membrane and thermal desalination families comprised RO and ED, and MSF and MED processes, respectively. The operating stage is indicated by blue branches that include the primary, secondary, preliminary, and post-treatment substages. Further, the red branches represent the non-operating stage, which was divided into the downstream and upstream substages. In addition, the details and exergy types are provided along the branches, and the minimum, median, and maximum records of each pathway are enclosed in brackets.

The recorded values of *EExW* varied widely from 0.000011 to 24.34 kWh/m^3. Owing to its significant sensitivity to water salinity changes, the ED recorded the greatest and smallest *EExW* among the desalination technologies. Further, the corresponding *EExW* rose from 0.42 kWh/m^3 for brackish water to 24.34 kWh/m^3 while treating 1.67 m^3/day high-salinity seawater. The degritting process during the preliminary treatment of batch and conventional wastewater treatment technologies yielded the smallest *EExW* (0.011 Wh/ m^3) because of the low electricity consumption in the mechanical degritting facilities of large-scale wastewater treatment plants. Most of the electrical exergy was destructed in aeration and pumping processes. Thus, the aeration and pumps of the secondary treatment substage of the MBR technology yielded the greatest *EExW* (4.23 kWh/m^3) among the wastewater treatment technologies. Overall, most of the *EExW* were assigned to the operating stage rather than the non-operating stages of the technologies. This was because of the considerable water production during the life cycle and better manufacturing and production pathways at the upstream stage of the water facilities. The highest median values of *EExW* belonged to the MSF (3.6 kWh/m^3) and RO (3.2 kWh/m^3) technologies. Both these technologies are dependent on electrical pumps to supply the required power. However, electricity is the only exergy source for running RO, whereas MSF required thermal sources as well. The *EExW* of desalination facilities is generally reported to be greater than that of wastewater treatment technologies during the operating stage. This may be attributed to the greater production capacities, shorter shut-down sessions, and lower effluent standards of the treatment facilities compared to desalination systems.

TExW and *CExW* were calculated using Eqs. and ; their values are summarized in Table 4. Detailed values of all the chemical substances and thermal streams can be found in the **Supplementary materials**.

Table 5
Exergy dissipation for product exergy and water loss for water production of the analyzed technologies

Power technology	*ExEx* Min.	Med.	Max.	Water technology	*WW* Min.	Med.	Max.
Solar PV	5.67	10.76	38.84	ASP	0.08	0.45	0.67
CSP	0.67	1.29	15.67	SBR	0.01	0.16	0.25
Coal	0.89	1.8	3.59	MBR	0.02	0.10	0.25
Natural gas	0.43	1.44	4.88	MSF	0.01	0.03	0.06
Wind	0.87	4.56	99	MED	0.06	0.14	0.60
Geothermal	0.2	1.31	3	RO	0.02	0.33	2.33
Nuclear	1.17	1.98	2.45	ED	0.32	0.43	1.00

The statistics and structure of the computed *TExW* and *CExW* data are shown graphically in Fig. 6 **(b).** As evident, *CExW* was negligible compared with *TExW* and *EExW* in municipal wastewater treatment and desalination processes. Hence, the non-operating *CExW* was neglected, except at the transportation substage, wherein significant chemical exergy was dissipated via diesel combustion. The minimum and maximum *CExW* was recorded during the transportation of excess sludge (2.7E-17 kWh/m^3) and decomposition (2.83 Wh/m^3) at operating and non-operating cycles of the ASP. Further, the quantity of *CExW* was dependent on the number and type of substances consumed in processes other than transportation. In this dataset, at least one and a maximum of 12 chemicals were counted while calculating *CExW*. The chemical exergy of the thermal desalination technologies can be neglected when compared with their thermal exergy values. In contrast to the low consumption of the chemicals, MSF yielded the greatest *TExW*, considering the median values. This can be attributed to the high heat consumption at high temperatures (approximately 120 ^{o}C) of MSF technology. Further, the minimum *TExW* (0.23 kWh/m^3) was recorded at 48 ^{o}C to preheat the RO inflow in a multigeneration system. However, there was a lack of any record of *TExW* in the wastewater treatment technologies data bank, although heat may be required at certain substages in real-world cases. Overall, the integrated processes consumed less heat, resulting in smaller *TExW* quantities.

ExEx and *WW* were computed as the operating indices of the power and water technologies, as defined in Section 2.2. Minimum (min), Maximum (max), and median (Med.) index amounts are summarized in Table 5. The smaller the *ExEx*, the more efficient the system produces power at the operating stage from the WExN perspective. Hence, geothermal plants exhibited the best performance considering the variation range of the *ExEx*. The binary, flash, and EGS sub-technologies yielded the smallest *ExEx* amounts. Neglecting the outliers, the solar PVs exhibited the worst exergy performance among all technologies in the operating stage. The a-si PVs yielded the highest *ExEx*, whereas the advanced m-si PVs exhibited the smallest *ExEx* among the PV types. Moreover, *ExEx* exhibited a very small standard deviation in nuclear power plants, indicating the stability of the exergy performance of this technology worldwide. According to WExNa, the smaller the *WW* quantity, the more effectively the system produces water at the operating stage. Hence, the MSF plants exhibited the best performance considering the variation range of the *WW*. Whereas, based on the calculated *WW* amounts, RO exhibited the worst performance among all technologies in the operating stage owing to a significant loss of volumes of water per produced potable water. In addition, the standard deviation of *WW* was very small in the MBR plants, indicating stability in the water losses of this technology. Thus, although membrane desalination technologies exhibit weak performance with respect to *WW*, they have been extensively employed in the industry. This can be attributed to the low value of saline feed water.

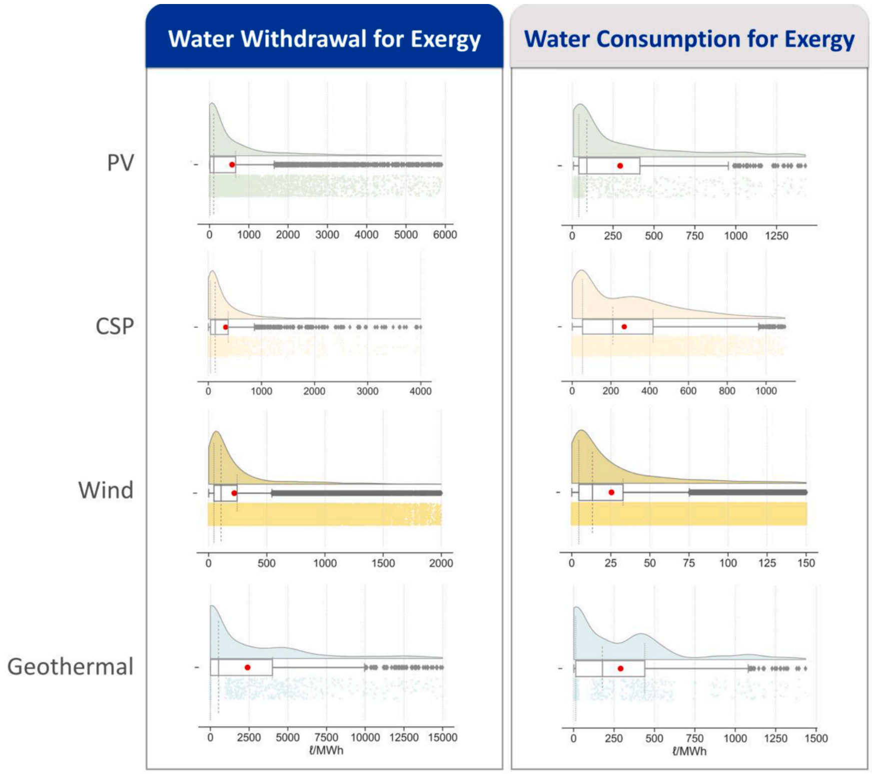
3.2. Stochastic life cycle model

Model uncertainties were considered while simulating the WExN-based behavior of the technologies. Non-realistic results could be obtained through a restricted number of observations if the uncertainties were ignored. Different exergy efficiency amounts covered several sub-technologies in a category, whereas different environmental, spatial, and temporal conditions were considered in a uniform distribution-based Monte Carlo simulation. The *WWEx* and *WCEx* variables were computed using the parameters presented in Tables 2 and 3. The results are shown in Fig. 7, wherein a kernel density estimation was employed to draw smooth graphs. A Parzen window technique was assigned to data samples to smoothen the graphs by estimating their probability densities. The *WCEx* and *WWEx* subplots are shown on the right and left sides of the figures, respectively. The mean values of the simulated data are shown with red circles in the box plots. The simulated data and the corresponding distribution probabilities are shown at the bottom and top of each box plot, respectively. Nuclear and geothermal plants are plagued by insufficient water for exergy data, while the remaining technologies enjoy rich data banks. Thus, 145 detailed plots of *WWEx* and *WCEx* are provided in the **supplementary file** for each sub-technology considering the labels at different levels for a better understanding.

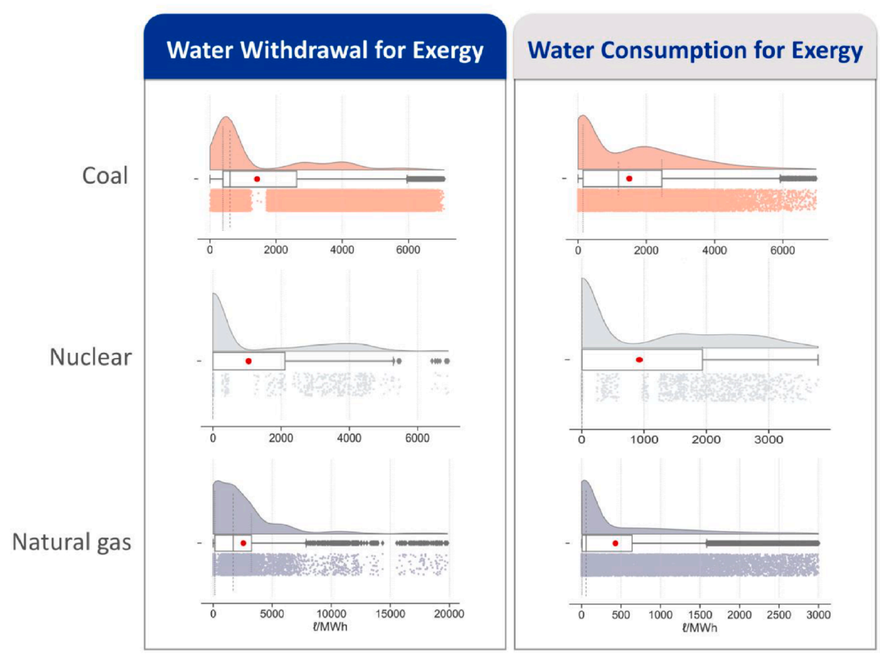
According to Fig. 7, natural gas and coal technologies by far withdrew significant water during their life cycle among the analyzed technologies. In addition to the significant water withdrawal for cooling, large amounts of water employed for shale gas extraction and underground coal mining culminated in poor results for these mature power production technologies. Owing to significant water withdrawal in cooling facilities, the nuclear and geothermal plants follow the two fossil fuel power plants with approximately 3 m^3/MWh of *WWEx* during the entire life cycle; considering the mean value of over 3 billion simulated cases. Despite enjoying similar environmental conditions in the simulation procedure, the CSP plants performed better than the solar PVs during their life cycle. This is primarily attributed to the lower exergy efficiency of the solar PVs than that of the CSPs. Despite the poor exergy behavior, the wind turbines withdrew minimal amounts of water for exergy, considering the entire life cycle. This demonstrates the governance of water for the operations and fuel cycles in the *WWEx* models. Thus, the production, operation, and decommissioning of wind turbines are recommended to be performed in dry regions in case of sufficient availability of resources.

Coal power plants exhibit the greatest *WCEx* among all power production technologies. Hence, coal technology is not recommended for power production when considering the variables of WExNa. Whereas, nuclear plants consume over 900 L/MWh for product electrical exergy during their life cycle. Further, in contrast to significant water withdrawal, gas power plants consume small amounts of water during shale and conventional natural gas production while employing non-tower cooling units. The simulated *WCEx* had similar distribution patterns, statistics, and quantities for CSP and geothermal plants. However, CSPs are not recommended for dry regions, particularly in trough configurations. Despite the small amount of recorded *WCEx* data for solar PVs, wind and solar PVs yielded acceptable *WCEx* values. Considering both *WWEx* and *WCEx* for the entirety of life cycle, wind, solar PV, and CSP systems can promise a sustainable future owing to exerting the least climate change impact compared with traditional fuel conversion technologies.

The *EExW*, *TExW*, and *CExW* methods are illustrated in Fig. 8. Although water cannot be processed without chemicals, *CExW* was much lesser than *EExW* and *TExW* in all the evaluated technologies. However, *CExW* was considerably greater in wastewater treatment than desalination technologies because it involved more complex chemical and biological processes, as well as greater contamination of the inflow. The *CExW* curves of the ASP exhibited two peaks at 0.38 and 32 Wh/m^3, wherein the second peak included the chemicals lost as transport fuel for the disposal of excess sludge. Thermal desalination technologies yielded the smallest mean *CExW* ($<$ 0.02 Wh/m^3) among all technologies, thereby indicating their negligible sensitivity to the chemicals during operation. However, MSF and MED dissipated the greatest amounts of



(a)

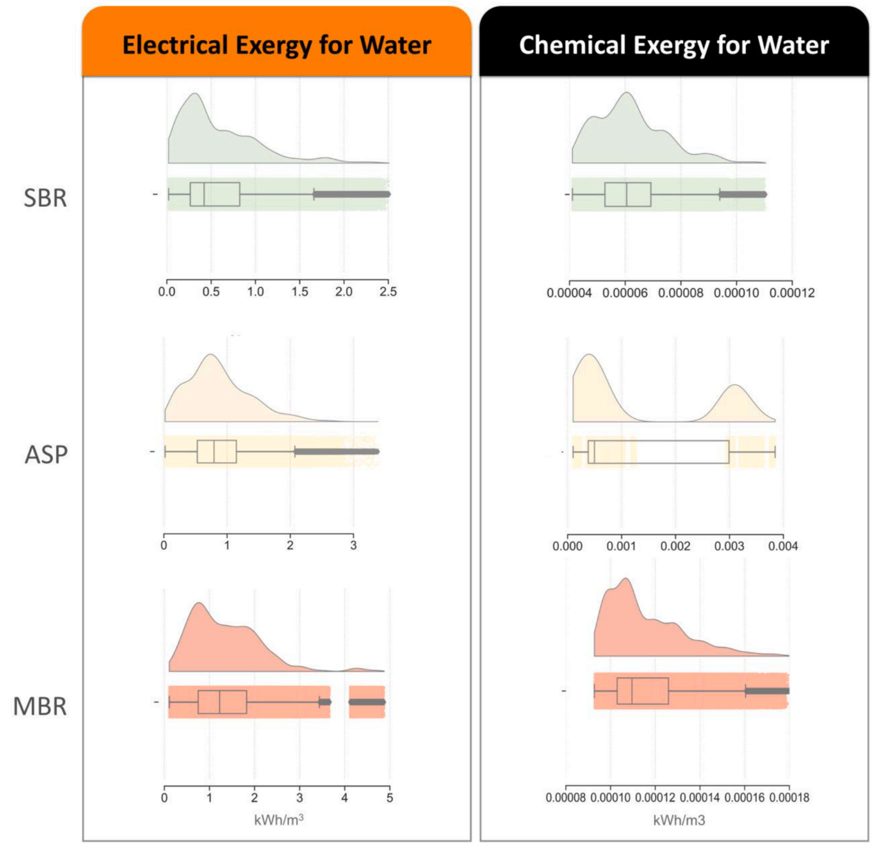


(b)

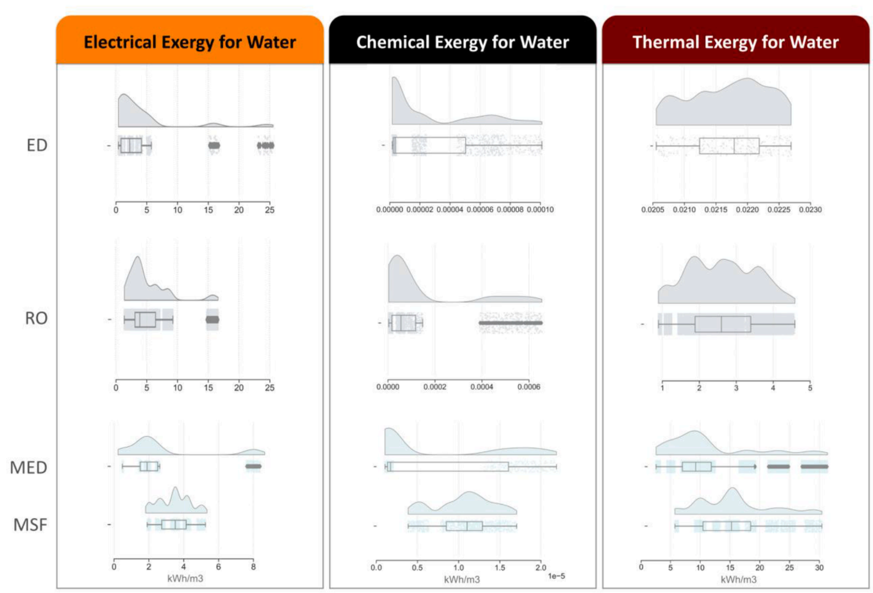
Fig. 7. Water for exergy considering the life cycle uncertainties of (a) renewable and (b) non-renewable power technologies

exergy for water production for destructing over 15.46 and 9.17 kWh/m^3 heat during their life cycle. Here, MSF yielded a greater *TExW* than MED because of its higher evaporation temperature. *TExW* of RO and ED desalination technologies represents the heat required during the manufacturing, inflow preheating, and decomposition stages. Despite the significant *TExW* at the non-operating stages of membrane desalination technologies, their operating *TExW* was much smaller than that of thermal technologies. Considering mean values of the simulated sequences, *TExW* of MED was 8.17 and 0.04 of that of the RO technology. Hence, thermal technologies are not recommended for desalination because of their significant exergy dissipation.

Therefore, similar to *TExW*, desalination technologies yielded



(a)



(b)

Fig. 8. Electrical, thermal, and chemical Exergy for water considering the life cycle uncertainties of (a) wastewater treatment and (b) desalination technologies

greater *EExW* than wastewater treatment technologies. This is mainly attributed to significant volumetric yield and lower effluent standards of the treatment facilities. Taking the whole life cycle into account, SBR has the smallest *EExW* among all technologies (0.55 kWh/m^3) considering the most probable cases. According to the simulation results, most of the electrical exergy is dissipated at the secondary treatment process of the wastewater treatment plants. This is due to electricity consumed by the pumping units at this stage of treatment. In contrast to the wastewater treatment technologies, brackish and seawater desalination technologies dissipate significant amounts of electricity at both operating and non-operating stages because of small water production. According to the stochastic model, RO consumes approximately 4.94 kWh/m^3

Table 6
A comparison between WEN- and WExN-based performance of power technologies

	WCEx [L/MWh]				*WCE* [L/MWh]		
	Mean	25%	50%	75%	Baseline	Low	High
Coal	1.50E+03	1.45E+02	1.19E+03	2.46E+03	2.08E+03	1.68E+03	3.02E+03
Nuclear	9.23E+02	0.00E+00	5.31E+00	1.93E+03	2.95E+03	2.71E+03	3.22E+03
Natural gas	6.38E+02	8.33E+00	6.04E+01	4.31E+02	8.03E+02	6.81E+02	9.92E+02
PV	2.95E+02	3.94E+01	9.17E+01	4.17E+02	3.22E+02	2.57E+02	6.13E+02
CSP	2.70E+02	5.22E+01	2.10E+02	4.16E+02	3.97E+03	3.18E+03	5.17E+03
Wind	2.55E+01	4.57E+00	1.34E+01	3.31E+01	3.79E+01	7.57E+00	4.54E+01
Geothermal	2.89E+02	1.28E+01	1.79E+02	4.40E+02	1.10E+03	1.06E+03	1.14E+03
	***WWEx* [L/MWh]**				***WWE* [L/MWh]**		
	Mean	**25%**	**50%**	**75%**	**Baseline**	**Low**	**High**
Coal	1.43E+03	3.95E+02	6.10E+02	2.63E+03	1.99E+03	9.46E+01	1.32E+05
Nuclear	1.05E+03	0.00E+00	0.00E+00	2.12E+03	4.35E+03	2.08E+02	1.78E+05
Natural gas	2.56E+03	1.40E+02	1.69E+03	3.24E+03	1.63E+03	4.54E+01	3.41E+04
PV	5.78E+02	1.86E+01	1.12E+02	6.68E+02	3.71E+02	4.54E+01	4.73E+02
CSP	3.28E+02	4.13E+01	1.28E+02	3.72E+02	3.41E+03	6.81E+02	4.24E+03
Wind	2.23E+02	4.73E+01	6.20E+01	2.46E+02	9.46E+01	9.08E+01	9.84E+01
Geothermal	2.42E+03	0.00E+00	5.32E+02	4.03E+03	1.09E+03	6.06E+01	1.94E+03

Table 7
A comparison between water technologies considering WEN and WExN criteria

	Mean	25%	50%	75%	Baseline	Low	High	Refs.
	***EExW* [kWh/m^3]**				***EEW* [kWh/m^3]**			
SBR	5.74E-01	2.63E-01	4.19E-01	8.18E-01	5.75E-01	4.50E-01	7.00E-01	[151]
ASP	8.67E-01	5.29E-01	7.94E-01	1.15E+00	8.50E-01	8.00E-01	1.65E+00	[139]
MBR	1.35E+00	7.50E-01	1.22E+00	1.82E+00	1.26E+00	8.33E-01	1.69E+00	[149]
ED	4.09E+00	7.98E-01	2.19E+00	3.97E+00	1.40E+00	4.20E+00	2.43E+01	[135]
RO	4.85E+00	3.10E+00	3.89E+00	6.45E+00	3.00E+00	8.90E-01	1.50E+01	[24,116,117]
MED	2.72E+00	1.50E+00	1.90E+00	2.50E+00	2.00E+00	5.00E-01	8.00E+00	[114]
MSF	3.47E+00	2.74E+00	3.51E+00	4.14E+00	3.60E+00	2.00E+00	5.00E+00	[121]
	***CExW* [kWh/m^3]**				**NA**			
SBR	6.20E-05	5.30E-05	6.10E-05	6.90E-05	-	-	-	
ASP	1.31E-03	3.82E-04	4.96E-04	2.99E-03	-	-	-	
MBR	1.15E-04	1.03E-04	1.10E-04	1.26E-04	-	-	-	
ED	2.40E-05	2.00E-06	3.00E-06	5.00E-05	-	-	-	
RO	1.42E-04	1.60E-05	5.50E-05	1.18E-04	-	-	-	
MED	7.00E-06	1.00E-06	2.00E-06	1.60E-05	-	-	-	
MSF	1.10E-05	8.00E-06	1.10E-05	1.30E-05	-	-	-	
	***TExW* [kWh/m^3]**				***TEW* [kWh/m^3]**			
ED	2.17E-02	2.12E-02	2.18E-02	2.22E-02	2.16E-02	1.95E-02	2.38E-02	[168]
RO	2.62E+00	1.88E+00	2.60E+00	3.39E+00	9.07E-01	2.33E-01	2.15E+00	[24,133,136]
MED	1.13E+01	7.00E+00	9.23E+00	1.18E+01	9.17E+00	2.75E+00	2.90E+01	[113,116,117]
MSF	1.57E+01	1.05E+01	1.53E+01	1.85E+01	1.54E+01	6.04E+00	2.90E+01	[116,117]

electricity with an acceptable confidence at its life cycle. Considering the mean values of *EExW*, the MSF dissipates 3.74 kWh/m^3 during the operating stage. This significant electricity is consumed to supply the required water head to operate this mature technology. Considering all three types of exergy, SBR and MBR dissipate the smallest and greatest quantities of exergy. This shows the governance of *EExW* to *TExW* and *CExW* in wastewater treatment. For desalination applications, MSF is not recommended due to its significant exergy dissipation, whereas ED can be extensively applied to save exergy.

3.3. Comparative results and future research

The results of the stochastic WExN models were compared to the those obtained by the WEN concept in the literature. The water consumption for energy (*WCE*) and water withdrawal for energy (*WWE*) quantities, calculated by Meldrum et al. [15], were used to evaluate the seven power production technologies concerning the similarity between the two methods. The baseline, low, high values of the WEN simulation are summarized versus the mean, first, second, and third quartiles of the WExN variables in Table 6. Considering the similarity between the exergy and energy values of power, the two models should report similar amounts of water use for the technologies. However, the variation of the simulation procedure, accuracy of the models, and comprehensiveness of the data banks result in slightly different values of *WCE* and *WCEx*. The mean *WCEx* and *WWEx* of non-renewable power production technologies are slightly smaller than the WCE and WWE at the baseline. This shows that the technologies, so their performance criteria, have improved in the recent decade. The differences between *WCEx* (and *WWEx*) and *WCE* (and *WWE*) are greater in renewable energy systems. This is mainly attributed to the consideration of both availability and capacity factor of the renewable technologies (Table 3) that yields realistic results in this study.

The water technologies were evaluated using WEN and WExN criteria, and the numerical results of the data-driven models are summarized in Table 7. Electrical energy for water (*EEW*) is conceptually similar to the proposed *EExW*. However, minor differences are observed in various references due to the model uncertainties. Unlike the previous WExN criteria, *CExW* does not have an energy equivalent, so this unique variable is one of the superiorities of the proposed WExN platform compared to the traditional WEN-based studies. *TExW* is meaningfully greater than the thermal energy for water (*TEW*). This difference highlights the quality of energy dissipated for water production in addition to the quantity of that during full life cycle of the technologies. As an instance, *TEW* of the MSF is significantly greater than that of the MED, whereas these desalination technologies have similar *TExW* in their life cycle. Considering greater *EExW*, *CExW*, and *TExW* of MSF in

```
INPUT: C, where C is selected Category from S={WWEx, WCEx, EExW, TCExW}
OUTPUT: Data Tree, Continuous probability density curves of observations in Data Tree
A := READ CSV file (terms Category, Type, Cycle, Label_4, Label_5, Label_6, Value)
T := CALL Tree( )
FOR every line in A  DO
        Remove line from A IF Category != C
FOR every sorted unique i in Type DO
        D(i) := CALL add_child(T, i)
        SET face label D to i
        SET background color to BG_color(i)
        FOR every sorted unique j in slice(i, Cycle) DO
                E(j) := CALL add_child(D(i), j)
                CASE line color OF
                        'Operating':  SET line color 'blue'
                        'Non-operating':  SET line color 'red'
                        'Fuel cycle':  SET line color 'green'
                FOR every sorted unique k in slice(i, j, Label_4) DO
                        F(k) := CALL add_child(E(j), k)
                        SET face label F to k
                        FOR every sorted unique l in slice(i, j, k, Label_5) DO
                                G(l) := CALL add_child(F(k), l)
                                SET face label G to l
                                FOR every sorted unique m in slice(i, j, k, l, Label_6) DO
                                        H(m) := CALL add_child(G(l), m)
                                        ET edge label H to [min, med, max] of values in slice(i, j, k, l, m)
                                EXCEPTION
                                        WHEN l AND m is empty
                                                SET edge label F to [min, med, max] of values in slice(i, j, k)
                                        WHEN l  is empty
                                                G(m) := CALL add_child(F(k), m)
                                                SET edge label G to [min, med, max] of values in slice(i, j, k, m)
                                        WHEN m is empty
                                                SET edge label G to [min, med, max] of values in slice(i, j, k, l)
STORE T in CSV file;
// Use the exact index from CSV file to develp Data bank manualy
FOR every leaf  DO
        Using CSV file GET M1, D1L, D1U, M2L,  M2U, and D2
        FOR every individual value (v) in leaf  DO
                N :=1
                WHILE counter1 < maximum number of iteration DO
                        D1:= GET Random value sampled following the uniform distrubiotion between D1L and D1U
                        B := M1 / D1
                        WHILE counter2 < maximum number of iteration  DO
                                M2:= GET Random value sampled following the uniform distrubiotion between M2L and M2U
                                B := B * M2
                                FOR every i in D2  DO
                                        B := B / i
                                        S(leaf,N) := v * B
                                        N += 1
                                INCREMENT counter2
                        INCREMENT counter1
FOR every Thechnology in T DO
        FOR every branch in Thechnology DO
                X(branch) := GET union sum of all combination taken S(leaf,1..N) for all leaf in branch
        W := GET union sum of all combination taken X(branch) for all branch
        CALL KDE(W)
        PRINT  distribution of observations in W
```

Fig. A1. The pseudocode of the developed mathematical program

comparison with the MED system, the former technology is not recommended from a WExN perspective. However, easier production and operation of the MSF can justify its more extensive application. It should be noted that further observations can lead to more accurate conclusions in these models.

WExN concept could be formulated in dynamic models to appraise time-dependent variations of the physical phenomena. It could be used for in-depth calculations of complicated processes. Here, it was simplified to provide new insight to the life cycle performance of engineering systems. Hence, a comprehensive data bank was developed as a decision-making tool to facilitate the analysis of power and water technologies. An optimal WExN-based mixture of various water and power production technologies can ensure sustainability in both the manufacturing and distribution stages. However, this initial attempt can be further pursued via the extension of the study to include more challenging pathways (bioenergies) or emerging technologies (pressure-retarded osmosis or various fuel cells). The present model was developed to facilitate the addition of any piece of new data to the available data bank to obtain more accurate results and draw more realistic conclusions. It is evident that more data pieces can result in a better calibration of the model at higher levels. Further, comprehensive WExNa can provide many details if a specific technology or process chain is studied with fewer analytical assumptions and methodological restrictions. Furthermore, dynamic exergy models can be used to control water-intensive processes. The present data bank can be retrofitted with economic indices to be used in optimal process selection and supply chain design models. Thus, it is anticipated that studying the nexus between exergy and water will open new gateways for sustainability in the future.

4. Conclusions

This study elucidated the WExN concept, proposed four new evaluation criteria, and then analyzed 14 power and water technologies considering modeling and operation uncertainties. For this, the life cycle dataset of WExNa was labeled to include all probable sub-technologies and production pathways. The following conclusions were drawn from this study:

The water for exergy data is governed by several operating factors during the life cycle of the power technologies such as the types of cooling facilities, exergy efficiency, availability, and capacity factor. Considering the *ExEx* index, geothermal plants had an acceptable function, whereas weather-driven solar and wind power exhibited erratic and inefficient performance.

According to WExNa, coal power production is not recommended when considering both *WWEx* and *WCEx* variables. In contrast to nonrenewable energy systems, CSP plants can be employed in dry regions if they are not equipped with wet cooling towers. Whereas, despite the low efficiency of weather-driven systems, wind turbines, solar PVs, and geothermal plants are recommended from the perspective of WExNa.

Good operation of water technologies does not ensure acceptable performance in the full life cycle. The MSF and ED technologies exhibited the best and worst performance in the operating stage by losing the smallest and greatest *WW* values, respectively. However, the ED and MSF dissipated the least and most exergy, respectively, for water production during their entire life cycle.

The results of this study showed that the operation coefficients are not sufficiently reliable for comparisons of the power and water technologies considering the cradle-to-grave life cycle. However, more up-to-date data and analyses of other technologies can result in more promising conclusions.

CRediT authorship contribution statement

Pouya Ifaei: Conceptualization, Methodology, Formal analysis, Writing – original draft, Data curation. **Amir Saman Tayerani Charmchi:** Methodology, Formal analysis, Visualization, Software, Data curation. **Mattheos Santamouris:** . **ChangKyoo Yoo:** Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This work was supported by Brain Pool Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (2019H1D3A1A02071051) and the National Research Foundation (NRF) grant funded by the Korean government (MSIT) (No. NRF- 2021R1A2C2007838), and Korea Ministry of Environment (MOE) as Graduate School specialized in Climate Change.

Appendix A

A new algorithm was developed and used to calculate and visualize the statistics of all observations. The corresponding pseudocode is drawn in Fig. A1.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2023.116960.

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