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A new evaluation framework for the assessment of wastewater heat recovery potential coupled with wastewater reuse

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ABSTRACT

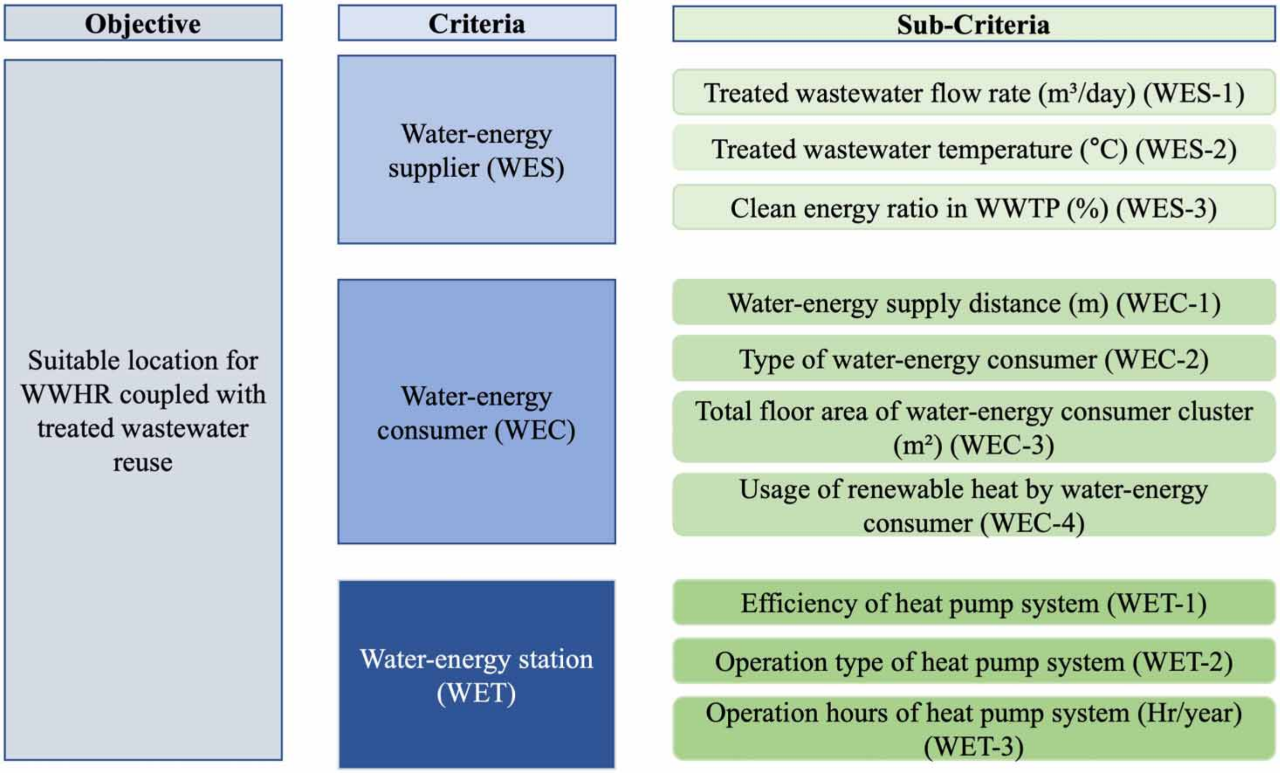
The integration of wastewater heat recovery (WWHR) and wastewater reuse offers a numerous advantage, making its application possible in various sectors. Nevertheless, this concept faced challenges to the identification of appropriate location. Existing research lacks comprehensive evaluation methods that encompass a various factor for effective decision-making. This study introduces a new evaluation framework that involves different aspects, including thermal energy potential and spatial distribution analysis. The novelty of this research lies in its unique focus on the combination of WWHR and wastewater reuse. Moreover, it introduces a structured evaluation framework that considers multiple criteria and expert opinions, enhancing decision-making precision. Multi-criteria decision analysis (MCDA) was applied to select assessment criteria, which were categorized into three aspects: water–energy supplier, water–energy consumers, and water–energy station. The relative importance of criteria was determined using the analytical hierarchical process (AHP). The results of the AHP highlight significance of factors: treated wastewater flow rate; treated wastewater temperature; water–energy supply distance, and type of water–energy consumer. These factors were assigned weight values of 0.297, 0.186, 0.123, and 0.096, respectively. It is emphasizing their influence in the decision-making process that potential locations depend on the water–energy supplier and water–energy consumer as supply and demand sources.

Key words: analytical hierarchy process, evaluation framework, multi-criteria decision analysis, wastewater heat recovery, wastewater reuse

HIGHLIGHTS

- The integration of heat recovery with treated wastewater reuse creates a powerful nexus between essential resources.
- An evaluation framework is a tool, empowering thoughtful water–energy planning and management.
- Water–energy supplier, consumer, and station stand as the key factor, shaping the future of water–energy integration.
- The analysis framework offers a comprehensive evaluation of optimal site selection.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Climate changes remain one of the most significant challenges faced by the global community. Sustainable energy plays a crucial role in combating climate changes and mitigates its impacts. Heat recovery from wastewater is a promising approach for sustainable and environmentally friendly energy utilization, offering advantages in terms of lower carbon emission compared to fossil fuel combustion. The thermal energy content of wastewater can be effectively recovered through a well-designed system that incorporates a heat exchanger and a heat pump installation. This system enables the extraction of thermal energy from wastewater, making it a valuable renewable heat source. In general, there are three different locations that are possible for heat recovery from wastewater: buildings, sewer systems, and the effluent of wastewater treatment plants (WWTPs) (Kretschmer *et al.* 2016a, 2016b; Huber *et al.* 2020). Recent studies have reported that heat recovery from WWTP effluent is advantageous in terms of stable flow rate and low variation temperature with a temperature drop of up to 8 °C (Spriet *et al.* 2020; Arnell *et al.* 2021; Nagpal *et al.* 2021), minimizing the fouling effect in the heat exchanger (Somogyi *et al.* 2018; Hao *et al.* 2019), while positively impacting the biological processes of the receiving water bodies (Neugebauer *et al.* 2015; Simperler 2015). Since the implementation of the heat recovery process within effluent WWTP, the decreased temperature due to thermal energy extraction does not have a negative impact on the biological nitrification process in WWTP (Wanner *et al.* 2005; Hao *et al.* 2019; Arnell *et al.* 2021). Thus, the high potential of heat recovery from WWTP effluent is evident when compared to heat recovery from other location. Additionally, the treated effluent resulting from the heat recovery process holds promise as a clean water resource suitable for wastewater reuse purposes.

The combination of heat recovery from WWTP effluent and its subsequent reuse has positively impact on sustainability and resource management. The recovery of thermal energy enhances the overall value of this renewable heat source, enabling its utilization in various applications like space heating, water heating, or industrial process. Concurrently, the utilization of treated WWTP effluent for non-potable purposes, including irrigation, industrial processes, and toilet flushing, significant water conservation is achieved, reducing the demand for freshwater resources (Lyu *et al.* 2016; Kehrein *et al.* 2020; Takeuchi & Tanaka 2020; Ofori *et al.* 2021). The concept of water–energy nexus (WEN) offers a scientifically approach to effectively integrate heat recovery and its subsequent reuse. This concept emphasizes the intricate interdependencies and interrelates between water and energy resources, highlighting the potential for integrated strategies to optimize resource utilization and enhance overall system efficiency (Hamiche *et al.* 2016; Magagna *et al.* 2019; Fayiah *et al.* 2020). Adopting the water–energy nexus perspective provide several key advantages including resource synergy and optimization, energy conservation and efficiency, as well as enhanced system efficiency (Baur *et al.* 2014; Lee *et al.* 2017; Dai *et al.* 2018).

The integration of heat recovery and treated wastewater reuse presents numerous advantages; however, the concept faced challenges in determining appropriate location for implementation. Key factors contributing to these challenges include geographical consideration and the variability in heat demand (Lichtenwoehrer *et al.* 2019). Additionally, the remote location of WWTPs often results in disadvantageous energy supply distances, leading to increased heat losses during distribution. Consequently, selecting an appropriate location is essential to ensure economic feasibility and process effectiveness. To address the challenges in determining appropriate locations, a comprehensive approach is essential, involving detailed feasibility studies, and site-specific evaluations. The approach for pre-assessment suitability locations was developed by applying relevance tree methods, which consider both energetic and wastewater perspective (Huber *et al.* 2020). The relevance tree in this method constitutes a scientifically rigorous tool for decision-making process with consider various criteria. However, the specific focus in this methodology lies in assessing the suitability location for sewer heat recovery, with a particular emphasis on predicting the effect of sewer heat recovery on the inflow temperature of WWTP. The study by Neugebauer *et al.* (2015) and Spriet *et al.* (2020) evaluated the performance of heat recovery location utilizing WWTP effluent, but the approach primary focus on spatial and temporal aspect, as well as energetic analysis.

Although these approaches have their strength, but existing literature lack a comprehensive evaluation framework that incorporates various criteria related to the combination of heat recovery and treated wastewater reuse for quick and efficient decision-making in selecting appropriate locations. To address this gap, this study develops a new evaluation framework to assess appropriate locations of WWHR coupled with treated wastewater reuse considering rigorous assessments of thermal energy potential, spatial distribution analysis, and infrastructure compatibility (potential consumer). A pre-assessment process was conducted to identify potential water–energy suppliers (WWTPs) and consumers, utilizing a geographical information system (GIS) to facilitate spatial analysis. The selection of assessment criteria and attributes was achieved through screening process, incorporating key criteria from the literature review and novel criteria generated from experts' group brainstorming. To evaluate the performance of criteria, the AHP was performed based on expert opinion. Through the application of the scientific evaluation framework, decision-makers gained valuable insights to determine the most suitable locations. The systematic integration of geospatial data, expert opinions, and assessment criteria ensured a thorough and objective analysis. To the best of authors' knowledge, this study presents the first conceptual evaluation framework specifically designed for identifying the suitable location of thermal energy recovery from WWTP effluent combined with wastewater reuse. The utilization of scientifically approach ensures the objectivity and reliability of the selection process suitable locations.

2. METHODOLOGY

The methodological approach to assess appropriate locations of WWHR coupled with treated wastewater reuse involves a systematic three main steps process, comprising pre-assessment, develops evaluation framework by applying MCDA methods, and site prioritization.

In the pre-assessment phase, relevant criteria are identified and selected to screening potential water–energy suppliers (WWTPs) and consumers. The selection of key criteria is critical to ensure a comprehensive evaluation of potential locations (Rahman *et al.* 2012; Sun *et al.* 2021). The next step involves the development of an evaluation framework using MCDA methods. MCDA is an analytical approach that supports complex decision-making by comparing criteria and alternatives using a scientific theory as a standard analysis (Plakas *et al.* 2016; Khosravi *et al.* 2019). In the context of this study, assessment criteria related to the integration thermal energy recovery and treated wastewater reuse were identified. The selection of attributes was carried out based on both spatial context and the operation characteristics of WWTPs in South Korea. These attributes were chosen to ensure a representation of assessment criteria. To ascertain the relative importance of all criteria, the AHP was applied. The AHP process involved expert opinion to determine the weightings of the criteria based on their impact (Kharat *et al.* 2016; Akhtar *et al.* 2021). Subsequently, the developed evaluation framework is applied in a case study to assess the selected potential WWTPs encompassing a consumer cluster. The assessment results are the utilized to identify priority sites. These priority sites represent locations with favorable conditions and potential for implementing the integration heat recovery and treated wastewater reuse. Figure 1 provides a representation of the detailed procedure of the methods in this study.

2.1. Study area

The target area in this study was selected based on the capacity of wastewater treatment facilities in South Korea, with a specific capacity of more than 500 m^3/day. Utilizing data from public authorities, in total 650 WWTPs were identified to have a capacity of more than 500 m^3/day across the country. Figure 2 illustrates the spatial distribution of wastewater treatment facilities, highlighting the sites that were considered as potential sources for the combination of heat recovery and treated wastewater reuse.

2.2. Pre-assessment of wastewater treatment facilities and consumer clusters

2.2.1. Selection of pre-assessment criteria

The objectives of the pre-assessment phase encompass the systematic screening of wastewater treatment facilities and consumers. This phase is designed to establish a comprehensive foundation for the subsequent stages of the evaluation process. To facilitate this, a set of pre-assessment criteria was defined. These criteria serve as guiding principles in the selection of WWTPs and consumer clusters, which fulfill the roles of water–energy suppliers and consumers, respectively. Table 1 lists the three pre-assessment criteria used in this process:

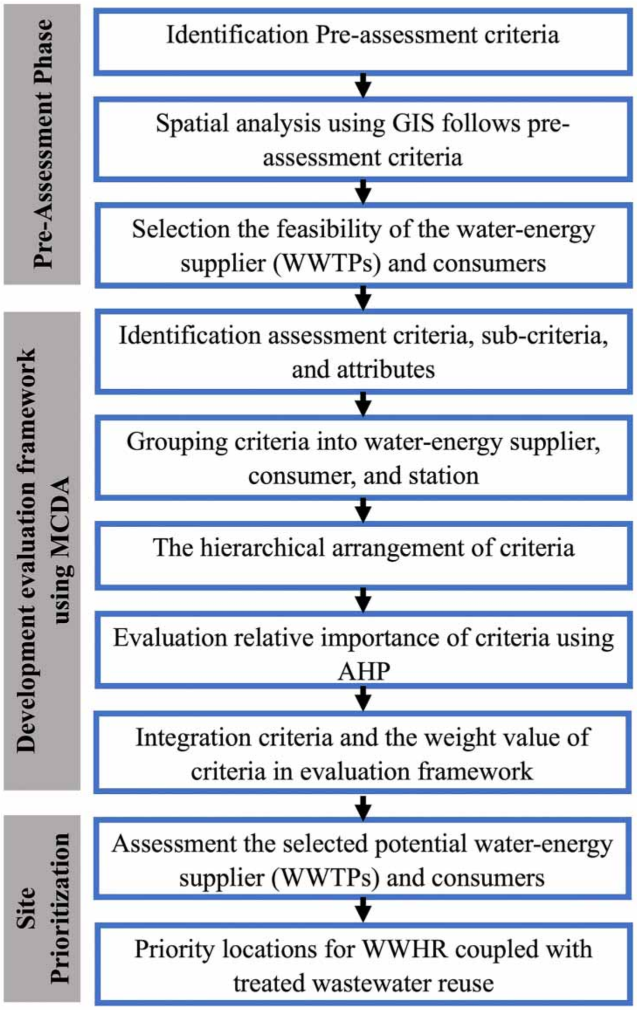


Figure 1 | Detailed procedure of the methods to assess appropriate location of WWHR coupled with treated wastewater reuse.

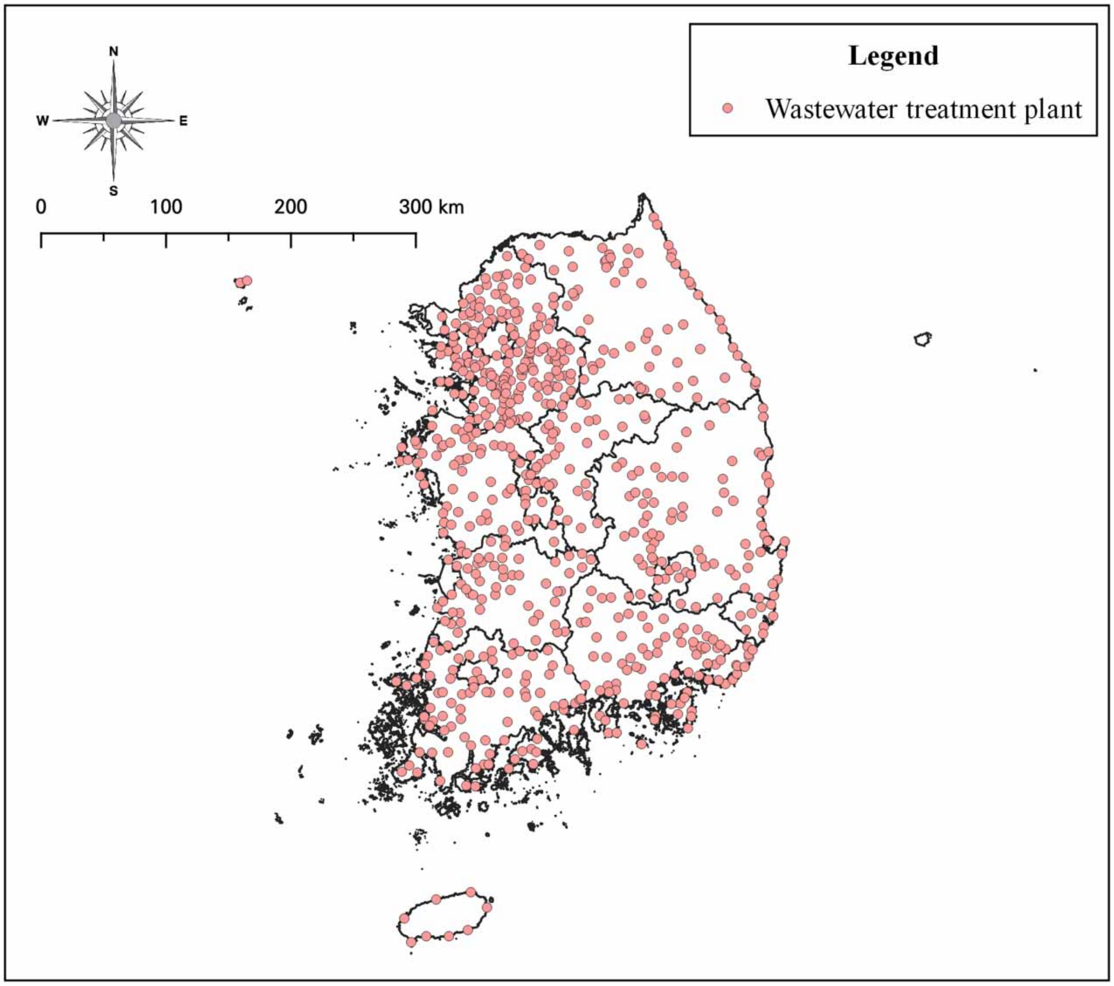


Figure 2 | Wastewater treatment facilities with a capacity of more than 500 m^3/day.

Table 1 | Pre-assessment criteria to select the candidate WWTPs and cluster consumers

No.	Criteria	Description
1	Capacity of the water–energy supplier (WWTP) (m^3/day)	The potential water–energy supplier (WWTP) has a minimum capacity of treating 10,000 m^3/day.
2	Distance between supplier to consumer (m)	The distance between the water–energy supplier and the consumer is less than 500 m.
3	Total floor area of the building cluster in water–energy consumer (m^2)	The potential water–energy consumer has a total floor area of the building cluster of more than 60,000 m^2.

The selection of the pre-assessment criteria involves a systematic consideration of key factors including the capacity of WWTP. This criterion serves as a defining parameter, quantifying both the water and heat energy potential (Kretschmer *et al.* 2016a, 2016b). According to the wastewater reuse policies in the enforcement decree of the act on promoting and supporting of water reuse (MOE 2022), Article 12 states that for a treatment facility that has a capacity of treating 5,000 m^3 of wastewater per day, at least 10% of the volume of treated wastewater should be reused a day. The capacity of WWTP assumes paramount significance within the context of our study, as it serves as an essential parameter delineating the thermal energy potential inherent in treated wastewater and, in parallel, the potential for wastewater reuse. This particular parameter exhibits an interdependence with the broader water–energy supply potential. In accordance with these pivotal parameters and regulatory standards, a minimum WWTP capacity is set at 10,000 m^3/day. This selection is predicated on the principle that such a WWTP can effectively operate as a potential water–energy supplier, which can fulfill the demands of a total floor area spanning approximately 60,000 m^2. Furthermore, the distance between WWTP and potential consumer emerges as a critical criterion, which reflects the economic feasibility of energy transmission. In consideration of the energy supply distance, the wastewater heat recovery manual for Japan have indicated an optimal spatial interval of approximately 500 m between a potential supplier and consumer (MLIT 2015). In addition, the total floor area of the buildings assumes significance as an indicator of potential consumers. This factor denotes the spatial capacity to accommodate the distribution and utilization of renewable thermal energy and treated wastewater reuse. Aligned with the enforcement decree of the act on promoting the new and renewable energy, specifically Article 15 (MOTIE 2021), and correspondingly in alignment with the enforcement decree of the act on promoting water reuse, particularly Article 11 (MOE 2022), we defined the minimum total floor area in the building cluster for the potential water–energy consumer of 60,000 m^2.

2.2.2. Evaluation of potential water–energy supplier and consumer

2.2.2.1. Spatial analysis using GIS. The fundamental goal underlying the spatial analysis through the utilization of geospatial information, pertains to the identification of potential consumers clusters that conform to the predefined criteria, specifically criterion 3 related to the demand area. The spatial analysis entails a comprehensive examination of potential consumers that fulfill the selected criteria (Scherson & Criddle 2014; Kollmann *et al.* 2017). Geospatial information data related to the total floor area of facilities were obtained from the national spatial data infrastructure (NSDI) portal. The geospatial information datasets were transferred into a GIS. Within this GIS layers, a features filtering process was applied to identified building facilities with a total floor area of 60,000 m^2 that align with the defined pre-assessment criteria, specifically criteria 3.

2.2.2.2. Selection the feasibility of the water–energy supplier (WWTPs) and consumers. The integration of the WEN concept was applied into the selection of potential water–energy suppliers and consumers. It is important to underline that the WEN concept represents the interdependencies between water and energy, indicating that water resources can be expressed as energy resources and vice versa (DeNooyer *et al.* 2016). The determination of feasible WWTPs and compatible consumer clusters depends on two critical criteria: the minimum capacity (criterion 1) and the distance between WWTP and consumer clusters (criteria 2). A dataset encompassing a total of 650 WWTP shown in Figure 2 was screened to identify those with a minimum capacity of over 10,000 m^3/day. Subsequently, the dataset of building facilities with total floor area more than of 60,000 m^2 from previous step (Section 2.2.2.1) was overlaid in GIS and analyzed together. The proximity of WWTP was analyzed in circular areas up to a maximum distance between WWTP and consumer of 500 m. Figure 3 serves a schematic depiction for the selection of feasibility water–energy suppliers with consumers.

2.3. Development evaluation framework using MCDA

MCDA is a part of the decision-making methodologies that has garnered significant attention across various fields due to its effectiveness in facilitating complex decision process (Jaiswal *et al.* 2015; Martin-Gamboa *et al.* 2017). These methodologies provide substantial support for conducting a comprehensive evaluation of both criteria and sub-criteria for decision options, thereby contributing to investigating the best alternative to achieve the objective (Yalcin *et al.* 2022). In the context of this study, MCDA was utilized as an important tool to develop an evaluation framework by identifying the important criteria and their associated attributes. The AHP a component of MCDA was used to evaluate the performance of criteria. By utilizing the AHP, this research measures the relative importance of each criterion, thus facilitating an objective evaluation process.

2.3.1. Identification of criteria and attributes

The identification of relevant criteria and their subsequent classification is conducted in four subsequent steps: (i) the presented criteria from the previous study are screened for key aspects in connection with WWHR and treated wastewater reuse. Water quality criteria represent an essential parameter in the context of treated wastewater reuse. A tertiary treatment process including filtration technologies and/or ultraviolet (UV) disinfection is required to obtain water quality suitable for high-quality reuse through the removal of contaminants and organic materials. Since the WWTP in South Korea has implemented an advanced treatment process, specifically ultrafiltration, advanced oxidation process (AOP), and UV disinfection this study not considered the water quality criteria; (ii) the novel criteria are identified based on experts' group brainstorming consisting of professors, researchers, and engineers that considered the impact of criteria; (iii) the identified

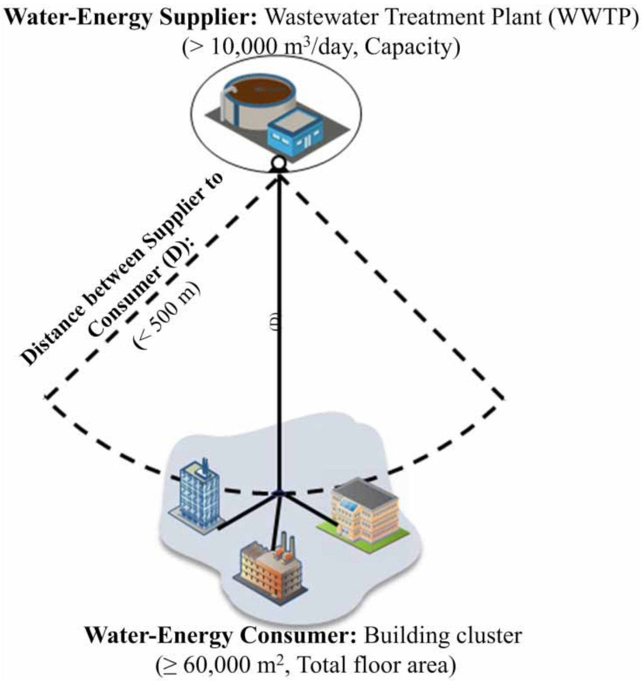


Figure 3 | Schematic layout of how a potential water–energy supplier and consumer are selected.

criteria are then compiled into a structured tabular format, constituting the foundation of an initial evaluation framework; (iv) the identified criteria are categorized into three aspects: water–energy supplier, water–energy consumers, and water–energy station. This categorization aligns with the proposed concept delineated in Figure 4, which underscores the integration of WWHR with treated wastewater reuse.

In order to effectively mitigate the challenge of heat losses during distribution and ensure compliance with the regulations outlined in renewable energy act policies, this research introduces the concept of a water–energy station. Notably, the suggested facility is strategically situated within the confines of the consumer cluster. The attributes associated with each criterion are identified through a brainstorming process guided by expert insights. This process takes into account the operational dynamics of WWTP in South Korea, relevant details regarding the information of the potential consumer, and pertinent findings from previous studies.

2.3.2. Evaluation criteria weight value based on the AHP

The AHP procedure was applied to determine the relative importance or weight value of the criteria based on expert opinion through the AHP survey. The questionnaire survey was carried out with the active participation of 10 experts specializing in wastewater resource management and environmental engineering that consist of water and energy experts. This panel of experts encompassed individuals with diverse professional backgrounds, including five professors, three researchers, and two engineers, ensuring a well-rounded perspective on the subject matter. The survey was carefully organized through the administration of a structured questionnaire, and data collection was meticulously conducted within a defined time frame, spanning 1 week. Each of the 10 experts received a questionnaire electronically and distributed via e-mail. The questionnaire was structured into two distinct sections. In the first part, the 10 experts were asked to evaluate the relative importance of the main criteria, following the reference materials associated with each question. In the subsequent section, these same 10 experts were directed to assess the significance of the sub-criteria. All 10 questionnaires were completed and subsequently collected, thereby constituting the complete dataset that comprehensive analysis. AHP is one of the techniques in the MCDA used to evaluate relative importance through scoring and weighting criteria using pairwise comparisons and final ranking (Abel *et al.* 2018). The extant literature from Darko *et al.* (2018), emphasizes that there is no strict requirement for a minimum sample size of judges or experts in AHP analysis. The adequacy of the sample size depends on two key factors: the consistency of the judgments provided by the experts and the practical validity of these judgments (Saaty & Ozdemir 2014).

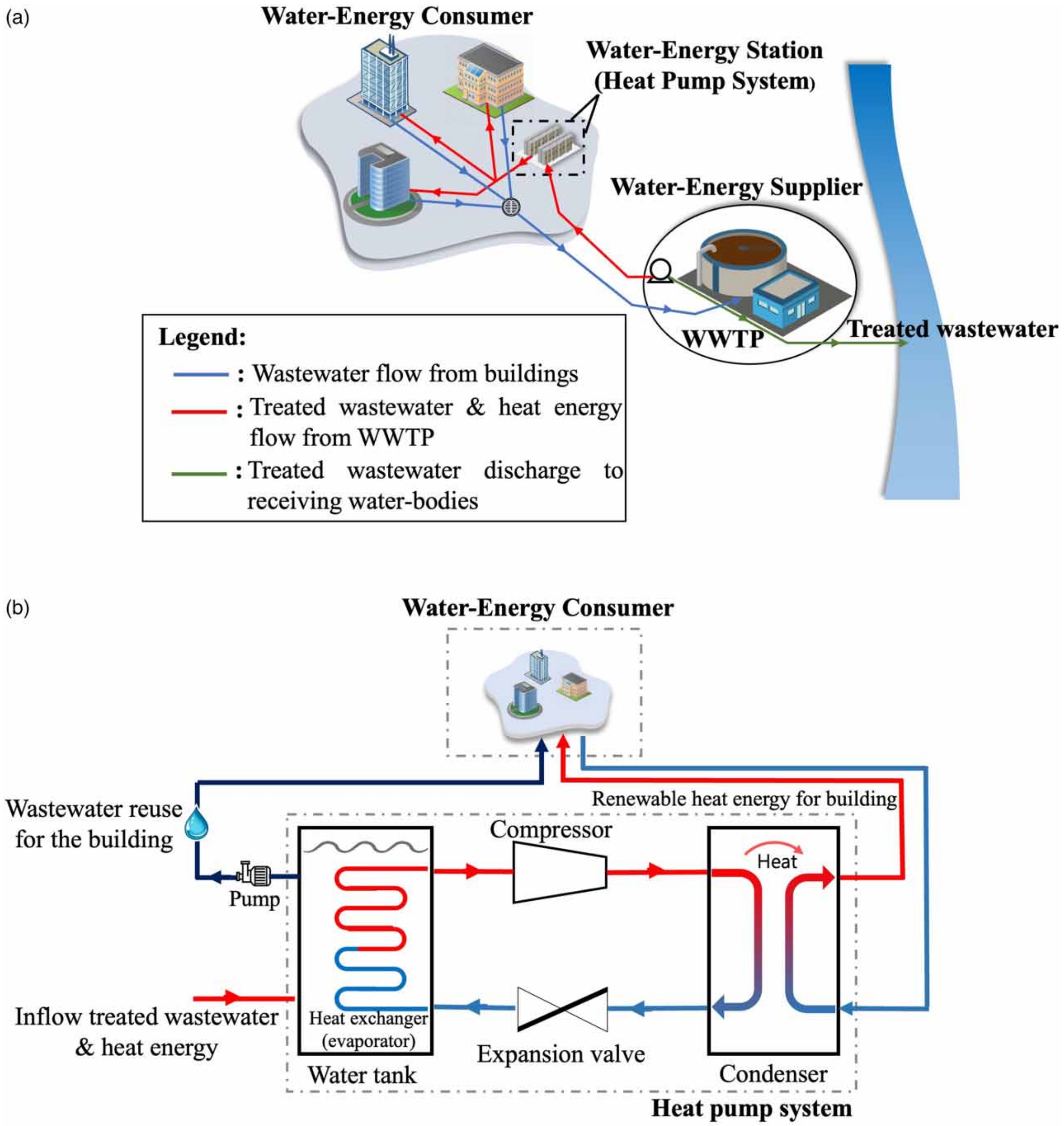


Figure 4 | Overview of WWHR coupled with wastewater reuse with details of the water–energy station: (a) a concept of wastewater heat recovery coupled with wastewater reuse consisting of the water–energy supplier, consumer, and station and (b) details the water–energy station with the heat pump system (HPS).

The initial steps in the AHP process include criteria identification, which was conducted to establish the hierarchical relationship between the criteria and sub-criteria. Once the objective and criteria were established, a weight is assigned to each criterion using pairwise comparison matrices as shown in Equation (1):

$$A = [a_{ij}] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{bmatrix} \tag{1}$$

The comparison matrix is denoted as A, a_{ij} is formed by comparing n number of row elements (a_i) with n number of column elements (a_j). Furthermore, the scoring is given based on expert opinion to determine the relative importance of the criteria. For proper decision-making, decision-makers are provided with qualitative and quantitative data for the assigned weight of each criterion in the multi-criteria evaluation (Odu 2019). The next step is to compute the principal eigenvector to obtain the local priorities of the criteria. Verifying the consistency index (CI) and consistency ratio (CR) is an important aspect to validate the consistency between the expert judgment. The CI is calculated using the following equation considering the maximum eigenvalue of the matrix ($\lambda_{\max}$) and number of elements or criteria (n):

$$\mathrm{CI} = \frac{(\lambda_{\max} - n)}{(n - 1)} \tag{2}$$

The consistency of expert knowledge can be determined by calculating the CR, which is defined as:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{3}$$

where CI and RI are the consistency index and random index, respectively, based on the number of alternatives and can be taken from a standard table provided by Saaty (2000). The evaluation criteria weight value of attributes depends on the score or ratings for each attribute from 1 to 5. The weight value is obtained by normalizing the score of each attribute and the sum value is 1.

2.3.3. Determination of an evaluation framework

The determination of an evaluation framework to assess the potential location of WWHR coupled with wastewater reuse is made up of three subsequent steps: (i) the selected criteria, sub-criteria, and attributes that have been grouped into three aspects are integrated into a table; (ii) in addition, the derived weight value assigned to criteria, sub-criteria, and attributes, as determined through the AHP are transferred into a table; (iii) the global weight value of all criteria is calculated by multiplying the weight value of the criteria, sub-criteria, and attributes. It is important to highlight that the sum of these global weight values is 1, wherein this cumulative global weight value serves as the basis for evaluation ratings. To demonstrate its practicability and usefulness, the developed evaluation framework is applied in a case study application to select priority sites by assessing the selected potential WWTP sites with consumers from pre-assessment results.

2.4. Selection of the priority sites

The prioritization of the most suitable locations was conducted through an assessment of selected potential WWTP sites with the consumer cluster from preliminary assessment (Section 2.2), using an innovative evaluation framework. This procedure consists of a subsequent step: (i) initial grouping involves categorizing the selected WWTP sites and consumer cluster based on their geographical administrative district; (ii) subsequently, the novel evaluation framework is applied to evaluate the WWTP sites, encompassing a straightforward analysis of several factors: the accessibility of feasible water and heat energy suppliers including clean energy ratio in WWTP, capable of providing resources for WWHR and treated wastewater reuse. The identification of demand sources (consumers) to benefit from renewable heat energy and water reuse, and the availability of heat supply depends on the operation of HPS; (iii) the total global weight values ascribed to each WWTP sites facilitates the determination of priority rankings for both potential WWTP sites and the associated consumer clusters.

3. RESULTS AND DISCUSSION

3.1. Potential WWTP sites with the consumer cluster

The identification of potential WWTP sites and consumers cluster was performed utilizing spatial analysis using GIS that was explained in the previous section (Section 2.2.2) that considers three pre-assessment criteria. The analysis of 650 WWTPs by applying pre-assessment criterion 1, resulting in the selection of 236 WWTPs that quantify as candidate water–energy suppliers with a capacity exceeding 10,000 m^3/day. In a parallel, the analysis of potential consumer clusters led to the selection of 893 building facilities designated as candidates for water–energy consumers. This selection criterion was based on total floor area exceeding 60,000 m^2 based on spatial data infrastructure. To optimize of heat distribution and the process effectiveness, the analysis of these candidate water–energy supplier and consumer were expanded. Specifically, water–energy consumers were narrowed down based on their proximity to the WWTPs, limiting the distance less than 500 m. In alignments with the heat recovery manual from Japan that have mentioned an optimal spatial interval of approximately 500 m between a potential supplier and consumer (MLIT 2015). The detailed information regarding the selected potential WWTP sites with the consumers cluster as the water–energy supplier and consumers, is presented in Table 2.

A total of 13 WWTPs sites with a cluster of water–energy consumers were selected as potential water–energy suppliers and consumers. The information related water–energy consumer encompasses two key aspects: the total of buildings within the respective cluster and the specific categorization of each building type or facility. The total floor area of the building cluster for sites W_{07} and W_{09} was determined by summing the total floor areas of all buildings in the cluster of water–energy consumers. The larger the total floor area of water–energy consumers, the higher the use of renewable heat energy and wastewater reuse increases economic and environmental benefits (Rezaie & Rosen 2012). The selected of these 13 potential WWTP will become case study sites for applying a novel evaluation framework in determining priority sites for WWHR coupled with wastewater reuse.

3.2. Assessment criteria from MCDA

To construct a novel evaluation framework for the assessment of potential WWTP sites with the cluster of consumers, the assessment criteria and attributes were selected through screening of key criteria from literature review and experts' group brainstorming. The assessment criteria were presented as a hierarchical structure as shown in Figure 5 and grouped into three aspects as shown in Table 3.

3.2.1. Water–energy supplier

- *Treated wastewater flow rate.* This criterion is a major factor reflecting the water and thermal energy source that determines the potential for WWHR and wastewater reuse. The higher the treated wastewater flow rate, the greater the water–thermal energy that can be recovered (Nagpal *et al.* 2021), strongly defining the potential locations for WWHR coupled with wastewater reuse. In alignment with the previously outlined concept and in compliance with the mandates of the water reuse act, a minimum threshold of 10% of the treated wastewater volume has been established as the requisite criterion for water–energy supply. Consequently, the attributes for the assessment were selected based on the potential of treated wastewater flow rate from the selected WWTP as the water–energy supplier as shown in Table 4.
- *Treated wastewater temperature.* As already mentioned before, this criterion is a major factor that determines the available heat energy potential for WWHR. Theoretically, the thermal energy potential can be calculated by following Equation (4)

Table 2 | Detailed information on the potential water–energy suppliers and consumers from the pre-assessment

	Criteria 1	**Criteria 2**	**Criteria 3**		
Site no.	**Capacity of the water–energy supplier (m^3/day)**	**Distance between supplier to consumer (m)**	**Total floor area of building cluster in water–energy consumer (m^2)**	**Total no. of buildings**	**Type of building**
1 (W_{01})	120,000	260	83,794	1	Factory
2 (W_{02})	65,000	367	114,240	1	Hospital
3 (W_{03})	120,000	435	84,904	1	Factory
4 (W_{04})	22,800	487	146,019	1	Factory
5 (W_{05})	330,000	483	101,443	1	Factory
6 (W_{06})	900,000	415	66,487	1	Office
7 (W_{07})	47,000	456	370,573	4	3 Office & 1 Education
8 (W_{08})	250,000	473	78,495	1	Railway station
9 (W_{09})	150,000	450	257,717	3	3 Commercial
10 (W_{10})	140,000	246	200,549	1	Warehouse
11 (W_{11})	65,000	490	66,561	1	Factory
12 (W_{12})	58,000	262	99,821	1	Warehouse
13 (W_{13})	32,000	459	199,678	1	Warehouse

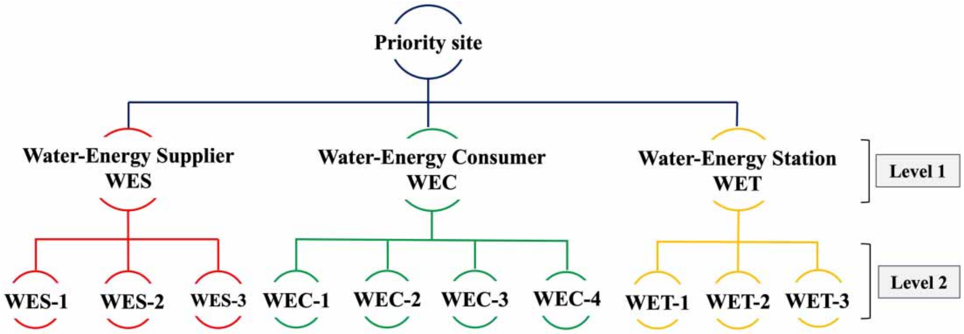


Figure 5 | Hierarchical structure based on the selected assessment criteria (Table 3).

Table 3 | Proposed assessment criteria for evaluation of potential WWTP sites with the consumer cluster grouped into water–energy supplier, consumer, and station

Criteria	Sub-criteria
Water–energy supplier (WES)	Treated wastewater flowrate (m^3/day) (WES-1)[a] Treated wastewater temperature (°C) (WES-2)[b] Clean energy ratio in WWTP (%) (WES-3)
Water–energy consumer (WEC)	Water–energy supply distance (m) (WEC-1)[c] Type of water–energy consumer (WEC-2) Total floor area of water–energy consumer cluster (m^2) (WEC-3) Usage of renewable heat by water–energy consumer (WEC-4)[d]
Water–energy station (WET)	Efficiency of HPS (WET-1)[e] Operation type of HPS (WET-2) Operation hours of HPS (Hour/years) (WET-3)[f]

Note: The key criteria were screened from [a]Huber *et al.* (2020); [b]Kretschmer *et al.* (2016a, 2016b); [c]Spriet *et al.* (2020); [d]Culha *et al.* (2015); [e]Nagpal *et al.* (2021); [f]Neugebauer *et al.* (2015).

Table 4 | The potential water–energy supply from the selected WWTP sites based on the volume of treated wastewater flow rate

Site no.	Volume treated wastewater flow rate (m^3/day)	The potential water and heat energy supply (m^3/day)
W_{01}	51,697	5,170
W_{02}	39,076	3,908
W_{03}	110,264	11,026
W_{04}	13,014	1,301
W_{05}	269,387	26,393
W_{06}	752,385	75,238
W_{07}	35,229	3,523
W_{08}	194,596	19,460
W_{09}	122,392	12,239
W_{10}	113,106	11,311
W_{11}	62,909	6,291
W_{12}	25,541	2,554
W_{13}	18,939	1,894

(modified from the original equation proposed by Chae & Kang, 2013):

$$E = Q_{\mathrm{ef}} \times \rho_{\mathrm{ef}} \times C_{\mathrm{p,ef}} \times \Delta T_{\mathrm{ef}} \tag{4}$$

where E is the thermal energy (kJ), Q_{ef} is the treated wastewater flow rate (m^3), ρ_{ef} is the density of effluent (kg/m^3), $C_{\mathrm{p,\ ef}}$ is the specific thermal capacity of effluent (kJ/kg. °C), and ΔT_{ef} is the decrease in temperature of effluent WWTP (°C) (extracted temperature from heat exchanger). The treated wastewater temperature in overall South Korea showed relatively small seasonal fluctuation, ranging between 12 and 28 °C as compared to atmospheric temperatures spanning −12 °C to 30 °C. The differences between the air and the effluent temperature varied with the seasons, with the maximum in winter (up to 26 °C) and the minimum in summer (0.4 °C) (Chae & Kang 2013). This observation suggest that the effluent water promise consistent heat source for cooling and heating during warmer and colder season. In this study, treated wastewater temperature was predicted to be directly related to the climate of the site's location, which was divided into upper, middle, and lower regions of the country. According to the data of treated wastewater temperature in overall the country, the treated wastewater temperature in the upper, middle, and lower regions in the fall season (November) is approximately 19–20 °C; 21–22 °C; and 23–24 °C, respectively.

- *Clean energy ratio in WWTP*. This criterion captures the use of renewable energy in WWTP. The use of renewable energy in the WWTP that gives an indirect impact on the WWHR and wastewater reuse, especially for pump systems of treated wastewater and heat energy flow in which the use of clean energy can reduce CO_2 emissions and operational costs in the facility. The attributes of this criterion were determined according to the data use of renewable energy in the selected WWTP from public authorities with the trend of clean energy ratio in the selected WWTP sites is approximately 1–23%.

3.2.2. Water–energy consumer

- *Water–energy supply distance*. This criterion determines the effectiveness of the WWHR, efficiency of water distribution, and energy efficiency in the process of heat recovery and wastewater reuse, which is associated with the water and energy supply to the water–energy consumer. This criterion reflects the impact of water–energy supply distance on economic feasibility regarding heat losses during distribution. Regarding the distance between supplier and consumer, the appropriate distance was set in the pre-assessment section of less than 500 m and as a benchmark in determining attributes for these criteria.
- *Type of water–energy consumer*. This criterion determines the technical aspects and economic conditions of the water–energy supply related to the demand side as well as the operation of the HPS. The type of water–energy consumer is a major factor in the energy supply concept that will affect the WWHR process (Kollmann *et al.* 2017). The size of the building, its thermal insulation, and heating-cooling requirements are factors that can impact the energy-consuming aspects of heat recovery (Cecconet *et al.* 2020; Wehbi *et al.* 2022). The type of water–energy consumer was divided into the living facility, medical facility, public facility, business and commercial facility, and another facility (station, airport, etc.). The evaluation of water–energy consumer types is conducted by a thorough assessment of their advantages associated with the utilization of renewable energy and wastewater reuse. Additionally, closely interrelated with the operation of HPS. The use of renewable energy and wastewater reuse in living facilities such as apartment complexes is more advantageous in terms of economic value and reduces fossil fuel consumption.
- *Total floor area of water–energy consumer*. The technical aspects of the HPS in terms of design, capacity, and operation consider the type and total floor area of the water–energy consumer cluster. It is also an important factor that defines the water–energy supply demands that impact energy efficiency as well as decrease the CO_2 emissions and freshwater demands. The minimum total floor area of the water–energy consumer was determined from the pre-assessment section with a minimum of 60,000 m^2. This information was used in determining the attributes of the criterion.
- *Usage of renewable heat energy by water–energy consumer*. The purpose of using renewable heat energy by the water–energy consumer is used to define economic feasibility, CO_2 emissions, and energy efficiency. The usage purpose of renewable energy depends on the type of facility in the consumer cluster. For factories, renewable heat energy is used for pre-heating and pre-cooling processes, whereas in offices, warehouses, and commercial facilities, it is used for space heating and cooling in buildings.

3.2.3. Water–energy station

- *Efficiency of HPS.* The coefficient of performance (COP) relates to the efficiency of HPS and directly depends on the treated wastewater temperature (Chae & Kang 2013; Culha *et al.* 2015). The COP is a major factor affecting the economic value, efficiency, and availability of thermal energy. The availability of thermal energy can be calculated following Equations (5) and (6):

$$E_c = E \times \frac{COP_c}{COP_c + 1} \tag{5}$$

$$E_h = E \times \frac{COP_h}{COP_h - 1} \tag{6}$$

  where E_c is the available energy for cooling purposes (kcal), and COP_c is the coefficient of performance for cooling. E_h is the available energy for heating (kcal), and COP_h is the coefficient of performance for heating purposes. The COP of the HPS was assumed based on the treated wastewater temperature, in which the average COP was approximately 5.35 for cooling purposes and 4.06 for heating purposes when the treated temperatures were 15–25 °C.
- *Operation type of HPS*. The energy supply-demand determines the operation type of HPS, where there is a correlation between the operation type of the HPS and the type of water–energy consumer that impacts on the efficiency and effectiveness of the HPS. The operation of HPS was divided into continuous and intermittent operations depending on the operation of the facility.
- *Operation hours of HPS.* The operating hours depend on the heat demands based on the type and total floor area of the water–energy consumers. The higher the operation hours of an HPS, the more efficiently it can be operated from an economic perspective. According to a study by Neugebauer *et al.* (2015), mixed facility structures such as residential buildings coupled with commercial uses such as offices and warehouses show operation hours of HPS of up to 4,500 full load hours, whereas simple residential buildings indicate1,500–2,200 full load hours. Based on these requirements, we considered operating hours of HPS for a medical facility up to 4,500 h per year or 12 h per day. For offices, factories, and warehouse facilities, the operating hours of a HPS were approximately 3,000–3,600 h per year or 8–10 h per day.

3.3. A novel evaluation framework

The selected assessment criteria and attributes have been integrated to construct an evaluation framework. To provide a better orientation for the user, the evaluation framework is grouped into three aspects: water–energy supplier, water–energy consumer, and water–energy station. Following the AHP steps to evaluate the performance criteria, the weight value was determined based on this obtained expert opinion. The pairwise comparison matrix was generated according to the expert answers from the AHP survey. The CI and CR were calculated with a CR of less than 0.1. Once the weight value of the criteria was obtained from the AHP process, a novel evaluation framework was structured consisting of criteria, sub-criteria, attributes, and detailed weight values which are listed in Table 5.

Simply multiplying the weight value of the criteria, sub-criteria, and attributes results in the global weight value. The sum of global weight is 1 and it is intended to be used as an evaluation grade for the assessment. According to the evaluation criteria by the AHP, the water–energy supplier is the most important criterion (0.560), followed by the water–energy consumer (0.319), and the water–energy station (0.121).

For the general assessment, the water–energy supplier that consists of treated wastewater flow rate, temperature, and clean energy ratio in WWTP becomes the first assessment criterion in the evaluation framework. Based on the results of local priorities from the AHP, treated wastewater flow rate and temperature are the most important factors as define the availability of water and thermal energy potential with the weight value of 0.297 and 0.186, respectively. Here, the attributes of each sub-criteria are determined according to the potentially treated wastewater flow rate indicated in Table 4, the overall treated wastewater temperature in South Korea, and the trend of clean energy ratio in the selected WWTP as discussed in Section 3.2.1. Water–energy supplier.

The next assessment criteria in the evaluation framework concern water–energy consumers as a demand side that consists of water–energy supply distance, type of water–energy consumer, total floor area of water–energy consumer, and usage of

Table 5 | A new evaluation framework consisting of the criteria, sub-criteria, and attributes with the weight value from the AHP process

Criteria		Sub-criteria		Attributes		Global weight
Water–energy supplier	0.560	Treated wastewater flow rate (m^3/day)	0.531	$V < 5,000$	0.067	0.020
				$5,000 \leq V < 7,500$	0.133	0.040
				$7,500 \leq V < 10,000$	0.200	0.059
				$10,000 \leq V < 12,500$	0.267	0.079
				$V \geq 12,500$	0.333	0.099
				Sub-total	**1.000**	
		Treated wastewater temperature (°C)	0.332	$T < 12$	0.067	0.012
				$12 \leq T < 16$	0.133	0.025
				$16 \leq T < 20$	0.200	0.037
				$20 \leq T < 25$	0.267	0.050
				$T \geq 25$	0.333	0.062
				Sub-total	**1.000**	
		Clean energy ratio in WWTP (%)	0.137	<5%	0.067	0.005
				5–10%	0.133	0.010
				10–15%	0.200	0.015
				15–20%	0.267	0.020
				>20%	0.333	0.026
		Sub-total	**1.000**	**Sub-total**	**1.000**	
Water–energy consumer	0.319	Water–energy supply distance (m)	0.388	$D < 200$	0.333	0.041
				$200 \leq D < 300$	0.267	0.033
				$300 \leq D < 400$	0.200	0.025
				$400 \leq D < 500$	0.133	0.016
				$D \geq 500$	0.067	0.008
				Sub-total	**1.000**	
		Type of water–energy consumer	0.299	Living facility	0.333	0.032
				Medical facility	0.267	0.026
				Public facility	0.200	0.019
				Business & Commercial facility	0.133	0.013
				Another facility	0.067	0.006
				Sub-total	**1.000**	
		Total floor area of water–energy consumer cluster (m^2)	0.206	<60,000	0.067	0.004
				60,00–70,000	0.133	0.009
				70,000–80,000	0.200	0.013
				80,000–90,000	0.267	0.018
				>90,000	0.333	0.022
				Sub-total	**1.000**	
		Usage of renewable heat by water–energy consumer	0.107	Water heating	0.067	0.002
				Water heating, Space cooling	0.133	0.005
				Water heating, Space heating	0.200	0.007
				Space heating & cooling or pre-heating & pre-cooling process	0.267	0.009
				Space heating & cooling, water heating	0.333	0.011
		Sub-total	**1.000**	**Sub-total**	**1.000**	
Water–energy station	0.121	Efficiency of HPS	0.540	$COP < 3.0$	0.067	0.004
				$3.0 \leq COP < 3.5$	0.133	0.009
				$3.5 \leq COP < 4.0$	0.200	0.013
				$4.0 \leq COP < 4.5$	0.267	0.017
				$COP \geq 4.5$	0.333	0.022
				Sub-total	**1.000**	
		Operation type of HPS	0.163	Continuous operation	0.667	0.013
				Intermittent operation	0.333	0.007
				Sub-total	**1.000**	

(*Continued.*)

Table 5 | Continued

Criteria		Sub-criteria		Attributes		Global weight
		Operating hours of HPS (hours/year)	0.297	$HP < 1,500$	0.067	0.002
				$1,500 \leq HP < 2,200$	0.133	0.005
				$2,200 \leq HP < 3,600$	0.200	0.007
				$3,600 \leq HP < 4,500$	0.267	0.010
				$\geq 4,500$	0.333	0.012
Sub-total	**1.000**	**Sub-total**	**1.000**	**Sub-total**	**1.000**	
Total						**1.000**

heat energy. According to the local priorities, water–energy supply distance and type of water–energy consumer are the third and fourth important factors with a weight value of 0.123 and 0.096, respectively. These results confirm that the potential of WWHR coupled with wastewater reuse depends on the water–energy supplier and water–energy consumer as supply and demand sources. The potential water–energy supplier depends on treated wastewater flow rate and temperature, as well as the potential consumers based on the water–energy supply distance and the type of water–energy consumer. The attributes of each criterion are defined following the potential water–energy consumer information indicated in Table 2 and discussed in Section 3.2.2. Water-energy consumer.

The last assessment criteria in the novel evaluation framework concern the water–energy station related to the availability of thermal energy based on the efficiency and operation of HPS. As discussed in Section 3.2.3. Water–energy station, the efficiency of HPS strongly depends on the treated wastewater temperature, and the operation of HPS depends on the type of water–energy consumers. Consequently, the attributes of each sub-criteria are determined in close relation to the two criteria as explained in Section 3.2.3. Water-energy station.

3.4. Case study application

The novel evaluation framework introduced in the preceding section will now be implemented in a case study to determine priority locations. This will be achieved through an assessment of the selected WWTP sites as outlined in Table 2. Thirteen identified potential WWTP sites with their respective consumer clusters, were systematically categorized into lower, middle, and upper region based on geographical administrative districts. This categorization led to the placement of sites W_{01} and W_{02} are in the lower region, sites W_{03}–W_{05} are in the middle region, and sites W_{06}–W_{13} are in the upper region of the country. Figure 6 illustrates the representation of the assessment by comparing of the 13 WWTPs, while the prioritized ranking outcomes resulting from the assessment process are documented in Table 6. In the case of the same weight value for two locations, the ranking of priority was based on the facility with a larger WWTP capacity.

Through the assessment of 13 potential WWTP sites with the cluster consumer, site W_{05} was selected as a priority site followed by sites W_{06} and W_{10} with the total global weight value of all criteria of 0.255, 0.240, and 0.229, respectively. As shown in Table 4, site W_{05} has a potential treated wastewater flow rate as a source of water and heat energy of up to 26,939 m^3/day. The treated wastewater temperature is approximately 20 °C and the clean energy ratio of the facility is 13.5%. Site W_{05} has a target consumer consisting of a factory facility at a supply distance of 483 m and a total floor area of 101,443 m^2, with the purpose of the use of renewable energy for the pre-heating and pre-cooling process. The operation of the HPS at up to 3,600 h per year with an intermittent operation.

Sites W_{06} and W_{10} have a potential treated wastewater flow rate of 75,238 and 11,311 m^3/day, respectively. The treated wastewater temperature is approximately 19 °C and the clean energy ratio of the facility is 20.2% in site W_{06}. Sites W_{06} and W_{10} have a target consumer consisting of office and warehouse facilities with the usage of renewable heat for space heating and cooling. The operation of HPS is approximately 3,000 h per year. Figure 7 presents information on the availability of the water–energy supplier, consumer, and station for the top three priority WWTP sites based on the weight value of the evaluation framework.

Additional studies involving other aspects, particularly micro-level studies, may help further validate the presented methodology, evaluation framework, and general results. The investigation or measurement of the treated wastewater temperature is strongly recommended for a more detailed site assessment.

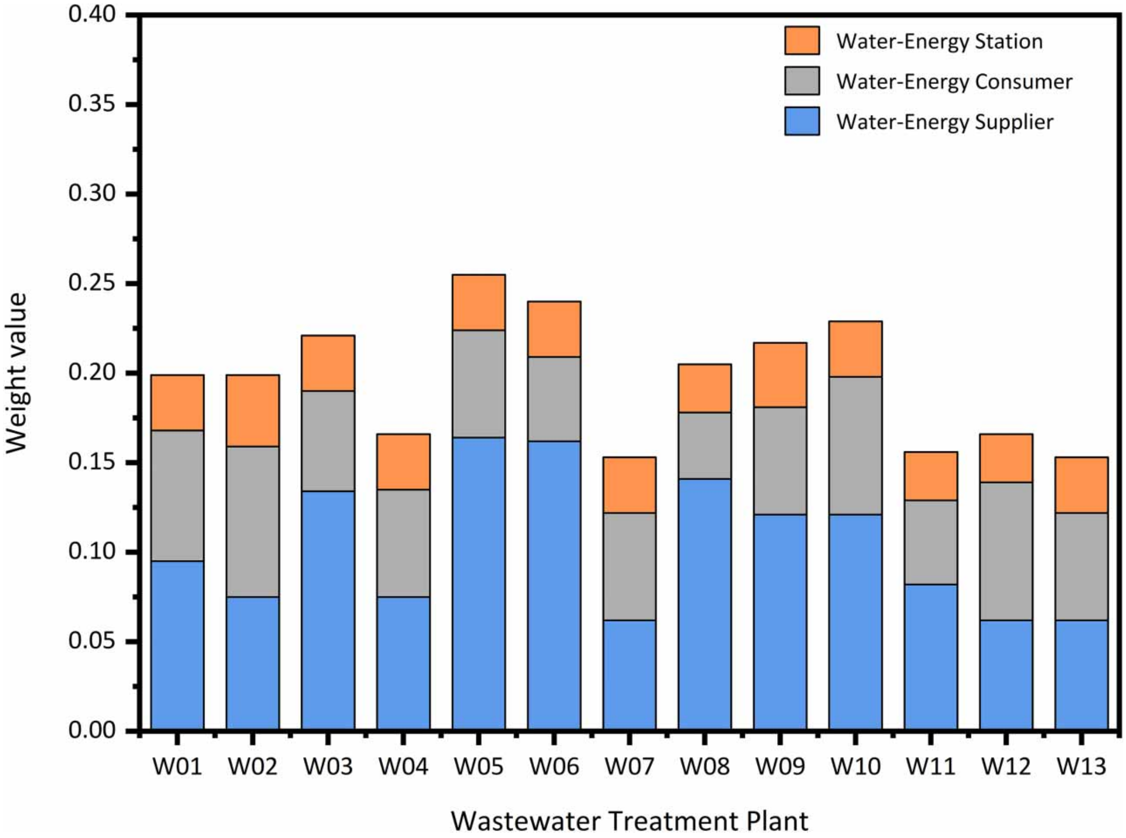


Figure 6 | Assessment comparison of 13 WWTPs with the total weight value of the water–energy supplier, consumer, and station.

Table 6 | Results of priority WWTP location ranking for WWHR coupled with wastewater reuse

WWTP	W_{01}	W_{02}	W_{03}	W_{04}	W_{05}	W_{06}	W_{07}	W_{08}	W_{09}	W_{10}	W_{11}	W_{12}	W_{13}
Capacity (10^3 m^3/day)	120	65	120	22.8	330	900	47	250	150	140	65	58	32
Total global weight value	0.199	0.199	0.221	0.166	0.255	0.240	0.153	0.205	0.217	0.229	0.156	0.166	0.153
Priority rank	7	8	4	10	1	2	12	6	5	3	11	9	13

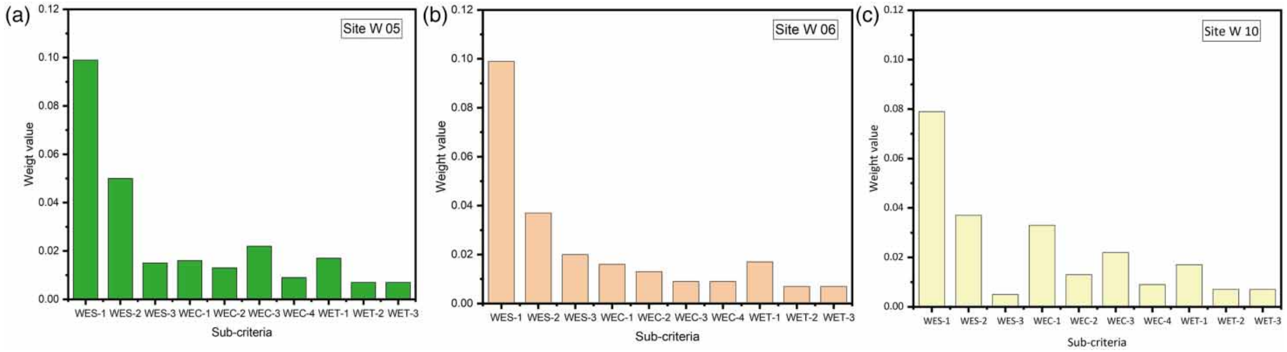


Figure 7 | Information related to the availability of the water–energy supplier, consumer, and station for the top three priority WWTP sites based on the weight value of the evaluation framework.

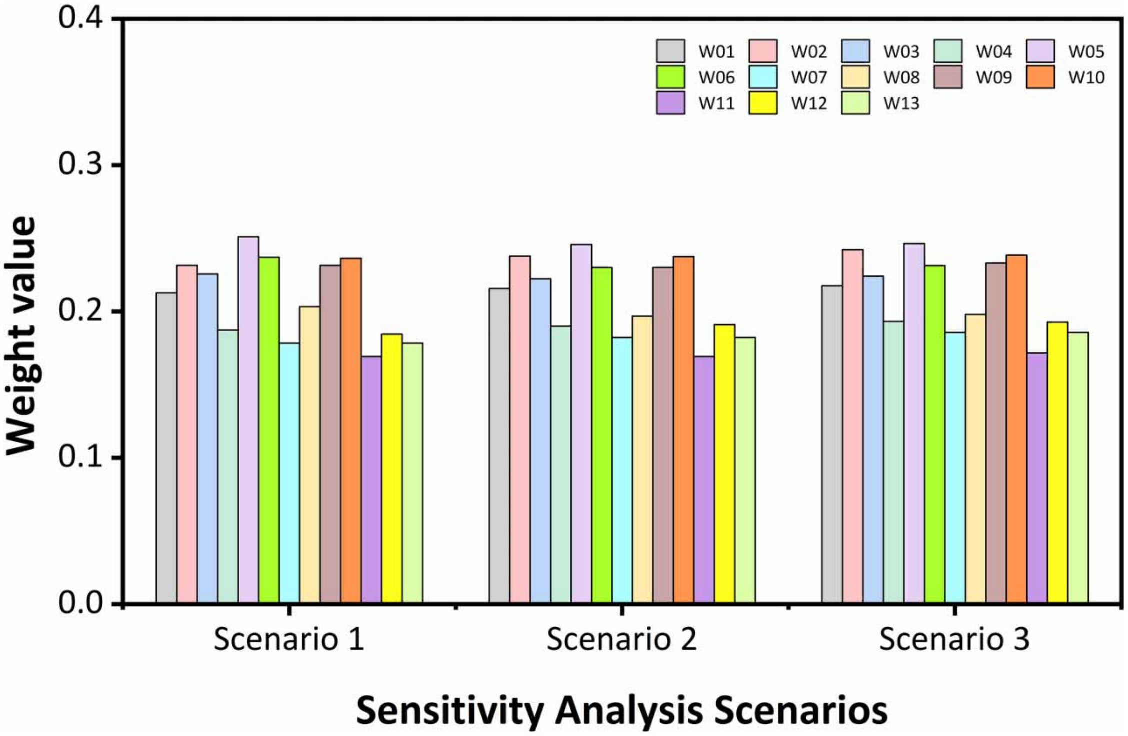


Figure 8 | Results of priority WWTP ranking obtained from sensitivity analysis in three-scenario assessment.

3.5. Sensitivity analysis

A series of sensitivity analyses was performed to both validate the accuracy of the AHP method and to comprehensively examine the influence of modifications to the weight values of the main criteria on the prioritization of WWTP sites for the WWHR combined with treated wastewater reuse. When the priority ranking remains consistent, it indicates the stability and robustness of the proposed model (Milutinovic *et al.* 2017). The sensitivity analyses encompass three distinct scenarios to evaluate the impact of variations in the weighting factors assigned to the criteria. These scenarios are as follows: (i) The criterion WES has a weighting factor of 40%, while the remaining criteria, WEC and WET, each held a weighting factor of 30%; (ii) both 'WES' and 'WEC' were attributed a weighting factor of 35%, whereas 'WET' received a weighting factor of 30%; and (iii) all criterion has equal weighting factors of 33.33%.

The outcomes of the sensitivity analyses, conducted across scenarios 1, 2, and 3, consistently showed that the priority ranking remained unchanged. In each scenario, Site W05 retained its position as a priority location for the implementation of WWHR combined with treated wastewater reuse. These consistent indicate the stability and robustness of the proposed model, facilitating suitability decision-making process. Detailed results of sensitivity analysis presented in Figure 8.

4. CONCLUSION

This study introduces a new evaluation framework that considers various factors, including thermal energy potential, spatial distribution analysis, and the compatibility of HPS, to assess suitable locations for WWHR coupled with treated wastewater reuse. The novelty of this research lies in its integrated approach, focusing on heat recovery coupled with treated wastewater reuse, and its structured framework that incorporates multiple criteria and expert opinions. The methodology approach consists of three-step process: pre-assessment process, develops evaluation framework by applying MCDA methods, and site prioritization. The pre-assessment phase involving the screening of potential WWTP and consumers clusters through GIS based on pre-assessment criteria. Subsequently, an evaluation framework is formulated by using MCDA methods. This phase encompasses the identification and categorization of criteria into three aspects: water–energy supplier, water–energy consumer, and water–energy station. To establish the relative importance of these criteria, the AHP is utilized. Finally, the evaluation framework is applied to ascertain and designate the priority locations for integration WWHR and treated wastewater reuse.

Through the pre-assessment process with the support of pre-assessment criteria, 13 potential WWTP sites were selected from a total of 650 WWTP with the capacity more than 500 m^3/day across South Korea. These selected sites are in proximity less than 500 m to consumer clusters. Analyzing of relative importance criteria indicates that the water–energy supplier is the most important criterion, followed by the water–energy consumer, and the water–energy station with weight values of 0.560, 0.319, and 0.121, respectively. The local priorities of criteria from AHP showed that, treated wastewater flow rate, treated wastewater temperature, water–energy supply distance, and type of water–energy consumer are the most important factor with weight values of 0.297, 0.186, 0.123, and 0.096, respectively. These results state that there is a strong correlation between the potential of WWHR coupled with wastewater reuse and the water–energy supplier as well as a water–energy consumer as supply and demand sources. A detailed comparison of the 13 potential WWTP sites confirms the selection of three priority locations: W_{05}, W_{06}, W_{10}. These sites exhibited higher total global weight values of 0.255, 0.240, and 0.229, respectively. Considering the findings and framework development from this study, future research could involve a comprehensive techno-economic analysis. Additionally, investigating the environmental impact and carbon footprint reduction resulting from the integration of these practices could provide valuable insights. Furthermore, the synergies between WWHR with other renewable energy sources, such as solar or wind, could offer optimizing energy utilization within the wastewater management.

AUTHOR CONTRIBUTIONS

E.R. contributed to conceptualization, methodology, validation, writing-original draft, formal analysis, data collection. J.O. contributed to conceptualization, methodology, validation, supervision, writing-review and editing, fund acquisition.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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