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Impacts of Non-Revenue Water on Energy Efficiency and Carbon Footprint: A National-Scale Case Study of Thailand's Provincial Waterworks Authority

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ABSTRACT

Non-Revenue Water (NRW) represents a major operational and sustainability challenge for water utilities, particularly in developing countries, where water losses are associated with avoidable energy consumption and indirect carbon emissions. This study evaluates the impacts of NRW on energy efficiency and carbon footprint in Thailand through a national-scale case study of the Provincial Waterworks Authority (PWA). An indicator-based analytical framework integrating water balance assessment, energy intensity analysis, and carbon emission estimation was applied to operational data from 2020 to 2024. The results indicate that NRW was associated with annual energy losses exceeding 200 million kWh and carbon emissions of approximately 122.7–132.2 million kgCO₂e. Scenario analysis further shows that reducing NRW from 27.47% to 15% could decrease embedded energy losses and associated carbon emissions by approximately 53.4%. These findings highlight the importance of incorporating NRW reduction into water-sector energy-efficiency, greenhouse-gas mitigation, and sustainable water-resource management strategies.

KEYWORDS

Non-Revenue Water, Water supply systems, Energy efficiency, Carbon footprint, Water-energy-carbon nexus, Sustainable water management.

INTRODUCTION

Non-Revenue Water has long been recognized as a major operational, financial, and resource-efficiency challenge for water utilities worldwide. It refers to the difference between the volume of water introduced into a distribution system and the volume billed to consumers, including real losses from physical leakage, apparent losses from metering inaccuracies and unauthorized consumption, and authorized but unbilled use [1]. In many developing countries, high levels of Non-Revenue Water continue to reduce water-use efficiency, increase production costs, and place additional pressure on limited freshwater resources [2].

International benchmarking indicates that well-performing utilities in developed countries generally maintain relatively low levels of Non-Revenue Water. Singapore reports levels below 5%, Denmark and Germany around 6–7%, Australia around 10%, and the United States approximately 13–14% of total water supplied [3], [4]. In contrast, many developing countries experience substantially higher levels. Thailand typically reports Non-Revenue Water of approximately 25–30% [5], while India and Indonesia often exceed 30% [6], [7]. In Vietnam, reported levels are commonly around 20–25% [8], whereas several urban water utilities in the

Philippines experience values of approximately 30–35% [9]. These differences reflect persistent challenges related to aging infrastructure, leakage management, metering accuracy, and operational efficiency.

Beyond water-resource losses, Non-Revenue Water has increasingly been recognized as part of the broader water–energy–carbon nexus. Water supply systems require electricity for abstraction, treatment, pumping, transmission, and distribution [10], [11]. When treated water is lost before reaching consumers, the energy used throughout these

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processes is also wasted. This embedded energy loss can generate indirect greenhouse gas emissions, particularly in countries where electricity generation remains dependent on fossil fuels [15]. Therefore, Non-Revenue Water can undermine progress not only toward Sustainable Development Goal 6 on water-use efficiency, but also toward energy-efficiency and climate-mitigation objectives under Sustainable Development Goals 7 and 13 [16], [17].

Recent studies have expanded the understanding of Non-Revenue Water reduction by emphasizing integrated technical, managerial, economic, and digital approaches. Farouk et al. systematically reviewed Non-Revenue Water reduction strategies. They showed that effective management requires a combination of leakage detection, pressure management, metering improvement, district metered areas, asset rehabilitation, and data-driven operational control [32]. AbuEltayef et al. further linked Non-Revenue Water reduction to broader sustainability objectives, including water security, resource efficiency, and progress toward the Sustainable Development Goals [33]. Santos also demonstrated that Non-Revenue Water remains a significant economic and managerial challenge for water utilities because unbilled water losses directly affect financial sustainability and system efficiency [34]. Nevertheless, most recent studies continue to focus primarily on physical and apparent losses, operational performance, and economic implications. In contrast, the embedded energy and carbon implications of Non-Revenue Water remain less frequently quantified.

Recent water–energy–carbon nexus studies have increasingly emphasized the role of water utilities in greenhouse gas mitigation and low-carbon urban infrastructure planning. Lam and van der Hoek showed that urban water systems can contribute to low-carbon transitions through energy-efficiency improvements and operational optimization beyond conventional utility boundaries [35]. Han et al. reviewed the water–carbon nexus in urban systems and highlighted the importance of understanding carbon emissions across water and wastewater processes [36]. Muhammetoglu et al. applied an energy-performance and greenhouse-gas assessment approach to the urban water cycle and demonstrated the value of scenario-based assessment for sustainability planning [37]. Harasymchuk et al. further showed that purchased energy and operational processes are major contributors to the carbon footprint of water supply and sewerage organizations [38]. More recently, Nagan and Seyam applied a water–energy–carbon nexus approach to a water supply system using a water-balance perspective, demonstrating the relevance of linking water losses with energy and carbon outcomes [39]. However, despite these advances, few studies have explicitly isolated Non-Revenue Water as a mechanism through which water losses are converted into embedded energy losses and indirect carbon emissions at the national scale.

Therefore, several important knowledge gaps remain. Existing Non-Revenue Water studies have predominantly focused on technical loss reduction, leakage management, utility performance, and economic impacts at local, city, or utility scales. Similarly, water–energy–carbon nexus studies have generally examined energy consumption and greenhouse gas emissions associated with water supply systems without explicitly quantifying the contribution of Non-Revenue Water to embedded energy losses and indirect carbon emissions. In Thailand, although Non-Revenue Water levels and management practices have been examined in previous utility reports and operational studies, the implications of Non-Revenue Water for energy efficiency and carbon emissions have not yet been comprehensively evaluated at the national scale. A national-scale assessment is important because local or utility-specific studies may not capture the cumulative effects of water losses, electricity consumption, and carbon emissions across an entire public water supply system. In countries where large public utilities serve extensive regional networks, an aggregated national assessment provides a policy-relevant basis for identifying system-wide inefficiencies and evaluating the potential contribution of Non-Revenue Water reduction to resource-efficiency and climate-mitigation objectives. This is particularly relevant to Thailand, where high levels of Non-Revenue Water coincide with an electricity mix that remains substantially carbon-intensive.

This study addresses these gaps by developing and applying an integrated analytical framework that links Non-Revenue Water, energy consumption, and carbon emissions using nationwide operational data from the Provincial Waterworks Authority of Thailand. Unlike previous studies that primarily assess Non-Revenue Water from operational or economic perspectives, this study conceptualizes Non-Revenue Water as a structural source of energy and carbon inefficiency embedded within water supply systems. By quantifying Non-Revenue Water-related energy losses and associated greenhouse gas emissions at the national scale, the study extends conventional water-loss assessment beyond utility performance evaluation. It advances research on the water–energy–carbon nexus.

Therefore, this study aims to assess the impacts of Non-Revenue Water on energy efficiency and carbon footprint in Thailand's public water supply system through a nationwide case study of the Provincial Waterworks Authority. Specifically, the study quantifies annual Non-Revenue Water volumes, estimates embedded energy losses and associated carbon emissions, evaluates potential energy and carbon savings under reduction scenarios, and discusses the policy implications of integrating Non-Revenue Water reduction into water-sector climate mitigation strategies. The findings are expected to support more integrated and sustainable water resource management and provide transferable insights for other developing countries facing similar challenges, including high water losses and carbon-intensive electricity systems.

METHODS

This study adopts an indicator-based analytical approach to evaluate the impacts of NRW on energy efficiency and carbon footprint in Thailand's public water supply system. The methodology integrates water balance analysis with energy consumption and carbon emission assessment, following the principles of the water–energy–carbon nexus framework [10], [29]. A nationwide case study of PWA is conducted to capture system-wide impacts rather than localized effects.

System boundary and analytical framework

The system boundary of this study covers the main stages of the public water supply chain, including raw water abstraction, water treatment, transmission, and distribution up to customer connections. NRW is considered to occur primarily within the transmission and distribution stages, consistent with the International Water Association (IWA) water balance framework [1], [12]. Energy consumption associated with each stage is accounted for, and the portion of energy embedded in NRW is quantified.

The analytical framework links NRW volumes to energy use and carbon emissions by assuming that water losses reflect the cumulative energy required for abstraction, treatment, and distribution before loss [13], [14]. This approach enables the estimation of indirect energy and carbon losses attributable to NRW at the national scale. The analysis is based on aggregated annual operational data covering all service areas under the PWA across Thailand, ensuring nationwide representativeness of the results. The dataset includes annual water production, billed consumption, NRW volumes, and electricity consumption associated with water abstraction, treatment, and distribution. All data are compiled at the national level and reflect the operational performance of the PWA system [29].

Comparison with Existing Assessment Frameworks

The proposed analytical framework was developed by integrating established approaches for Non-Revenue Water assessment, energy intensity analysis, and carbon emission estimation. The International Water Association (IWA) Water Balance framework provides a standardized methodology for quantifying Non-Revenue Water and classifying water losses into real losses, apparent losses, and authorized unbilled consumption [1]. However, the IWA framework primarily focuses on water-loss accounting and operational performance and does not explicitly quantify the associated energy losses or carbon emissions.

Recent carbon accounting approaches for water utilities have extended environmental assessment by estimating greenhouse gas emissions from electricity consumption and water supply operations. Likewise, water–energy–carbon nexus studies have emphasized the interactions among water use, energy consumption, and climate impacts. Nevertheless, these approaches generally evaluate energy use and greenhouse gas emissions independently of Non-Revenue Water or focus on utility-level applications.

In contrast, the framework proposed in this study integrates water balance assessment, energy intensity analysis, and carbon emission estimation within a unified national-scale analytical framework. By interpreting Non-Revenue Water as a mechanism through which water losses become embedded energy losses and indirect greenhouse gas emissions, the proposed framework extends conventional operational assessment toward broader sustainability evaluation.

Table 1 compares the proposed analytical framework with existing assessment approaches commonly used for Non-Revenue Water evaluation, carbon accounting, and water–energy–carbon nexus analysis.

Table 1. Comparison between Existing Assessment Frameworks and the Proposed Framework

<i>Framework</i>	<i>Primary Objective</i>	<i>Water Loss Assessment</i>	<i>Energy Assessment</i>	<i>Carbon Assessment</i>	<i>Spatial Scale</i>	<i>Main Limitation</i>
<i>IWA Water Balance</i>	NRW quantification	✓	✗	✗	Utility	Does not quantify energy or carbon impacts
<i>Carbon Accounting</i>	GHG inventory	✗	✓	✓	Utility/National	Does not explicitly consider NRW
<i>Water–Energy–Carbon Nexus</i>	Resource interaction	Partial	✓	✓	Mostly local	NRW is generally treated indirectly
<i>Proposed Framework</i>	Integrated NRW–Energy–Carbon assessment	✓	✓	✓	National	Applicable for policy evaluation

As shown in Table 1, the IWA Water Balance framework provides a standardized methodology for quantifying and classifying Non-Revenue Water. Still, it does not explicitly evaluate the associated energy losses or carbon emissions. Carbon accounting approaches

primarily focus on greenhouse gas inventories for water supply operations. In contrast, water–energy–carbon nexus studies generally assess interactions among water, energy, and environmental systems, often at utility or local scales. In contrast, the proposed framework integrates water-loss assessment, energy-intensity analysis, and carbon-emission estimation within a unified national-scale approach. This integration enables the quantification of embedded energy losses and indirect greenhouse gas emissions attributable to Non-Revenue Water, thereby extending conventional operational assessment toward broader sustainability evaluation.

Data sources and scope of analysis

The analysis utilizes national-level operational data obtained from the Provincial Waterworks Authority (PWA), including annual water production, billed consumption, Non-Revenue Water volumes, and electricity consumption across all PWA service areas [29]. Supplementary information on Thailand’s electricity generation mix and nationally approved greenhouse gas emission factors was obtained from the Thailand Greenhouse Gas Management Organization (TGO). The emission factor for tap water produced by the Provincial Waterworks Authority was obtained from the Thailand Greenhouse Gas Management Organization’s Carbon Footprint of Products (CFP) database. This factor, which covers raw water abstraction, treatment, and distribution processes, is 0.5410 kgCO₂e/m³ based on data updated in July 2022 [30].

The analysis focuses on aggregated national-level data to ensure consistency across service areas and to support policy-oriented sustainability assessment, including SDG 6.4 on water-use efficiency [31]. Although regional variability exists among PWA service areas, the use of aggregated nationwide data enables a comprehensive evaluation of system-wide operational performance. It provides an appropriate basis for national-level policy analysis. The implications of using aggregated national-level data and the associated sources of uncertainty are further discussed in the Limitations section.

Water balance and Non-Revenue Water assessment

NRW is quantified using the standard IWA water balance, defined as the difference between system input volume and authorized billed consumption [1]. NRW is conceptually divided into real losses (physical leakages) and apparent losses (metering inaccuracies and unauthorized consumption); however, due to data limitations at the national scale, the analysis focuses on total NRW volumes, consistent with previous large-scale assessments [2], [12].

The NRW ratio is calculated as the percentage of NRW volume relative to total system input volume, providing a normalized indicator for cross-year and cross-system comparison.

Energy intensity assessment

Energy efficiency of the water supply system is evaluated using energy intensity indicators, expressed as electricity consumption per unit volume of water supplied (kWh/m³), following established methodologies in water–energy nexus studies [11], [13].

To estimate the energy embedded in NRW, the average energy intensity is multiplied by the volume of NRW, assuming that lost water has undergone energy-intensive processes similar to those of delivered water [14]. This approach has been widely used to assess energy losses associated with water inefficiencies [11]. Due to data availability constraints at the national scale, this assumption may mask local-level variability but is appropriate for national-scale assessment and consistent with previous large-scale water–energy nexus studies. A uniform average energy intensity is assumed for water production and distribution. This energy intensity represents the combined electricity consumption for abstraction, treatment, and distribution processes, consistent with previous large-scale water–energy nexus studies. The total energy loss associated with NRW is estimated by multiplying NRW volumes by the average energy intensity.

Sensitivity Analysis

Sensitivity analysis was conducted to evaluate the potential impact of uncertainty in the assumption of a uniform average energy intensity. Three energy-intensity scenarios were considered, including a low-intensity case (-20% of the baseline value), the baseline case, and a high-intensity case (+20% of the baseline value). This range was selected to represent plausible variation in energy consumption across different water supply systems and operational conditions. The sensitivity analysis allows assessment of the robustness of the estimated energy losses and associated carbon emissions attributable to NRW.

Carbon emissions attributable to Non-Revenue Water

Carbon emissions associated with water supply operations are estimated by applying grid-based electricity emission factors to the calculated electricity consumption, in accordance with the IPCC guidelines for indirect Scope 2 emissions [5]. Carbon intensity is expressed as kilograms of carbon dioxide equivalent per cubic meter of water supplied (kgCO₂e/m³).

The carbon emissions from NRW are calculated by multiplying the energy embedded in NRW by the corresponding emission factor, providing an estimate of indirect carbon losses due to water inefficiencies [10], [11]. This indicator enables the assessment of NRW as a contributor to climate change impacts within the water supply sector.

Indicator-based evaluation

To support comparability and policy relevance, the results are presented using a set of standardized indicators, including NRW ratio (%), energy intensity (kWh/m³), carbon intensity (kgCO₂e/m³), and the proportion of energy and carbon losses attributable to NRW. These indicators are aligned with international sustainability assessment practices and provide a basis for evaluating the potential co-benefits of NRW reduction strategies [10], [31].

Mathematical formulation and indicator definitions

To quantitatively assess the impacts of NRW on energy efficiency and carbon footprint, a set of standardized indicators and equations is employed, following established practices in water–energy nexus and carbon accounting studies [11], [13], [15].

Non-Revenue Water Ratio. The NRW ratio is calculated as the proportion of NRW volume relative to the total system input volume, consistent with the IWA water balance framework [1], [12]:

$$NRW_{ratio} = \frac{V_{NRW}}{V_{SIV}} \times 100 \quad (1)$$

Where

V_{NRW} = volume of Non-Revenue Water (m³/year),
 V_{SIV} = total system input volume (m³/year).

Energy Intensity of Water Supply. The average energy intensity of the water supply system is defined as the total electricity consumption per unit volume of water produced [11], [13]:

The calculated Non-Revenue Water volumes were subsequently used to estimate the embedded energy losses associated with water losses in the distribution system.

$$EI = \frac{E_{total}}{V_{SIV}} \quad (2)$$

Where

EI = energy intensity of water supply (kWh/m³),
 E_{total} = total electricity consumption of the water supply system (kWh/year).

Energy Embedded in Non-Revenue Water. The energy embedded in NRW is estimated by multiplying the average energy intensity by the volume of NRW, assuming that lost water has undergone similar abstraction, treatment, and distribution processes as delivered water [11], [14]:

$$E_{NRW} = V_{NRW} \times EI \quad (3)$$

Where

E_{NRW} = energy embedded in Non-Revenue Water (kWh/year)

Carbon Footprint of Water Supply. The carbon footprint associated with water supply operations is calculated using grid-based electricity emission factors, in accordance with IPCC guidelines for indirect (Scope 2) emissions [15]:

$$CF = E_{total} \times EF \quad (4)$$

Where

CF = total carbon emissions from electricity consumption (kgCO₂e/year),
 EF = electricity emission factor (kgCO₂e/kWh).

Carbon Emissions Attributable to Non-Revenue Water. The carbon emissions attributable to NRW are estimated by applying the same emission factor to the energy embedded in NRW [10], [11]:

$$CF_{NRW} = E_{NRW} \times EF \quad (5)$$

Where

CF_{NRW} = carbon emissions attributable to Non-Revenue Water (kgCO₂e/year),
 EF = electricity emission factor (kgCO₂e/kWh).

Based on the analytical framework shown in Figure 1, the assessment first quantifies system input volume, billed consumption, and NRW using aggregated operational data from the Provincial Waterworks Authority. These water balance components provide the basis for estimating the energy intensity of the water supply system and the associated energy and carbon losses attributable to NRW.

The analysis follows a sequential calculation procedure. First, energy intensity is calculated as the ratio of total electricity consumption to system input volume (Eq. 2). Subsequently, the embedded energy associated with NRW is estimated by multiplying the calculated energy intensity by NRW volume (Eq. 3). Finally, carbon emissions linked to both total system energy use and NRW-related energy losses are estimated using an electricity emission factor (Eqs. 4 and 5).

All variables are expressed annually, with water volumes reported in cubic meters (m³), energy consumption in kilowatt-hours (kWh), and carbon emissions in kilograms of CO₂ equivalent (kgCO₂e).

The overall analytical framework adopted in this study is presented in Figure 1.

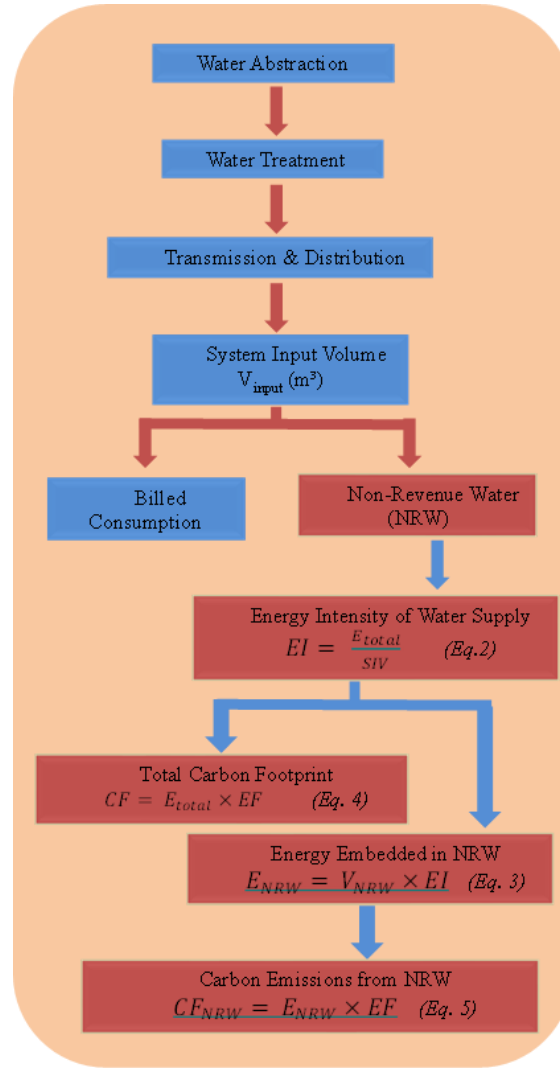


Figure 1. Analytical framework for quantifying energy and carbon losses associated with Non-Revenue Water

Figure 1 illustrates the proposed analytical framework integrating the IWA water balance, energy-intensity assessment, and carbon-emission estimation to quantify embedded energy losses and indirect greenhouse gas emissions attributable to Non-Revenue Water.

RESULTS AND DISCUSSION

National-level Non-Revenue Water characteristics and energy losses

The nationwide assessment reveals that NRW remains persistently high within Thailand's Provincial Waterworks Authority (PWA) system throughout the study period (2020–2024). Although annual system input volumes exhibit only minor fluctuations, NRW consistently represents a substantial proportion of treated water, indicating structural inefficiencies in the distribution network. Specifically, the national average NRW for the PWA system during the study period is estimated at 27–29%, more than double the typical levels observed in well-performing water utilities in developed countries.

To provide an overview of water balance components at the national level, Table 2 summarizes the annual system input volume, billed authorized consumption, and non-revenue water of the PWA system during 2020–2024.

Table 2. Summary of annual water input, billed consumption, and NRW in the PWA system (2020–2024)

Year	System Input Volume (m ³)	Billed Consumption (Revenue Water)	Non-Revenue Water (NRW)	% NRW
2020	1,990,194,532	1,379,248,180	610,946,353	30.70
2021	1,991,812,328	1,399,104,319	592,708,009	29.76
2022	2,003,204,790	1,436,356,691	566,848,100	28.30
2023	2,079,828,799	1,508,973,992	570,854,807	27.45
2024	2,186,035,145	1,585,585,145	600,450,000	27.47

As shown in Table 2, NRW consistently accounts for a substantial proportion of treated water throughout the study period, confirming the persistence of structural losses within the distribution system.

When expressed in energy terms, NRW represents an annual energy loss of more than 200 million kWh, as shown in Figure 2. This magnitude of energy loss reflects the cumulative electricity consumed during water abstraction, treatment, and pumping processes that ultimately do not deliver billed services. The results demonstrate that energy inefficiency in the water sector is not solely driven by demand growth but is strongly linked to distribution-level losses.

NRW-related energy consumption is further illustrated in Figure 2, which depicts the annual trends in NRW-related energy losses over the study period.

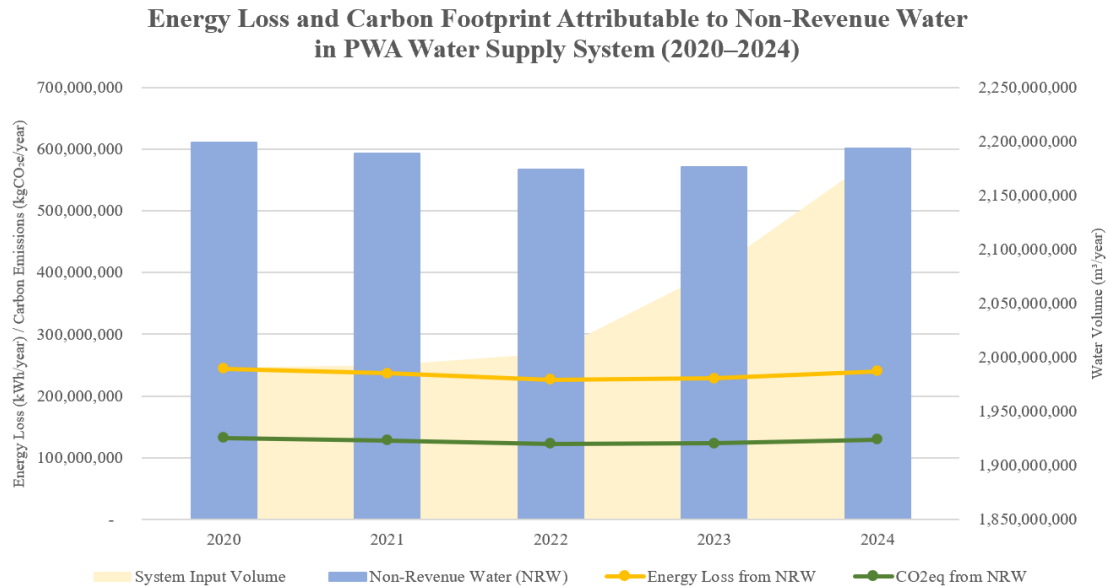


Figure 2. Trends of NRW in PWA’s system and its energy loss and carbon emissions from 2020 to 2024.

Figure 2 shows trends of NRW, associated energy losses, and CO₂-equivalent emissions in the PWA water supply system.

While the lines indicate the corresponding energy losses and carbon emissions attributable to NRW, the system input volume is included for context.

The results presented above provide a quantitative basis for examining the magnitude and temporal trends of energy loss and carbon emissions attributable to NRW in Thailand’s water supply system. The following section discusses these findings in relation to system performance, policy implications, and national carbon neutrality objectives.

Figure 2 indicates that despite relatively stable system input volumes, NRW-related energy losses remain persistently high, exceeding 200 million kWh annually. This finding highlights that energy inefficiency in the water supply system is primarily driven by distribution-level losses rather than increased water demand.

In comparison, water utilities in developed countries typically report NRW levels below 15%, with several leading utilities achieving values under 10% through advanced leakage management, pressure control, and asset renewal programs [1], [12]. By contrast, Thailand’s NRW level during 2020–2024 remains significantly higher, resulting in disproportionately larger energy losses embedded in non-revenue water on both an absolute and relative basis. Consequently, the energy losses embedded in NRW in these systems are significantly lower, both in absolute terms and relative to total energy consumption. This contrast highlights the substantial, largely untapped potential for energy savings and carbon emissions reduction in Thailand’s water supply system through NRW reduction alone.

Carbon footprint attributable to Non-Revenue Water

To quantify the energy and carbon implications of NRW in more detail, Table 3 summarizes the estimated energy losses and associated carbon emissions attributable to NRW at the national level.

Table 3. Energy loss and carbon emissions associated with NRW in the PWA system (2020–2024)

Year	Non-Revenue Water	Energy Loss from NRW	CO ₂ e from Non-Revenue Water
2020	610,946,353	244,378,541	132,208,791
2021	592,708,009	237,083,204	128,262,013
2022	566,848,100	226,739,240	122,665,929
2023	570,854,807	228,341,923	123,532,980
2024	600,450,000	240,180,000	129,937,380

The estimated carbon footprint associated with NRW demonstrates a direct relationship with energy losses, as shown in (Eq.5). Over the five years, carbon emissions attributable to NRW range between approximately 122.7–132.2 million kgCO₂e per year, with a slight upward trend observed toward 2024.

This increase can be attributed primarily to sustained high NRW volumes combined with the carbon-intensive nature of Thailand’s electricity generation mix [15]

The results confirm that NRW represents not only water resource inefficiency but also a hidden source of greenhouse gas emissions embedded within water utility operations. This aligns with previous studies indicating that energy-related emissions from water supply systems are often underestimated when NRW is excluded from carbon accounting frameworks [10].

In contrast, utilities in OECD countries achieve lower NRW-related emissions not only through reduced water losses but also through structurally lower energy intensity and cleaner electricity systems, underscoring the compounded disadvantage faced by carbon-intensive grids.

Scenario Analysis of Non-Revenue Water Reduction Targets

Table 4. Scenario analysis of potential energy and carbon savings under alternative NRW reduction targets (based on 2024 operational conditions)

<i>NRW (%)</i>	<i>NRW Volume (m³)</i>	<i>Energy Loss (kWh)</i>	<i>CO₂e from NRW (kgCO₂e)</i>	<i>Energy Reduction (%)</i>	<i>Carbon Reduction (%)</i>
27.47 (Baseline)	600,450,000	240,180,000	129,937,380	0.0	0.0
25	528,528,382	211,411,353	114,373,542	12.0	12.0
20	396,396,286	158,558,515	85,780,156	34.0	34.0
15	279,809,143	111,923,657	60,550,699	53.4	53.4
10	176,176,127	70,470,451	38,124,514	70.7	70.7

To provide a more policy-relevant interpretation of the results, a counterfactual scenario analysis was conducted using the 2024 operational conditions as the baseline. The analysis evaluated the potential reductions in embedded energy losses and associated carbon emissions under progressively lower NRW levels of 25%, 20%, 15%, and 10%, while maintaining the same billed water consumption.

The results demonstrate that substantial energy and carbon savings could be achieved through NRW reduction (Table 4). Under the 25% NRW scenario, energy losses decreased from 240.18 million kWh to 211.41 million kWh, corresponding to a reduction of approximately 12.0%. Similarly, carbon emissions attributable to NRW decreased from 129.94 million kgCO₂e to 114.37 million kgCO₂e.

More substantial benefits are observed under the 15% NRW scenario, where embedded energy losses are reduced to 111.92 million kWh and associated carbon emissions decline to 60.55 million kgCO₂e, representing reductions of approximately 53.4% compared with the baseline condition. Under the 10% NRW scenario, energy losses and carbon emissions are reduced by approximately 70.7%, highlighting the significant mitigation potential associated with aggressive NRW management strategies.

These findings indicate that NRW reduction can generate substantial co-benefits extending beyond water conservation, including improvements in energy efficiency and reductions in indirect greenhouse gas emissions. The results, therefore, reinforce the importance of incorporating NRW reduction targets into broader sustainability and climate mitigation strategies in the water sector.

Comparative Indicators of Non-Revenue Water-Related Energy and Carbon Losses

To improve the interpretability of the results, comparative indicators were developed to express the energy and carbon implications associated with each percentage point of NRW. Based on the 2024 operational conditions, each one-percentage-point reduction in NRW corresponds to approximately 8.74 million kWh of embedded energy loss and 4.73 million kgCO₂e of indirect carbon emissions (Table 5). These indicators provide a simplified representation of the energy and carbon burden associated with NRW and facilitate comparisons across utilities, regions, and future NRW-reduction scenarios.

Table 5. Comparative Indicators of NRW-Related Energy and Carbon Losses

<i>Indicator</i>	<i>Value</i>
<i>Energy loss per 1% NRW</i>	8.74 million kWh
<i>Carbon emissions per 1% NRW</i>	4.73 million kgCO ₂ e

Sensitivity Analysis of Energy-Intensity Assumptions

Table 6. Sensitivity analysis of NRW-related energy losses and carbon emissions under alternative energy-intensity assumptions (2024)

<i>Energy Intensity Scenario</i>	<i>Energy Intensity (kWh/m³)</i>	<i>Energy Loss (kWh)</i>	<i>CO₂e (kgCO₂e)</i>
<i>Low (-20%)</i>	0.32	192,144,000	103,949,904
<i>Baseline</i>	0.40	240,180,000	129,937,380
<i>High (+20%)</i>	0.48	288,216,000	155,924,856

A sensitivity analysis was performed to evaluate the influence of the uniform energy-intensity assumption on the estimated energy losses and carbon emissions attributable to NRW (Table 6). The results indicate that NRW-related energy losses range from 192.14 million kWh under the low-intensity scenario to 288.22 million kWh under the high-intensity scenario. Correspondingly, estimated carbon emissions range from 103.95 million kgCO₂e to 155.92 million kgCO₂e.

Although the absolute values vary with the assumed energy intensity, the overall relationship among NRW, energy consumption, and carbon emissions remains consistent across all scenarios. These findings suggest that the analytical framework is robust and that the principal conclusions of the study are not substantially affected by reasonable variations in energy-intensity assumptions.

Structural energy and carbon inefficiency associated with Non-Revenue Water.

Although minor fluctuations in NRW-related energy loss are observed across years, no substantial reduction trend is evident. This suggests that existing NRW management measures have not yet translated into measurable energy or carbon savings on the national scale.

From an energy-efficiency perspective, reducing NRW offers a dual benefit, lowering operational electricity consumption and reducing indirect carbon emissions without requiring additional low-carbon energy investments.

These findings reinforce the argument that NRW reduction should be considered a climate mitigation strategy within the water sector, consistent with the principles of SDG 6.4 and national climate policy objectives [11].

The results indicate that NRW should not be interpreted solely as a loss of water resources. In Thailand, where electricity generation remains heavily dependent on fossil-fuel-based energy sources, NRW also represents a structural source of energy and carbon inefficiency. Water lost before reaching consumers embodies the cumulative energy required for abstraction, treatment, transmission, and distribution. Consequently, NRW generates indirect greenhouse gas emissions without providing corresponding economic or social benefits. This perspective extends conventional NRW assessment beyond operational efficiency metrics and highlights the interconnected nature of water, energy, and climate systems. Therefore, NRW reduction should be viewed not only as a water conservation measure but also as an energy-efficiency and climate-mitigation strategy within the broader water–energy–carbon nexus.

Non-Revenue Water-Related Emissions in Water-Sector Greenhouse Gas Accounting

Although water utilities increasingly monitor operational energy consumption and greenhouse gas emissions, emissions attributable specifically to Non-Revenue Water (NRW) are often overlooked in conventional accounting frameworks. Existing greenhouse gas inventories typically focus on total electricity consumption associated with water abstraction, treatment, and distribution, without distinguishing between water that reaches consumers and water ultimately lost within the system. As a result, the indirect carbon emissions embodied in NRW remain largely invisible in performance assessments and climate reporting. This omission may underestimate the broader environmental implications of NRW and limit recognition of NRW reduction as a climate mitigation measure. The findings of this study highlight the importance of explicitly incorporating NRW-related energy losses and associated emissions into sustainability assessments of water utilities.

Contribution to Water–Energy–Carbon Nexus Research

The proposed framework contributes to the development of water–energy–carbon nexus research by integrating operational NRW assessment with national-scale energy and carbon accounting. While previous studies have often examined water losses, energy consumption, or carbon emissions separately, the present study explicitly links these dimensions within a unified analytical framework. The results demonstrate that NRW serves as a conduit through which water inefficiencies translate into additional energy consumption and indirect greenhouse gas emissions. By quantifying the interactions among water losses, energy consumption, and greenhouse gas emissions using nationwide operational data, the proposed framework broadens the application of water–energy–carbon nexus assessment from utility performance evaluation toward national-scale sustainability assessment. Furthermore, the framework provides a transferable analytical approach that can support integrated resource-efficiency and climate-mitigation planning in other developing countries.

Policy implications and relevance to carbon neutrality

Although NRW-related energy losses represent only a fraction of Thailand’s total electricity consumption, the associated carbon emissions remain significant from a water-sector perspective. The scenario analysis indicates that reducing NRW from the current level of 27.47% to 15% could decrease embedded energy losses and associated carbon emissions by approximately 53.4%. Consequently, NRW reduction can contribute to national resource-efficiency objectives and support Thailand’s long-term greenhouse gas mitigation commitments under its Nationally Determined Contribution (NDC).

From a policy perspective, the findings demonstrate that reducing Non-Revenue Water is among the most immediate opportunities to improve energy efficiency and reduce indirect greenhouse gas emissions in Thailand’s public water supply system. At the national scale, the magnitude of energy losses associated with Non-Revenue Water represents a missed opportunity to achieve carbon reductions without increasing water production or implementing additional demand-side interventions. From a climate policy perspective, the results indicate that NRW reduction constitutes a low-regret mitigation option. Unlike renewable energy investments or major infrastructure transitions, NRW control measures—such as leakage reduction, pressure management, and meter accuracy improvement—directly reduce electricity demand while maintaining service levels. This dual benefit aligns with international findings that efficiency-based mitigation in the water sector offers high emission reduction potential at relatively low cost [10], [11].

Importantly, Thailand’s current carbon mitigation strategies predominantly focus on the energy and transport sectors, while energy-related emissions embedded in water services remain largely invisible in national greenhouse gas inventories. The results of this study suggest that excluding NRW-related emissions may lead to a systematic underestimation of the water sector’s contribution to national carbon emissions. Integrating NRW-induced energy losses into climate accounting frameworks would improve transparency and support more comprehensive mitigation planning, particularly in the context of Thailand’s long-term carbon neutrality and net-zero commitments [15].

Carbon Footprint Attributable to Non-Revenue Water

Table 7 compares NRW levels, embedded energy losses, and carbon intensity indicators between Thailand and selected developed countries. The comparison provides an international benchmark for evaluating the relative performance of Thailand’s public water supply system. It highlights the potential sustainability benefits achievable through further reductions in NRW.

Table 7 Comparison of NRW, Energy Loss, and Carbon Intensity: Thailand vs. Developed Countries.

Indicator	Thailand (PWA – Nationwide)	Developed Countries (OECD Typical Range)
Non-Revenue Water (NRW)	~25–35% of system input volume	<15% (best practice <10%)
NRW Management Approach	Predominantly reactive / project-based	Proactive, long-term asset management
Energy Loss Attributable to NRW	>200 million kWh/year (national scale)	Significantly lower due to reduced NRW
Energy Loss per m ³ of NRW	High, due to pumping and treatment intensity	Lower, supported by efficient systems
Electricity Carbon Intensity	High (fossil-fuel-dominated grid)	Low to moderate (higher renewable share)
Carbon Footprint of NRW	~122.7–132.2 million kgCO ₂ e/year	Substantially lower per-unit water loss
Role of NRW in Climate Policy	Largely unaccounted for	Increasingly integrated into energy/climate strategies
Contribution to Carbon Neutrality	High mitigation potential, underutilized	Incremental but already optimized

As shown in Table 7, Thailand exhibits considerably higher NRW levels than most developed countries, where NRW is typically kept below 15% through advanced leakage management, infrastructure maintenance, and operational monitoring. The higher NRW levels observed in Thailand are associated with correspondingly greater embedded energy losses and indirect carbon emissions. These findings suggest that reducing NRW could provide substantial co-benefits not only for water conservation but also for improving energy efficiency and reducing greenhouse gas emissions. The comparison further indicates that achieving NRW levels comparable to those of developed countries could significantly enhance the sustainability performance of Thailand's water supply sector.

The international comparison presented in Table 7 is further discussed in relation to previous NRW and water–energy–carbon nexus studies.

International Comparison with Previous Studies

The findings of this study are generally consistent with previous international research demonstrating that Non-Revenue Water contributes not only to water losses but also to embedded energy consumption and indirect greenhouse gas emissions. Studies conducted in urban water systems in Australia, Europe, and the Middle East have similarly reported that water losses are a significant source of avoidable energy use, as energy is consumed throughout the abstraction, treatment, and distribution processes before water reaches end users [18], [37]. Recent water–energy–carbon nexus studies have further highlighted that improving operational efficiency and reducing water losses can generate simultaneous benefits for water conservation, energy efficiency, and greenhouse gas mitigation [35], [39]. The present study extends these findings by providing a nationwide assessment using aggregated operational data from Thailand's public water supply system, thereby offering evidence at a broader spatial scale than most utility-level investigations.

Data Resolution and Methodological Differences

Differences between the present results and those reported in previous studies may partly reflect variations in data resolution and methodological approaches. Many existing investigations employ utility-level, district-level, or distribution-zone data, enabling detailed analysis of leakage patterns, pumping requirements, and operational characteristics. In contrast, the present study utilizes aggregated national-level operational data to provide a system-wide assessment of NRW-related energy losses and carbon emissions. While this approach improves policy relevance

and national representativeness, it may mask local variability in infrastructure conditions, topography, treatment requirements, and energy intensity. Consequently, the results should be interpreted as national-scale estimates rather than precise representations of individual service areas.

Policy Implications of Methodological Uncertainty

Despite these methodological limitations, the overall policy implications remain robust. The sensitivity analysis indicates that reasonable variations in energy-intensity assumptions affect the magnitude of estimated energy losses and carbon emissions but do not alter the overall relationship between NRW, energy consumption, and greenhouse gas emissions. Therefore, the study provides a useful evidence base for policymakers seeking to integrate NRW reduction into broader resource-efficiency and climate-mitigation strategies. Future assessments using higher-resolution operational data could further improve the precision of estimates while maintaining the conceptual framework proposed in this study.

Implications for utility-level decision-making and national planning

At the utility level, the results suggest that prioritizing NRW reduction projects based on carbon abatement potential per unit of investment could significantly enhance the cost-effectiveness of mitigation strategies. This approach would enable water utilities such as the Provincial Waterworks Authority to justify NRW reduction not only on economic grounds, but also as a measurable contribution to national climate commitments.

At the national level, incorporating NRW-related energy and carbon indicators into regulatory benchmarking and performance reporting could shift investment priorities toward interventions with the highest climate co-benefits. Such integration would position the water supply sector as an active participant in Thailand's transition toward carbon neutrality, rather than a passive energy consumer.

Specific Policy Recommendations for Thailand

For Thailand, NRW reduction should be incorporated into national resource-efficiency and climate-mitigation strategies rather than being treated solely as an operational performance target. The Provincial Waterworks Authority (PWA) could integrate NRW reduction targets into energy-efficiency and greenhouse-gas management plans by prioritizing leakage-control programs, district-metered area (DMA) implementation, pressure management, smart-metering technologies, and infrastructure rehabilitation. Furthermore, NRW-related energy losses and associated carbon emissions could be included as supplementary performance indicators within utility sustainability reporting frameworks. Such measures would strengthen the alignment between water-sector management and Thailand's long-term Carbon Neutrality 2050 and Net Zero Greenhouse Gas Emissions 2065 policy objectives.

International Best-Practice Examples

International experience demonstrates that substantial NRW reduction can be achieved through integrated technical and managerial interventions. Singapore has consistently maintained NRW levels below 5% through advanced asset management, real-time monitoring systems, and proactive leakage control programs. Similarly, Denmark and Germany have achieved NRW levels below 10% through long-term infrastructure investment, pressure management, and systematic network maintenance. These examples suggest that sustained NRW reduction requires not only technological solutions but also institutional commitment, continuous monitoring, and long-term investment strategies. Adapting selected elements of these approaches to the Thai context could improve the sustainability performance of the national water supply system.

Mitigation Pathways and Implementation Strategies

The findings also indicate several potential mitigation pathways for reducing NRW-related energy losses and carbon emissions. In the short term, utilities may focus on operational measures such as active leakage detection, pressure optimization, and improved meter management. Medium-term strategies include network rehabilitation, replacement of aging infrastructure, and expansion of district metered areas. In the longer term, NRW reduction initiatives could be integrated with renewable-energy deployment, digital water management systems, and carbon-neutral utility strategies. Such an integrated approach would enable simultaneous improvements in water conservation, energy efficiency, and greenhouse gas mitigation while supporting broader sustainability objectives.

Broader implications for carbon-neutral water supply systems

The results of this nationwide case study underscore the need to reconceptualize water supply systems as energy–carbon systems, rather than solely hydraulic infrastructures. Achieving carbon-neutral water services will require not only cleaner energy sources but also systematic reductions in energy waste embedded in water losses.

In this context, NRW reduction is a foundational strategy for a carbon-neutral water supply, particularly in countries where electricity grids remain carbon-intensive. The analytical framework developed in this study provides a scalable approach for quantifying NRW-related carbon impacts. It can be applied to other national or regional water utilities seeking to align operational efficiency with climate mitigation goals.

The findings also have important implications for the transition toward carbon-neutral water supply systems. Traditionally, decarbonization strategies in the water sector have focused on improving pumping efficiency, adopting renewable energy technologies, and reducing operational energy consumption. However, the present study demonstrates that NRW reduction can provide an additional pathway for greenhouse gas mitigation by avoiding unnecessary energy use throughout the water supply chain. Consequently, NRW management should be considered an integral component of carbon-neutral water utility strategies rather than solely a water conservation measure. Integrating NRW reduction targets with energy-efficiency and decarbonization initiatives may therefore generate multiple sustainability benefits across water, energy, and climate sectors. These results collectively demonstrate that NRW reduction represents a critical leverage point for improving energy efficiency and reducing carbon emissions in Thailand's water supply sector.

Limitations and Future Research

The assumption of a uniform average energy intensity may introduce uncertainty in estimating NRW-related energy losses. In practice, energy intensity varies across water supply systems depending on factors such as source-water characteristics, treatment requirements, pumping distances, and topographical conditions. Consequently, using a national average may lead to overestimation or underestimation of actual NRW-related energy losses in specific service areas. However, the sensitivity analysis demonstrates that the overall relationship between NRW, energy consumption, and carbon emissions remains stable across plausible energy-intensity ranges. Therefore, while the absolute values may vary, the principal conclusions of the study remain robust and suitable for national-scale assessment.

Another limitation arises from the use of aggregated national-level operational data. Although the national-scale approach provides a comprehensive overview of the performance of Thailand's public water supply system, it may mask important regional variations in NRW levels, infrastructure conditions, source-water characteristics, pumping requirements, treatment processes, and operational practices across service areas. Consequently, the results should be interpreted as system-wide estimates rather than precise representations of individual Provincial Waterworks Authority branches or regions. Furthermore, the availability of detailed branch-level operational and energy-consumption data remains limited, restricting the ability to evaluate spatial variability and identify location-specific drivers of NRW-related energy losses and carbon emissions.

Additional uncertainty arises from the system-wide assumptions adopted in the analytical framework. The study applies a uniform average energy intensity and a nationally representative emission factor to estimate NRW-related energy losses and carbon emissions. While these assumptions are appropriate for a national-scale assessment and improve comparability across years, they may not fully capture local differences in treatment complexity, distribution-network characteristics, electricity consumption patterns, and electricity-generation mixes. Nevertheless, the sensitivity analysis indicates that reasonable variations in energy-intensity assumptions do not substantially alter the overall relationship between NRW, energy consumption, and carbon emissions. Therefore, the principal conclusions remain robust despite inherent uncertainties associated with aggregated data and system-wide assumptions.

CONCLUSION

Non-Revenue Water in the water supply system represents a systemic inefficiency with significant energy and carbon implications that extend far beyond conventional interpretations of water loss. A nationwide assessment of the Provincial Waterworks Authority reveals that NRW is responsible for substantial embedded energy losses and associated carbon emissions, which persist over time with no clear downward trend.

When compared with water utilities in developed countries, a pronounced performance gap becomes evident. While many OECD countries have successfully reduced NRW to levels below 15% through long-term asset

management, advanced monitoring, and performance-based regulation, Thailand continues to experience substantially higher NRW levels. This gap directly translates into higher energy losses per unit of water delivered and a disproportionately larger carbon footprint, particularly given the carbon-intensive nature of Thailand's electricity generation mix.

Importantly, the findings indicate that the climate impact of NRW is not solely a function of the volume of water loss but also of structural differences in energy efficiency and decarbonization pathways between developing and developed economies. In countries with low-carbon electricity systems, the residual emissions associated with NRW are comparatively limited. In contrast, in Thailand and similar contexts, NRW magnifies indirect greenhouse gas emissions, making it a critical yet underrecognized source of carbon inefficiency.

The results underscore that continuing to evaluate NRW solely through volumetric or percentage-based indicators risks underestimating its broader sustainability impacts. Without explicitly accounting for energy consumption and carbon emissions embedded in NRW, progress toward national and international targets, particularly SDG 6.4 on water-use efficiency and SDG 13 on climate action, may be overstated.

From a policy perspective, this study highlights that NRW reduction is among the most immediate and cost-effective opportunities to improve energy efficiency and advance carbon neutrality in the water sector. Bridging the gap between Thailand and developed countries will require reframing NRW reduction as a strategic climate mitigation measure, supported by integrated water–energy–carbon performance metrics and nationally coordinated intervention programs.

Beyond the Thai context, the findings provide broader implications for developing countries where NRW levels remain high, and electricity systems continue to rely heavily on fossil fuels. The analytical framework developed in this study demonstrates that NRW can be interpreted as a hidden source of energy and carbon inefficiency embedded within water supply systems. This perspective offers a transferable basis for integrating NRW reduction into climate mitigation and resource-efficiency strategies. Future studies may apply the framework to different national contexts to evaluate how NRW reduction contributes simultaneously to water conservation, energy efficiency improvement, and greenhouse gas mitigation.

Ultimately, achieving carbon-neutral water supply systems will depend not only on cleaner energy sources but also on eliminating avoidable energy waste embedded in water losses. Addressing NRW is therefore not optional but foundational to aligning Thailand's water sector with long-term sustainability and carbon-neutrality goals.

Recognizing and addressing NRW as an energy and carbon issue, rather than solely a water-loss problem, is essential for transitioning toward truly sustainable, carbon-neutral water supply systems.

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