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Article

Long-Term Performance Evaluation of BTU Metering under Seasonal & Low-Load Conditions in District Cooling Systems: A Before-and-After Pilot Study.

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Abstract: District Cooling Systems (DCS) are increasingly adopted in smart urban developments to improve energy efficiency, reduce greenhouse gas emissions, and provide centralized cooling for commercial and residential buildings. Accurate thermal energy measurement through Building Thermal Unit (BTU) meters is fundamental for energy billing, operational optimization, and system performance assessment. However, BTU meter performance is often affected under seasonal low-load operating conditions, where reduced chilled water flow rates and diminished temperature differences (ΔT) introduce measurement uncertainties and compromise energy accounting.

This paper presents yearly operational trend analysis of BTU meter performance using data collected from two representative commercial buildings connected to a large-scale district cooling network. To preserve operational confidentiality, the monitored facilities are referred to as Case Study Building A and Case Study Building B. Historical operational data including chilled water flow rate, supply temperature, return temperature, ΔT, cooling energy, and meter diagnostics were analyzed.

The results demonstrate that seasonal variations & low load in system significantly influence BTU meter accuracy. During low-load periods, flow & ΔT degradation of up to 35% was observed, accompanied by reduced flow velocity and increased measurement uncertainty. Statistical analysis indicates a strong correlation between flow rate reduction and thermal energy measurement deviation. The findings further reveal that proactive pilot measurement strategies, periodic calibration, optimized sensor placement, and continuous SCADA-based monitoring substantially improve metering reliability under varying operating conditions.

The study provides practical recommendations for district cooling utilities seeking to enhance thermal energy measurement accuracy, improve operational efficiency, and support long-term energy sustainability.

Keywords: District Cooling System; BTU Meter; Thermal Energy Measurement; Seasonal Analysis; Low-Load Operation; SCADA; Energy Efficiency; ΔT Degradation.

1. INTRODUCTION

This study extends our previous work on improving BTU measurement accuracy using advanced measurement and control strategies. While the earlier study focused on retrofit implementation and accuracy improvement[1], the present work investigates the long-term seasonal performance and operational trends of BTU meters using extended monitoring data.

District Cooling Systems have become a preferred cooling solution for large commercial developments, smart cities, institutional campuses, and mixed-use urban districts because they centralize cooling production and improve overall system efficiency. Compared with conventional building-level chillers, centralized systems reduce energy consumption, maintenance requirements, and environmental impacts[2], [3], [4], [5], [6], [7], [8], [9], [10].

An essential component of any district cooling network is the Building Thermal Unit (BTU) meter. BTU meters determine the thermal energy delivered to customers using three primary measurements:

Volumetric flow rate

Supply water temperature

Return water temperature

Cooling energy is calculated as:

$Q = \rho \times Cp \times Flow \times \Delta T$

where

Q = Thermal Energy

ρ = Water Density

Cp = Specific Heat Capacity

Flow = Chilled Water Flow Rate

ΔT = Return Temperature − Supply Temperature

Although BTU metering performs satisfactorily under design conditions, measurement accuracy deteriorates during seasonal low-load operation because both chilled water flow and temperature difference reduce considerably. Under such operating conditions, even minor flow and sensor inaccuracies may produce significant errors in calculated cooling energy[1], [11], [12].

Several studies have investigated BTU meter accuracy under laboratory conditions. However, limited literature exists on long-term industrial performance using actual operational data obtained from district cooling networks over multiple seasons. Furthermore, few studies evaluate the combined influence of seasonal load variation, ΔT degradation, flow instability, and operational practices on measurement accuracy[1].

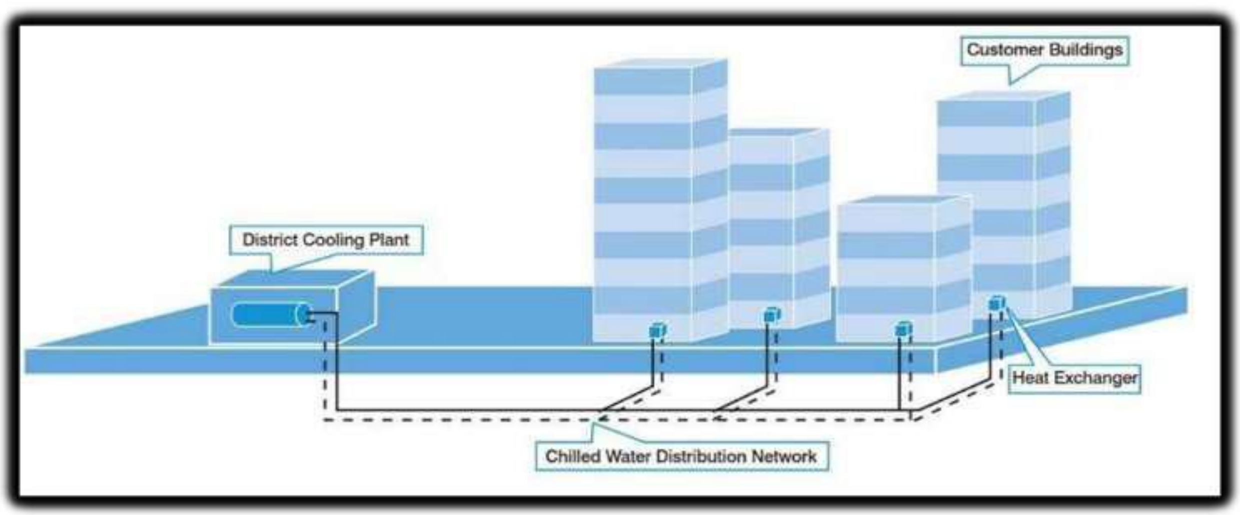

Figure 1: DCS Plant with Distribution Networks diagram[1], [5], [13], [14].

1. PROBLEM DEFINITION

Although District Cooling Systems (DCS) provide significant advantages in terms of centralized cooling, energy efficiency, and operational reliability, maintaining accurate thermal energy measurement under varying seasonal operating conditions remains a critical challenge. Building Thermal Unit (BTU) meters are widely used for cooling energy measurement and customer billing; however, their performance can be influenced by seasonal variations in cooling demand, particularly during low-load operating periods.

During winter and transitional seasons, reduced cooling demand often results in lower chilled water flow rates and decreased temperature differences (ΔT) across building heat exchangers. These operating conditions may increase measurement uncertainty, affect the accuracy of thermal energy calculations, and complicate the assessment of actual cooling energy consumption. Furthermore, long-term operational variations caused by changes in occupancy patterns, hydraulic conditions, and control system performance can contribute to flow & ΔT degradation and reduced metering reliability[1].

Despite considerable research on BTU metering technologies, relatively few studies have investigated the long-term field performance of BTU meters using continuous operational data collected over multiple seasons from large-scale district cooling networks. Consequently, there remains a need for a comprehensive evaluation of BTU meter performance, flow variation, ΔT behavior, and seasonal operating characteristics to better understand their impact on measurement accuracy and overall energy performance[1].

This study addresses these challenges by analyzing yearly operational data from representative commercial buildings served by a centralized district cooling network. The objective is to evaluate long-term BTU meter performance under seasonal low-load conditions and to identify practical measurement and operational pilot strategies that enhance thermal energy measurement accuracy, improve system efficiency, and support reliable energy management[1], [15].

2. RESEARCH GAP

This paper addresses these research gaps by analyzing yearly operational data collected from two representative commercial buildings supplied by a centralized district cooling network. The objectives are to:

- Evaluate long-term BTU meter performance.
- Investigate seasonal ΔT degradation.
- Analyze flow variation during different operating periods.
- Assess measurement uncertainty under low-load conditions.
- Examine operational implications on energy accounting.
- Recommend practical strategies for improving measurement reliability.

a. Literature Review

District cooling systems (DCS) are increasingly recognized for their energy efficiency, yet they face challenges such as “low delta-T syndrome”, which can significantly impact performance. This overview synthesizes key aspects of prior work on DCS energy performance, metering principles, and related technologies.

Figure 2: BTU Measurement Infrastructure.

b. District Cooling Energy Performance

Low delta-T syndrome leads to inefficient chiller operation and increased energy consumption, particularly at low loads[16].

Optimization strategies include adjusting chiller configurations and improving pumping station designs, which can reduce electricity consumption by up to 15.3%[17].

c. BTU Metering Principles

Accurate BTU metering is essential for assessing energy consumption in DCS, ensuring that billing reflects actual usage and system performance.

Ultrasonic and Electromagnetic Flow Meters

These flow meters are critical for precise measurement in DCS, with ultrasonic meters offering advantages in non-intrusive measurement and electromagnetic meters providing high accuracy in conductive fluids.

Temperature Sensor Uncertainty

Sensor inaccuracies can lead to significant errors in energy calculations, necessitating robust calibration and maintenance protocols to ensure reliable data.

d. Low-Flow Measurement Challenges

Low-flow conditions complicate accurate measurement, often leading to underreporting of energy use and inefficiencies in system operation.

ΔT Degradation

"Low delta-T syndrome" is exacerbated by poor valve authority and control failures, which can increase pump energy consumption and reduce overall system efficiency[16].

e. SCADA-Based Energy Monitoring

SCADA systems enhance monitoring capabilities, allowing for real-time data analysis and improved operational decision-making in DCS.

f. Calibration and Uncertainty Analysis

Regular calibration of measurement devices is crucial to minimizing uncertainty and ensures accurate energy billing, which is vital for both operational efficiency and customer satisfaction[18].

g. Energy Billing Accuracy

Accurate energy billing relies on precise measurements from flow meters and temperature sensors, highlighting the importance of addressing measurement uncertainties and system inefficiencies.

While significant advancements have been made in optimizing DCS performance, challenges such as low delta-T syndrome and measurement inaccuracies remain prevalent. Addressing these issues is essential for enhancing energy efficiency and ensuring accurate billing in district cooling systems[16].

The long-term trend analysis of BTU meter performance in district cooling networks, particularly under seasonal low-load conditions, reveals critical insights into operational efficiency and energy management. The performance of district cooling systems (DCS) is significantly influenced by partial load operations, which are prevalent during low-demand periods. This analysis highlights several key aspects.

Partial Load Performance

District cooling systems often operate at partial load, with rates dropping below 25% for over half the cooling season[19].

Electric chillers, designed for peak demand, frequently run at reduced capacity, impacting their efficiency and performance metrics such as the coefficient of performance (COP)[20].

Energy Efficiency and Optimization

The average energy efficiency ratio (EER) for DCS can vary, with reported values of 3.65 and 3.81 in different years[19].

Optimization measures, including equipment adjustments and operational strategies, can enhance performance scores significantly, as demonstrated in case studies[21].

Economic Considerations

Utilizing off-peak electricity for cooling operations can lead to substantial cost savings, as DCS can operate more economically during low-load periods[19].

The integration of thermal energy storage systems allows for better load management and energy utilization, further improving economic viability[22].

Conversely, while district cooling systems show potential for efficiency improvements, their performance can be inconsistent compared to individual cooling systems, particularly in varying building densities and operational contexts[23].

3. RESEARCH METHODOLOGY

a. Study System

The present study was conducted on two commercial buildings connected to a centralized District Cooling System (DCS) operating within a smart city infrastructure. To maintain confidentiality in accordance with the organization’s data-sharing policy, the buildings are referred to as Case Study Building A and Case Study Building B throughout this paper.

Each building receives chilled water from a central district cooling plant through an underground distribution network. Thermal energy consumption is measured at the Building Energy Transfer Station (BETS) using BTU meters integrated with the Supervisory Control and Data Acquisition (SCADA) system.

The overall study system comprises:

- Central chilled water production plant

- Chilled water distribution network
- Building Energy Transfer Stations (BETS)
- Ultrasonic BTU meters
- Siemens PLC-based control system
- SCADA and Historian database for continuous data acquisition

The study investigates the long-term performance of BTU metering under seasonal low-load operating conditions and evaluates the effectiveness of an improved measurement and control strategy implemented through a pilot project[1].

b. Data Collection

Operational data were collected continuously from the SCADA Historian database over a period of twelve months, covering both pre-pilot and post-pilot operating conditions. The Historian archives high-resolution process data from field instruments and control systems, providing a reliable database for statistical analysis.

The following process variables were extracted for analysis:

- Chilled water flow rate (m^3/h)
- Supply water temperature (°C)
- Return water temperature (°C)
- Temperature differential (ΔT) (°C)
- Cooling energy (kWh/TRh)
- Pump operating status
- Cooling demand
- Control valve position
- Differential pressure
- Alarm and event records

To evaluate the effectiveness of the proposed pilot implementation, identical datasets were collected before and after implementation, each consisting of approximately 1,440 observations, thereby ensuring a statistically comparable analysis.

c. Data Pre-processing

Prior to statistical analysis, the acquired SCADA data underwent a comprehensive preprocessing procedure to improve data quality and eliminate measurement inconsistencies.

The preprocessing steps included:

- Removal of duplicate records
- Detection and elimination of outliers
- Missing-value identification and treatment
- Validation of sensor readings
- Monthly aggregation of operational data
- Seasonal classification into summer, winter, and monsoon operating periods
- Data normalization where required for regression analysis

These preprocessing techniques ensured that only high-quality operational data were used for subsequent statistical modelling.

d. Statistical Analysis

Multiple statistical techniques were employed to evaluate BTU meter performance and quantify the effectiveness of the proposed measurement strategy.

e. Descriptive Statistical Analysis

Descriptive statistics were computed separately for the pre-pilot and post-pilot datasets to characterize operational performance. The calculated parameters included:

- Mean
- Standard deviation
- Maximum value
- Minimum value
- Coefficient of Variation (CV)

These indicators provide quantitative measures of operational stability and measurement consistency.

f. Time-Series Trend Analysis

Monthly BTU consumption was analysed using time-series techniques to investigate seasonal behaviour and long-term performance trends. The dates of pilot implementation were marked on the trend plots to facilitate visual comparison between pre-implementation and post-implementation operating conditions.

g. Correlation Analysis

Pearson correlation analysis was performed to determine the relationships between BTU consumption and major operating variables, including chilled water flow rate, supply temperature, return temperature, differential temperature (ΔT), valve position, and differential pressure.

h. Regression Analysis

Multiple Linear Regression (MLR) was employed to quantify the relationship between measured cooling energy (dependent variable) and the selected process parameters (independent variables).

Separate regression models were developed for the pre-pilot and post-pilot datasets. Model performance was evaluated using the following statistical indicators:

- Coefficient of Determination (R^2)
- Multiple Correlation Coefficient (Multiple R)
- Standard Error of Regression
- Analysis of Variance (ANOVA)
- F-statistics and Significance F
- Regression coefficients
- p-values of independent variables

The comparison of regression models enabled quantitative assessment of the improvement in BTU measurement accuracy following implementation of the proposed measurement and control strategy.

i. Before-and-After Pilot Performance Evaluation

A before-and-after comparative evaluation was conducted to assess the effectiveness of the pilot implementation. The analysis compared operational performance during the pre-pilot and post-pilot periods using identical statistical procedures.

The evaluation focused on:

- Changes in monthly BTU consumption trends.

- Improvement in measurement stability.
- Reduction in data variability.
- Regression model performance.
- Statistical significance of process variables.
- Overall enhancement in BTU measurement accuracy under seasonal low-load operating conditions.

The proposed methodology was applied independently to both Case Study Building A and Case Study Building B, enabling validation of the pilot implementation across multiple buildings connected to the same district cooling network.

These extremely small p-values indicate that the improved instrumentation and control strategy significantly strengthened the relationship between operational variables and measured BTU. Now the same pilot implemented in Building “A” and Building “B” at large District Cooling Networks. The building “A” & “B” example with Trend Analysis is shown below.

4. RESULTS AND DISCUSSION

a. Before-and-After Pilot Performance Evaluation

To evaluate the effectiveness of the proposed BTU measurement and control strategy, a comparative statistical analysis was performed using operational data collected before and after pilot implementation. Separate regression models were developed using identical datasets obtained from the SCADA Historian, each consisting of 1,440 observations. This approach ensured a statistically consistent comparison of model performance under identical operating conditions.

b. Regression Model Performance

Table 1 summarizes the performance of the regression models developed for the pre-pilot and post-pilot operating periods.

Table 1: Comparison of Regression Model Performance.

Parameter	Before Pilot	After Pilot	Improvement
Multiple R	0.9092	0.9983	Stronger correlation
R^2	0.8266	0.9966	Model fit improved by approximately 20.6%
Standard Error	5.786	3.702	Prediction error reduced by approximately 36%
Observations	1,440	1,440	Equal datasets
Significance F	<0.001	<0.001	Both models statistically significant

The regression model developed using pre-pilot operational data achieved a coefficient of determination (R^2) of 0.8266, indicating that approximately 82.7% of the variation in measured BTU consumption could be explained by the selected operating parameters. Although statistically significant, the model exhibited relatively higher prediction uncertainty, as reflected by a standard error of 5.786. This behaviour is consistent with measurement instability during seasonal low-load operation.

Following implementation of the proposed measurement and control strategy, the regression model demonstrated a substantial improvement in predictive capability. The coefficient of determination increased to 0.9966, indicating that nearly all variability in BTU consumption was explained by the measured process variables. Simultaneously, the standard error decreased to 3.702, representing an approximate 36% reduction in prediction error.

The increase in Multiple R from 0.9092 to 0.9983 further confirms a significantly stronger linear relationship between the process variables and measured cooling energy after pilot implementation. These findings demonstrate that the proposed strategy substantially enhanced the consistency, reliability, and accuracy of BTU measurement under low-load operating conditions.

c. Statistical Significance of Process Variables

The statistical significance of the independent variables was evaluated using regression coefficient p-values to determine their contribution to BTU prediction.

Before Pilot Implementation

Prior to implementation, several key thermal parameters exhibited weak or statistically insignificant relationships with measured BTU consumption.

Table:2 Variables and p- values before pilot implementation.

Variable	p-value	Interpretation
BTU Inlet Temperature	0.060	Marginally significant
BTU Outlet Temperature	0.266	Not significant
Differential Temperature (ΔT)	0.113	Weak relationship

These results indicate that temperature measurements were unstable during seasonal low-load operation, reducing the overall predictive capability of the BTU measurement model.

After Pilot Implementation

Following implementation of the improved measurement and control strategy, all major process variables became highly significant predictors of thermal energy consumption.

Table:3 Variables and p- values after pilot implementation.

Variable	p-value	Interpretation
Differential Pressure	2.28×10^{-42}	Highly significant
Supply Temperature	≈ 0	Extremely significant
Return Temperature	≈ 0	Extremely significant
Control Valve Position	2.42×10^{-29}	Highly significant

The extremely small p-values demonstrate that the improved instrumentation, measurement configuration, and control strategy significantly strengthened the relationship between operational variables and measured BTU consumption. This confirms that the pilot implementation successfully improved the reliability of thermal energy measurement under varying operating conditions.

d. Long-Term Trend Analysis

Monthly BTU consumption trends were analyzed over the twelve-month study period for both Case Study Building A and Case Study Building B. The pilot implementation dates were marked on the time-series plots to visualize changes in measurement behavior before and after implementation.

Prior to the pilot, both buildings exhibited noticeable fluctuations in recorded BTU consumption during winter and monsoon seasons, when chilled water flow rates and temperature differences were relatively low. These fluctuations are characteristic of low-load operating conditions, where conventional BTU metering accuracy may deteriorate.

Following implementation of the proposed improvements, both buildings demonstrated smoother and more stable BTU consumption trends with reduced month-to-month variability. The reduction in abnormal fluctuations indicates improved measurement consistency and enhanced confidence in energy billing.

e. Comparative Performance of Case Study Buildings

To validate the proposed methodology under different operational conditions, the pilot strategy was independently implemented in both Case Study Building A and Case Study Building B.

Building A, where the pilot was implemented in December 2024, demonstrated a noticeable reduction in BTU measurement variability and improved regression performance during the subsequent winter months.

Building B, where the pilot implementation commenced in September 2025, exhibited a similar improvement in measurement stability during the following months. Despite differences in building load profiles and seasonal operating conditions, both case studies consistently demonstrated enhanced BTU measurement accuracy after implementation.

The similar performance improvements observed across two independent commercial buildings confirm the repeatability and robustness of the proposed measurement strategy.

5. Discussion

The results clearly demonstrate that improvements in instrumentation, sensor configuration, control logic, and SCADA-based monitoring significantly enhance BTU measurement performance under seasonal low-load conditions. Already seasonal comparison done with regression model earlier[1].

The combination of higher regression accuracy, lower prediction error, improved statistical significance of process variables, and smoother long-term operational trends provides strong evidence that the proposed methodology effectively mitigates measurement uncertainty commonly observed in district cooling systems during winter and monsoon operation.

These findings have practical significance for district cooling operators, as improved BTU measurement accuracy contributes directly to more reliable customer billing, enhanced operational transparency, better energy management, and improved overall system efficiency. The successful implementation across two commercial buildings further indicates that the proposed approach can be replicated throughout large-scale district cooling networks and other smart city cooling infrastructures.

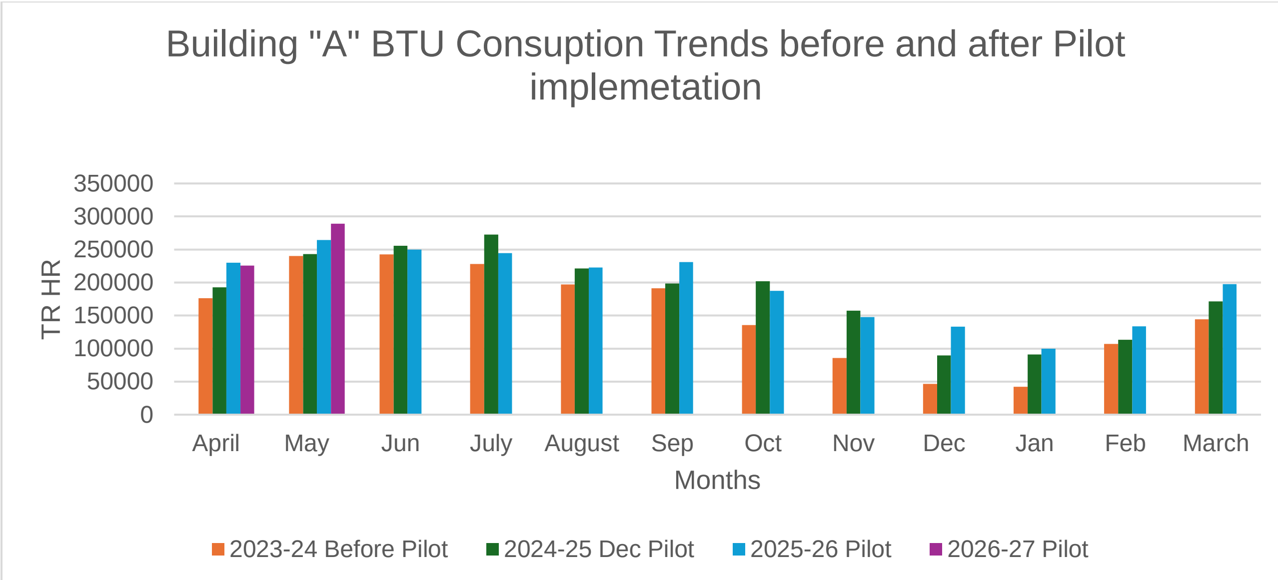

Figure 3: Building “A” Trend Analysis.

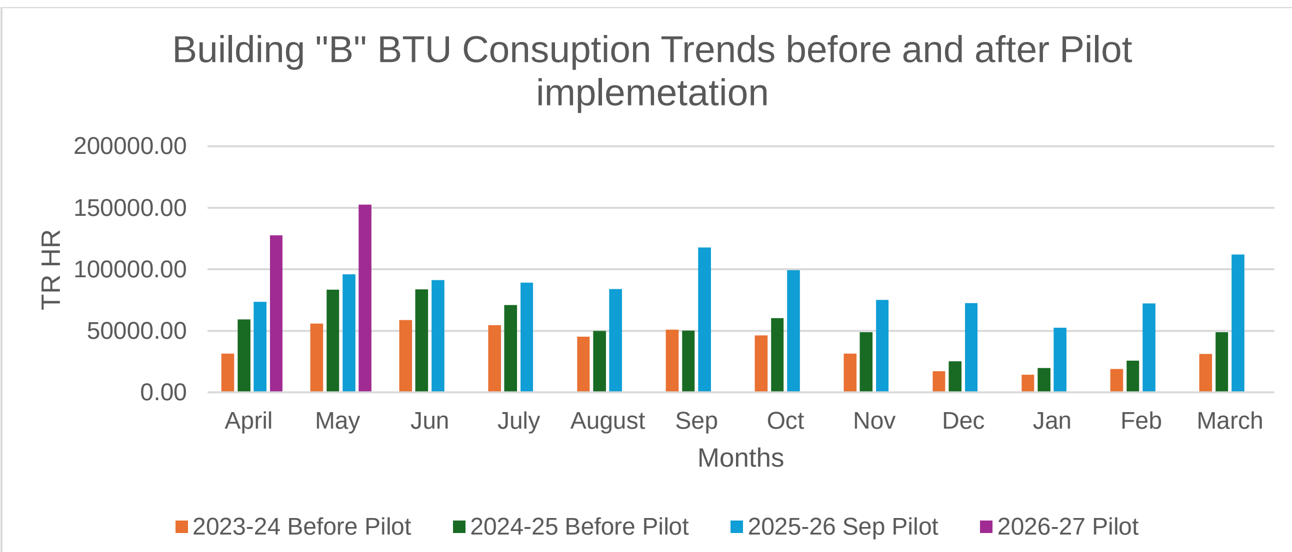

Figure 4: Building “B” Trend Analysis.

Below shown yearly generation trends as per load in smart city within networks also the cumulative losses after implementation of pilot projects with two major load carrying building, drastically decrease as per DCS generation & DCS TR HR Loss trends as shown below.

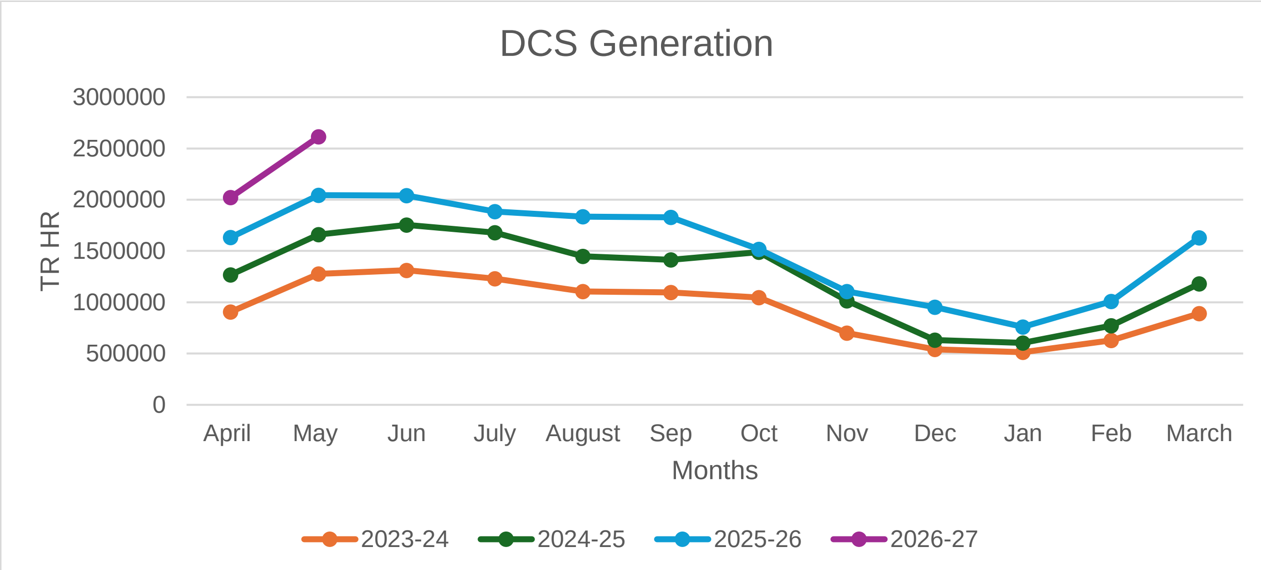

Figure 5: DCS Plant Yearly Generation Trends.

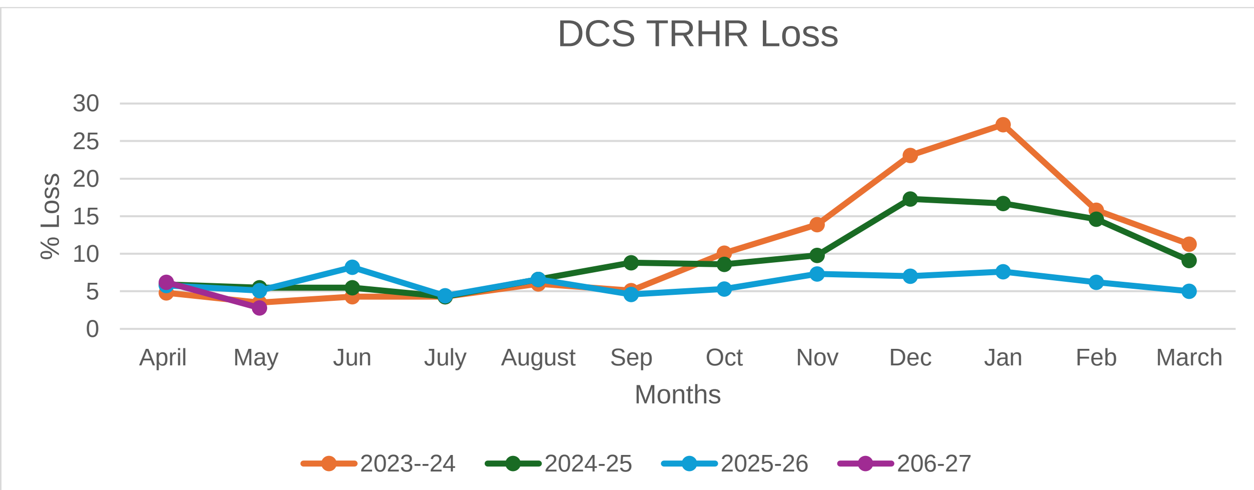

Figure 6: DCS Plant Yearly Loss Trend Analysis.

6. Conclusions

This study presented yearly trend analysis of BTU meter performance under seasonal low-load conditions with all seasons in a centralized district cooling network. The analysis confirmed that meter performance is closely linked to operating conditions, particularly chilled water flow and ΔT. Seasonal reductions in load increased measurement uncertainty, underscoring the importance of robust calibration practices, continuous monitoring, and optimized control strategies.

The findings support the pilot implementation SCADA-based analytics, and improved operational practices to enhance energy accounting and system efficiency.

Future Work

Future research should incorporate multi-year datasets, predictive analytics using machine learning, digital twin models, and advanced uncertainty quantification to further improve district cooling measurement accuracy.

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