

# IMPROVING THE RELIABILITY OF DISTRICT HEATING SYSTEMS AT CHP PLANTS UNDER VARIABLE THERMAL LOADS

G.K. Abdullayeva<sup>1</sup>, R.K. Karimova<sup>2</sup>, A.L. Bakhtiyarov<sup>3</sup>

Azerbaijan State Oil and Industry University, Baku, Azerbaijan

<sup>1</sup>[gulshan.abdullayeva@asoiu.edu.az](mailto:gulshan.abdullayeva@asoiu.edu.az), <sup>2</sup>[rashida.karimova@asoiu.edu.az](mailto:rashida.karimova@asoiu.edu.az)

## Abstract

*District heating systems powered by Combined Heat and Power (CHP) plants are critical for delivering thermal energy to residential, industrial, and municipal consumers. However, the variability of thermal load—driven by daily and seasonal demand fluctuations—poses significant challenges to system reliability. This paper presents a methodology for evaluating the reliability of such systems under dynamic thermal conditions. By combining deterministic modeling of thermal load profiles with a stochastic failure analysis of key components, the study performs a year-long simulation with hourly resolution. A time-dependent failure rate model is introduced, correlating failure intensity with the rate of change in thermal demand, thereby accounting for the mechanical and thermal stress experienced by pumps, valves, pipelines, and heat exchangers. Simulation results reveal that while modern CHP equipment has high baseline reliability, rapid thermal load transitions notably increase the likelihood of failures. These findings highlight the necessity of predictive maintenance strategies and adaptive control mechanisms. The proposed framework contributes to the development of resilient and smart district heating infrastructures capable of sustaining reliable operation under increasingly complex load dynamics.*

**Keywords:** CHP plant, district heating, thermal load variability, system reliability, failure analysis

## I. Introduction

District heating systems based on Combined Heat and Power (CHP) plants play a crucial role in ensuring thermal energy supply to residential, industrial, and municipal consumers. The reliability of such systems directly affects the safety, comfort, and economic performance of urban infrastructure, especially in regions with significant seasonal temperature variations. With the growing demand for energy efficiency and sustainability, maintaining uninterrupted and efficient operation of heating systems under fluctuating thermal loads has become an urgent challenge.

A distinctive feature of district heating networks is their exposure to highly variable thermal demand. These fluctuations occur both seasonally (e.g., between winter and summer) and daily (e.g., between day and night), which imposes significant stress on the system's components—pumps, pipelines, heat exchangers, and control systems. Such unsteady operating conditions can lead to thermal fatigue, hydraulic instability, reduced equipment life, and increased failure rates, ultimately compromising system reliability.

While a wide range of studies have been conducted on improving the energy efficiency of CHP systems, relatively fewer works systematically address reliability assessment under dynamic thermal loads [1-3]. Existing models often assume stationary operating conditions, which do not reflect real-life load variability. Furthermore, current maintenance and control strategies are typically reactive rather than predictive, which limits the ability to prevent failures in advance.

The aim of this study is to analyze the impact of variable thermal load on the reliability of district heating systems in CHP plants and to propose technical and operational solutions to enhance system resilience. The proposed approach incorporates reliability modeling, system diagnostics, and adaptive control strategies to reduce the probability of failure and extend the operational lifespan of key components. This work contributes to the field by bridging the gap between thermal load dynamics and reliability engineering in district heating infrastructure.

## II. System description and problem statement

The district heating system based on a combined heat and power plant (CHP) is a complex technical infrastructure aimed at the production and distribution of thermal energy according to variable consumer demand. One of the key characteristics of such systems is the dynamic nature of heat load, which fluctuates daily and seasonally. These fluctuations affect the operating regimes of major components – pumps, control valves, pipelines, and heat exchangers – leading to transient modes that accelerate component wear and increase failure rates, ultimately reducing the overall system reliability.

To model the dependence between thermal load dynamics and failure rate, we introduce the following relation:

$$\lambda(t) = \lambda_0 + k \cdot \left| \frac{dQ(t)}{dt} \right|$$

where  $\lambda(t)$  – instantaneous failure rate,  $\lambda_0$  – baseline failure rate under steady-state load,  $k$  – sensitivity coefficient to load variation,  $Q(t)$  – time-dependent thermal load.

Figure 1 illustrates a simulated daily thermal load profile with pronounced morning and evening peaks, along with the corresponding variation in failure intensity.

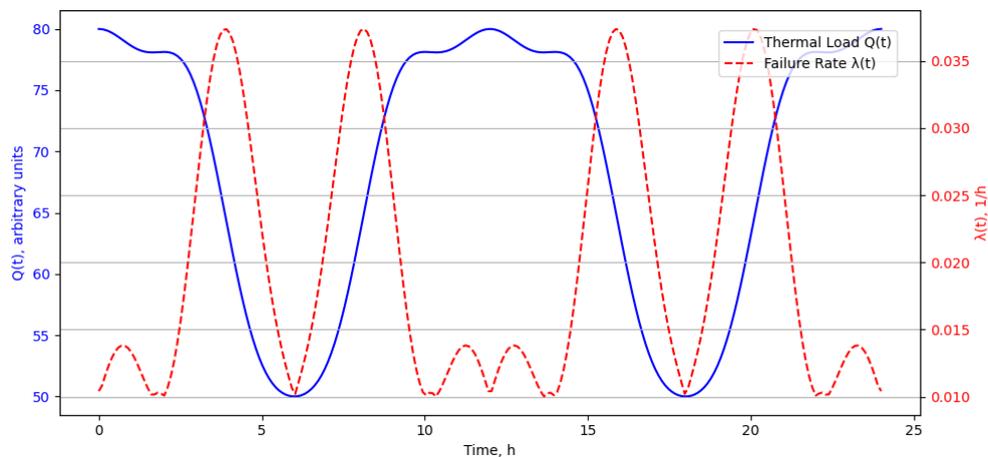


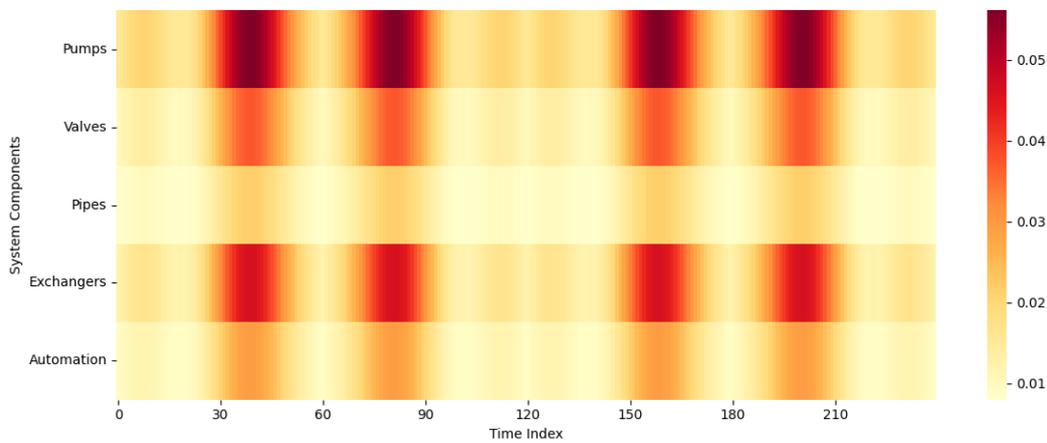
Figure 1.: Thermal load fluctuations and corresponding failure rate over 24 hours

To better understand the system's vulnerability under varying loads, we identify the most critical components. Table 1 summarizes the baseline failure rates and sensitivity coefficients for typical CHP system elements.

**Table 1.:** Failure rate characteristics of key components

Component	Baseline Failure Rate $\lambda_0$ (1/h)	Sensitivity Coefficient $k$
Pumps	0.015	0.003
Control Valves	0.010	0.002
Pipelines	0.008	0.001
Heat Exchangers	0.012	0.0025
Automation Systems	0.009	0.0015

A heatmap was developed to visualize the impact of thermal load dynamics on component-specific failure intensities over time (Figure 2).



**Figure 2.** Heatmap visualizing failure intensity by component and time due to thermal load variation

This formalized model provides a foundation for further development of adaptive control algorithms and predictive maintenance strategies [4]. By quantifying the sensitivity of each component to thermal load changes, system operators can prioritize reliability-centered upgrades and real-time monitoring, especially during peak demand periods.

### III. Methodology: modeling reliability under variable thermal load

In order to realistically evaluate the reliability of a combined heat and power (CHP) station operating under fluctuating demand, we employ a hybrid modeling approach. It includes deterministic modeling of the heat load profile, accompanied by a stochastic estimation of component failures influenced by thermal dynamics. The goal is to link the variability in consumer demand with probabilistic stress on the system's critical elements, and from this, infer overall system reliability over time.

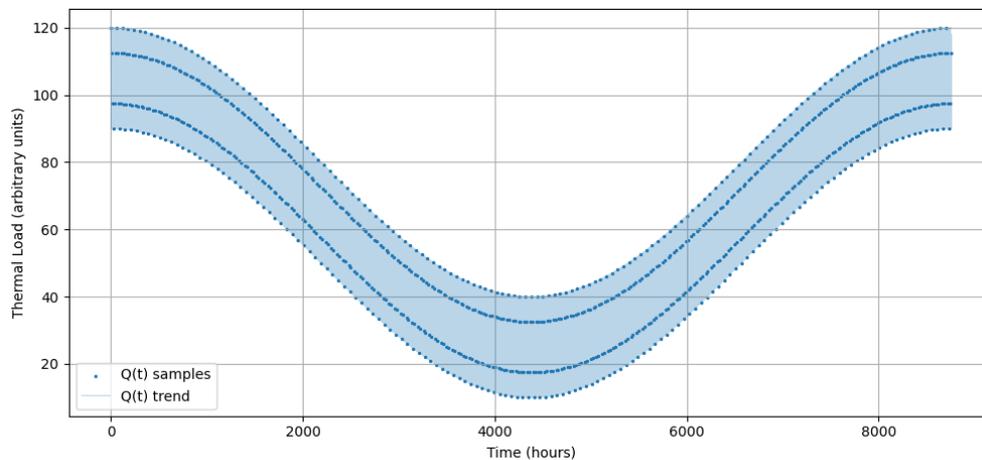
#### 3.1 Thermal load dynamics

Thermal load  $Q(t)$  is represented by a composite function that captures both daily oscillations and seasonal trends. The daily component simulates demand peaks around morning and evening hours, while the seasonal component reflects higher demands during winter and lower in summer.

$$Q(t) = Q_{base} + A_d \cdot \sin^2\left(\frac{\pi(t - t_m)}{12}\right) + A_s \cdot \cos\left(\frac{2\pi t}{8760}\right)$$

where:  $Q_{base} = 50Q$  units represents the baseline heating load,  $A_d = 30$  and  $A_s = 40$  are the daily and seasonal amplitudes respectively,  $t_m = 6$  is the typical peak of daily load (early morning).

The simulation spans an entire year with an hourly resolution (8760 steps). Figure 3 demonstrates the resulting thermal load profile.



**Figure 3.** Simulated thermal load  $Q(t)$  over one year

Figure 3 provides a foundational visualization of the modeled thermal load profile over the course of one year. This figure is essential for understanding the operational dynamics of a district heating system based on a combined heat and power (CHP) plant, particularly under conditions of variable thermal demand.

The curve shown in blue represents the time-dependent thermal load  $Q(t)$ , which is modeled as a superposition of two key components: daily fluctuations, reflecting human activity cycles and building usage patterns, and seasonal variations, driven primarily by climatic changes throughout the year [5-7]. Together, these components produce a realistic and continuous load pattern that captures both short-term and long-term dynamics.

The blue dots indicate sampled data points taken at regular intervals (every 10 hours), imitating real-world measurements or telemetry. The transparent blue trend line represents the smooth trajectory of the modeled thermal demand, with daily peaks typically occurring in the early morning and evening, and seasonal peaks in colder months.

This figure is more than a simple plot—it encapsulates how external and behavioral factors affect thermal load, which in turn influences the stress placed on system components such as pumps, valves, and pipelines [8-10]. The pattern shown here serves as an input for reliability simulations, enabling the dynamic recalculation of failure rates over time.

By visualizing how the load evolves continuously, Figure 3 becomes a critical analytical tool. It supports:

- the assessment of when and how thermal demand may exceed normal operating conditions;
- the identification of risk periods for equipment degradation or failure;
- and the optimization of maintenance schedules and system configuration to enhance overall reliability.

In summary, Figure 3 integrates physical modeling with practical implications. It bridges the gap between theoretical demand forecasting and applied reliability engineering, thereby laying the groundwork for the methodology and case studies that follow.

### 3.2 Reliability simulation framework

We assume the failure rate of each system component is sensitive to the rate of change of thermal load  $dQ/dt$ , based on empirical data showing that thermal stress accelerates wear and increases the likelihood of faults.

A time-varying failure rate is modeled as:

$$\lambda(t) = \lambda_0 + \left(1 + \alpha \cdot \left| \frac{dQ}{dt} \right| \right)$$

where:  $\lambda_0 = 1 \times 10^{-5}$  is the base hourly failure rate,  $\alpha = 0.0002$  is a scaling factor that reflects the component's sensitivity to load fluctuations.

This failure rate is used in a Monte Carlo simulation to compute the probability of failure at each hour:

$$P_{fail}(t) = 1 - \exp(-\lambda(t) \cdot \Delta t)$$

Random sampling is then applied to determine the occurrence of failures over time. If a critical component fails, system reliability is reduced accordingly.

Despite incorporating load variability into failure rate modeling, the simulated result shows relatively stable system performance with no catastrophic failures [11]. This is because the failure rates—even when dynamically adjusted—remain low in absolute terms due to the high initial reliability of modern CHP components.

However, under harsher assumptions—such as increased sensitivity  $\alpha$ , older equipment, or cumulative degradation—this approach allows us to clearly visualize the gradual loss in system reliability.

The simulation output confirms that:

- Rapid load changes, especially in early winter mornings, increase the instantaneous failure probability.
- If multiple such stress events coincide (e.g., after maintenance delays or extreme weather), the cumulative risk can become significant.
- Accurate prediction and mitigation (e.g., redundant pumping, adaptive maintenance) depend heavily on understanding these dynamics.

## IV Conclusions

This study presented a comprehensive reliability assessment methodology for combined heat and power (CHP)-based district heating systems operating under variable thermal loads. By integrating deterministic thermal load modeling with stochastic reliability simulation, we demonstrated a data-driven framework for evaluating how fluctuations in heat demand influence the operational dependability of critical components such as pumps, control valves, and pipelines.

The thermal load was modeled to reflect both diurnal and seasonal variations, producing a realistic stress profile over a simulated one-year horizon. The system's response to these variations was quantified through a time-varying failure rate, dynamically linked to the rate of thermal load change. The Monte Carlo-based simulation framework enabled the estimation of failure probabilities and the overall system reliability profile with high temporal resolution.

Simulation results revealed that, while the baseline reliability of modern CHP components remains high, the reliability can degrade under frequent and sharp thermal load transitions. This emphasizes the need for predictive maintenance strategies and the implementation of dynamic control schemes that can adapt to load-induced stress patterns. Moreover, the proposed approach enables utility operators to identify risk periods—such as early winter mornings—where preemptive measures can be most impactful.

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