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Methods for Calculating the Heating Efficiency of Industrial Facilities with Water Cooling of Mining Equipment

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Abstract
This article presents an algorithmic solution for calculating the heating efficiency of an industrial facility when water cooling is used as the setup for mining farm equipment. Crypto mining belongs to industries that are actively developing, and a high volume of electricity consumption is generated. Efficient usage of wasted heat is a key factor in energy efficiency improvement, and also contributes to sustainability within energy systems. In this paper, this study occupies a vital place, as an increase in the more efficient exploitation of thermal resources leads not only to reduced consumption but also to reduced carbon emissions. That means dual targets-environmental and economic are achieved. The novelty lies in collecting and applying an integrated methodology for assessing the effectiveness of heating systems while addressing water cooling for mining equipment. It will use the three approaches: energy balance, exergy analysis, and CFD technology simulation, together with a short review of regulatory requirements such as ASHRAE and Energy Reuse Factor, to give an appropriate thermal potential assessment and loss source identification, hence optimization of design and operation for heating systems based on mining farms. The main conclusions are that a simple energy balance is sufficient for small-scale facilities. At the same time, more complex methods, such as exergy analysis and CFD simulation, are required for large data centers and industrial sites with higher loads. System efficiency improves drastically with the application of heat pumps, along with a reduction in hydraulic and pump equipment losses. The economic benefits of heat utilization from mining farms will be able to compete with traditional heat sources, such as gas boilers. This will be of interest to engineers, designers, and researchers working on energy efficiency. This will attract investors interested in sustainable yet economically viable solutions that can be used for heating industrial facilities.

Keywords: heat recovery, mining, water cooling, exergy analysis, energy balance, CFD modeling, heat pumps, energy saving, sustainable development

Introduction

In the last five years, the cryptocurrency mining industry went from being a small part to becoming a large share of the world's electricity market: by mid-2025, it is estimated that the annual electricity consumption of the Bitcoin network is about 176 TWh, comparable with a country such as Poland (Digiconomist, 2025). Against this backdrop, the entire network of data centers—ranging from hyperscalers to distributed ASIC mining farms—already accounts for around 1% of global electricity demand, with the share exceeding 20% in some countries (Spencer & Singh, 2024). The growth rate of hash rates, the race for higher computational density, and the increase in the average power of facilities create an acute need for effective heat dissipation, which, if not managed, limits further scalability.

The physics of the process is simple: almost all electrical energy supplied to chips and power electronics inevitably turns into low-potential heat. In traditional air cooling systems, this heat is released into the atmosphere, requiring significant costs for ventilation and air conditioning. The economics of the facility suffer twice in this approach—first from the high price of electricity, and then from the cost of dissipating it.

Another option is the reuse of heat. As the International Energy Agency notes, waste heat from data centers can be utilized to supply nearby homes and offices with their hot water, thereby reducing the need for fossil fuels in the heating sector (IEA, 2023). The easiest medium for this is also water: liquid cooling of mining rigs enables stable temperatures that are already beneficial for low-temperature underfloor heating systems, ventilation heat recovery units, or cascade heat pumps, with minimal reheating necessary.

Materials and Methodology

The study is based on a thorough review of existing methods and technologies related to heat recovery. Theoretical background research includes works that discuss opportunities for utilizing excess heat from data centers, articles revealing the potential for heat recovery enabled by the computing power of mining farms, and methods for transferring this heat to heating systems (Yuan et al., 2023; Pakere et al., 2024). The effects of different heat exchange and cooling methods on the efficiency of heat recovery were examined, enabling us to identify key indicators and calculation methodologies, such as energy balance and exergy assessment.

The study draws upon several primary stages. The first stage is the energy balance, which forms the baseline for obtaining the maximum thermal potential that can be garnered for heating, with a particular, detailed, quantitative estimation of heat losses by pumps, pipelines, and heat exchange systems (Oliver & Pan, 2017). Exergy analysis is the second stage, denoting work potential and the quality of heat at different temperature regimes. According to Liu et al. (2023), research findings indicate that exergy efficiency can be lost in significant magnitudes at low temperatures. Therefore, heat pumps are used to increase the temperature, allowing systems to operate at their normal state of efficiency.

To better model system efficiency, the numerical simulation method employed CFD (Computational Fluid Dynamics) simulations, as they enable visualization of both temperature and coolant flow distribution inside containers, including miners and pipelines. This will make it easier to determine possible issues with hydraulic imbalance and overheating. One of the significant inputs into calculations consists of information on temperature limit regulatory standards, such as ASHRAE TC 9.9, that prescribe classes of allowable temperatures for liquid cooling systems and heat recovery systems.

Additionally, the study examines the impact of environmental and economic factors on it. Such factors include CO_2 emission reductions as well as the cost of substitute fuels like natural gas (Innovation Norway, 2016; Trading Economics, 2025). The environmental aspect is desirable, as every megawatt-hour not consumed by a gas boiler saves carbon emissions for the environment. This is a crucial consideration for investors and regulatory bodies when making investment decisions.

Finally, the research methodology involves a systematic analysis of regulatory requirements, including EU directives on energy efficiency and standards for heat exchange systems, to ensure that the designed solutions comply with existing legal restrictions and industry standards (Danfoss, 2023).

Results and Discussion

Accurate evaluation of the efficiency of systems that direct heat from the water cooling of mining farms to industrial sites is needed primarily because the farms themselves have long since grown to the scale of a significant energy facility. Ignoring such an extensive secondary resource means leaving the largest item in the facility’s energy balance uncontrolled.

At the same time, a correct calculation makes it possible to understand what proportion of electrical expenditures can be reallocated into useful heat. Literature on data-center heat recovery indicates that without deep engineering modifications, it is possible to extract 20–50% of the dissipated thermal power (Yuan et al., 2023). With optimized schemes that employ heat pumps and raise the circuit temperature, the extraction rate can reach up to 55% (Pakere et al., 2024). Such benchmarks are essential not only for designers of heat exchangers and pumping stations, but they also determine the scale of pipelines, thermal storage units, and the break-even point of the entire complex.

The economic effect is directly linked to the price of the substituted fuel. On the European TTF hub in mid-July 2025, natural gas traded at approximately 35 €/MWh, as shown in Fig. 1 (Trading Economics, 2025).

Fig. 1. One-Year Price Trend of EU Dutch TTF Natural Gas (Trading Economics, 2025)

The environmental component further strengthens the project's economics. Each megawatt-hour that does not need to be produced by a gas boiler reduces emissions by approximately 185 kg CO_2, as shown in Fig. 2 (Innovation Norway, 2016).

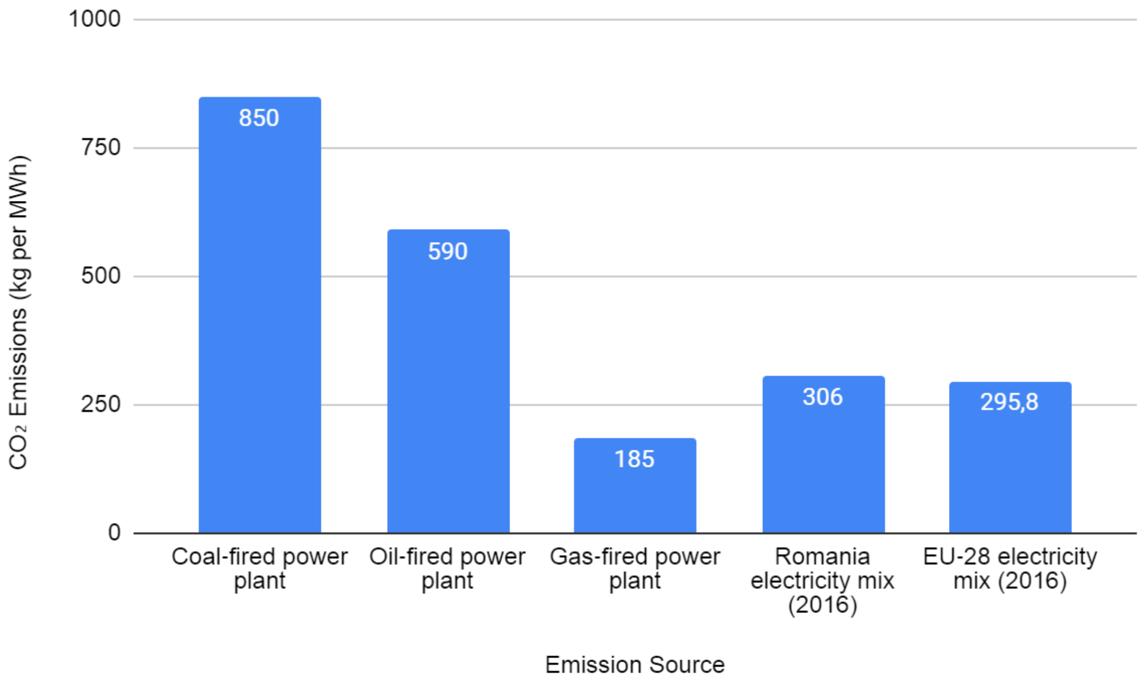

Fig. 2. Specific CO_2 Emission Intensities of Electricity Generation Technologies (Innovation Norway, 2016)

Ultimately, the ESG factor is becoming an increasingly direct driver of capital. According to a Georgeson survey, 75% of institutional investors identified climate transition as a key priority for their portfolios in 2025 (Moote & Vasantham, 2025). Without a transparent methodology for calculating the efficiency of heat recovery from mining farms, projects risk losing access to low-cost financing or preferential tariffs. Thus, analytical efficiency assessment is not merely an engineering formality but a prerequisite for the economic viability and investment attractiveness of heating schemes based on water cooling of miners.

The methodologies for evaluating the efficiency of heating systems operating on heat recovery from liquid cooling of miners can logically be viewed as complementary, since each addresses its key question:

how much heat can be recovered, what usefulness it has, how competitive that usefulness is, where local losses occur, and how regulations constrain permissible regimes.

The most direct approach is the energy balance. It accounts for all power flows passing through the mining farm and the heat-exchange circuit, allowing for a rapid understanding of the range of thermal power available to the end user after accounting for irreversible losses in pumps, pipelines, and heat-transfer surfaces. Such a balance sets the upper limit from which all more detailed models proceed.

The energy diagram, however, does not distinguish the quality of heat. For this, an exergy analysis is applied, which calculates the portion of the low-temperature energy that can perform work or, in our case, provide effective heating without additional equipment. Recent studies of low-potential heat exchange in computing centers show that at water temperatures of 40–45 °C, exergy efficiency can be three times lower than pure energetic efficiency, highlighting the need either to raise the source temperature or to use a heat pump to bring it to a comfortable 55–60 °C in an industrial circuit (Liu et al., 2023).

A practical metric for investors and operational engineers is the COP heat recovery indicator. Unlike the classical COP of a heat pump, this includes not only the compressor work but also the entire electrical load of the IT equipment, pumps, and power automation. When it is necessary to understand why the calculated COP is not achieved in practice, numerical modeling is consulted. CFD simulations provide a picture of temperature and velocity distributions in miner containers, heat shafts, and production halls. Such analysis serves as a link between theoretical potential and real operational efficiency.

Finally, any calculation must remain within the field of regulatory constraints. ASHRAE TC 9.9 and the Datacom Series establish allowable temperature classes for liquid cooling, extending the upper limit of IT equipment inlet temperatures to 45°C, which directly increases the share of heat suitable for heating (ASHRAE, 2016). The European Code of Conduct for energy-efficient data centers complements these requirements with KPI metrics for annual energy reuse. It obliges operators to disclose data on heat recovery, thereby stimulating the use of transparent efficiency calculation methodologies. Together, the regulations set the minimum standard below which any calculation loses practical significance and form a common basis for comparing projects across different markets.

Thus, the sequential application of energy balance, exergy assessment, COP heat recovery, CFD modeling, and regulatory coefficients provides a holistic understanding of the efficiency of heating schemes based on water cooling of mining equipment, enabling substantiated decision-making at all stages—from concept to operation.

The choice of a specific methodology for calculating the efficiency of heat recovery from water cooling of miners is initially determined by the scale of the facility and the allowable error. For a standalone container farm with a capacity of several hundred kilowatts, a simple energy balance is sufficient; a ±10% error does not affect the selection of standard plate heat exchangers and pumps. When the total IT load exceeds 5–10 MW, the magnitude of piping losses, temperature distribution along the manifold, and regime dynamics become critical for the capital expenditures of pipelines and storage units; therefore, exergy assessment and COP heat recovery calculation are added to the balance. Finally, when connecting to a district heating network, it is vital to predict local overheating and hydraulic imbalances: here, CFD simulations are indispensable, especially given that the updated classification ASHRAE TC 9.9 (class W45) has officially raised the permissible inlet water temperature to 45 °C, encouraging projects with higher useful-heat recovery rates (Ashrae, 2021).

Climatic background and the length of the heating season impose a second layer of requirements. According to Eurostat, the average number of heating degree-days in the EU for 1979–2022 is 3199, but varies from 5656 in Finland to 534 in Malta, as shown in Fig. 3 (European Commission, 2023).

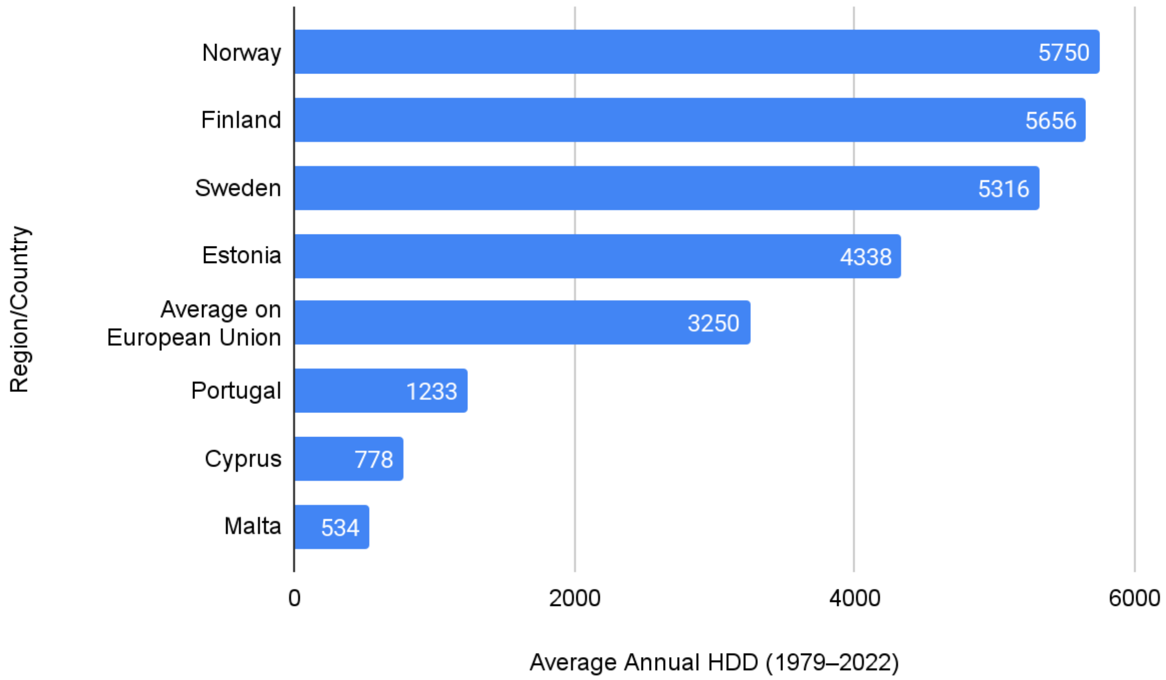

Fig. 3. Average Annual Heating Degree Days for Selected European Regions (European Commission, 2023)

Where heating degree-days (HDD) are high, even a conservative energy balance yields a stable thermal load for most of the year. In mild climates, however, it is worth evaluating exergy and considering a heat pump to increase the value of low-temperature heat during the short winter period. A telling Swedish example demonstrates this: the combination of district heating and heat pumps already covers over 75 % of the country's total heat demand, and the share of oil in heat supply has fallen below 5 %—an achievement made possible precisely by the high potential of seasonal demand and the centralized utilization of heterogeneous sources, including data centers (Bryant, 2025).

Stakeholder interests set the third criterion. For investors, a metric that is comparable across projects is crucial. The Robeco-2025 survey found that 62% of European institutional investors still consider climate goals to be key and are prepared to increase investments in heat-recovery solutions despite political fluctuations (Segal, 2025). Regulators, in turn, are moving from recommendations to mandates: the revised Directive 2023/1791 on energy efficiency requires data centers with IT power above 1 MW to demonstrate the technical and economic feasibility of excess-heat extraction and to disclose their annual Energy Reuse Factor (Danfoss, 2023). Heat consumers often only require information on guaranteed supply temperature and schedule, making an aggregated COP heat recovery suitable for them. In contrast, investors and regulators request more detailed exergy reports or CFD maps to confirm the absence of local hot spots and compliance with standards. The confluence of these factors creates a logical, sequential framework: the larger the facility, the harsher the climate, and the stricter the stakeholder requirements, the deeper the methodological development, progressing from a simple energy balance to a comprehensive digital twin model.

The cooling-water temperature regime remains the primary lever determining the useful thermal potential of mining farms. With direct liquid or immersion cooling, outlet temperatures can be stably maintained at 50–60 °C without compromising equipment reliability, which roughly doubles the exergy value of each kilowatt-hour compared to traditional 30 °C circuits of CRAH/CRAC air-cooling systems (Reuter et al., 2022).

Once the heat leaves the farm, the network's thermohydraulics come to the fore. Measurements on operational 90/40 °C piping sections show that at a diameter of 28.5 mm, specific losses are about 7.3 W/m, whereas on a 125 mm main line, they rise to 19 W/m; each additional 100 m of pipe thus consumes 0.6–1.6 % of the facility's thermal power. This discrepancy is particularly critical for small sites: at a 250 kW load, circulation power can reach 30 % of all network losses, while at 5 MW it falls to 8–10 %, underscoring the importance of selecting pipe diameter and insulation thickness correctly at the design stage (Oliver & Pan, 2017).

Within the recovery system itself, the balance is further shifted by pumps, valve actuators, and automation modules. Full-scale experiments with submerged (SPLIC) circuits recorded partial PUE values of 1.03–1.17, meaning the specific penalty for circulation and control ranges from 3–17 % of the IT load. When fluid viscosity increases or pumps operate at high frequency, auxiliary equipment consumption grows faster than the delivered heat. Employing variable-frequency drives and optimizing flow to the actual heat-demand profile can save up to a tenth of a PUE point (Robinson, 2023).

The remaining gap between the available and required temperatures is closed by hybrid schemes that utilize heat pumps. In practice, raising water from 40 °C to 65–70 °C via water-to-water units delivers a seasonal COP of 6–7, and for more minor lifts (40 → 67 °C) point COP values of ≈ 6.8 are observed; as a result, up to 75 % of the electricity used for computation is returned as useful heat for district networks or process needs (Danfoss, 2024). A proper combination of high inlet temperature, minimized network losses, and optimized pump infrastructure enables the integrated heat-recovery COP to approach levels competitive with modern gas boilers, making mining-farm heating a sustainable solution both ecologically and economically.

When assessing the suitability of a mining-equipment heat-recovery scheme, developers first note the compact container stations, which can be sited adjacent to an agri-park or greenhouse complex. The modest electrical load of such farms becomes a steady source of low-temperature heat, closely matching plant growth requirements. Short pipe runs, low system inertia, and the ability to modulate output in steps according to climate-control signals make these installations a convenient means for farmers to reduce traditional fuel costs. An additional advantage is that failure or decommissioning of one or two modules does not halt the entire heating scheme, thereby minimizing risk to crops.

Integration into municipal heat networks imposes entirely different requirements. A large data center must deliver tens of megawatts of heat across multiple circuits of varying temperature. It is critical to ensure hydraulic balancing with the district medium, synchronize supply and return schedules, and install buffer accumulators to smooth nightly or seasonal IT-load fluctuations. Part of the heat can be directly fed into low-temperature district loops, while the remainder is boosted to municipal standards via heat pumps. Such a configuration enhances central boiler resilience, reduces peak CO_2 emissions, and simultaneously provides a commercial service for the data-center operator, creating a second revenue stream without expanding energy infrastructure.

An even more pronounced effect occurs in northern regions, where cold climates produce long heating seasons and high thermal loads on industrial parks. Here, a mining farm becomes an almost ideal shield against fossil-fuel price spikes. The temperature differential between cold ambient air and warm cooling water simplifies the system thermodynamics: the heat pump operates more efficiently, and part of the heat can be supplied directly to radiators or air curtains. Of course, long pipe runs and extreme winter conditions require robust insulation and backup systems. Still, the benefit of stable, low-cost heat outweighs the additional capital costs, mainly when alternatives include diesel imports or remote boiler construction. Ultimately, mining infrastructure sited close to the load becomes a key element of local energy independence and the sustainable development of Arctic industrial clusters.

Conclusion

The study demonstrates that recovering low-potential heat from water-cooled mining farms is a multi-level challenge that requires a comprehensive methodological toolkit. The primary energy balance establishes the maximum recoverable thermal potential; however, without exergy considerations, it is impossible to assess the quality of the transferred energy and its suitability for direct heating or preheating of the carrier. Integrating exergy analysis with COP heat recovery calculation not only quantifies the shares of useful heat but also pinpoints loss sources in pumps, piping, and junctions.

Further refinement via CFD modeling provides detailed maps of temperature and coolant flow within containers and mains, critically informing piping design and diameter selection. Regulatory constraints, including ASHRAE TC 9.9, European Codes of Conduct, and Energy Reuse Factor directives, establish minimum standards for project compliance and mandate reporting requirements for operators and investors.

Method selection depends on facility scale, climate, and stakeholder requirements. Small container farms (with hundreds of kilowatts of IT load) may rely on energy balance and COP estimates with an accuracy of ±10%. In contrast, large centers (>5–10 MW) require comprehensive exergy calculations, numerical modeling, and dynamic-mode analysis. In regions with long heating seasons and high HDD, simple schemes yield stable performance, while mild climates justify the use of heat pumps to boost carrier temperature and exergy value.

Heat-recovery systems for liquid-cooled miners can reduce industrial and residential fuel costs and lower carbon footprints by directly replacing gas boilers. With high inlet temperatures, optimized hydraulics, and modern pumping, an integrated heat-recovery COP comparable to modern gas-boiler efficiency is achievable, making this technology both economically and environmentally competitive.

Thus, the sequential application of energy balance, exergy analysis, COP heat recovery calculation, CFD modeling, and regulatory compliance provides a holistic understanding of water-cooled miner heating schemes, enabling sound design and investment decisions from concept through operation, and ensuring reliability, cost-effectiveness, and alignment with modern sustainability standards.

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