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Architectural Models for Integration of Mining Installations into Existing IoT-Controlled HVAC Systems

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Abstract: This paper examines an architectural model for integrating mining installations into existing building HVAC systems and urban district heating networks using IoT control. The relevance of the study is justified by the rapid growth in the share of low-grade heat from server farms and mining centers in the overall energy consumption balance. The objectives are to develop a comprehensive five-level architecture for connecting computational modules to low-temperature loops; to perform a comparative analysis of three basic schemes (by-pass, series-loop, and hybrid-grid) in terms of PUE and heat utilization factor; and to formulate IoT algorithms for dynamic balancing between computational load and the needs of heat receivers. The novelty of the paper lies in unifying technical, economic, regulatory, and cybernetic aspects into a single model: for the first time, a five-layer integration structure is proposed—from retrofit of heat-exchange loops to an edge + cloud platform and interfaces with BMS/SCADA; the advantages of immersion cooling for direct connection to heating systems at temperatures up to 60 °C are demonstrated; predictive algorithms based on LightGBM for forecasting thermal load and dynamically controlling the hash rate are described; and recommendations are given for minimizing financial, technological, and informational risks at all levels of the architecture. The main findings show that, for mining power up to 30 % of the building's heat demand, the optimal scheme is the by-pass with minimal intervention in existing engineering networks; when heat power is comparable to the object's load, it is more advantageous to apply the series-loop with immersion cooling, yielding

up to 98 % savings on mechanical chillers. For district networks, the hybrid-grid topology with buffer accumulators and complex flow distribution is preferable. OPC UA and MQTT are brought together for assured telemetry. Digital twins and demand-response programs bring energy efficiency and equipment reliability. Multi-level OT security, combined with support for financial hedging instruments, ensures assured resilience against both cyberattacks and crypto-market volatility. Such a paper would be of interest to engineers designing building heating, cooling, and ventilation systems; data center energy efficiency specialists; as well as IoT solution developers for thermal process management.

Keywords: integration of mining installations; HVAC; IoT control; immersion cooling; digital twin; thermal load optimization; by-pass; series-loop; hybrid-grid; OPC UA; MQTT; PUE; heat utilization factor; cyber-physical security

Introduction

Over the past five to seven years, server infrastructure has transformed from an invisible electricity consumer into a significant source of low-grade heat. According to the International Energy Agency, the total electricity consumption of global data centers, excluding mining, rose to 240–340 TWh in 2022, equivalent to approximately 1–1.5% of global generation. Meanwhile, telecommunications networks added another 260–360 TWh (IEA, 2023). Recognizing the resource potential of such excess heat, regulators are shifting from voluntary to mandatory recovery mechanisms: the new German Energy Efficiency Act requires that all data centers commissioned after 1 July 2026 deliver at least 10 % of their thermal output to external heat networks, rising to 20 % from 2028 (Judge, 2023). Thus, rather than viewing IT load solely as a cooling challenge, the industry is increasingly treating it as a marketable thermal resource to be integrated into existing building HVAC systems and urban heating loops.

Practical benefits of this strategy are already measurable. In Sweden's capital, the Open District Heating scheme had connected two dozen IT sites by 2022 and annually extracts enough heat to warm around 30,000 modern apartments, reducing the network's specific emissions by 50 g CO_2 per kWh delivered (European Commission, 2023). For HVAC designers, this presents a stable source of medium-temperature heat that can be easily incorporated via plate heat exchangers and managed by the same IoT controllers that govern the rest of the building's engineering systems.

Mining farms, in particular, offer exceptionally high heat-flux density. At the network scale, this provides a notable contribution: Bitcoin mining consumption was estimated by the IEA to be 110 TWh in 2022, twenty times the 2016 level (IEA, 2023). Such concentrated boilers are well-suited for liquid cooling: immersion baths or coolant loops can feed radiator circuits directly, eliminating the need for high-lift heat pumps. A pilot in Finland's Satakunta region demonstrated that even a 2 MW installation can supply heat to approximately 11,000 residents via the local district heating system (Gooding, 2024).

Thus, excess heat from IT equipment—especially crypto-mining—ceases to be a passive byproduct and becomes an active element in low-carbon building architecture. The following sections will examine how to select the appropriate integration scheme for incorporating heat into existing HVAC loops and which IoT algorithms to employ to balance computational load against heat consumer requirements.

Materials and Methodology

This section is based on an analysis of 24 sources, including academic studies, industry reports, pilot project case studies, and regulatory documents. Among the works reviewed were global data-center consumption and heat-recovery potential assessments (IEA, 2023), German regulatory requirements for heat recovery (Judge, 2023) and the EU Energy Efficiency Directive (Uptime Intelligence, 2023), Swedish and Finnish project experiences (European Commission, 2023; Gooding, 2024), and technical descriptions of air and immersion cooling equipment (BitMain, 2020; Zhou et al., 2024). Additionally, retrofit guidelines for HVAC systems (Simmons, 2020), specifications for OPC UA and MQTT protocols (OPC Foundation, 2024; Dave, 2024), and research on edge+cloud platforms for predictive control (Petri et al., 2021) were examined.

The theoretical foundation comprised assessments of mining-module heat-flux density and their integration into heating loops. BitMain (2020) and Zhou et al. (2024) indicate that, in practice, immersion cooling can deliver heat at temperatures up to 60°C. It is, therefore, attractive for direct connections with low-temperature systems. Alfalaval (2024) and Profile IT Solutions (2025) provide an assessment of three topologies—bypass, series-loop, and hybrid-grid—regarding their capital and operational expenditures. Meanwhile, AMR (2025) and Uptime Intelligence (2023) assessed the scalability of solutions at the building and district levels.

Methodologically, the work combines four approaches. First, a comparative analysis of heat-extraction schemes: contrasting air and immersion cooling, as well as the three architectural configurations by PUE and heat utilization factor (Alfalaval, 2024; Profile IT Solutions, 2025). Second, it reviews the regulations and industrial prescriptions in scope (Judge, 2023; Uptime Intelligence, 2023; European Commission, 2023) to synthesize criteria for ethical and safe implementation. Third, a content analysis of pilot cases—comprising the Swedish Open District Heating scheme (European Commission, 2023) and the Finnish Satakunta project (Gooding, 2024)—was conducted, which returned heat return rates as well as impacts on CO_2 emissions. The empirical experiment then runs modeling using a digital twin of an HVAC system and the LightGBM algorithm (Shi et al., 2024; Zanetti et al., 2025), as well as thermal load forecasting models and dynamic hash rate control strategies.

Besides the technical and regulatory reviews, the current paper provided an economic analysis of demand-response programs (Gracia, 2022; Riot Platforms, 2025), a review of cyber-risk based on incident statistics (Kaspersky, 2025), and results from a study in chip degradation under conditions of thermal stress (El-Sayed et al., 2012).

Results and Discussion

The integration architecture comprises five interrelated layers, each of which must simultaneously satisfy thermal engineering, electrical, and telemetry constraints, ensuring that the computing node's excess heat is converted into useful thermal power for the building without compromising controllability. This approach requires the coordinated selection of equipment, protocols, and algorithms, since a change in parameters at one layer immediately affects the balances of the others.

At the computational-source level, GPU farms and specialized ASIC racks are distinguished. The latter achieves a record heat-flux density: a typical Bitmain S19 Pro at a hash rate of 110 TH/s consumes approximately 3.25 kW, all of which is dissipated as heat (Bitmain, 2020). In GPU solutions, the total load is distributed among graphics cards and fans, reducing the specific density but providing flexibility in frequency and voltage control. For HVAC architects, the key factor is the method of heat extraction. With air cooling, the specific heat flux is limited; however, immersion cooling allows the coolant to be delivered at temperatures of up to 60 °C, which is suitable for direct connection to low-temperature heating circuits (Zhou et al., 2024).

The subsequent chain begins with an HVAC retrofit. In most existing facilities, it is expedient to install plate or rotary heat exchangers, since they do not require a complete overhaul of shafts and can recover over 80 % of the sensible heat from exhaust air (Simmons, 2020). Given that the fluid temperature from immersion baths is significantly higher than the supply temperature, a hydraulic insert into the existing heating loop and re-tuning of VAV fans to maintain the required airflow in the premises are sufficient.

To render the heat flux predictable, IoT infrastructure is integrated into the loop: temperature, flow, and vibration sensors transmit data via OPC UA or MQTT. OPC UA defines the address space structure and mutual device authentication mechanism, ensuring compatibility between the OT and IT layers (OPC Foundation, 2024). In contrast, MQTT provides a lightweight broker for event-driven messages and is used when minimal latency or cellular-network operation is required (Dave, 2024). A typical gateway consolidates both protocols and translates the data into a format understandable by the cloud or a local processing server.

The next level hosts the management platform, where an edge node stores second-level telemetry series, constructs basic digital twins, and runs optimization algorithms. Experiments on university campuses have demonstrated that transitioning from purely cloud-based analytics to a distributed edge and cloud approach reduces the HVAC peak power draw through more accurate predictive control (Petri et al., 2021). The digital twin enables adjustment of the miners' operating point (partially disabling ASIC units or altering GPU frequency) just enough to keep the heat-receiver demand and the PUE limit in balance.

The final layer comprises interfaces with BMS and SCADA. Most modern building systems support BACnet/IP; the BACnet-BMS market is projected to reach USD 17 billion by 2025, with further annual growth of 3–4%, as shown in Fig. 1 (AMR, 2025).

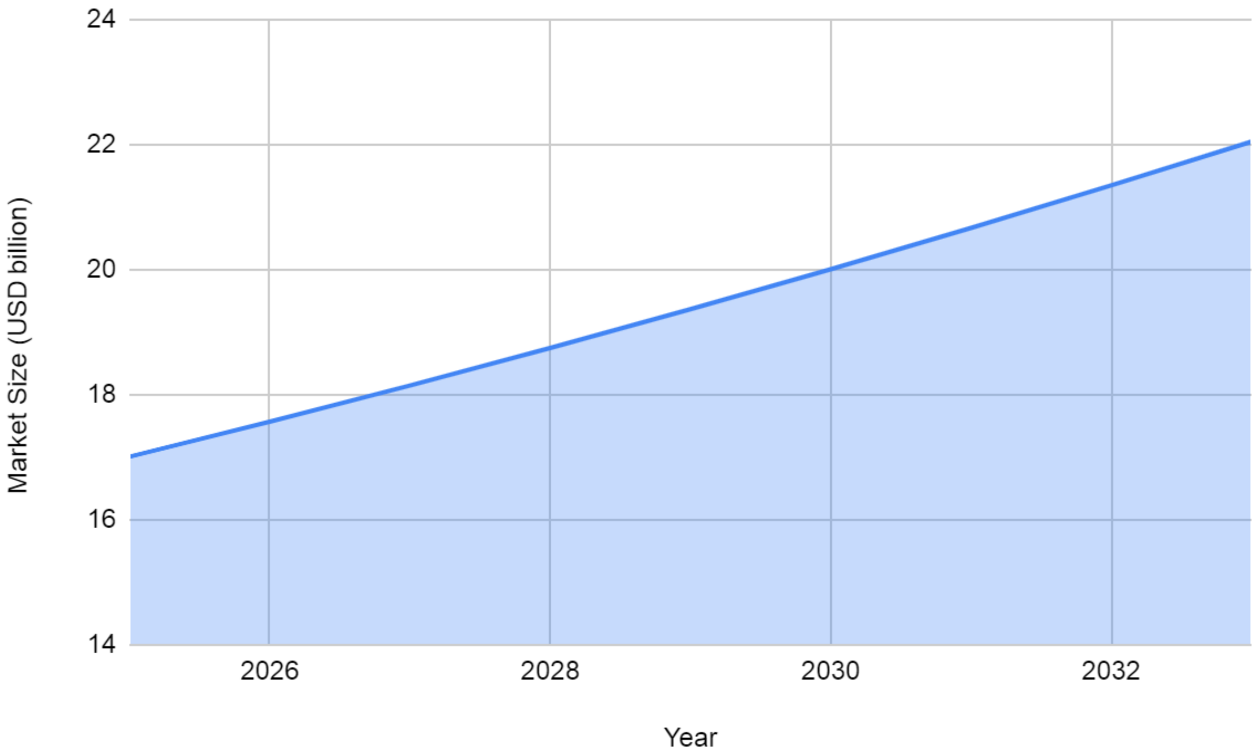

Fig. 1. The BACnet Building Management System Market Size (AMR, 2025)

Modbus RTU or Modbus TCP is typically adequate for local units. Climate equipment manufacturers currently provide gateways that enable up to 100 Modbus devices to be linked to a single KNX or BACnet bus without requiring any additional programming (Trane, 2023). Findings from an API-compatibility study revealed that REST interfaces to BMS facilitate the integration of external IoT platforms, thereby accelerating data delivery to analytics by nearly a factor of two when benchmarked against traditional point-to-point mapping (Yefi et al., 2024).

Together, these components form a closed technological loop in which the real-time reheated output of the miners is converted into a controllable energy resource for the building. At the same time, open protocols reduce integration costs and ensure solution scalability.

At the conceptual design stage, the choice of mining-node connection scheme to the existing HVAC system is determined by two variables—the share of heat that the building can accept without reconstructing the heat-exchange loop, and the temperature level of that heat. The revised EU Energy Efficiency Directive prioritizes economic recovery by obliging all data centers to recover heat whenever possible, or to demonstrate technical infeasibility regarding heat extraction. If a data center does not consume extracted heat, details must be provided on its use in external systems (Uptime Intelligence, 2023). An example system is illustrated in Fig. 2. This, therefore, brings three basic topologies that can scale the solution from one building up to a district heating network, preserving controllability via the IoT loop.

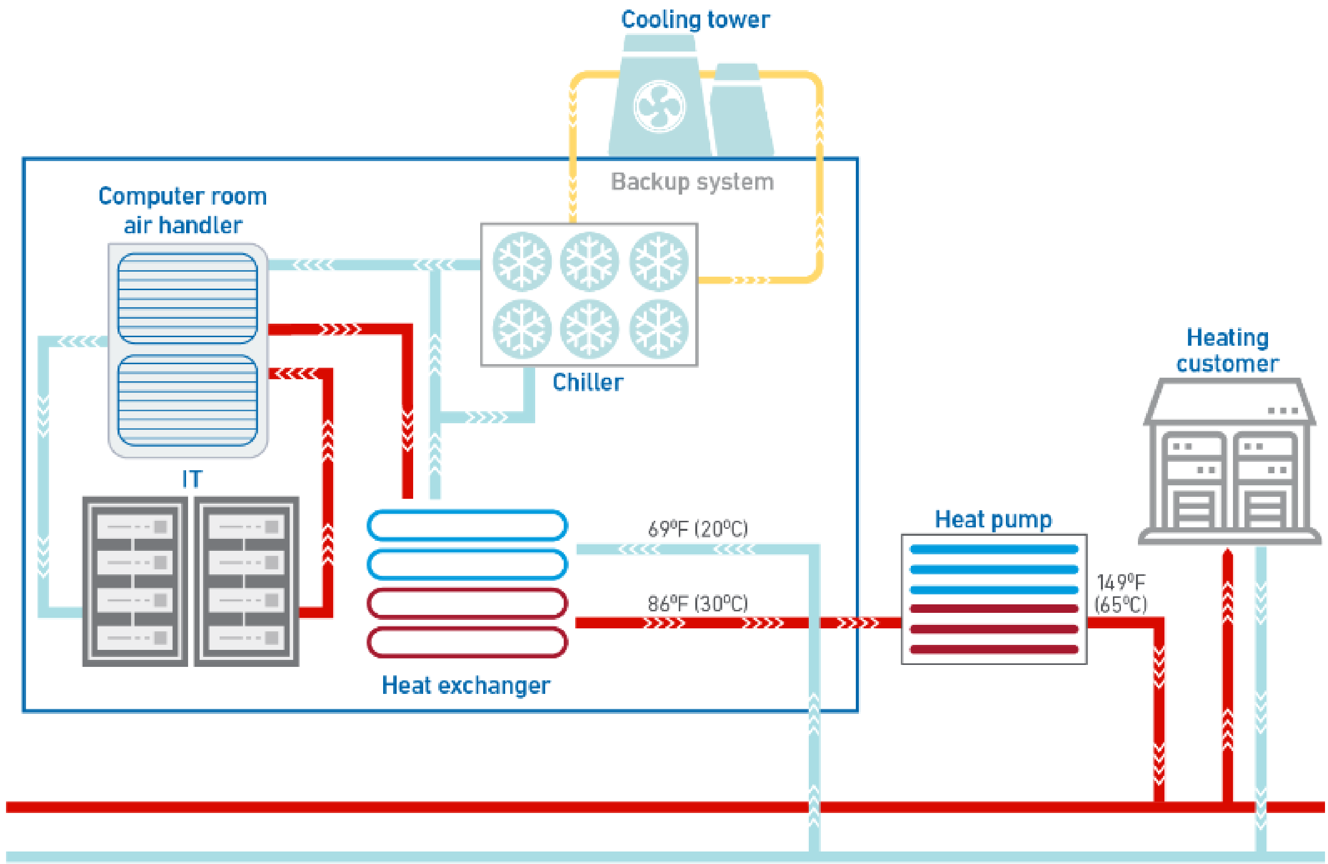

Fig. 2. Data Center Waste Heat Export to District Heating Network (Uptime Intelligence, 2023)

Parallel, or by-pass, configuration is intended for buildings where mining can supply no more than one-third of the peak thermal load, thereby minimizing intervention in the primary ventilation scheme. Hot air or fluid from the racks is routed to a heat recovery unit and then blended into the supply duct. When demand drops, VAV dampers automatically open the bypass, and the system reverts to normal operation. This approach aligns well with regulations such as the German Energy Efficiency Act, which sets a target threshold for heat reuse of 30 % from 2024 and 40 % from 2027 for new sites (Judge, 2023). Capital expenditures are limited to the installation of a heat exchanger and a few sensors, making the scheme attractive for rapidly deployable edge nodes.

The sequential, or series-loop, model is employed when the thermal output of mining is comparable to the facility's requirements and the temperature regime permits operation without a heat pump. The fluid, which extracts up to 200 kW from each rack via direct crystal cooling, returns directly to the building's hydraulic circuit after passing through a plate heat exchanger (Alfalaval, 2024). Mechanical cooling is scarcely utilized, and energy savings for cooling reach 98 % compared to traditional air cooling. To maintain this regime, an IoT platform regulates miners' hash rate via a predictive thermal-balance model, synchronously adjusting pump speeds and three-way valve positions.

When the heat source must serve multiple buildings, a cascade or hybrid-grid scheme is preferred. In this architecture, heat from the mining module is first stored in a buffer accumulator, after which distribution stations deliver it through a four-pipe network to residential and commercial buildings. A Finnish pilot provides practical validation: a 2-MW crypto center in the Satakunta region supplies district heating for approximately 11,000 residents by feeding thermal energy into the municipal network (Gooding, 2024). Load distribution among multiple consumers reduces seasonal variability but requires additional valves, commercial metering units, and expanded IoT-SCADA functions to balance flows in real-time.

The final solution is selected by comparing the building's specific thermal load, investment constraints, and expected equipment lifecycle. At approximately 10 MW capacities, the shift between air and immersion cooling, as required for a Series-Loop and a Hybrid-Grid, reduces capital expenditure by an average of 41% with lower annual cooling energy expenses (Profile IT Solutions, 2025). However, as the share of recovered heat increases, the backup removal systems for thermal network failure become more expensive. This again increases payback periods. Therefore, facilities with a limited thermal share more frequently adopt the parallel bypass, whereas new or extensively modernized buildings with high thermal loads move to the sequential scheme, and urban clusters with developed district infrastructure utilize cascade networks. This matrix approach enables flexible integration of mining-generated heat into existing HVAC landscapes while remaining within regulatory limits for energy efficiency and emissions.

High-level algorithms link mining-rack telemetry, building heating parameters, and energy-market price signals into a unified decision-making model. At its core is a predictive thermal balance: a LightGBM gradient-boosting model trained on two seasons of historical data achieved a mean absolute percentage error of 6.2 % for 15-minute heat-load forecasts (Shi et al., 2024), enabling the operator to reduce annual cooling electricity consumption by 12 % without compromising indoor climate (Zanetti et al., 2025).

When forecasts indicate a mismatch between the potential heat output of computational modules and the required heat supply, the system regulates the hash rate. ERCOT practice in Texas has demonstrated the scale of this maneuver: during extreme heat, industrial miners synchronized shutdowns, freeing over 1,000 MW—i.e., more than 1 GW—for the grid, equivalent to approximately 1% of the state's peak load (Gracia, 2022).

Access to demand-response programs makes such behavior economically attractive. For example, Riot Platforms' June 2025 report shows that participation in ERCOT and MISO schemes yielded USD 1.8 million in demand-response credits and USD 3.8 million in price credits—USD 5.6 million in total—reducing the weighted average cost of electricity to 3.4 ¢/kWh (Riot Platforms, 2025). These figures define the upper bound of savings that a predictive controller can incorporate into its objective function alongside PUE and heat-utilization metrics.

Finally, service-oriented diagnostics close the equipment sustainment loop. In a case study of a major manufacturer implementing augmented reality for step-by-step technician guidance, repair times decreased by 30% while error rates fell by 40%, directly improving mining-cluster availability and reducing the risk of unexpected thermal deficits (Fatfinger, 2024).

Together, predictive forecasting, dynamic hash-rate adjustment, integration with demand-response programs, and service-oriented diagnostics form a self-tuning cycle that maintains thermal and energy efficiency at levels required by modern regulations and business metrics.

The risk landscape of integrating mining installations into HVAC circuits extends far beyond thermal-balance calculations: cryptocurrency price fluctuations, hardware failures, regulatory constraints, and cyberattacks can undermine the business case even in flawless designs. Volatility is the primary and most obvious threat. In 2022, Bitcoin lost 65 % year-on-year amid the Terra USD collapse and FTX bankruptcy—the industry's worst annual performance since 2018 (McCarthy, 2022). To mitigate such downturns, operators tie mining regimes to thermal and grid signals: when coin prices are low and heat demand is high, the farm continues operating for the heat-network contract, generating off-exchange revenue; when excess electricity and rising coin prices occur, a boost mode activates, selling hash rate to the market. Cash-flow gaps are further insured by fixing part of profits in forward electricity contracts and cryptocurrency collar options—a practice now employed by major public miners in North America.

Technological risk manifests in two forms. Overheating and thermal shock cycles accelerate chip degradation. A server-reliability study found that for every 10°C above 21°C, the lifespan of electronic components is halved (El-Sayed et al., 2012). Immersion cooling stabilizes crystal temperature and acts as a humidity shield. Meanwhile, dew-point and corrosion sensors are also integrated into the IoT loop, along with the application of a selective conformal lacquer to the circuit boards. At the policy level, an N + 10% spare-rack rule allows equipment to be worked on without removing it from the building's thermal output.

Because mining modules generate heat continuously, non-fulfillment of requirements is liable to be fined and may also carry a suspension in operations. Risk can be mitigated at the feasibility stage: a digital twin of the HVAC scheme simulates at least three heat-demand scenarios—normal, anomalously warm season, and network-failure emergency—and demonstrates to regulators the ability to dissipate power safely without overheating. Additionally, an isolated dry-cooling circuit is reserved and automatically engaged if the fluid temperature exceeds permissible limits.

Cyber threats are among the critical factors. In Q4 2024 alone, Kaspersky ICS-CERT recorded 107 publicly confirmed incidents in industrial networks, 50 % of which involved ransomware and 12 % resulting in production-line shutdowns (Kaspersky, 2025), with most incidents occurring in the USA, as shown in Figure 3.

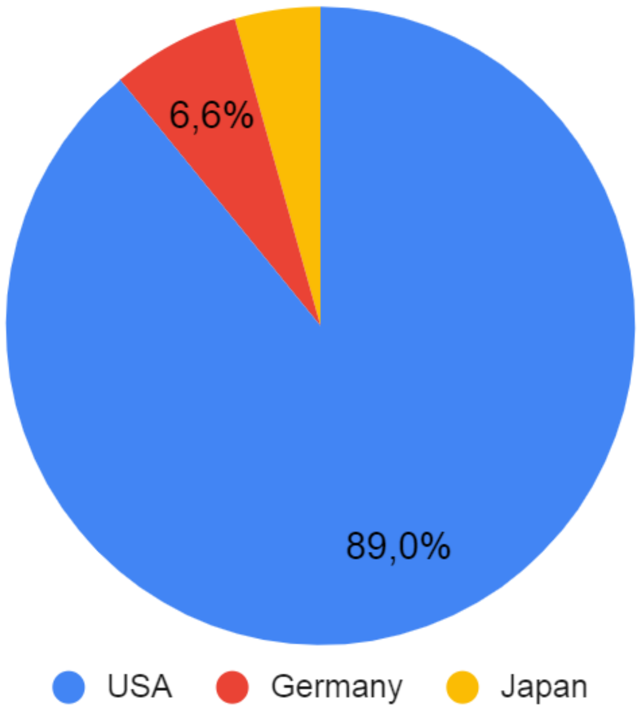

Fig. 3. Countries with the highest number of reported incidents (Kaspersky, 2025)

In mining–HVAC topologies, a breach of the OT segment entails the simultaneous loss of hash rate and thermal generation; therefore, segmentation according to an east–west firewall principle and Zero Trust VPNs between layers of IIoT gateways and the BMS becomes a mandatory requirement. ASIC firmware is stored in a repository with integrity verification, and critical PLCs receive a unidirectional data-diode channel to SCADA, preventing any reverse writing. These measures, together with regular red-team attack simulations, reduce intrusion detection time and limit damage to the scope of an isolated segment.

Thus, financial, technological, regulatory, and cybernetic risks jointly define the framework for integration architecture. It enables a highly dispersed source to become a vital component of low-carbon systems while still operating, by implementing specific measures and actions, ranging from investing in crypto to multiple layers of OT safety.

Conclusion

This study will build a detailed model of how to fit mining installations into existing HVAC systems with IoT control at five related levels: starting from the computational modules that produce heat, moving through retrofit heat-exchange loops, including a telemetry network, using an edge-plus-cloud management platform, and finally ending with BMS/SCADA interfaces. The key characteristics of various equipment types are described—from high-density ASIC rigs dissipating up to 3.25 kW per device to flexible GPU farms—and the benefits of immersion cooling in maintaining coolant temperatures sufficient for direct connection to low-temperature heating systems are demonstrated. Meanwhile, the selection of recuperators and adaptation of VAV fans in retrofit scenarios can achieve up to 80 % recovery of sensible heat, minimizing capital expenditures and the risk of interference with a building's primary engineering infrastructure.

Analysis of the three basic integration topologies—parallel (bypass), sequential (series-loop), and cascade (hybrid-grid)—has shown that each is optimal under specific conditions: the building's recoverable thermal-load fraction, the coolant temperature level, and the scale of the territorial network. The bypass configuration is ideally suited for rapid deployment at edge sites with moderate thermal output. The series-loop delivers maximum energy savings on mechanical cooling at coolant temperatures up to 60°C, and the hybrid-grid enables solution scaling to district and municipal networks with buffer accumulators and complex flow distribution. IIoT gateways supporting OPC UA and MQTT, integration into BACnet/IP and Modbus loops, and the implementation of digital twins and LightGBM predictive models ensure precise balancing between miners' computational loads and heat-sink demands.

It is attentive not just technically, but also economically, regulatorily, and cybersecurity-wise: from the fluctuations in cryptocurrency prices and hardware failures to requirements under the Energy Efficiency Act and threats in the OT segment. The self-tuning cycle proposed—dynamic hash-rate adjustment inclusive, demand-response programs, augmented–reality–assisted service diagnostics, and multi-layered OT protection—ensures minimized unplanned disruption and financial losses. Ultimately, the integration of excess heat from mining installations emerges not as a byproduct of IT infrastructure but as an active resource for low-carbon buildings and urban thermal networks, capable of enhancing overall energy efficiency and making a meaningful contribution to CO2 emissions reduction.

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