

CHAPTER 2 - LITERATURE REVIEW

2.1 Introduction

This chapter critically reviews and synthesizes literature relevant to the management and governance of cooling efficiency within data centers. Given rising concerns regarding energy consumption, environmental sustainability, and operational costs, this literature review emphasizes the integration of advanced cooling technologies and formalized IT governance practices, specifically ITIL 4 frameworks. The review identifies research gaps, highlights existing studies, and demonstrates how ITIL 4's Drive Stakeholder Value (DSV) module supports stakeholder collaboration and sustainable data center cooling management practices.

2.2 Definition and Components

A data center refers to a dedicated facility designed to store, process, manage, and distribute large volumes of data and information through interconnected computing resources, including servers, storage systems, networking equipment, and supporting infrastructure (Masanet et al., 2020). Effective data center operations require careful management of multiple interconnected components, particularly the cooling infrastructure, due to significant energy demands and the critical need to maintain optimal operational conditions for IT equipment (d'Orgeval et al., 2024).

Key components within a typical data center architecture include:

1. **Computing Equipment:** Servers and storage arrays that execute computational tasks, data storage, and management services critical to business operations (ASHRAE, 2021).
2. **Network Infrastructure:** Communication networks, switches, routers, and connectivity devices that facilitate data transmission internally and externally (Fadaeefath Abadi et al., 2020).
3. **Cooling Systems:** Infrastructure designed to control and manage temperature and humidity to prevent overheating, reduce the risk of equipment failure, and optimize energy consumption. Typical cooling technologies include traditional

- Heating, Ventilation, and Air Conditioning (HVAC), liquid immersion cooling, free-air cooling (Haghshenas et al., 2022).
4. Power Systems: Reliable power sources and backup systems, including generators, uninterruptible power supplies (UPS), and renewable energy sources such as solar power integration to ensure consistent and uninterrupted data center operations (Yeasmin et al., 2023).
 5. Monitoring and Control Systems: Advanced sensor-based technologies, IoT (Internet of Things) monitoring, and analytics systems that provide real-time performance data and predictive maintenance capabilities, significantly enhancing cooling efficiency, reliability, and sustainability of operations (Rostami et al., 2024).
 6. Physical Security and Infrastructure: Comprehensive security measures to protect against unauthorized access, physical threats, and environmental hazards, ensuring the integrity and operational continuity of data center resources (Fadaeefath Abadi et al., 2020).
 7. Governance and Management Frameworks: Structured governance frameworks, such as ITIL 4 and COBIT 5, that provide standardized processes, guidelines, and practices for aligning IT services and infrastructure management with business and stakeholder goals (Hunnebeck, 2019; ISACA, 2019).

2.2.1 Importance of Sustainable Data Center Cooling Practices

With a surge in digital services and cloud computing, the movements of the data centers have soared and thus energy consumption has become an important issue. Cooling systems, which are the necessary component to keep optimal operating temperatures, consume a large share of total energy for a data center. In this light, the adoption of energy efficient cooling solutions is crucial, not just to improve energy use efficiency and maximize operational savings, but also to limit the environmental impact of data centers.

Air based cooling techniques have always been known for being energy hungry and are often unable to meet the requirement of modern high-density data centers. This led to the development of innovative cooling solutions such as liquid immersion cooling,

which have shown to greatly reduce the power usage. In fact, research indicates that energy consumption can be reduced by around 50% while occupying two-thirds less physical space compared to traditional air cooling solutions with immersion cooling (Haghshenas et al., 2022). By doing so, these developments also enhance the stability of the underlying infrastructures of data centers.

And even apart from energy efficiency, data centers pose environmental threats such as high carbon emissions and a huge amount of water consumption. Implementing sustainable approaches to cooling can lessen these effects by incorporating renewable energy sources and innovative cooling systems. This can be seen, for example, in the emerging waste heat recovery system, which captures the waste heat produced in data centers for other applications, greatly reducing energy consumption. Since its construction in 2010, the Aquasar supercomputer, which employs a hot water cooling system, has reduced carbon emissions by 85% by using waste heat to heat buildings (Zimmermann et al., 2012). These initiatives highlight how sustainable cooling practices can align with global environmental objectives while helping businesses remain operationally efficient.

The incentives for implementing sustainable cooling solutions are also driven by regulatory compliance and corporate responsibility. With more localized emissions regulations being enacted every year, data centers will need to adopt energy-efficient measures to meet industry standards and corporate sustainability agreements. Digitalisation enhances real-time tracking capabilities, while implementing advanced cooling technologies helps organizations to fulfil legal requirements, mitigate operational risks, and improve their image among stakeholders. And sustainable initiatives offer access to environmental certifications, incentives, and cost savings.

Advancing cooling efficiency and innovation technology are key to attaining and retaining competitive advantage. Generative AI and Pivotal – We have been here before with thermal systems real-time monitoring and optimization of cooling are part of many systems with AI and AI-driven thermal management systems. Data centers can be much more energy efficient, avoid downtime, and improve resource utilization by using AI-powered cooling solutions. Automation and mainstream technologies put

organizations ahead of the curve of sustainability and energy-efficient infrastructure that is becoming common in business as a way to stay competitive.

2.3 Overview of ITIL 4 Framework

The Information Technology Infrastructure Library (ITIL) is a globally recognized framework designed to effectively manage and govern IT services, aligning these services with business objectives and stakeholder requirements. Released as an evolution from ITIL v3, ITIL 4 provides an agile and comprehensive approach that places emphasis on value co-creation, continuous improvement, and stakeholder engagement in service management.

Central to ITIL 4 is the Service Value System (SVS), a holistic model designed to illustrate how organizational components and activities collaborate to generate value. The SVS includes critical elements such as the Guiding Principles, Governance, Service Value Chain (SVC), Practices, and Continual Improvement[®]. This system ensures a coherent approach to IT service management, integrating processes, stakeholders, and technologies to deliver sustained value.

Within ITIL 4, the Service Value Chain (SVC) is particularly prominent, outlining six interconnected activities Plan, Engage, Design and Transition, Obtain/Build, Deliver and Support, and Improve that collectively generate and deliver value through products and services. Each activity incorporates principles of agility, flexibility, and continual improvement, enabling organizations to respond effectively to dynamic environmental and technological changes.

Furthermore, ITIL 4 introduces the Four Dimensions of Service Management, consisting of (1) Organizations and People, (2) Information and Technology, (3) Partners and Suppliers, and (4) Value Streams and Processes. These dimensions facilitate a structured, comprehensive approach to addressing the complexities of IT service delivery, emphasizing a balanced focus on technical, organizational, and human factors essential for successful service management.

The framework also emphasizes practical governance, clearly delineating roles, responsibilities, and accountabilities within service management, promoting transparency and proactive stakeholder involvement. Additionally, ITIL 4 explicitly addresses stakeholder engagement through specialized modules like the Drive Stakeholder Value (DSV), which emphasizes structured interactions, collaboration, and ongoing value co-creation with stakeholders throughout service.

In the context of sustainable data center cooling efficiency, ITIL 4 provides robust methodologies to systematically integrate innovative cooling technologies, enforce regulatory compliance, and maintain continuous stakeholder engagement. Its structured governance and continuous improvement processes offer a coherent framework for managing and optimizing data center operations, particularly emphasizing sustainability and energy efficiency outcomes (Rostami et al., 2024).

Thus, the ITIL 4 framework serves as a foundational governance structure, promoting sustainable operational practices, stakeholder collaboration, and continual improvement within modern IT environments, including data center operations.

2.3.1 Case Studies of ITIL Implementation in Data Centers

Case Study 1: Equinix AI-Driven Cooling Optimization

Global data center provider Equinix increased its cooling efficiency through ITIL-aligned processes. Equinix achieved substantial energy savings by implementing AI-driven monitoring systems, optimizing energy consumption specifically for data center cooling. This aligns with ITIL's Continuous Service Improvement process, which focuses on consistent improvement of efficiency in service delivery.

Case Study 2: Intel's Data Center Facilities Risk Management

Intel implemented this [ITIL framework] to improve and standardize risk management of data center facilities. Intel applied ITIL's management modules to elevate data collection from reactive to proactive, allowing for improved management of cooling systems and infrastructure as a whole. This proactive methodology is in line with the Service Operation phase of ITIL, where services are delivered in effective and efficient manner.

Case Study 3: Nlyte's Data Center Service Management Integration

Nlyte Software integrated Data Center Infrastructure Management (DCIM) with ITIL processes, creating a Data Center Service Management (DCSM) solution. This allowed IT service management information to be more accurate and enhanced cooling efficiency through better measurement and management of energy consumption. The result was streamlined processes. These also corresponds to ITIL's Service Transition step, which allows for smooth transition of new/changed services.

2.4 ITIL 4 Drive Stakeholder Value (DSV) within IT Service Management (ITSM)

The ITIL 4 Drive Stakeholder Value (DSV) module represents a specialized segment of the broader Information Technology Service Management (ITSM) framework, providing structured approaches to maximize stakeholder engagement and value co-creation within service management practices. ITSM, as guided by ITIL 4, systematically aligns IT services and technological processes with strategic business goals, ensuring that stakeholder expectations are continuously met or exceeded.

Within ITIL 4, the DSV module, show in Figure 2.1 is specifically oriented toward enhancing stakeholder experiences across the service lifecycle. This structured module involves seven clearly defined steps: Explore, Engage, Offer, Agree, Onboard, Co-create, and Realize. Each of these steps is designed to systematically build and sustain effective stakeholder relationships, clearly identify service expectations, and actively engage stakeholders in continuous service improvement efforts.

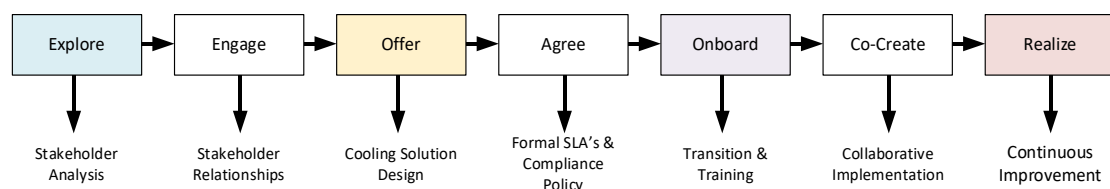


Figure 2.1. ITIL 4 Drive Stakeholder Value Framework

Application of ITIL 4 DSV to Sustainable Data Center Cooling Efficiency

In the context of this thesis "Sustainable Data Center Practices for Cooling Efficiency: A Case Study of Sinergy Data Center" the principles outlined by ITIL 4 DSV offer a robust framework to effectively manage stakeholder expectations related to sustainable cooling practices, energy efficiency goals, and regulatory compliance.

1. Explore

At Sinergy Data Center, the Explore phase involves detailed stakeholder analysis, identifying the cooling efficiency requirements of critical stakeholders including data center operators, compliance officers, sustainability managers, IT management teams, and regulatory authorities. Utilizing structured methods such as stakeholder mapping, PESTLE analysis, and SWOT analysis ensures that all stakeholder needs and regulatory considerations particularly ISO 50001 and ASHRAE TC 9.9 compliance are effectively captured and prioritized.

2. Engage

The Engage phase emphasizes building and maintaining transparent, ongoing communication with stakeholders. Effective engagement strategies at Sinergy Data Center include regular collaborative meetings, workshops, and updates on cooling system performance metrics such as Power Usage Effectiveness (PUE), Cooling Efficiency Ratio (CER), and carbon emissions data. Transparent engagement builds stakeholder trust, enhances compliance, and improves long-term operational sustainability (Hunnebeck, 2019).

3. Offer

In the Offer phase, Sinergy Data Center designs and presents clear, tailored cooling solutions, explicitly aligning with identified stakeholder requirements. These offerings include the adoption of innovative cooling technologies, such as liquid immersion cooling, AI-driven predictive cooling optimization, and renewable energy integrations. Such structured offerings directly address the stakeholder demands for sustainability, cost reduction, and regulatory compliance (Rostami et al., 2024).

4. Agree

At this stage, Sinergy Data Center clearly defines and formalizes cooling efficiency agreements with stakeholders. Explicit documentation through

Service Level Agreements (SLAs) and outlines specific performance PUE targets, operational responsibilities, and compliance obligations. These agreements ensure mutual clarity, accountability, and alignment with corporate sustainability and governance goals.

5. Onboard

The onboarding process at Sinergy Data Center ensures stakeholders and operational teams are effectively trained, informed, and transitioned onto new cooling technologies and practices. Structured onboarding programs and comprehensive documentation support stakeholders in adapting quickly, thus enabling successful implementation and seamless operational continuity.

6. Co-create

The Co-create phase involves active collaboration between stakeholders and the Sinergy Data Center management team, continuously optimizing cooling performance through stakeholder feedback, real-time IoT monitoring data, and proactive joint problem-solving activities. By fostering a collaborative service management culture, stakeholders actively contribute to ongoing innovation, ensuring continuous improvement and operational adaptability (Hunnebeck, 2019).

7. Realize

Finally, the Realize stage systematically evaluates and measures the value delivered through implemented sustainable cooling policies. Continuous performance assessments against established PUE inform regular reviews and improvements. These evaluations help Sinergy Data Center maintain operational excellence, ensuring long-term stakeholder satisfaction and sustainable environmental performance (Rostami et al., 2024).

2.5 Framework of ITIL 4 Related to This Project

This research adopts the ITIL 4 framework, particularly the Drive Stakeholder Value (DSV) module, to establish a structured methodology for improving cooling efficiency and sustainability in data center operations. Specifically, this framework is applied within the context of the current case study: "Sustainable Data Center Practices for

Cooling Efficiency: A Case Study of Sinergy Data Center." ITIL 4 provides a coherent and robust governance approach, facilitating systematic stakeholder engagement, technological integration, and continuous performance improvement.

The framework proposed by ITIL 4 DSV for Sinergy Data Center involves systematically integrating stakeholder engagement, sustainability management, innovative cooling technologies, and structured governance processes. The key components of the framework are clearly outlined as follows:

1. Stakeholder Exploration and Analysis

In this initial stage, Sinergy Data Center systematically identifies and assesses stakeholders, including operational staff, management teams, regulatory authorities, and sustainability officers. Stakeholder needs and expectations related to cooling efficiency, sustainability standards, and compliance requirements (ISO 50001, ASHRAE TC 9.9) are carefully analyzed through structured analytical methods such as PESTLE, SWOT, and stakeholder mapping.

2. Stakeholder Engagement and Communication

This phase emphasizes continuous, structured engagement with identified stakeholders. Regular communications, stakeholder meetings, workshops, and feedback sessions are held to clarify expectations, build trust, and enhance transparency. Effective engagement ensures stakeholder alignment and informed decision-making processes, critical for successful implementation of sustainable cooling practices.

3. Service Offering Design

In this phase, Sinergy Data Center develops tailored cooling efficiency solutions incorporating advanced technologies such as liquid immersion cooling, AI-driven predictive thermal management, renewable energy integration, and real-time IoT-based performance monitoring. These offerings clearly address identified stakeholder expectations, regulatory compliance requirements, and strategic sustainability goals.

4. Service Level Agreements and Compliance

Structured and clearly documented Service Level Agreements (SLAs) and Experience Level Agreements (XLAs) are formulated, explicitly outlining cooling efficiency targets (e.g., Power Usage Effectiveness (PUE), Cooling Efficiency Ratio (CER), carbon emission reductions). Clearly defined agreements promote mutual accountability, effective stakeholder alignment, and sustained compliance with relevant regulatory frameworks such as PP No. 70 Tahun 2009.

5. Stakeholder Onboarding and Training

Effective onboarding and comprehensive training are provided to stakeholders and operational teams regarding newly implemented cooling technologies and processes. Structured transition planning and support ensure stakeholders are adequately equipped to manage and optimize cooling systems effectively, ensuring smooth operational transitions and immediate adoption of sustainable practices.

6. Collaborative Co-creation and Optimization

Stakeholders actively collaborate with Sinergy Data Center management to optimize and continuously improve cooling performance. Utilizing real-time IoT monitoring data, AI-driven analytics, and regular stakeholder feedback, collaborative problem-solving and iterative improvement processes are undertaken. This co-creative approach fosters innovation, responsiveness, and continuous operational sustainability improvements (Rostami et al., 2024).

7. Value Realization and Continual Improvement

Finally, the effectiveness of implemented sustainable cooling practices is systematically measured and monitored using defined performance metrics such as PUE and carbon emission reductions. Regular stakeholder evaluations and structured feedback loops facilitate continual refinement and enhancement of cooling strategies, ensuring sustained operational excellence, regulatory compliance, and stakeholder satisfaction (Yeasmin et al., 2023).

2.6 Governance and Policy Management in Data Center Sustainability

Governance plays a critical role in shaping sustainable data center operations by ensuring that technical implementations are aligned with regulatory requirements,

organizational goals, and stakeholder expectations. Within the IT governance framework, particularly COBIT 5 and ISO 50001, policy development is a foundational mechanism for translating strategic sustainability objectives into enforceable actions. In the context of data center cooling, policies dictate energy thresholds, temperature setpoints, access controls, incident escalation, and maintenance schedules.

Effective policy development involves stakeholder consultation, risk identification, and alignment with sustainability standards such as ISO 50001 and ASHRAE TC 9.9. It requires structured documentation, version control, and approval workflows. However, policy creation alone is insufficient without robust policy testing a process that validates policy clarity, compliance, and operational viability. Testing may include simulation drills, audit checklists, and review of historical data to evaluate whether thermal thresholds and SOPs are functioning as intended.

Literature also emphasizes the importance of governance feedback loops, where continuous monitoring and stakeholder feedback are used to refine policies. For example, ITIL 4's Continual Improvement model encourages organizations to regularly assess policy effectiveness through metrics like compliance rate, audit success, and incident recurrence. This study adopts such a governance-informed approach to cooling efficiency, advocating not only for technical optimization but also for institutional accountability through well-developed and rigorously tested policies.

2.7 Policy Development and Testing in Data Center Governance

The development of this study's framework is not solely anchored in theoretical and technical models, but also guided by emerging policies and regulatory frameworks that shape data center operations. Policies related to energy management, IT governance, and sustainability provide both constraints and opportunities for innovation in data center cooling.

At the national level, Indonesia's compliance with PP No. 70/2009 on Energy Conservation mandates energy audits and efficiency improvements in large-scale facilities, including data centers. Internationally, standards from organizations such as ASHRAE TC 9.9 and ISO 50001 for energy management systems establish benchmarks that influence design, monitoring, and optimization of cooling strategies.

Policy development must follow a structured process that includes stakeholder involvement, risk-based considerations, and alignment with IT assets and services. The process is often cyclical, involving identification of needs, drafting and validation, approval, dissemination, and revision. ITIL 4's Service Value System (SVS) underscores the importance of continual improvement, where policies are reviewed and revised based on feedback, audit results, or changes in environmental factors.

Furthermore, the COBIT 5 governance framework particularly domains like BAI09 (Manage Assets) and MEA01 (Monitor, Evaluate, and Assess Performance and Conformance) provide governance touchpoints that integrate technical operations with policy compliance. These frameworks ensure that sustainable practices are not only technically sound but organizationally accountable.

The research framework of this study, therefore, synthesizes technical best practices with policy requirements to produce a contextually relevant model for improving cooling efficiency in data centers. Policy considerations are embedded as boundary conditions, indicators, and validation criteria throughout the framework to ensure both applicability and compliance.

2.8 Previous Studies on Sustainable Data Center Cooling Practices

The following table summarizes recent studies focusing on sustainable data center cooling practices (see Table 2.1) and referring to the weakness and strength journal (see Table 2.2):

Table 2. 1. Recent Studies and Key Findings

Title	Authors	Year	Key Findings
"Transforming Cooling Optimization for Green Data Center via Deep Reinforcement Learning"	(Li et al., 2020)	2020	AI-based cooling control achieved ~11% cost savings.

"Linearized Data Center Workload and Cooling Management"	(Rostami et al., 2024)	2024	Thermal-aware workload management cut cooling power by 30%.
"Towards Improved Datacenter Assessment: Review and Framework Proposition"	(d'Orgeval et al., 2024)	2024	Proposed assessment framework based on environment, economy, ecosystem, and external factors.
"IT Infrastructure of Data Center Services Based on ITIL"	(Tomoda, 2010)	2010	ITIL-based service infrastructure improves standardized data center processes.
Towards Building a Sustainable System of Data Center Cooling and Power Management Utilizing Renewable Energy	(Yeasmin et al., 2023)	2023	Hybrid cooling and power system using wind/solar energy tailored to location feasibility.

Table 2. 2. Reference Paper with Strength and Weakness

Paper Title	Strength	Weakness
"Transforming Cooling optimization for Green Data Center via Deep Reinforcement Learning" (Li et al., 2020)	The study introduces an end-to-end deep reinforcement learning (DRL) framework for data center cooling optimization, significantly reducing energy consumption by 11-15%. It successfully integrates machine learning-based automation to enhance cooling efficiency, reducing the reliance on manual interventions. The method is validated using EnergyPlus simulations and real-world data from the National Super Computing Centre (NSCC) of Singapore, ensuring practical applicability and scalability	Despite the effectiveness of the proposed framework, real-world implementation constraints remain a challenge. The model is simulation-based, and its direct application in real-time data center environments is untested. Furthermore, deep reinforcement learning (DRL) requires extensive computational resources and long training times, which may hinder real-time adaptability and scalability for large-scale data center operations.
"Linearized Data Center Workload and Cooling Management" (Rostami et al., 2024)	The study introduces a linearized framework for thermal-aware workload distribution, significantly reducing cooling power consumption by more than 30%. It effectively simplifies complex nonlinear power optimization problems,	Despite the promising results, the model assumes homogeneous server characteristics, which limits applicability to real-world data centers with heterogeneous workloads and hardware configurations. Additionally, the

	making them computationally feasible for real-world applications. The proposed heuristic improves scalability and eliminates the need for computationally expensive function evaluations, making it suitable for time-sensitive data center operations	linearization approach may lead to approximation errors, potentially reducing optimization accuracy in complex cooling scenarios where nonlinear interactions significantly impact thermal behavior
Towards Improved Datacenter Assessment: Review and Framework Proposition (d’Orgeval et al., 2024)	The study presents a comprehensive framework for assessing data centers, incorporating environmental, economic, ecosystem, and external influences. It highlights multi-criteria assessment methodologies, improving decision-making processes for sustainable data centers. The research also emphasizes real-world energy consumption challenges, providing valuable insights into regulatory impacts and grid constraints, particularly in Europe and the US	Despite its holistic approach, the study lacks empirical validation through real-world case studies or experimental data. It relies on theoretical frameworks and secondary sources, which may limit practical applicability. Additionally, the study focuses primarily on broad sustainability metrics, with limited exploration of specific cooling efficiency strategies, an essential aspect of data center sustainability

"IT Infrastructure of Data Center Services Based on ITIL" (Tomoda, 2010)	The study presents a structured ITIL-based framework for data center service management, improving service standardization, incident management, and operational efficiency. It effectively enhances service quality while reducing operational costs, making it highly applicable to large-scale data center environments. Additionally, the framework integrates configuration management databases (CMDB) and automation tools, enabling scalability and centralized control over IT infrastructure	Despite its structured approach, the study lacks empirical validation of long-term impacts on sustainability and energy efficiency. It focuses primarily on service management improvements, with limited exploration of how ITIL enhances cooling efficiency in data centers. Furthermore, the framework primarily targets Fujitsu's operations, which may limit general applicability across different data center models
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Towards Building a Sustainable System of Data Center Cooling and Power Management Utilizing Renewable Energy (Yeasmin et al., 2023)	The study presents an integrated framework for data center cooling and power management using renewable energy, providing a sustainable approach to reducing energy consumption and carbon footprint. It highlights real-world applications and showcases the feasibility of combining renewable energy with advanced cooling techniques, offering a scalable and adaptable model for modern data centers	Despite its promising findings, the study lacks extensive experimental validation in large-scale commercial data center environments. The reliance on simulated models and theoretical analysis raises concerns about practical deployment challenges, including cost-effectiveness, infrastructure constraints, and integration with existing systems
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2.9 Gaps in Existing Research

The table below presents the gap analysis, emphasizing key differences in architecture and operational aspects between typical data center cooling methods and the sustainable (see Table 2.3), ITIL 4-integrated cooling architecture proposed in this research:

Table 2. 3. Gap Analysis

Criteria	Typical Data Center Cooling Architecture	Proposed Sustainable Cooling Architecture	Gap (Improvements Offered)
Cooling Technologies	Traditional HVAC systems and air-based cooling	Liquid immersion cooling, AI-driven thermal management, free-air cooling	Advanced, energy-efficient cooling technologies implemented
Energy Efficiency	Generally lower efficiency with higher Power Usage Effectiveness (PUE ≥ 1.7)	Higher energy efficiency with targeted low Power Usage Effectiveness (PUE ≤ 2)	Significant improvement in energy efficiency metrics
Environmental Impact	Higher carbon emissions due to higher energy consumption	Reduced carbon footprint with renewable energy integration	Considerable reduction in carbon emissions and energy use
Operational Costs	Higher operational expenditures due to inefficient cooling	Lower operational expenditures through optimized cooling	Cost savings through efficiency and reduced energy usage

Reliability & Downtime	Increased risk of cooling system failures and downtime	Enhanced reliability through AI-driven predictive maintenance and IoT monitoring	Improved reliability and reduced downtime risks
Scalability	Limited scalability due to infrastructure constraints	High scalability due to modular, adaptive cooling architecture	Enhanced scalability, easy adaptation to future demands
Monitoring & Control	Manual monitoring and limited real-time adjustments	Automated, IoT-driven real-time monitoring and dynamic control	Real-time adaptability, automated adjustments, higher precision
Compliance & Standards	Often partially compliant, difficulty adhering to newer sustainability standards	Fully compliant with ISO 50001 and standards or PP No. 70 Tahun 2009	Enhanced regulatory compliance and stakeholder trust
Governance Framework	Limited or no integration with formal governance frameworks	Clearly integrated with ITIL 4 and COBIT 5 governance frameworks	Structured, holistic governance and clear accountability
Stakeholder Engagement	Reactive stakeholder engagement, limited transparency	Proactive stakeholder engagement and value co-creation	Improved stakeholder satisfaction, continuous value co-creation

		(ITIL 4 Drive Stakeholder Value)	
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Refer to Table 2.3 explanation of Gap below:

1. Cooling Technologies:
Traditional architectures depend heavily on conventional HVAC and air-cooling methods, which often result in high energy consumption. In contrast, the proposed architecture incorporates advanced liquid immersion cooling and AI-driven solutions, significantly reducing energy use and environmental impacts (Haghshenas et al., 2022).
2. Energy Efficiency (PUE):
The typical data center exhibits higher Power Usage Effectiveness (PUE), often above 1.7, indicating lower efficiency (Shehabi et al., 2016). The proposed architecture aims for a significantly lower PUE (≤ 2), indicating greater energy efficiency, cost savings, and sustainability.
3. Environmental Impact:
Typical data centers generate substantial carbon emissions due to high energy usage. The proposed architecture significantly reduces environmental impacts by integrating renewable energy and optimizing cooling operations, aligning with global sustainability initiatives and industry standards (Yeasmin et al., 2023).
4. Operational Costs:
Operational expenditures (OPEX) in traditional cooling setups remain high due to inefficient cooling methods. The proposed architecture significantly reduces OPEX by adopting highly efficient, adaptive cooling technologies and real-time monitoring systems.
5. Reliability & Downtime:
Traditional cooling systems are prone to unexpected failures, increasing downtime risks. AI-driven predictive maintenance and real-time IoT monitoring

in the proposed architecture dramatically enhance reliability, reducing downtime risks significantly (Li et al., 2020).

6. Scalability:

Scalability in traditional cooling is limited due to rigid infrastructure and manual controls. The proposed architecture employs modular solutions, facilitating seamless scalability aligned with dynamic business needs and technological advancements.

7. Monitoring & Control:

Traditional methods rely heavily on manual monitoring and static control measures. The proposed system introduces comprehensive IoT-based monitoring and automation, allowing continuous adjustments and precise real-time management of cooling resources.

8. Compliance & Standards:

Typical data centers often face challenges meeting evolving energy management standards. The proposed architecture ensures full compliance with ISO 50001 and PP No. 70 Tahun 2009, significantly enhancing regulatory compliance and operational transparency.

9. Governance Framework:

Traditional architectures lack structured governance frameworks. The proposed architecture integrates IT governance frameworks (ITIL 4 and COBIT 5), providing clearly defined roles, responsibilities, and accountability for cooling efficiency and sustainability initiatives.

10. Stakeholder Engagement:

Conventional setups rarely prioritize proactive stakeholder engagement. Adopting ITIL 4's Drive Stakeholder Value approach ensures active stakeholder participation, transparent communication, and continuous co-creation of value, significantly improving stakeholder satisfaction and operational effectiveness (Hunnebeck, 2019).

2.10 Limited Industry-Specific Studies

The application of ITIL-based sustainable cooling practices across different industries is still an underexplored area. We could also look at industry-related studies, as specific

industries may have unique requirements and challenges when it comes to data center operations and cooling needs. Learning these nuances is imperative to create tailored solutions that are in accordance to both ITIL framework as well as industry-specific requirements.

2.11 Variable

The effectiveness of cooling technologies in achieving sustainable data center operations is influenced by various interacting factors. To ensure a structured and rigorous analysis, the variables in this study are categorized into three main types: independent, dependent, and control variables. These classifications facilitate a clearer understanding of causal relationships and help isolate the specific impact of cooling technologies on energy efficiency outcomes.

Table 2.4 presents the classification and measurement of variables employed in this research.

Table 2. 4. Variable Type

Variable Type	Variable Name	Description / Measurement	Indicator(s)
Independent	Cooling technology type	Traditional vs. advanced cooling system	- Type of cooling used CRAC - Cooling architecture design - Automation in thermal control
Dependent	Cooling efficiency	Measured using PUE, energy savings, sustainability	- PUE (Power Usage Effectiveness) value - Total energy consumption (kWh/year) - % Energy savings compared to baseline
Control	IT load, ambient temperature	Fixed across cases or normalized in analysis	- Server utilization rate (% load) - Total IT equipment power (kW) - Ambient temperature range (°C) - HVAC setpoints and thresholds

The table above illustrates the research variables related to data center cooling efficiency. The independent variable is the type of cooling technology, which includes the use of conventional or advanced systems, such as cooling architecture design, temperature control automation, and CRAC (Conditioning Room Computer). Cooling efficiency is the dependent variable measured by indicators such as PUE (Power Usage Efficiency) value, total annual energy consumption (kWh/year), and percentage of energy savings compared to baseline. At the same time, control variables include IT load and ambient temperature set or normalized during the analysis process. Server utilization rate, total IT device power, ambient temperature range, and AC settings are the indicators. This method is used to ensure that the research findings are not biased by external variables.

2.12 Variable X: Cooling technology type

Table 2.5 presents a comparative synthesis of cooling performance indicators and best practices compiled from leading researchers and industry white papers. This table aggregates empirical metrics and evaluation standards to assess cooling technology types across various domains such as efficiency, reliability, sustainability, and architecture.

Table 2. 5. Indicator of Cooling Technology Type from some scientist

Name of scientist	Indicators	Summary
(Patterson, 2008) The Effect of Data Center Temperature on Energy Efficiency. Intel Corporation White Paper.	1. PUE (Power Usage Effectiveness), main metric indicating how much total energy is used per unit of IT energy. 2. Cooling System Energy Consumption (kWh), total energy used by HVAC, CRAC/CRAH, chillers, pumps, fans. 3. Ambient Temperature and Setpoint (°C), data center inlet temperature settings affecting	1. Type of cooling used CRAC 2. Cooling architecture design 3. Automation in thermal control

	cooling load. 4. Delta-T (Temperature Differential), difference between supply and return air affects airflow and cooling demand.	
(Tierney & Yevgeniy, 2015) Design for Reliability in Critical Infrastructure Cooling. Uptime Institute Journal.	1. Mean Time Between Failure (MTBF), average operational time before the cooling system encounters a failure. 2. System Uptime (%), percentage of time the cooling system operates without causing service interruptions. 3. Thermal Recovery® Time (seconds/minutes), how quickly the system can return to stable temperatures after a thermal spike or failure. 4. Redundancy Level (N, N+1, 2N), presence of backup cooling capacity to handle failures without disrupting IT operations. 5. Fault Tolerance Capability, ability of the system to operate correctly even if one or more components fail. 6. Hotspot Frequency, number of occurrences where localized overheating exceeds safe operating limits.	
(Belady, 2007) In the Data Center, Power and Cooling	1. Energy Star / LEED / ISO 50001 Certification, whether the data center	

Costs More Than the IT Equipment it Supports. Electronics Cooling, 23(1), pp.56–59.	achieves recognized sustainability certifications for energy performance. 2. Power Usage Effectiveness (PUE), lower PUE values indicate more efficient use of power, often required for green certification. 3. Annual Energy Savings (kWh/year), reduction in energy consumption due to improved cooling designs. 4. Carbon Emission Reduction (CO₂ eq), amount of CO₂ saved annually through cooling efficiency improvements. 5. Water Usage Effectiveness (WUE), efficiency of water use in cooling systems (important in green cooling frameworks). 6. Lifecycle Cost Savings (OpEx reduction), long-term operational savings achieved through sustainable cooling implementations.	
(Shah, A., 2009) Best Practices for Datacenter Thermal Management. Intel IT White Paper.	1. Temperature Differential (ΔT), the difference between supply and return air temperature; higher ΔT indicates more efficient zoning. 2. Hotspot Frequency, the number of occurrences where localized areas exceed safe thermal thresholds. 3. Aisle Containment	

	Implementation, presence and quality of physical separation between hot and cold aisles (e.g., containment systems). 4. Rack Inlet Temperature Consistency (°C), stability and uniformity of intake air temperature across racks. 5. Airflow Efficiency (%), ratio of useful airflow reaching equipment vs. total airflow generated. 6. Cooling Load Reduction (%), percentage of cooling power saved due to zoning practices like containment and directed airflow.	
(Rasmussen, 2006) The Advantages of Economizer Modes of Cooling for Data Centers. APC White Paper #59.	1. Hours of Economizer Operation per Year, total number of hours the cooling system operates in free cooling mode annually. 2. Energy Savings (kWh/year), measurable reduction in energy consumption compared to traditional mechanical cooling. 3. OpEx Reduction (%), percentage decrease in operational costs due to reduced mechanical cooling usage. 4. Ambient Temperature Utilization, degree to which outside air or water temperatures are effectively harnessed for cooling. 5. Annualized PUE Improvement,	

	reduction in PUE during months where free cooling is active. 6. Carbon Emission Reduction (CO ₂ /year), environmental impact reduction due to lower power consumption from chillers and compressors.	
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The table 2.5. summarizes the indicators of drying technology types from five most renowned scientists. (Patterson, 2008) highlights technical metrics such as Delta-T, PUE, and energy consumption of the cooling system, which indicate the efficiency of automation and design. (Tierney & Yevgeniy, 2015) concentrate on MTBF, uptime, and fault tolerance capabilities to improve system reliability. Various sustainability elements, such as green certification, annual energy savings, and carbon emission reduction. Factors such as airflow efficiency, inlet temperature consistency, and containment implementation are of primary concern to (Shah, A., 2009). However, (Rasmussen, 2006) proposes an economizer method that utilizes ambient temperature for natural cooling, reducing emissions and operating costs. These indicators collectively show how difficult it is to assess cooling technologies in terms of efficiency, reliability, and sustainability.

2.13 Variable Y: Cooling efficiency

This study refers to several established theories and performance metrics from published academic and technical sources in order to build a robust measurement framework for evaluating cooling efficiency in data centers. The objective of this review is to locate the key variables, their corresponding indicators, and the empirical methods that have been previously used to measure cooling effectiveness. This methodology supports the development of both the instrument design and evaluation benchmarks that will be used in later stages of the research.

A summary of indicators in Table 2.6 is taken from prominent studies and technical guidelines published by experts. The selected literature covers a wide range of cooling

performance dimensions, including scalability, energy ratios, system responsiveness, and environmental impact.

Table 2. 6. Indicator of Cooling efficiency from some scientist

Name of scientist	Indicators	Summary
(Koomey, n.d.)Turning Numbers into Knowledge: Mastering the Art of Problem Solving, 2nd ed. Oakland, CA: Analytics Press.	1. Power Usage Effectiveness (PUE), ratio of total facility energy to IT equipment energy. Reflects efficiency of cooling and support systems. 2. PUE Trend Over Time, monitoring how PUE changes quarterly/annually to track efficiency improvements or regressions. 3. IT Load Power (kW), power consumed specifically by computing equipment (denominator in the PUE formula). 4. Non-IT Load Power (Cooling, etc.), power consumed by HVAC, UPS losses, lighting, etc. (the differential from total power). 5. Peak vs. Average PUE, evaluates fluctuations in efficiency under varying operational conditions.	1. PUE (Power Usage Effectiveness) value 2. Total energy consumption (kWh/year) 3. % Energy savings compared to baseline
(Rasmussen, 2011) Calculating Total Power Requirements for Data Centers. White Paper No. 3, APC by Schneider Electric.	1. Power Usage Effectiveness (PUE), primary metric showing the ratio of total facility energy to IT equipment energy. 2. Non-IT Power Load (kW), amount of energy used by cooling, lighting, UPS losses, and other support infrastructure.	

	3. Cooling System Energy Share (%), percentage of total facility energy consumed by cooling systems. Lower % implies higher efficiency. 4. Cooling Technology Type, presence of advanced systems (e.g., liquid cooling, evaporative, economizers). 5. Sustainable PUE Threshold (<1.5), indicates that the data center is operating with advanced efficiency standards. 6. Load Proportionality of Cooling Power, how closely cooling power consumption scales with IT load more proportional = better efficiency.	
(Hirzel & Edelmann, 2009). Energy Efficiency in Data Centers. In: R. Schnitzer, ed. Sustainability and Resource Efficiency. Springer, pp.103–114.	1. Cooling Energy Share (%), proportion of total electricity used specifically for cooling (e.g., HVAC, CRAC, chillers). 2. Total Cooling Load (kW or kWh/year), absolute value of power or energy consumed by the cooling infrastructure annually. 3. Cooling-to-IT Load Ratio, ratio comparing energy used for cooling vs. energy used directly for computing. 4. Power Usage Effectiveness (PUE), metric used to assess total facility efficiency; high cooling loads result in higher PUE values. 5. Cooling System COP (Coefficient	

	of Performance), measures efficiency of the cooling equipment (higher COP = better efficiency). 6. Opportunity Reduction Margin (%), theoretical or target percentage by which cooling consumption can be reduced with improved tech.	
(Kreitz & Niemann, 2020) Green IT: Reduce Your Data Center's Carbon Footprint. Berlin: Springer Vieweg.	1. Annual Energy Savings (%), percentage of total energy saved due to machine learning-based optimization of cooling systems. 2. ML-Driven Cooling Optimization Presence, whether AI/ML algorithms are deployed for real-time[®] or predictive thermal management. 3. Chiller Efficiency Improvement (%), gain in chiller performance through adaptive load scheduling and predictive maintenance. 4. Cooling System Response Time (sec/min), time taken by the cooling system to adjust based on dynamic ML input. 5. Carbon Emission Reduction (kg CO₂/year), decrease in greenhouse gas emissions as a result of reduced energy usage via ML optimization. 6. Cooling Load Forecasting Accuracy (%), accuracy of ML models in predicting thermal load patterns, enabling more efficient cooling cycles.	

Tate, D. and Parolini, L., 2012. Thermal Guidelines for Data Processing Environments, 4th ed. ASHRAE.	1. Baseline Energy Savings (%), percentage of energy saved by implementing modular, scalable cooling compared to traditional systems. 2. Cooling System Scalability Index, the ability to scale cooling capacity based on IT load growth or zoning needs (qualitative/quantitative). 3. Airflow Containment Effectiveness (%), degree to which airflow management (e.g., hot/cold aisle containment) prevents mixing and improves cooling. 4. Overcooling Reduction (%), measured reduction in overcooling (i.e., unnecessary sub-ambient air delivery). 5. Cooling System Zoning Flexibility, system's ability to deliver targeted cooling to specific zones or racks based on heat load. 6. Inlet Air Temperature Stability (°C), consistency and control of supply air temperature across IT equipment under modular systems.	
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This table combines indicators of air conditioning effectiveness from various scientists pays special attention to the PUE metric, long-term efficiency trends, and comparison of IT versus non-IT power consumption. (Rasmussen, 2006) shows the efficiency of the supporting system through power sharing, type of cooling technology, and load proportionality. (Hirzel & Edelmann, 2009) include the ratio of cooling load

to IT load and the coefficient of performance (COP) as measures of technical efficiency. (Kreitz & Niemann, 2020) use machine learning to optimize cooling to save energy and reduce carbon emissions. However, (Tate & Parolini, 2012) concentrate on modularity, airflow control, and overcooling reduction. When combined, these indicators provide a more comprehensive way to assess cooling efficiency, encompassing state-of-the-art technology, energy, and sustainability.

2.14 Variable Control (Mediator)

Table 2.7 compiles critical indicators used by scholars to measure IT load, ambient temperature conditions, and cooling infrastructure responsiveness in data centers. These indicators are essential for understanding the relationship between computing demand and thermal management. Metrics such as server utilization, thermal headroom, and energy waste highlight operational inefficiencies and their thermal consequences.

Table 2. 7. Indicator of IT load, ambient temperature from some scientist

Name of scientist	Indicators	Summary
(Barroso & Hölzle, 2009). The Datacenter as a Computer: An Introduction to the Design of Warehouse-Scale Machines. 2nd ed. San Rafael, CA: Morgan & Claypool.	1. Server Utilization Rate (%), percentage of compute capacity actively in use; directly correlates with heat generation. 2. Heat Output per Rack (BTU/hr or kW), thermal energy emitted from racks as server utilization increases. 3. Cooling Load per Utilization Unit (kW/% load), amount of cooling energy required per percentage of server load. 4. Thermal Density (kW/m ²), concentration of heat generated per square meter in the data center space.	1. Server utilization rate (% load) 2. Total IT equipment power (kW) 3. Ambient temperature range (°C) 4. HVAC setpoints and thresholds

	5. Workload Consolidation Efficiency (%), degree to which active workloads are compacted onto fewer, more efficient servers to reduce spread-out thermal load. 6. Dynamic Thermal Headroom (%), margin between current thermal load and maximum cooling capacity; smaller headroom indicates high risk.	
(Pelley et al., 2010). Power Capping: A Prelude to Power Shifting in Data Centers. In: Computer Architecture and High Performance Computing. Springer.	1. Server Idle Power Draw (Watts/server), amount of power consumed by underutilized or idle servers, even when not processing workloads. 2. Utilization-to-Capacity Ratio (%), proportion of actual workload compared to the total provisioned server capacity. 3. PUE (Power Usage Effectiveness), higher PUE values indicate that more non-IT energy is used per unit of computing output. 4. Cooling Energy Waste (kWh/year), energy spent cooling idle or underutilized servers, representing inefficiency. 5. Power Capping Implementation, whether dynamic power management or capping mechanisms are in place to reduce	

	unnecessary power use. 6. Energy Proportionality Index, a metric expressing how closely energy consumption aligns with actual workload demands.	
(ASHRAE, 2011). Thermal Guidelines for Data Processing Environments, 3rd ed. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.	1. Server Inlet Temperature (°C), the temperature of the air entering IT equipment; must be kept within ASHRAE's recommended range (18–27°C). 2. Ambient Room Temperature Stability, degree to which the overall room temperature remains within the recommended threshold during operation. 3. Hardware Failure Rate (%), frequency of component failure attributed to thermal stress outside ASHRAE's recommended range. 4. Cooling Setpoint Accuracy (°C), how precisely the HVAC system maintains target temperature levels across the data hall. 5. Energy Use per Cooling Degree Hour (kWh/CDH), energy required to cool the data center per degree above thermal baseline; used for benchmarking. 6. Deviation Hours (%), percentage of operational hours in which ambient temperature	

	exceeded or dropped below the ideal range.	
(Tate & Parolini, 2012). Energy Efficient Data Center Design. ASHRAE Datacom Series.	1. HVAC Supply Air Setpoint (°C), target temperature of the air supplied by the cooling system to the IT environment. 2. Cooling Energy Consumption (kWh/year), total annual energy used by cooling systems, influenced by supply air temperature. 3. Cooling Energy Savings (%), percentage reduction in energy usage due to increased HVAC setpoints (e.g., up to 30%). 4. System Reliability (Downtime / MTBF), measured stability of IT operations after temperature setpoint changes (e.g., no increase in failure). 5. Temperature Compliance Rate (%), proportion of time the environment remains within ASHRAE-recommended thresholds (18–27°C). 6. Chiller Load Reduction (%), decrease in chiller usage or runtime due to higher supply air temperature.	

(Donovan, 2010). Data Center Cooling Best Practices. Boca Raton: CRC Press.	1. Zone-Based Server Consolidation Index, degree to which high-load servers are physically grouped in thermally managed zones. 2. Targeted Cooling Utilization (%), portion of the cooling system directed specifically at high-load zones (e.g., in-row, rear-door systems). 3. Airflow Containment Effectiveness (%), efficiency of airflow separation (hot/cold aisle, containment barriers) in consolidated zones. 4. Temperature Deviation in High-Load Zones ($^{\circ}\text{C}$), difference between setpoint and actual inlet temperatures in high-density areas. 5. Cooling Load per Zone (kW), measured cooling energy delivered per thermal zone; shows distribution efficiency. 6. Energy Efficiency per Rack (kWh/unit), energy used per server rack, reflecting the benefits of localized cooling and containment.	
(Koomey, n.d.). Turning Numbers into Knowledge: Mastering the Art of Problem Solving, 2nd ed. Oakland, CA: Analytics Press.	1. Real-Time IT Load (kW), the actual power draw of computing equipment in real-time; directly correlates with heat generation.	

	2. Thermal Output Forecast Accuracy (%), precision of predictive models estimating heat load based on real-time IT power data. 3. HVAC Runtime Adaptation (min/hr), degree to which HVAC schedules are adjusted dynamically based on IT load variation. 4. Cooling Energy per IT kW (kWh/kW IT), amount of cooling energy consumed per unit of IT energy, a proxy for adaptive efficiency. 5. Lag Time Between Load Change & HVAC Response (sec/min), how quickly the cooling system responds to shifts in thermal demand. 6. Cooling System Responsiveness Index, a composite measure of how well the cooling infrastructure aligns with real-time IT load fluctuations.	
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This table 2.7. shows the indicators of control variables (mediators), namely IT load and ambient temperature from several experts. (Barroso & Hölzle, 2009) emphasized load consolidation efficiency, heat output per rack, and server capacity. (Pelley et al., 2010) concentrated on three main aspects of cooling efficiency: idle power consumption, energy proportionality, and power coverage usage. Guidelines for maintaining system reliability include server inlet temperature, room temperature stability, and HVAC setpoint accuracy (ASHRAE, 2011; Tate & Parolini, 2012).

(Donovan, 2010) emphasized that servers are grouped based on high-load zones and airflow effectiveness. (Koomey, n.d.) used the cooling response to actual load to provide a predictive perspective. To maintain the validity of the research results by stabilizing external components that affect cooling efficiency, all of these indicators are very important.

2.15 Expert Appraisal in IT Governance Context

In the IT Governance practice, particularly trusting COBIT 5 and ITIL 4 frameworks, expert appraisal is a key part in proving that an IT service, process or system is aligned with predefined expected business outcomes. Review by experts is the systematic review performed by domain specific technical and contextual knowledgeable specialist, who determine interpretability of system outputs ask inputs how to improve them and what recommendations are preferred.

This aspect is reinforced by the COBIT MEA (Monitor, Evaluate and Assess) domain, which covers surveillance aspects where there are processes for monitoring governance and management objectives through internal and external assessments. The MEA01 process (“Monitor, Evaluate and Assess Performance and Conformance”) specifically includes the participation of SMEs to evaluate strategic alignment, benefits realization and conformity. These professional assessments are vital for high-stakes environments like data centers to verify that while the systems work well, they are not inadvertently breaking industry regulations or sustainability goals.

In ITIL 4, the same is true with Continual Service Improvement CSI leverages expert opinion to review services performance and assess opportunities for improvement in terms of value to stakeholder. In technical infrastructure sectors, such as the cooling efficiency of data centers pragmatic judgment and expert appraisals are particularly relevant when interpreting: PUE trends, environmental thresholds, system resilience under load.

This research falls within the level of expert appraisal and is a validation layer to check whether cooling technologies deployed, as well as operational frameworks installed at Sinergy Data Center, fulfil any benchmarked performance for sustainable development.

This is meant to provide credibility of data and support the conclusions derived from the research.

2.16 Evaluation Approach in IT Governance Frameworks.

In the context of IT Governance, this evaluation style is a structured methodology used to evaluate performance, value delivery and strategic alignment between IT services activities. Moreover, both COBIT 5 and ITIL 4 highlight evaluation practices in order to evaluate the practice and verify that it works properly not only complies with what you should do but also contribute to what you are supposed to achieve as an organization.

In the guidelines of COBIT 5 Evaluation is embedded in the MEA (Monitor, Evaluate and Assess) domain where it includes: MEA03 (Evaluate Compliance with External Requirements), and MEA01 (Evaluate Performance and Conformance). These processes are mechanisms to find out if IT capabilities, including infrastructure services (like cooling systems), meet predefined targets and key performance indicators. COBIT proposes a governance focused external needs view including performance metrics stakeholder requirements and compliance obligations.

ITIL 4, on the other hand, considers assessment as an essential part of the Service Value System (SVS) process mainly in the Plan, Improve and Deliver and Support service value chain actions. Decision gates are built into ITIL 4 through a process of continual monitoring and review loops when it comes to Change Control, Monitoring and Event Management, Continual Improvement, etc. Here, evaluation means checking how service performance is matching the business need, customer satisfaction and operational resilience.

In this research, the practice of evaluation is applied as a methodological lens to examine how well data center cooling technologies align with sustainability objectives. Between expert interviews, validation testing, SLA metrics, and PUE tracking then combines the qualitative with house data to provide a more well-rounded performance assessment. The study itself is built upon the internationally acknowledged best practices for IT governance and service management evaluation standards, COBIT, and ITIL.

2.17 Validation Approach in IT Service and Governance Frameworks

Validation, both are in the operation of IT systems/as well as/or services is paramount to provide confidence that not only systems and processes have been correctly implemented but are also accomplishing what they were intended too. Validation is a core ingredient in IT governance frameworks, like ITIL 4 and COBIT 5 that needs to be an integral part of your overall strategy to ensure the quality of service, maintain alignment with business demands and comply with governance standards

In ITIL 4, validation is directly referred to in practices like Service Validation and Testing which inspects that before moving into the in-scope environment all services or their components are identified against requirements and user expectations. This ensures that the value promised to stakeholders by IT-enabled services is delivered and that operational risks are minimized.

COBIT 5, for instance, through such domains as BAI08 (Knowledge Management) and MEA01 (Evaluate Performance and Conformance), also highlights the need to ensure rigorous validation via performance indicators, measurement systems and stakeholder reporting channels. Design Factor in COBIT method also helps to design metrics for other system components and for assessing maturity and realization of objectives with real-life cases.

This thesis uses these guidelines for a three-phase validation process: Usability Testing, User Acceptance Testing and Expert Appraisal as described in the following sections. These phases represent the perspectives of stakeholder groups (operational users, service managers, domain experts) and together are intended to validate that the proposed data center cooling sustainability framework itself is viable for use. This is further reinforced through qualitative and quantitative validation such as PUE metrics, SLA compliance, accessibility review process, survey results etc.

Utilizing ITIL 4 and COBIT 5 validation principles as what the research methodology embedded with, this study guarantees a thorough standards-based evaluation of cooling performance for sustainable enhancement. This has a dual effect of improving academic

rigor while increasing the practicality and relevance of the research to its application within the context of the Sinergy Data Center.

2.18 Research Foundations: ITSM, COBIT 5 and Policy Architecture.

The research framework is built on the ITSM and COBIT 5 principles, which provide structured approaches for managing IT services and aligning them with business goals. The framework consists of three key components:

2.18.1 ITSM Framework for Cooling Efficiency

IT Service Management (ITSM) is a globally recognized framework that ensures IT services are aligned with business goals while optimizing operational processes (Hunnebeck, 2019). ITSM enables structured cooling service management, ensuring energy efficiency through the ITIL (Information Technology Infrastructure Library) lifecycle:

1. Service Strategy

The Service Strategy phase emphasizes aligning cooling technologies with organizational sustainability objectives. This involves understanding current and future cooling demands, assessing environmental impacts, and formulating strategies that support both operational efficiency and sustainability goals. Integrating sustainability into the core strategy ensures that cooling solutions meet immediate requirements and contribute to long-term environmental objectives. For instance, adopting energy-efficient cooling methods can lead to substantial reductions in energy consumption, aligning with broader sustainability targets. (Fadaeefath Abadi et al., 2020)

2. Service Design

Service Design focuses on creating cost-effective, AI-driven cooling mechanisms. This includes designing systems that leverage artificial intelligence to optimize cooling efficiency, reduce energy consumption, and adapt to varying workloads. For example, AI can predict temperature fluctuations and adjust cooling systems accordingly, leading to significant

energy savings. Implementing such intelligent systems requires meticulous planning to ensure seamless integration with existing infrastructure and alignment with organizational requirements.

3. Service Transition

The Service Transition phase ensures that new cooling technologies are implemented with comprehensive risk assessment and change management. This involves planning and managing the deployment of new cooling solutions to minimize disruptions and align with business objectives. Effective change management practices are essential to address potential risks and ensure that the transition to new technologies enhances overall service quality. (Juan Miquel Durán, 2014)

4. Service Operation

Service Operation centers on monitoring and automating cooling efficiency through IoT-based sensors. Utilizing Internet of Things (IoT) technologies enables real-time monitoring of temperature and humidity levels, facilitating proactive adjustments to cooling systems. This real-time data collection allows immediate responses to environmental changes, ensuring optimal operating conditions and energy efficiency. For example, integrating IoT sensors with AI analytics can lead to predictive maintenance and improved operational reliability

5. Continual Service Improvement (CSI)

The Continual Service Improvement phase emphasizes benchmarking and enhancing cooling performance over time. This involves regularly analyzing performance data, identifying areas for improvement, and implementing changes to optimize cooling efficiency. Fostering a culture of continuous improvement enables organizations to adapt to evolving demands and technological advancements, ensuring sustained efficiency in their cooling strategies. For instance, implementing predictive maintenance strategies can

lead to significant energy savings and enhanced equipment uptime. (Arroba et al., 2018)

2.18.2 COBIT 5 Governance for Compliance

COBIT 5, developed by ISACA, is a comprehensive framework that provides governance and control mechanisms for aligning IT processes with enterprise sustainability goals. Its principles are instrumental in enhancing data center cooling efficiency and ensuring compliance with energy management standards. We can see Cobit 5 key principles at Figure 2.2.

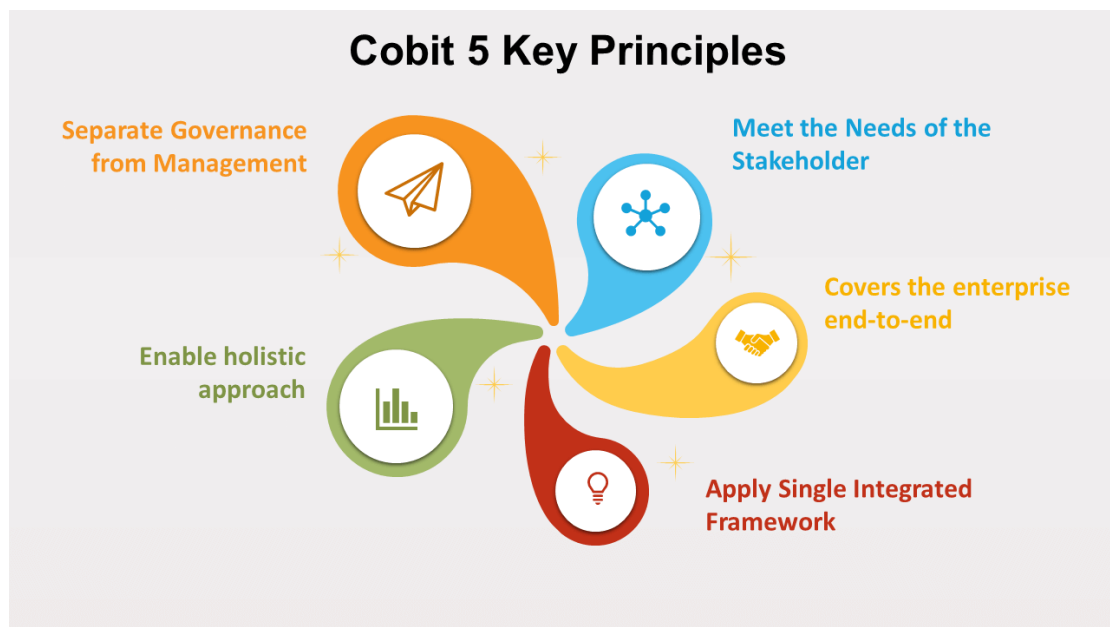


Figure 2.2. Cobit 5 Key Principles

The following COBIT 5 principles are particularly relevant:

1. Principle 1: Meeting Stakeholder Needs

This principle emphasizes that governance should ensure that stakeholder needs are evaluated to determine balanced, agreed-on enterprise objectives, set direction through prioritization and decision-making, and monitor performance and compliance against set objectives. In the context of data center cooling, aligning cooling efficiency with energy policies ensures that the data center's

operations meet both regulatory requirements and stakeholder expectations for sustainability and cost-effectiveness.

2. Principle 2: Covering the Enterprise End-to-End

COBIT 5 advocates for a holistic approach, ensuring that governance and management encompass all functions and processes within the enterprise. Applying this to data center cooling involves ensuring compliance with PP No. 70 Tahun 2009, which provide a framework for establishing policies for more efficient energy use. This comprehensive coverage ensures that all aspects of energy consumption, including cooling systems, are managed effectively to enhance overall energy performance.

3. Principle 3: Applying a Single Integrated Framework.

This principle emphasizes the importance of considering all enablers, including processes, organizational structures, and information flows, in governance and management activities. Managing cooling data through predictive analytics involves utilizing data-driven insights to anticipate cooling demands and potential issues, thereby enhancing efficiency and reliability. A holistic approach ensures that all relevant factors are considered in decision-making processes, leading to more effective governance outcomes.

4. Principle 4: Enabling a Holistic Approach

This principle emphasizes the importance of considering all enablers, including processes, organizational structures, and information flows, in governance and management activities. Managing cooling data through predictive analytics involves utilizing data-driven insights to anticipate cooling demands and potential issues, thereby enhancing efficiency and reliability. A holistic approach ensures that all relevant factors are considered in decision-making processes, leading to more effective governance outcomes.

5. Principle 5: Separating Governance from Management.

COBIT 5 distinguishes between governance, which involves setting objectives and monitoring performance, and management, which focuses on planning and executing activities to achieve those objectives. Defining clear roles for data center operators and IT teams in sustainability ensures that responsibilities are appropriately allocated, promoting accountability and effective implementation of sustainability initiatives. This separation facilitates better oversight and management of IT processes, contributing to improved compliance and performance.

2.18.3 Rationale for Selecting COBIT 5 as Governance Framework

In the specific context of sustainable cooling practices in data centers such as in the current research at Sinergy Data Center the use of COBIT 5 is particularly justified due to several compelling reasons. These reasons include addressing significant governance gaps, ensuring regulatory compliance, managing risk, improving transparency and accountability, and enhancing continuous performance monitoring and improvement (De Haes & Van Grembergen, 2008; ISACA, 2019).

1. Strategic Governance Alignment

COBIT 5 explicitly promotes alignment between IT initiatives and strategic organizational goals. Data center operations often involve complex technological decisions, such as the selection and integration of advanced cooling technologies (liquid immersion cooling, AI-driven thermal management, renewable energy integration), that must align clearly with organizational sustainability targets, business goals, and stakeholder expectations (Haghshenas et al., 2022). Studies indicate that misalignments between IT investments especially in critical areas like sustainability and organizational strategy often result from insufficient governance structures. COBIT 5 directly addresses this by providing structured processes to establish strategic alignment, ensuring decisions related to cooling efficiency technologies are systematically integrated with organizational objectives, stakeholder priorities, and compliance requirements (Bartens, Y. et al., 2022).

2. Enhanced Regulatory Compliance and Risk Management

Data center operations, particularly related to cooling and energy management, must comply with stringent international standards (ISO 50001, ASHRAE TC 9.9). COBIT 5 explicitly supports organizations in addressing these compliance requirements by establishing robust governance processes for risk identification, management, and regulatory alignment (ASHRAE, 2021). It provides structured mechanisms for identifying compliance risks, systematically managing potential operational disruptions, and transparently documenting regulatory adherence. This structured governance is critical in the context of Sinergy Data Center, ensuring the organization consistently meets sustainability and regulatory standards, avoids compliance penalties, and proactively mitigates related risks (De Haes et al., 2020).

3. Clear Accountability and Transparency

COBIT 5's structured approach clearly defines stakeholder roles, responsibilities, and accountability within IT management processes, significantly enhancing transparency and organizational clarity. Governance deficits in accountability and transparency can lead to operational inefficiencies, stakeholder dissatisfaction, and sustainability challenges within data center operations (Bartens, Y. et al., 2022). COBIT 5 addresses these issues explicitly by outlining governance processes that define clear responsibilities for cooling management, compliance adherence, performance monitoring, and stakeholder reporting. This clarity of roles and responsibilities facilitates transparent communication, enhances stakeholder trust, and supports the achievement of sustainable cooling objectives (De Haes et al., 2020).

4. Systematic Performance Monitoring and Continuous Improvement

The governance mechanisms provided by COBIT 5 include systematic monitoring, evaluation, and continuous improvement of IT performance. In the context of data center cooling efficiency, clear performance indicators such as Power Usage Effectiveness (PUE), Cooling Efficiency Ratio (CER), and carbon emissions reductions must be consistently monitored and optimized. COBIT 5

provides structured methods to establish performance measurement systems, evaluate outcomes against set targets, and continuously improve operational performance. This structured governance approach ensures systematic tracking, transparent reporting, and continual improvement initiatives that align with long-term sustainability and efficiency objectives.

5. Complementarity with ITIL 4

The combination of COBIT 5 with ITIL 4 is beneficial and complementary. While ITIL 4 provides detailed operational guidance focused on service management, stakeholder engagement, and continual improvement, COBIT 5 provides explicit governance structures that complement and enhance the strategic alignment, accountability, risk management, and compliance aspects. This integrated approach ensures comprehensive management of technological initiatives and stakeholder engagement, providing a holistic governance and management structure particularly suited to Sinergy Data Center's sustainable cooling management practices (Bartens, Y. et al., 2022).

2.18.4 Policy Development for Sinergy Data Center

The primary output of this research is a structured policy framework to enhance cooling efficiency and sustainability at Sinergy Data Center. This policy framework leverages IT Service Management (ITSM) and COBIT 5 to achieve regulatory compliance, operational effectiveness, and environmental sustainability.

Data centers use ICT equipment (servers, storage drives, and network devices), which are electrically powered. The operation of ICT requires non-ICT equipment, or data center physical infrastructure (DCPI), e.g., cooling to remove ICT heat, lighting (see Figure 2.3). The top items of energy consumptions are cooling and servers, estimated as 43% each, followed by storage drives and network devices (11% and 3%, respectively).

Other estimations are roughly 52% ICT, 38% cooling system, and 10% other equipment.

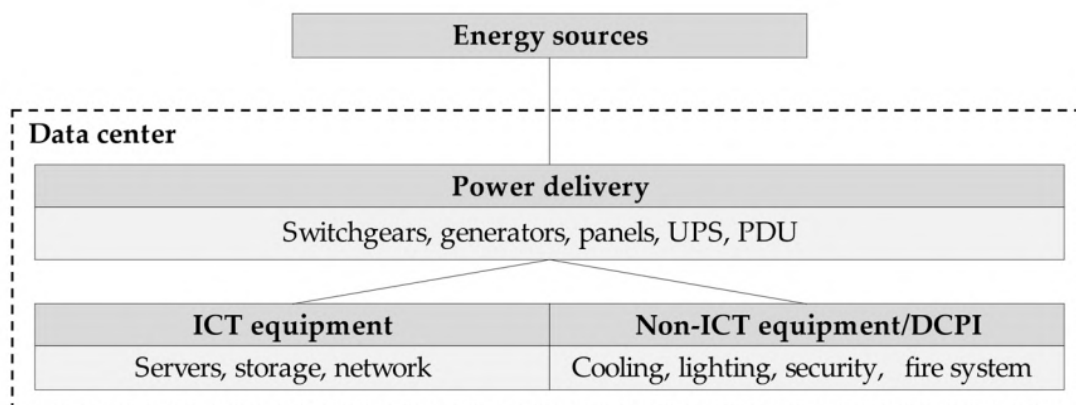


Figure 2.3. Energy use in a data center

Power flows in a typical data center are illustrated in figure 2.4.

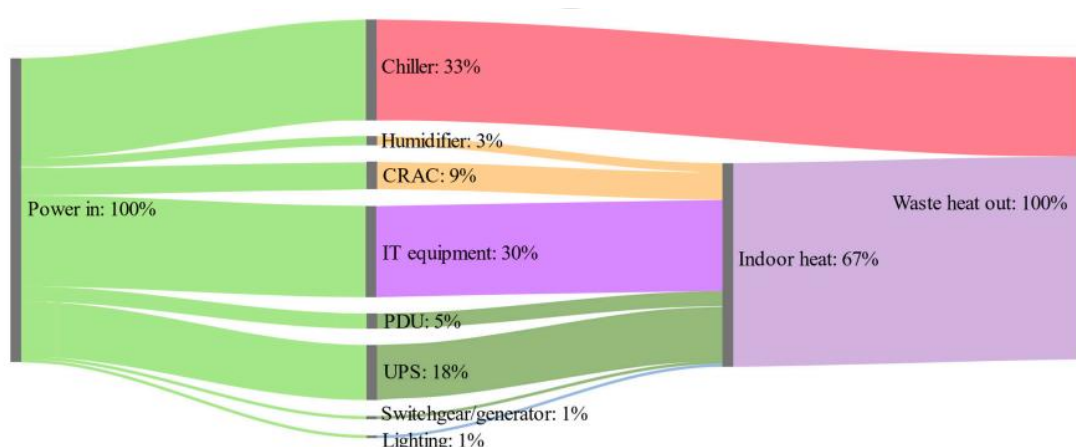


Figure 2.4. Power flows in a typical data center

The policy development includes four primary areas:

1. Energy Efficiency Policy.

The Energy Efficiency Policy aims to establish and achieve specific Power Usage Effectiveness (PUE) targets, recognized as the standard for evaluating the energy efficiency of data centers. According to (Shehabi et al., 2016) achieving optimal PUE levels significantly reduces data center energy costs and aligns

operational practices with global sustainability goals. Setting clear PUE targets encourages continuous performance monitoring and drives improvements, ensuring Sinergy Data Center maintains industry-leading efficiency standards (Shehabi et al., 2016).

2. Risk Management Policy.

The Risk Management Policy involves implementing predictive maintenance strategies powered by Artificial Intelligence (AI) to proactively identify and mitigate cooling system failures. AI-driven predictive analytics allow the identification of potential equipment faults before they result in downtime, substantially enhancing operational reliability and reducing maintenance costs (Shuja et al., 2016). This approach aligns with COBIT 5's holistic approach, ensuring continuous service improvement and operational resilience.

3. Compliance Policy.

The Compliance Policy mandates adherence to international sustainability and energy management standards, specifically ISO 50001 (Energy Management Systems) and ASHRAE TC 9.9 (Data Center Thermal Guidelines). These standards help Sinergy Data Center systematically manage and continually improve energy performance, supporting regulatory compliance and sustainable practices. Compliance with these guidelines promotes operational transparency, enhances market reputation, and supports stakeholder confidence in environmental management efforts (ASHRAE, 2021).

4. Technology Integration Policy

The Technology Integration Policy mandates the adoption of advanced cooling technologies, such as liquid immersion cooling and IoT-based monitoring systems. Liquid cooling significantly reduces cooling energy consumption by effectively dissipating heat directly from servers, lowering energy usage by approximately 50% compared to traditional air cooling methods (Haghshenas et al., 2022). IoT-enabled monitoring systems provide real-time data collection, allowing for dynamic adjustments and optimized cooling operations, significantly improving energy management capabilities and reducing operational costs (Rostami et al., 2024).

Implementing these policies positions Sinergy Data Center as an industry leader in sustainable practices, ensuring regulatory compliance, optimized cooling efficiency, cost reduction, and alignment with global sustainability goals.

2.18.5 Architecture Guidelines

Effective architecture guidelines establish standardized, structured frameworks that govern the integration, management, and operation of cooling technologies within data centers, show in Figure 2.5.

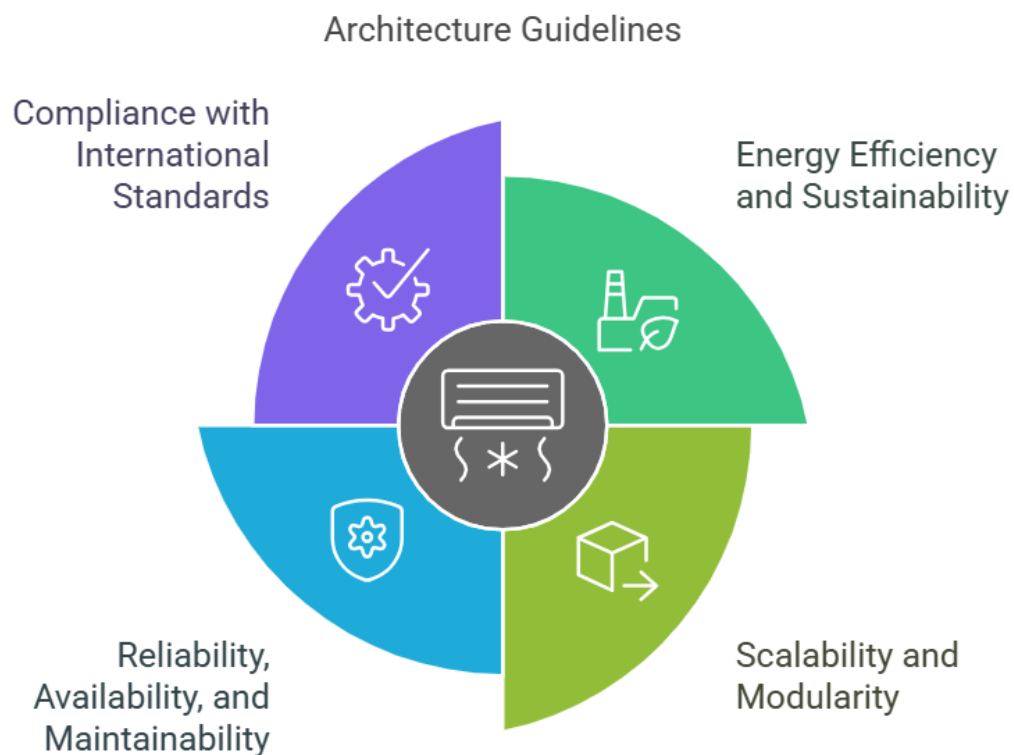


Figure 2.5. Architecture Guidelines

For Sinergy Data Center, these architecture guidelines clearly include:

1. Energy Efficiency and Sustainability

The architecture explicitly mandates integrating sustainable cooling technologies such as liquid immersion cooling, AI-driven thermal optimization,

renewable energy integration (solar or wind), and free-air cooling, significantly improving energy efficiency (Haghshenas et al., 2022; Yeasmin et al., 2023). These guidelines clearly specify targeted energy efficiency metrics such as Power Usage Effectiveness ($PUE \leq 2$), Cooling Efficiency Ratio ($CER \geq$ optimal levels), and defined carbon emission reduction targets aligned with organizational sustainability strategies.

2. Scalability and Modularity

Architecture guidelines specifically advocate scalable, modular cooling solutions to ensure flexibility and future adaptability. This scalability enables data centers to dynamically adjust cooling capacity based on operational demands, technology evolution, and business expansion, supporting long-term sustainability and operational resilience (Rostami et al., 2024).

3. Reliability, Availability, and Maintainability (RAM)

Guidelines mandate that cooling infrastructures must adhere to robust reliability, availability, and maintainability standards. Incorporating redundant cooling systems, predictive maintenance technologies (IoT sensors and AI-driven analytics), and structured preventive maintenance schedules ensures operational continuity, reduced downtime, and enhanced long-term system reliability (Fadaeefath Abadi et al., 2020).

4. Compliance with International Standards

Architecture guidelines explicitly incorporate compliance with international regulatory standards such as ISO 50001 (Energy Management Systems) and ASHRAE TC 9.9 (Thermal Guidelines for Data Centers). Compliance adherence within architecture guidelines ensures operational transparency, structured risk management, and regulatory accountability.

2.18.6 Policy Recommendations

Clearly structured policies complement architecture guidelines by explicitly defining roles, responsibilities, operational protocols, and compliance expectations, show in Figure 2.6.

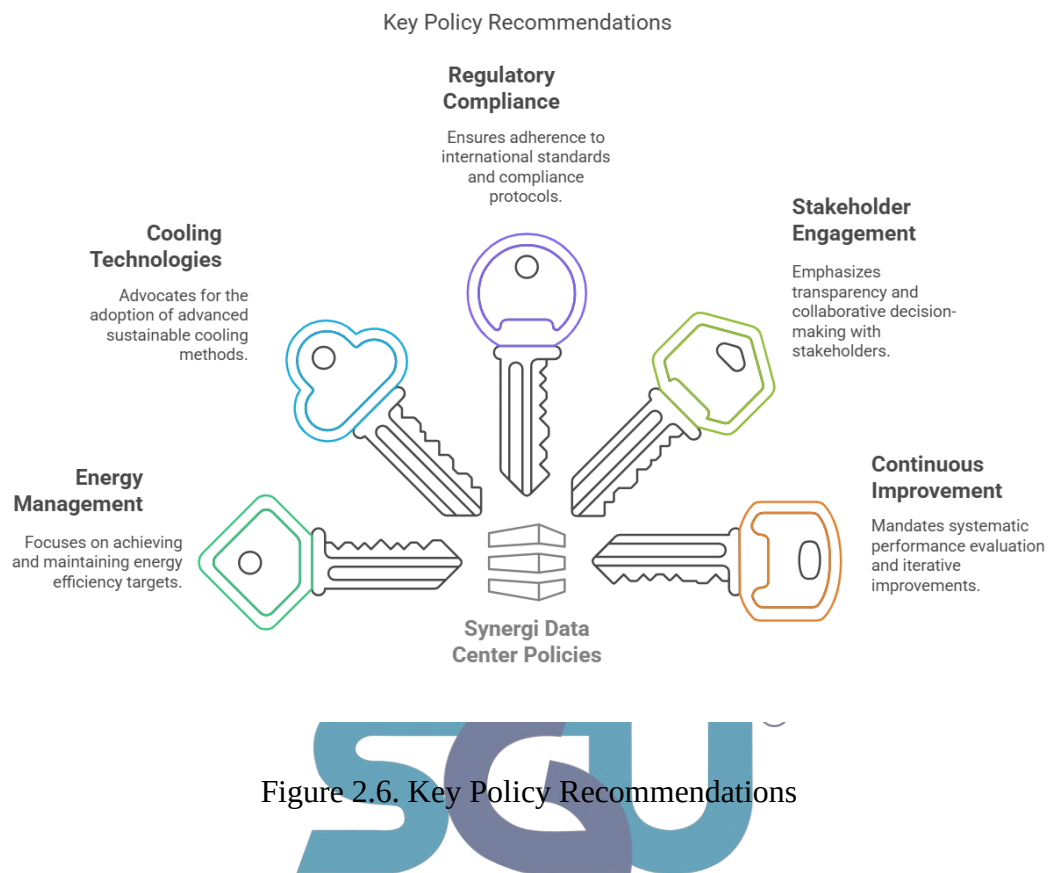


Figure 2.6. Key Policy Recommendations

Key policy recommendations for Sinergy Data Center include:

1. Energy Management and Efficiency Policy

This policy explicitly mandates that data center operations achieve defined energy efficiency targets, including achieving and maintaining a Power Usage Effectiveness (PUE) below defined thresholds. The policy specifies roles and accountability for continuous monitoring, reporting, and optimizing energy performance metrics.

2. Sustainable Cooling Technologies Adoption Policy

This policy clearly requires adopting advanced sustainable cooling technologies, such as liquid immersion cooling, AI-driven predictive management, renewable energy integration, and IoT-based real-time monitoring. It outlines structured decision-making criteria, budgetary

considerations, and stakeholder accountability for implementing these technologies (Haghshenas et al., 2022).

3. Regulatory Compliance and Risk Management Policy

The compliance policy ensures adherence to international standards, such as ISO 50001 and ASHRAE TC 9.9. This policy explicitly outlines protocols for compliance management, systematic risk identification and mitigation strategies, documentation and reporting standards, and procedures for responding to regulatory audits and inspections.

4. Stakeholder Engagement and Transparency Policy

This policy emphasizes structured stakeholder engagement, transparency in operational reporting, and collaborative decision-making processes. It requires regular stakeholder updates on cooling performance, compliance status, sustainability achievements, and clearly structured feedback mechanisms, ensuring stakeholder alignment, trust, and sustained operational improvements.

5. Continuous Improvement and Performance Monitoring Policy

Structured continuous improvement policies mandate systematic performance evaluation, monitoring, and iterative improvements to sustainable cooling systems. Regular assessments against key performance indicators (PUE, CER, carbon emissions reductions), structured stakeholder reviews, and clearly documented improvement initiatives ensure sustained operational excellence and value realization.

2.19 Development of the Research Framework

The formulation of the research framework presented in Chapter 3 is grounded in the findings of this literature review and shaped by the convergence of several academic models, industry standards, and operational practices identified in recent studies. Through systematic synthesis of prior research on sustainable cooling technologies, IT governance models (e.g., ITIL 4 and COBIT 5), and operational performance metrics (such as PUE and CER), the study identifies a conceptual intersection where governance, cooling technology, and energy efficiency interact.

Specifically, the reviewed literature emphasized three core pillars:

1. The impact of ITIL and COBIT frameworks on sustainable IT operations (Hunnebeck, 2019; ISACA, 2019).
2. Empirical evaluations of cooling performance in real-world data center settings (Haghshenas et al., 2022; Shehabi et al., 2016).
3. Policy formulation and governance alignment in green IT practices (Shao & Li, 2025).

These insights collectively informed the variables and structural components of the proposed model, which seeks to explore how cooling technology, IT load, and ambient temperature influence overall cooling efficiency, with IT governance practices acting as a mediating factor.

Furthermore, the model was constructed to bridge specific gaps identified in the literature particularly the lack of integrated evaluations that simultaneously consider technical infrastructure and governance maturity. Drawing from best practices in ITSM and data center energy optimization, the proposed framework aims to provide a holistic evaluation of cooling efficiency from both operational and policy perspectives.

This integrative process underpins the structure of the research framework, offering a theoretically sound and practically relevant model that guides the analytical approach described in Chapter 3.