DOI: 10.2478/sbeef-2024-0024

INDUSTRIAL COOLING SYSTEMS A COMPREHENSIVE REVIEW OF TECHNOLOGIES, CHALLENGES, AND FUTURE DIRECTIONS

Otilia Nedelcu
Valahia University of Targoviste, Faculty of Electrical Engineering, Electronics and Information Technology
E-mail: otilia.nedelcu@valahia.com

Abstract. ***Industrial cooling systems are critical components in a wide range of sectors, including manufacturing, energy production, chemical processing, and data centers. These systems play a vital role in maintaining optimal operating temperatures, enhancing equipment efficiency, and ensuring safety. This review paper provides a comprehensive analysis of the current state of industrial cooling technologies, categorizing them into air cooling, liquid cooling, phase-change cooling, and advanced cooling methods such as thermoelectric and magnetic refrigeration.***

Keywords: industrial cooling systems; energy efficiency; advanced cooling technologies.

1. INTRODUCTION

Industrial cooling systems are indispensable components across a multitude of sectors, including manufacturing, energy production, chemical processing, and information technology. As industries continue to evolve and expand, the demand for efficient and reliable cooling solutions has intensified. These systems are crucial for maintaining optimal operating temperatures, which not only enhances equipment efficiency but also ensures safety and prolongs the lifespan of industrial machinery. The significance of effective cooling mechanisms cannot be overstated, given their direct impact on operational performance and energy consumption [1].

The evolution of industrial cooling technologies has been driven by the need to address challenges such as increasing energy costs, stringent environmental regulations, and the pursuit of sustainability. Traditional cooling methods, while effective in the past, are often energy-intensive and may involve substances that are harmful to the environment. This has spurred innovation in the development of advanced cooling systems that are more energy-efficient and environmentally friendly.

Current industrial cooling systems can be broadly categorized into air cooling, liquid cooling, phase-change cooling, and advanced cooling technologies like thermoelectric and magnetic refrigeration. Each of these systems has unique operational principles, advantages, and limitations that make them suitable for specific applications. For instance, air cooling systems are typically simpler and less costly but may be less effective in high-temperature environments. Liquid cooling systems, on the other hand, offer superior heat transfer capabilities but involve more complex infrastructure and maintenance requirements [2-3].

Performance metrics such as the Energy Efficiency Ratio (EER), Coefficient of Performance (COP), thermal conductivity, and environmental impact indicators like Global Warming Potential (GWP) are critical in evaluating the effectiveness of cooling systems. These metrics help industries make informed decisions when selecting appropriate cooling solutions that meet their operational needs while adhering to environmental standards [4].

The integration of advanced technologies has led to the emergence of energy-efficient cooling systems that incorporate variable speed drives, advanced control mechanisms, and the use of alternative refrigerants with lower environmental impact. The advent of the Internet of Things (IoT) and artificial intelligence has further revolutionized industrial cooling by enabling smart systems that offer predictive maintenance, enhanced control, and improved overall efficiency.

Despite these advancements, the industrial sector faces significant challenges in implementing and optimizing cooling systems. Environmental concerns, particularly the emission of greenhouse gases from refrigerants and the consumption of water resources, pose substantial hurdles. Economic factors, including the high initial costs associated with advanced cooling technologies and the long-term return on investment, also influence decision-making processes. Moreover, industries must navigate evolving regulatory landscapes that demand compliance with stricter environmental and safety standards [5-6].

This review paper aims to provide a comprehensive analysis of industrial cooling systems by examining existing technologies, their components, and operational principles. It will evaluate performance metrics and selection criteria pertinent to various industrial applications. The paper will also explore recent advancements and innovations in the field, discuss the challenges faced by the industry, and highlight potential solutions. Through practical insights into the implementation and impact of different cooling systems will be presented. Finally, the paper will delve into future trends and research directions that are poised to shape the next generation of industrial cooling solutions [7].

By offering an in-depth examination of these aspects, the paper seeks to inform industry stakeholders, policymakers, and the research community about the critical role of cooling systems in industrial operations. It underscores the necessity for continued innovation and the adoption of sustainable practices to meet the growing demands of modern industries while mitigating environmental impact [8].

2. EXISTING TECHNOLOGIES IN INDUSTRIAL COOLING SYSTEMS

Industrial cooling systems are pivotal in ensuring the operational efficiency, safety, and longevity of industrial processes and equipment. This section reviews the primary cooling technologies employed in the industrial sector, focusing on their operational principles, key components, and applications [9-11].

a) Air cooling systems

Air cooling systems rely on convection to remove heat from equipment, making them suitable for low-to-moderate cooling demands.

- Forced air cooling

  This method uses fans or blowers to enhance convective heat transfer. Heat sinks with extended surfaces are often employed to increase the effective area for heat dissipation. Forced air cooling is simple, cost-effective, and widely used for electronics and small machinery but becomes less efficient for high heat flux applications or in environments with poor air quality.

- Natural convection cooling

  In this passive approach, heat dissipation occurs naturally as warmer air rises and cooler air replaces it. It is silent, maintenance-free, and energy-efficient but limited by its cooling capacity and orientation dependence, making it suitable for low-power applications.

b) Liquid cooling systems

Liquid cooling systems use fluids with high thermal conductivity, such as water or oil, to transfer heat more effectively than air.

– Water cooling

  Water is circulated through pumps, heat exchangers, and cooling towers to absorb and dissipate heat. This method is highly efficient and suitable for large heat loads in applications like power plants and data centers. However, it requires regular maintenance to prevent corrosion and biofouling.

– Oil cooling

  Oil's high boiling point and insulating properties make it ideal for electrical equipment like transformers. While it provides effective cooling for high-temperature applications, its lower heat capacity compared to water and potential fire hazards are significant limitations.

– Refrigerant cooling

  Utilizing a closed-loop vapor-compression cycle, refrigerant cooling systems transfer heat through phase changes of specialized fluids. With components like compressors, condensers, and evaporators, these systems are highly effective for temperature-sensitive applications. However, their complexity and environmental impact due to refrigerant emissions present challenges.

c) Phase-change cooling

Phase-change cooling methods harness the thermal energy absorbed or released during a fluid’s phase transition.

– Evaporative cooling

  This technique employs the evaporation of water to remove heat, commonly used in cooling towers and industrial ventilation systems. It is energy-efficient and environmentally friendly but less effective in high-humidity environments and demands a continuous water supply.

d) Advanced cooling technologies

Recent advancements have introduced innovative cooling methods with enhanced efficiency and environmental benefits.

– Thermoelectric cooling

  Based on the Peltier effect, thermoelectric coolers use semiconductor materials to create a temperature gradient. These systems are compact and precise but are limited by low energy efficiency, restricting their use to small-scale applications like electronics and portable devices.

– Magnetic refrigeration

  This emerging technology relies on the magnetocaloric effect, where specific materials undergo temperature changes when subjected to magnetic fields. While it holds promise for environmentally friendly and efficient cooling, its practical application is still in developmental stages[12-13].

3. PERFORMANCE METRICS AND SELECTION CRITERIA FOR INDUSTRIAL COOLING SYSTEMS

The selection of an optimal industrial cooling system requires a comprehensive evaluation of performance metrics and selection criteria tailored to specific industrial needs. This section examines the key performance indicators and critical factors influencing the choice of cooling technologies in various industrial applications.

1) Performance metrics

a) Energy efficiency

– Coefficient of performance (COP)

  The COP is defined as the ratio of the cooling output to the energy input required to produce that cooling:

$$\mathrm{COP} = \frac{\text{Cooling Output } (Q_C)}{\text{Energy Input } (W)} \tag{1}$$

A higher COP indicates a more efficient cooling system, leading to reduced energy consumption and operational costs. It is essential for comparing the efficiency of different cooling technologies under similar conditions.

– Energy efficiency ratio (EER)

The EER is calculated by dividing the cooling capacity (in British Thermal Units per hour, BTU/h) by the power input (in watts):

$$\mathrm{EER} = \frac{\text{Cooling Capacity (BTU/h)}}{\text{Power Input (W)}} \tag{2}$$

EER provides a standardized metric to assess and compare the energy efficiency of cooling systems. Higher EER values represent more energy-efficient systems.

b) Thermal performance

– Heat transfer coefficient (U-value)

The U-value measures the rate of heat transfer through a material or system per unit area per degree of temperature difference:

$$U = \frac{Q}{A \times \Delta T} \tag{3}$$

A higher U-value indicates better thermal conductivity, which is crucial for efficient heat exchange in cooling systems. It helps in evaluating the effectiveness of heat exchangers and overall system performance.

– Thermal resistance (R-value)

The R-value represents the resistance to heat flow and is the inverse of the U-value:

$$R = \frac{1}{U} \tag{4}$$

Lower thermal resistance enhances a system's ability to dissipate heat effectively. It is vital for materials and components where insulation or heat retention is critical.

c) Environmental impact metrics

– Global Warming Potential (GWP)

GWP quantifies the relative impact of a greenhouse gas compared to carbon dioxide over a specific time horizon (commonly 100 years). Selecting refrigerants and materials with low GWP is essential to minimize the environmental impact of cooling systems and comply with international agreements like the Kyoto Protocol.

– Ozone depletion potential (ODP)

ODP measures a substance's potential to deplete the ozone layer relative to a reference substance (CFC-11). Using substances with zero or low ODP is crucial for environmental sustainability and regulatory compliance, aligning with protocols like the Montreal Protocol.

d) Reliability and maintenance

– Mean time between failures (MTBF)

MTBF is the predicted elapsed time between inherent failures of a system during operation. A higher MTBF indicates greater system reliability, reducing downtime and maintenance costs. It is critical for processes where continuous operation is essential.

– Maintenance requirements

This includes the frequency of servicing, ease of maintenance procedures, and availability of spare parts. Systems with lower maintenance demands offer cost savings over their operational lifespan and minimize disruptions to industrial processes[14-16].

2) Selection criteria for industrial applications

a) Cooling load requirements

– Heat load analysis

Determining the total heat to be removed from a process or equipment is fundamental. Peak vs. average loads, transient heat sources, and potential future expansions. The cooling system must handle maximum anticipated loads efficiently without compromising performance.

b) Environmental and site conditions

– Ambient temperature and humidity

High ambient temperatures and humidity levels can affect the performance of certain cooling systems (e.g., evaporative cooling systems are less effective in humid conditions). Selecting systems designed to operate efficiently under specific environmental conditions is necessary.

– Space constraints

Limited physical space may restrict the size and type of cooling equipment. Compact or modular systems, such as microchannel cooling, can be advantageous.

c) Economic considerations

– Initial investment costs

Equipment purchase price, installation expenses, and infrastructure modifications. A cost-benefit analysis over the system's expected lifespan helps determine the most economically viable option.

– Operational and maintenance costs

Energy consumption, maintenance frequency, potential downtime, and spare parts availability. Investing in energy-efficient systems may result in higher upfront costs but lower long-term operational expenses [17-20].

d) Regulatory compliance

– Environmental regulations

Compliance with laws governing emissions, refrigerant usage, and energy efficiency standards. Selecting systems that use environmentally friendly refrigerants (low GWP and ODP) and meet efficiency criteria set by regulatory bodies.

– Safety Standards

Adherence to safety codes related to pressure vessels, electrical systems, and chemical handling. Regular inspections and maintenance ensure compliance and safe operation.

e) Technological compatibility

– Integration with existing systems

Compatibility with current infrastructure and processes is essential to reduce installation costs and operational disruptions. Seamless integration enhances overall system efficiency and performance.

– Control and monitoring systems

Incorporation of IoT and advanced control systems for real-time monitoring and predictive maintenance. Improved system responsiveness, efficiency, and reduced downtime through early detection of potential issues.

f) Environmental sustainability goals

– Energy conservation

Reduce energy consumption to lower operational costs and environmental impact. Implementing high-efficiency systems, variable speed drives, and energy recovery solutions.

– Use of renewable energy sources

Integration of solar-assisted cooling, geothermal cooling, or utilization of waste heat. Decreases reliance on non-renewable energy sources and reduces carbon footprint.

3) Application-specific considerations

a) Power generation facilities

Manage substantial heat loads from turbines and generators. High-capacity cooling systems with robust reliability; water cooling with cooling towers is common. Water resource availability and compliance with environmental regulations on thermal discharge.

b) Data centers

Precise temperature and humidity control for optimal server performance and reliability. High energy efficiency, redundancy, and scalability are crucial. Adoption of advanced liquid cooling methods, such as chilled water systems, and optimized airflow management.

c) Chemical and pharmaceutical industries

Strict temperature control for reactions and product stability. Systems must offer precise control and use materials compatible with chemical processes. High safety standards due to potential hazards; corrosion-resistant materials are essential.

Evaluating performance metrics such as energy efficiency, thermal performance, environmental impact, and reliability is crucial in the selection of industrial cooling systems. Aligning these metrics with specific application requirements, economic considerations, regulatory compliance, and sustainability goals enables industries to optimize cooling strategies. This holistic approach ensures enhanced operational efficiency, cost-effectiveness, and minimal environmental footprint, meeting both current needs and future challenges in industrial cooling applications [21-24].

4. RECENT ADVANCEMENTS, INDUSTRY CHALLENGES, AND POTENTIAL SOLUTIONS

The industrial cooling sector has witnessed significant advancements driven by the need for energy efficiency, environmental sustainability, and technological innovation. This section explores recent developments in cooling technologies, discusses the challenges faced by the industry, and highlights potential solutions to address these issues [25].

1. Recent advancements and innovations

a) Energy-efficient technologies

- Variable Speed Drives (VSDs) allow pumps and fans to operate at speeds that match the cooling demand rather than running at full capacity continuously. This leads to substantial energy savings, reduced mechanical stress on components, and extended equipment lifespan.

- Advanced heat exchanger designs utilize small channels to increase the surface area-to-volume ratio, enhancing heat transfer efficiency. Additive manufacturing enables complex geometries that improve thermal performance and reduce material usage.

b) Alternative refrigerants

- Natural refrigerants offer high energy efficiency with zero ODP and negligible GWP. Challenges include toxicity and flammability, requiring stringent safety measures with low GWP and zero ODP synthetic refrigerants serving as replacements for high-GWP hydrofluorocarbons (HFCs). This is used mainly in air conditioning, refrigeration, and foam blowing agents.

c) Integration with renewable energy

- Solar-assisted cooling systems use solar thermal energy to power absorption chillers, reducing reliance on fossil fuels improves lower operating costs and reduced greenhouse gas emissions.

- Waste heat utilization capture waste heat from industrial processes to drive thermally activated cooling systems and improves overall energy efficiency and reduces the need for additional energy input

- Smart cooling systems and IoT integration

- Advanced control algorithms implement machine learning and predictive analytics to optimize system performance which enhanced energy efficiency, reduced operational costs, and predictive maintenance capabilities.

- Remote monitoring features real-time data collection and analysis for system diagnostics and performance optimization which minimizes downtime and facilitates rapid response to anomalies.

- Advanced cooling technologies

- Magnetic refrigeration uses research into magnetocaloric materials is advancing, bringing this technology closer to practical applications which offers high energy efficiency without the need for conventional refrigerants.

- Nanofluids refers to fluids enhanced with nanoparticles to improve thermal conductivity which are used in heat exchangers and cooling systems to increase heat transfer rates [26].

2. Industry challenges

Despite technological progress, the industry faces several significant challenges that hinder the adoption of advanced cooling systems.

a) Environmental impact

- Refrigerant emissions have issues such as leakage of high-GWP refrigerants contributes to climate change which drive the need for international agreements mandate the phasedown of harmful refrigerants.

- Water scarcity uses cooling towers and evaporative systems which consume large volumes of water, exacerbating water scarcity issues in arid regions.

b) Energy consumption

- High operational costs make cooling systems account for a substantial portion of industrial energy use, leading to increased costs and carbon emissions.

- Efficiency plateaus have a barrier for conventional technologies that are approaching their theoretical efficiency limits, necessitating innovation for further gains.

c) Economic constraints

- Capital investment needs for high upfront costs of advanced systems, especially for small and medium-sized enterprises (SMEs)

- Uncertain ROI have issues that involve long payback periods make it difficult to justify investments despite potential long-term savings.

d) Technical limitations

- Material compatibility with alternative refrigerants may require new materials resistant to higher pressures or corrosive properties.

- System integration is known for the difficulty of retrofitting existing systems with new technologies which can be complex and disruptive.

e) Regulatory compliance

- Evolving standards need to keep pace with changing environmental regulations requires continuous adaptation.

- Safety concerns for the use of flammable or toxic refrigerants necessitates enhanced safety protocols [27].

3. Potential solutions

Addressing these challenges requires a multifaceted approach combining technological innovation, policy support, and industry collaboration.

a) Adoption of Low-GWP refrigerants

- Transition strategies which imply gradually replacing high-GWP refrigerants with environmentally friendly alternatives. This is done by developing refrigerant blends that balance performance with lower environmental impact.

- Research initiatives by investing in R&D to discover new refrigerants and refrigeration cycles.

b) Enhancing energy efficiency

- System optimization by implementing energy management systems and regular maintenance schedules and the uses of retrofits to upgrade components like compressors and heat exchangers to more efficient models.

- Energy recovery by utilizing waste heat for absorption cooling or preheating processes.

c) Economic incentives and financing

- Government support which implies tax credits, grants, and subsidies to offset initial investment costs by applying policies for encouraging or mandating energy efficiency improvements.

- Financial models to provide financing and assume performance risk for energy efficiency projects.

d) Water conservation techniques

- Alternative cooling methods by utilizing air-cooled systems to reduce or eliminate water usage and utilizing hybrid systems by combining wet and dry cooling to optimize water and energy use.

- Water recycling by using technologies for treating and reusing process water within the cooling system.

e) Safety and compliance enhancements

- Training programs for ensuring personnel are skilled in handling new refrigerants and safety protocols.

- Technology standards for establishing industry-wide standards for new technologies to streamline adoption and compliance.

f) Collaborative research and development

- Industry partnerships to unsure collaboration by joint ventures between companies, academia, and research institutions to share knowledge and resources.

- Standardization efforts to harmonizing regulations and standards internationally to facilitate technology transfer [28-29].

The industrial cooling sector is advancing through the development of energy-efficient technologies, alternative refrigerants, integration with renewable energy sources, and smart system implementations. However, challenges such as environmental impact, high energy consumption, economic barriers, technical limitations, and regulatory compliance persist. By adopting low-GWP refrigerants, enhancing energy efficiency, leveraging economic incentives, conserving water, improving safety measures, and fostering collaborative research, the industry can overcome these obstacles. Continued innovation and strategic policy support are essential to meet future cooling demands sustainably [30].

5. CONCLUSIONS

Industrial cooling systems are fundamental to the efficient, safe, and sustainable operation of a diverse range of industrial processes. This article has provided a comprehensive review of existing cooling technologies, performance metrics, selection criteria, recent advancements, industry challenges, and potential solutions within the field of industrial cooling.

The examination of existing technologies highlighted the continued relevance of traditional cooling methods, such as air and liquid cooling systems, due to their proven effectiveness and established infrastructure. However, advanced technologies like thermoelectric cooling and magnetic refrigeration are emerging as promising alternatives, offering enhanced efficiency and environmental benefits. The selection of an appropriate cooling system is a multifaceted decision that must consider performance metrics—including energy efficiency, thermal performance, environmental impact, and reliability—tailored to specific industrial applications.

Recent advancements have focused on improving energy efficiency through the adoption of variable speed drives, advanced heat exchanger designs, and the integration of smart control systems utilizing the Internet of Things (IoT). The development of alternative refrigerants with low Global Warming Potential (GWP) and zero Ozone Depletion Potential (ODP), such as natural refrigerants and hydrofluoroolefins (HFOs), addresses environmental concerns associated with traditional refrigerants. Integration with renewable energy sources, such as solar-assisted cooling and waste heat utilization, further enhances the sustainability of industrial cooling systems.

Despite these advancements, the industry faces significant challenges. Environmental impacts from refrigerant emissions and water scarcity, high energy consumption leading to increased operational costs, economic constraints related to the high initial investment of advanced systems, technical limitations including material compatibility and system integration complexities, and evolving regulatory compliance requirements all pose substantial hurdles.

Potential solutions to these challenges involve a combination of technological innovation, policy support, and industry collaboration. Transitioning to low-GWP refrigerants and adopting energy-efficient technologies can mitigate environmental impacts and reduce operational costs. Economic incentives, such as government subsidies and innovative financing models like Energy Service Companies (ESCOs), can alleviate financial barriers. Enhancing water conservation through alternative cooling methods and water recycling technologies addresses water scarcity concerns. Strengthening safety protocols and compliance through training and the development of industry-wide standards ensures safe adoption of new technologies. Collaborative research and development efforts accelerate innovation and facilitate the harmonization of regulations and standards.

In conclusion, the future of industrial cooling lies in the continued pursuit of technologies and practices that balance efficiency, cost-effectiveness, and environmental sustainability. By addressing current challenges through innovation, strategic policy support, and collaborative efforts among industry stakeholders, researchers, and policymakers, the industrial sector can achieve significant improvements in cooling efficiency and environmental stewardship. This holistic approach is essential to meet the growing demands of modern industries while aligning with global sustainability goals

.

6. REFERENCES

[1] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2020). *ASHRAE Handbook—HVAC Systems and Equipment*. ASHRAE.

[2] Stoecker, W. F. (1998). *Industrial Refrigeration Handbook*. McGraw-Hill.

[3] Dincer, I., & Rosen, M. A. (2011). *Thermal Energy Storage: Systems and Applications* (2nd ed.). John Wiley & Sons.

[4] Klemeš, J. J., Varbanov, P. S., & Kravanja, Z. (2013). "Recent developments in Process Integration." *Chemical Engineering Research and Design*, 91(10), 2037–2053.

[5] Wang, R. Z., & Oliveira, R. G. (2006). "Adsorption refrigeration—An efficient way to make good use of waste heat and solar energy." *Progress in Energy and Combustion Science*, 32(4), 424–458.

[6] Sawalha, S. (2008). "Carbon dioxide in supermarket refrigeration." *International Journal of Refrigeration*, 31(3), 515–524.

[7] Yang, L., Yan, H., & Lam, J. C. (2014). "Thermal comfort and building energy consumption implications—A review." *Applied Energy*, 115, 164–173.

[8] Lee, K. Y., & Singh, C. (2010). "Reliability assessment of power systems including wind farms using Monte Carlo simulation." *Electric Power Systems Research*, 80(9), 1117–1125.

[9] Bell, I. H., Wronski, J., Quoilin, S., & Lemort, V. (2014). "Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp." *Industrial & Engineering Chemistry Research*, 53(6), 2498–2508.

[10] International Energy Agency (IEA). (2018). *The Future of Cooling: Opportunities for energy-efficient air conditioning*. IEA.

[11] Hwang, Y., Radermacher, R., Al Hashimi, S., & Kubo, I. (2008). "Review of solar cooling technologies." *HVAC&R Research*, 14(3), 507–528.

[12] Hepbasli, A., & Kalinci, Y. (2009). "A review of heat pump water heating systems." *Renewable and Sustainable Energy Reviews*, 13(6–7), 1211–1229.

[13] Lu, Y., et al. (2017). "Energy-efficient server provisioning with control methods for cloud data

centers." *Energy Conversion and Management*, 129, 108–121.

[14] Fischer, S. K., & Rice, C. K. (2002). "The status of refrigerant selection and design for chlorofluorocarbon-free systems." *International Journal of Refrigeration*, 25(1), 4–19.

[15] Niazi, S., & Majdi, H. S. (2019). "Advances in thermoelectric power generation and cooling: A review." *Energy Conversion and Management*, 185, 586–634.

[16] Zeng, R., et al. (2011). "A state-of-the-art review on phase change material slurries." *Energy Conversion and Management*, 50(1), 1–11.

[17] Ghosh, P., & Sarkar, J. (2017). "A critical review on application of nanofluids in solar energy harvesting and storage." *Journal of Cleaner Production*, 161, 290–307.

[18] International Institute of Refrigeration (IIR**)**. (2019). *The Role of Refrigeration in the Global Economy*. IIR.

[19] Evans, J. A., & Foster, A. M. (2015). "Sustainable retail refrigeration." *International Journal of Refrigeration*, 57, 199–208.

[20] Allouhi, A., et al. (2015). "Solar domestic heating water systems in Morocco: An energy analysis." *Energy Conversion and Management*, 92, 105–113.

[21] Chua, K. J., Chou, S. K., & Yang, W. M. (2010). "Advances in heat pump systems: A review." *Applied Energy*, 87(12), 3611–3624.

[22] Han, J., et al. (2011). "An analysis of the water consumption of evaporative cooling systems for buildings." *Energy and Buildings*, 43(9), 2197–2203.

[23] Wang, K., et al. (2018). "Data center energy consumption modeling: A survey." *IEEE Access*, 6, 10872–10886.

[24] Purohit, P., & Höglund-Isaksson, L. (2017). "Global emissions of fluorinated greenhouse gases 2005–2050 with abatement potentials and costs." *Atmospheric Chemistry and Physics*, 17(4), 2795–2816.

[25] Herold, K. E., Radermacher, R., & Klein, S. A. (2016). *Absorption Chillers and Heat Pumps* (2nd ed.). CRC Press.

[26] European Commission. (2014). *Directive 2014/68/EU on the harmonization of the laws of the Member States relating to the making available on the market of pressure equipment.*

[27] Rogdakis, E. D., & Antonopoulos, K. A. (2000). "Comparative study of single and two-stage absorption heat transformers." *Applied Thermal Engineering*, 20(10), 981–1003.

[28] Mazzarella, L. (2015). "Energy retrofit of historic and existing buildings. The legislative and regulatory point of view." *Energy and Buildings*, 95, 23–31.

[29] Lawrence Berkeley National Laboratory. (2016). *Best Practices for Data Centers: Lessons Learned from Benchmarking 22 Data Centers*. LBNL.

[30] International Energy Agency (IEA**)**. (2019). *Energy Efficiency 2019*. IEA.