DOKUZ EYLÜL UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

THE EFFECTS OF DIGITALIZATION ON CLIMATE CHANGE

by

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February, 2025

İZMİR

THE EFFECTS OF DIGITALIZATION ON CLIMATE CHANGE

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by

Işıl ASLAN

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İZMİR

M.S. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"THE EFFECTS OF DIGITALIZATION ON CLIMATE CHANGE"** completed by **IŞIL ASLAN** under supervision of **PROFESSOR DOCTOR NURDAN BÜYÜKKAMACI** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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Finally, I dedicate this work to my son, whose presence inspires me every day and for whom all my efforts are devoted. Everything I do is for his brighter future, and his love provides the driving force behind my perseverance and determination.

Işıl ASLAN

THE EFFECTS OF DIGITALIZATION ON CLIMATE CHANGE

ABSTRACT

Digitalization has rapidly transformed industries, economies, and societies, offering opportunities for innovation, enhanced efficiency, and growth. However, this transformation also brings significant environmental challenges, particularly in its contribution to climate change. This thesis investigates the complex relationship between digitalization and environmental sustainability, with a primary focus on how digital technologies impact resource consumption, energy use, and greenhouse gas emissions that contribute to climate change.

Energy and water consumption in data centers is very high. Within the scope of the thesis, a data center was selected as a pilot facility and data on energy and water consumption was collected. The study evaluates opportunities for mitigating the environmental costs of data centers through renewable energy integration and green practices to reduce the sector's carbon footprint. Evaluations were made regarding the use of renewable energy sources to reduce the environmental damage caused by energy consumption and the implementation of water recycling systems to protect clean water resources.

The proliferation of smart devices, IoT systems, and cloud computing generates vast e-waste, demands energy-intensive data center operations, and accelerates resource depletion. The lifecycle emissions of digital devices further contribute to global greenhouse gas levels. By advocating circular economy principles this research addresses the environmental pressures of digital technologies.

By critically analyzing the interplay between digitalization and climate change, the study underscores the urgency of integrating climate resilience into the digital revolution. It provides actionable recommendations for achieving a balanced approach. This thesis contributes to a growing body of knowledge aimed at transforming digital innovation into a force for climate action, ensuring that

technological progress supports, rather than undermines, the planet’s ecological and climatic stability.

Keywords: Digitalization, climate change, data center, sustainability, carbon footprint, energy consumption, water consumption, e-waste management

DİJİTALLEŞMENİN İKLİM DEĞİŞİKLİĞİNE ETKİLERİ

ÖZ

Dijitalleşme, endüstrileri, ekonomileri ve toplumları hızla dönüştürerek yenilik, gelişmiş verimlilik ve büyüme fırsatları sunmuştur. Ancak bu dönüşüm, özellikle iklim değişikliğine katkısı bakımından önemli çevresel zorluklar da beraberinde getirmektedir. Bu tez, dijitalleşme ve çevresel sürdürülebilirlik arasındaki karmaşık ilişkiyi, dijital teknolojilerin iklim değişikliğine katkıda bulunan kaynak tüketimini, enerji kullanımını ve sera gazı emisyonlarını nasıl etkilediğine odaklanarak incelemektedir.

Veri merkezlerinde enerji ve su tüketimi çok yüksektir. Tez kapsamında bir veri merkezi pilot tesis olarak seçilmiş ve enerji ve su tüketimine ilişkin veriler toplanmıştır. Çalışma, sektörün karbon ayak izini azaltmak için yenilenebilir enerji entegrasyonu ve yeşil uygulamalar yoluyla veri merkezlerinin çevresel maliyetlerini azaltma fırsatlarını değerlendirmektedir. Enerji tüketiminin neden olduğu çevresel hasarı azaltmak için yenilenebilir enerji kaynaklarının kullanımı ve temiz su kaynaklarını korumak için su geri dönüşüm sistemlerinin uygulanması konusunda değerlendirmeler yapılmıştır.

Akıllı cihazların, IoT sistemlerinin ve bulut bilişimin yaygınlaşması, büyük miktarda e-atık üretmekte, enerji yoğun veri merkezi operasyonları gerektirmekte ve kaynak tükenmesini hızlandırmaktadır. Dijital cihazların yaşam döngüsü emisyonları, küresel sera gazı seviyelerine daha da katkıda bulunmaktadır. Bu araştırma, dairesel ekonomi ilkelerini savunarak dijital teknolojilerin çevresel baskılarını ele almaktadır.

Çalışma, dijitalleşme ve iklim değişikliği arasındaki etkileşimi eleştirel bir şekilde analiz ederek, iklim dayanıklılığını dijital devrime entegre etmenin aciliyetini vurgulamaktadır. Dengeli bir yaklaşım elde etmek için uygulanabilir öneriler sunmaktadır. Bu tez, dijital inovasyonu iklim eylemi için bir güce dönüştürmeyi ve teknolojik ilerlemenin gezegenin ekolojik ve iklimsel istikrarını baltalamak yerine

desteklemesini sağlamayı amaçlayan giderek artan bir bilgi birikimine katkıda bulunmaktadır.

Anahtar kelimeler: Dijitalleşme, iklim değişikliği, veri merkezi, sürdürülebilirlik, karbon ayak izi, enerji tüketimi, su tüketimi, e-atık yönetimi

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CHAPTER ONE
INTRODUCTION

Digitalization, defined as the process of converting information into a digital format, is profoundly reshaping every facet of modern life, fundamentally altering the operational paradigms of industries worldwide. This transformative process, central to Industry 4.0, leverages digital technologies like the Internet of Things (IoT), artificial intelligence (AI), machine learning, and big data analytics to enhance efficiency, productivity, and foster innovation (Parviainen et al., 2017). The global pivot towards digitalization is not just a pursuit of operational excellence but also a strategic move to reduce costs, accelerate production, and elevate customer satisfaction levels. This digital transformation journey, while more advanced in developed nations due to their sophisticated digital infrastructures, is also gaining momentum in developing countries, acknowledging digitalization as a key driver for economic development and global competitiveness (Matthess & Kunkel, 2020).

Beyond economic ramifications, digitalization is revolutionizing societal norms and modes of communication, enabling unprecedented forms of interaction. However, the environmental footprint of digital technologies, particularly their significant energy consumption and contribution to carbon emissions, raises critical concerns. The digital sector's role in global carbon pollution underscores a paradoxical scenario where the pursuit of digital economy growth potentially conflicts with environmental sustainability goals (Chen et al., 2020).

This thesis aims to unravel the complex interaction between digitalization and the environment, and to examine both the positive and negative effects of digital technologies on ecological sustainability. Strategies for reducing environmental impacts in the digital age have been examined, and a roadmap has been created to create a sustainable path where digital progress and environmental stewardship coexist harmoniously. Thus, the necessity of economic growth being in balance with ecological protection and the role of digitalization in sustainable development have been emphasized.

This thesis focuses on the issue of data centers, which are the key to digital technology and use too much energy and water, which is an area not emphasized enough in digitalization. These centers need too much power to operate and too much water to stay cool. In this study, a data center was examined as an example to better understand how much energy and water it uses. The current situation of this data center was analyzed, and suggestions were developed to make data centers more environmentally friendly.

CHAPTER TWO
DIGITALIZATION AND THE ENVIRONMENT

The spread of digitalization has positive environmental impacts, but it also has many negative ones. While Goel et al. (2024) stated that it has positive effects such as increasing resource efficiency, reducing emissions, facilitating the monitoring and management of resources, they also reported negative effects such as increasing energy consumption and the generation of electronic waste. Figure 2.1 shows these impacts schematically and they are explained in detail below.

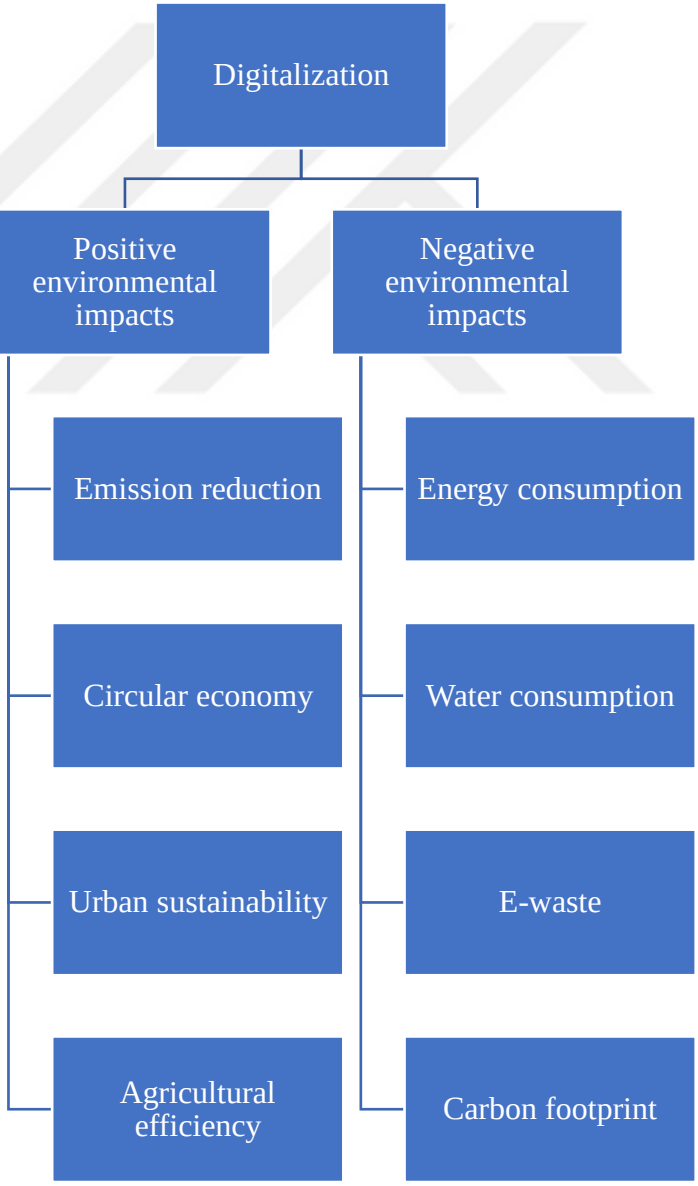

Figure 2.1. Digitalization and its environmental impacts

2.1 Environmental Advantages of Digitalization

2.1.1 Energy Sector and Digital Technologies

In today's world, energy is a fundamental requirement for humanity, underpinning every facet of modern life (IEA, 2023). The increasing demand for energy across various fields amplifies the sector's global significance. Hence, emission reductions through digitalization in this sector are crucial for the entire planet.

Key areas where digital technologies have brought significant progress include advanced grid management, incorporation of renewable energy, and predictive maintenance. Smart grid innovations improve the efficiency of energy distribution, and enable the seamless integration of renewable energy sources, which is essential for developing sustainable energy systems. (Smith, 2021; Jones et al., 2022). Smart grids, powered by advanced analytics and IoT (Internet of Things) technologies, facilitate real-time monitoring and management of energy flows, enhancing efficiency and reliability. In renewable energy, digital tools like AI and machine learning algorithms are employed for optimizing energy production from sources such as solar and wind, predicting output, and efficiently integrating this energy into the power grid. These digital tools for energy efficiency play a key role in optimizing energy consumption and reducing waste (Doe & Roe, 2023). These advancements signify a transformative era in the energy sector, driven by digital innovation and a commitment to sustainability. Moreover, predictive maintenance, using sensors and AI, is revolutionizing the way energy infrastructure is managed, allowing for early detection of potential failures and reducing downtime. These technologies, along with blockchain for secure energy transactions and big data analytics for customer insights, are pivotal in driving the digital transformation in the energy sector (Chwiłkowska-Kubala et al., 2023).

This transformation, driven by the integration of human, technological, and financial resources, is pivotal not only in enhancing efficiency and innovation but also in substantially reducing emissions. The digital readiness of the sector, involving aspects like organizational culture and governance, plays a mediating role in this

transformation. Therefore, the pursuit of digitalization in the energy sector, with its focus on both technological advancement and organizational adaptability, is of paramount importance for global sustainability and environmental preservation (Chwiłkowska-Kubala et al., 2023).

2.1.2 Circular Economy and Digital Innovation

Circular Economy (CE) and Digital Innovation represent a synergy where digital technologies enable a shift towards more sustainable and resource-efficient business models. CE focuses on reducing waste and maximizing the use of resources, often through recycling, reusing, and refurbishing materials and products. Digital Innovation in this context involves using technologies like IoT, big data, and AI to track resource flows, optimize production processes, and create more efficient supply chains. This integration facilitates the transition to CE by providing real-time data, enhancing process efficiency, and offering innovative solutions to minimize environmental impact while maintaining economic growth.

The use of machine learning, AI, and image recognition to automate waste segregation and reduce labor risks. RFID and wireless communications enhance material traceability, supporting circular economy principles. The study emphasizes the need for comprehensive integration of these technologies across the solid waste management chain, highlighting the current lack of coherent application on a larger scale. The transition to digitalized, interconnected systems promises significant improvements in managing solid waste efficiently and sustainably (Ranta et al., 2020).

AI-driven circular business model innovations enhance industrial firms' ability to intensify the use of their assets and contribute to the circular economy. These business models focus on optimization and autonomous solutions, aiming to reduce effectively, reuse, and recycle materials and energy resources (Sjödin et al., 2023).

2.1.3 Digitalization in Urban Sustainability

By 2030, it is expected that urban regions will be home to 60% of the world's population, with one in three individuals residing in cities that have a population of at least half a million (United Nations, 2018). Energy demands are expected to increase due to this projected population growth. Therefore, sustainable development is becoming increasingly important for urban centers. This situation leads cities to digitalization for; monitoring systems for natural phenomena, implementing clean technologies and data management strategies (Caragliu & Del Bo, 2019).

One of the key advantages of digitalization is its impact on improving regional labor quality and total factor productivity. This is vital for sustainable urban development as it leads to more efficient and effective use of resources and human capital.

Digitalization plays a pivotal role in driving high-quality economic development in urban areas. This includes stimulating innovation, optimizing industrial structures, and enhancing the efficiency of various economic activities (Tian & Guo, 2023).

As efforts continue to establish a circular economy that is both environmentally sustainable and low in emissions, while also promoting balanced growth across economic, social, and ecological dimensions, enhancing urban green technology innovation emerges as a critical priority (Dian et al., 2023).

2.1.4 Agricultural Practices and Climate Change

Digital tools such as GPS mapping and drone technology have enabled farmers to adopt precision agriculture, which ensures the targeted and efficient use of water, fertilizers, and pesticides. This practise reduces waste and minimizes the environmental footprint. By leveraging sensors to monitor soil health and crop conditions, farmers can precisely allocate resources only where necessary, thereby improving efficiency and sustainability. Precision Agriculture (PA) serves as a promising pathway for implementing smart technologies in farming, promoting the

use of appropriate inputs in optimal amounts, at the right time and location (Balkrishna et al., 2023).

Sudden and extreme environmental changes caused by agricultural activities, including the cultivation of land and livestock management, are often referred to as agricultural disasters. Big data analytics in agriculture helps in predicting weather patterns, understanding crop rotation benefits, and identifying potential pest infestations. This data-driven approach leads to more informed decisions, reducing unnecessary resource usage and minimizing the ecological footprint (Jaber et al., 2022).

The use of automated tractors and harvesters powered by AI algorithms has made farming more efficient. These technologies help in reducing fuel consumption and lower greenhouse gas emissions, contributing to a more sustainable agricultural sector (Wakchaure et al., 2023).

IoT (Internet of Things) technologies enable real-time monitoring of water usage and soil conditions. This can significantly reduce water wastage through precise irrigation and help in maintaining soil health, thereby ensuring sustainable agricultural practices (Manocha et al., 2023).

2.1.5 ICT's Contribution to Climate Research

The digitization of climatic data has revolutionized weather prediction and the development of prevention and adaptation methods. By transforming extreme weather prediction, digitalization aids in creating more effective climate change strategies (Alant & Bakare, 2021).

2.2 Environmental Disadvantages of Digitalization

2.2.1 Resource and Energy Intensity of Digitalization

Cloud and data services have seen a steady rise in demand since their introduction. These technologies are highly resource-intensive, requiring significant raw materials for production. Whether for complex computations, digital storage, blockchain activities, or hosting digital services, data plays an increasingly crucial role in society. However, with the growing presence of data centers, the demand for both electricity and water in the digital services sector has also increased (Farfan, 2023). Data centers, in particular, are associated with high levels of water and energy consumption. Although advancements in energy efficiency have been achieved, the increasing computational workload—rising by 550% between 2010 and 2018—has still led to a 6% overall increase in energy usage (Silva -Llanca et al., 2023).

2.2.2 E-Waste and Environmental Pollution

E-waste is globally recognized as one of the fastest-growing and most valuable waste streams (Figure 2.1). Although many countries are increasingly addressing the issue by developing policies and regulations to manage electronic waste, a significant portion of e-waste remains unaccounted for (Andeobu et al., 2023).

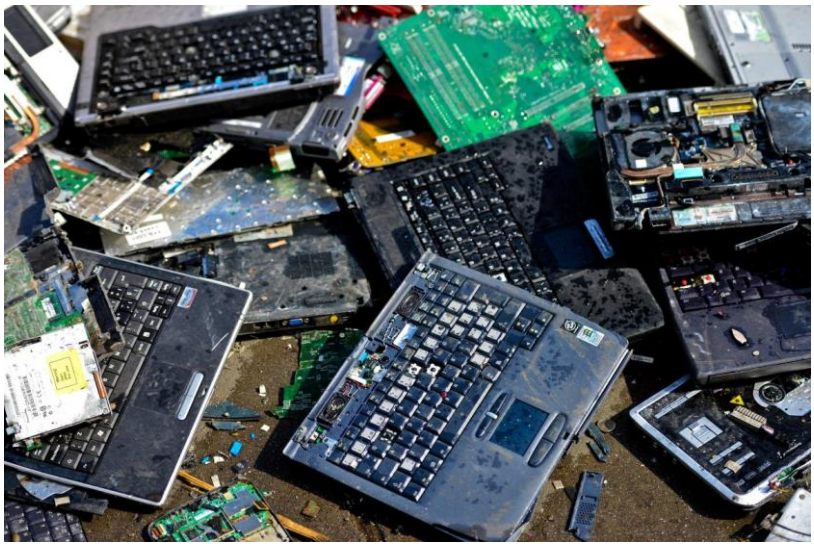

Figure 2.2 E-waste, a digitalization problem (https://www.diggitmagazine.com/articles/e-waste-and-infrastructures-digitalization).

The rapid obsolescence of digital devices exacerbates the generation of e-waste, which poses significant environmental and health risks. It is predicted that 11 billion smart devices will have entered our lives by 2040 (U.S. Energy Information Administration [EIA], 2017).

In addition to environmental risks, the precious metals that may be contained in these wastes have an economic value. When correct recycling methods are not applied or when they are disposed of unconsciously, there is a risk of losing the precious metals contained in the content. It is known that only 22.3% of the 62 million tons of electronic waste generated worldwide in 2022 was properly recycled. This situation reveals the need for effective electronic waste management worldwide (Forti et al., 2024).

2.2.3 Data Centers and Climate Change

Data centers are a prime example of the environmental challenges brought about by digitalization. These facilities are significant energy consumers, with cooling systems contributing substantially to their carbon footprint. Globally, data centers are estimated to use approximately 1% to 1.5% of global electricity consumption and contribute around 1% of global greenhouse gas emissions (International Energy Agency [IEA], 2023)

Cooling systems alone account for nearly 40% of the total energy consumed by IT equipment, making cooling expenses a significant portion of operational costs for large data centers (Arroba et al., 2023). Although advancements in server technology and cooling methods have improved energy efficiency, the ever-increasing demand for data traffic continues to drive high energy usage.

2.2.4 Rebound Effects and Increased Consumption

Enhancing energy efficiency is widely regarded as an effective strategy for minimizing energy waste and achieving carbon neutrality. However, it can sometimes lead to the rebound effect, where the anticipated energy savings are offset by increased

energy consumption, ultimately hindering the expected reductions in energy use (Kong et al., 2023).

Efficiency improvements in digital technologies often lead to rebound effects, where the gains in efficiency result in increased overall consumption. For instance, as data transfer and storage become more energy-efficient and less costly, the demand for these services escalates, leading to a net increase in energy use. This phenomenon is known as the Jevons paradox, where increased efficiency in resource use can lead to higher overall consumption rates (Lange et al., 2021).

2.2.5 Digitalization and Indirect Environmental Impacts

Digitalization has indirect environmental consequences through the promotion of a consumerist culture. The ease of online shopping, for instance, encourages increased consumption patterns, which in turn intensifies production, packaging, and transportation, all contributing to a higher carbon footprint (Wang & Tang, 2022).

2.3 Digitalization and Sustainability

Through the use of smart systems and Internet of Things (IoT) technologies, digital innovations provide significant opportunities to contribute to the United Nations Sustainable Development Goals (SDGs). These technologies enhance sustainable food production, improve access to clean water, and promote the use of renewable energy sources. Such advancements are vital for creating a sustainable future, where digitalization supports efficient manufacturing processes and addresses the health and well-being of underserved populations (Mondejar et al., 2021).

Digitalization also brings advanced predictive capabilities and improved connectivity, offering both opportunities and challenges for achieving sustainability targets. Integrating digital technologies into sustainability research is critical for identifying pathways to a more environmentally and socially responsible future (Seele & Lock, 2017).

2.3.1 Strategies to Reduce Water Consumption

Data centers are hungry water consumers. These studies present innovative data center cooling technologies, emphasizing the shift towards more sustainable and water-efficient solutions.

Radiative Free Cooling: Potential of leveraging thermal radiation to dissipate heat in data centers reduce the reliance on traditional, water-intensive cooling systems, offering a way to save both energy and water.

Silica Gel-Water Adsorption Chiller: Using of a compact silica gel-water adsorption chiller for waste heat driven cooling in data centers can effectively utilize waste heat, reducing the need for additional water for cooling purposes.

Integrated Cooling and Waste Heat Recovery: A system that integrates data center cooling with waste heat recovery can significantly lower energy and water consumption (Chen, 2021).

Elevating Operational Temperatures: Strategies such as those implemented by Microsoft to increase operational temperatures can lead to substantial reductions in water use. This approach underscores the industry's effort to balance operational efficiency with environmental responsibility (Microsoft, 2023).

Using of Reclaimed Water Technologies: Google's development of 'climate-conscious' cooling technologies, including the use of recycled "grey" water systems and immersion cooling, further demonstrates the industry's commitment to reducing water consumption while maintaining high-energy efficiency (Google, 2023).

Lastly, research on the optimal setting of cooling system parameters under different climate zones has shown that water-side free cooling can be significantly improved. (Mytton, 2021). By analyzing the optimal chilled water supply temperature, temperature difference, and return temperature, the study suggests that annual energy consumption could be reduced by 23.5%–60.8% across various climate zones. The

importance of local climatic conditions in determining the optimal settings and proposes a dual-working condition cooling system is helpful for future data center designs.

2.3.2 Strategies to Reduce Energy Consumption

Green Computing and Load Balancing: The concept of Green Data Centers (Green DC) emphasizes the importance of energy efficiency due to the environmental impact and operational costs associated with energy consumption1. Load balancing algorithms have been developed to distribute workloads effectively, minimizing energy usage without compromising performance. The integration of renewable energy sources is also considered a vital aspect of Green DC (Silva et al, 2023).

Software-Defined Networking (SDN): SDN-based dynamic management methods have been proposed to centralize control over data center equipment layers, allowing for real-time monitoring and intelligent energy management. This approach aims to optimize global energy consumption through a unified management platform (Peng et al, 2021).

Virtual Machine (VM) Placement: Optimized VM placement strategies, such as the MIPS-Aware VM Placement, have been shown to reduce VM migrations and improve system performance, leading to significant energy savings. By preventing additional workload allocation on overloaded and underloaded hosts, these approaches also enhance the quality of service (QoS) (Li et al, 2022).

High-Performance Computing (HPC): In the realm of HPC and cloud computing, energy-efficient systems are being developed to optimize the trade-off between application performance and system heterogeneity. Machine learning algorithms are increasingly used to optimize data center operations, including primary cooling and waste heat reuse (Bose et al, 2021).

Programmable Data Plane: Techniques leveraging SDN and programmable data plane concepts, such as P4Green, have been designed to consolidate traffic and shift

workloads towards servers powered by renewable energy. This system operates without a centralized controller, enhancing scalability and failure resistance (Han, 2021).

Air Conditioning Systems: Air conditioning systems account for a significant portion of data center energy consumption. Optimizing air distribution through various air-conditioning methods, using simulation software to identify energy-saving opportunities (Grigoryan et al., 2023).

Renewable Energy and UPS Systems: The use of on-site renewable energy sources, coupled with distributed UPS systems, can improve the efficiency and reliability of data centers. Strategies like REDUX manage the energy supply smartly, balancing energy costs and system performance (Tao, 2021).

Carbon Emissions Control: Controlling power consumption through Power Usage Efficiency standards and rationalizing equipment power usage can lead to operational savings and a reduced carbon footprint, even with increasing server counts and user numbers (Al-Fatlawi & Al_Barazanchi, 2023).

Mini Data Centers: Optimization approaches for mini data centers focus on joint migrations of jobs and energy, exploiting energy harvesting, storage, and transport capabilities. This can significantly reduce utility electricity consumption and support less energy-efficient servers (Bheda et al., 2021).

Power Control for Hot Spot Elimination: This approach aims to achieve sustainability and stability by minimizing hot spots and energy consumption. The Modified Differential Evolution algorithm optimizes power control set points, demonstrating energy savings with zero hot spots (Höb & Kranzlmüller, 2023).

Combined System Implication: By integrating the feasibility of implementing free cooling, waste heat reuse, and renewable energy systems, data centers can achieve zero energy consumption, making a significant leap towards environmental sustainability.

This approach not only reduces the operational costs associated with energy use but also diminishes the carbon footprint of data centers (Güğül et al., 2023).

Waste Heat Recovery: Waste heat recoveries in data centers emphasize the potential of harnessing waste heat as a valuable resource. By reusing waste heat, data centers can significantly reduce their reliance on external cooling solutions, leading to a decrease in overall energy consumption (Yuan et al., 2023).

2.3.3 Strategies to Reduce E-waste Generation

The growing concern over e-waste, characterized by discarded electronic devices, presents significant environmental challenges, including resource depletion and pollution. However, technological innovations and strategic initiatives by leading tech companies offer promising pathways to mitigate these issues.

Recent studies highlight the pivotal role that technological advancements play in improving e-waste recycling methods. Rene et al. (2021) emphasize the necessity of developing more advanced recycling techniques to recover valuable materials from electronic waste, thereby minimizing the environmental harm caused by its disposal. This approach aligns with the broader objective of establishing a circular economy, where waste is significantly reduced, and materials are continuously reused and repurposed (Rene et al., 2021).

In parallel, industry giants like Microsoft and Amazon are setting ambitious targets to address the e-waste challenge. Microsoft's commitment to achieving zero waste by 2030 includes the innovative concept of "circular centers" within their data centers. These centers aim to sort, reuse, and recycle electronic equipment, keeping it onsite at server farms, thus significantly reducing direct waste production. This initiative is a testament to Microsoft's broader sustainability efforts, which also encompass greener design and recycling of goods (GeekWire, 2020).

Amazon's approach to waste reduction exemplifies the application of the waste hierarchy framework, prioritizing waste avoidance through improved design and

operational efficiencies. When elimination is not feasible, Amazon increases the amount of material reused, repaired, and recycled. Notably, Amazon has achieved a significant reduction in per-shipment packaging weight by 41% since 2015, demonstrating the company's commitment to reducing its carbon footprint and minimizing waste (Amazon, 2022).

Moreover, Redzepagic, Dakic, and Moric (2023) advocate for utilizing refurbished hardware in new data centers as a practical solution to lower e-waste. This approach not only extends the lifespan of electronic components but also contributes to the environmental sustainability of data center operations. By repurposing existing hardware, the need for new electronic production is reduced, thereby decreasing the overall volume of e-waste generated (Redzepagic et al., 2023).

These insights from both academia and industry underscore the potential for innovative solutions and strategic initiatives to address the e-waste challenge effectively. By harnessing advanced recycling technologies, adopting sustainable design principles, and embracing the circular economy model, the tech industry can significantly reduce its environmental impact.

2.3.4 Synthesizing the Environmental Impacts of Digitalization

The comprehensive review of digitalization's environmental impacts reveals a complex interplay of benefits and challenges. While digital technologies offer remarkable advancements in energy efficiency, circular economy, urban sustainability, agriculture, and climate research, they also present substantial challenges, including resource intensity, e-waste, and indirect environmental impacts.

2.3.5 Balancing Benefits and Challenges

The positive impacts of digitalization, particularly in energy sector optimization, waste management in circular economies, and enhancing agricultural efficiency, are undeniable. Digital technologies have facilitated significant strides towards sustainability. However, the juxtaposition of these benefits with the adverse impacts

underscores the need for a balanced approach. The rise in resource and energy intensity, particularly in data centers, alongside the increasing problem of e-waste, poses serious environmental concerns.

2.3.6 Addressing the Jevons Paradox

A critical finding of this study is the manifestation of the Jevons paradox in the digital realm. While efficiency improvements in digital technologies are commendable, they inadvertently lead to increased overall consumption. This paradoxical situation demands a nuanced understanding of efficiency gains and their broader implications.

2.3.7 Strategies for Mitigation

To mitigate the adverse impacts, several strategies emerge from this study. Firstly, enhancing awareness and promoting responsible usage of digital technologies can curb the indirect environmental impacts. Secondly, the implementation of stricter e-waste management regulations is crucial. Finally, a more sustainable design of data centers, focusing on renewable energy sources and efficient cooling systems, can significantly reduce their environmental footprint.

2.3.8 Policy Implications and Future Research

Policies that encourage green ICT practices, incentivize sustainable design, and regulate e-waste management are essential. Future research should focus on developing more sustainable digital technologies and exploring innovative solutions to tackle the rebound effects.

CHAPTER THREE
MATERIAL AND METHODS

3.1 Selected Data Center

Within the scope of this thesis, a data center was selected and research was conducted to determine the environmental effects of digitalization in basis of this data center. The data center, strategically situated in İzmir, spans over 10,000 square meters (Figure 3.1). Annually, it consumes 16,430 cubic meters of water and 87,732,071 kilowatt-hours of electricity, reflecting its substantial operational scale and the energy-intensive nature of maintaining optimal data storage conditions.



Figure 3.1 Overview from the selected data center (Personel archive, 2024)

The facility boasts an array of high-capacity equipment, including diverse cooling systems with capacities ranging from 126 kilowatt to 1,264 kilowatt to ensure the

servers are kept at optimal temperatures for reliability and performance. The recommended temperature range for data centers is between 18°C and 27°C to balance energy efficiency and system reliability (Alkrush et al., 2024). With a total energy capacity of 750 kilowatts, but currently utilizing 299 kilowatts, it demonstrates significant room for expansion. The data center can store vast amounts of data, supported by its sophisticated infrastructure, which includes advanced servers and storage systems, capable of meeting the growing demands of digital storage and processing.

To better understand the environmental impact of energy consumption in the data center, a comprehensive carbon footprint analysis will be conducted under three different energy scenarios:

- fossil fuel derived electricity,
- solar or wind energy,
- and other renewable resources such as hydropower, biomass.

By evaluating the emissions associated with each energy source, this study will highlight the potential reductions achievable through renewable energy adoption. The following sections will present the detailed calculations and comparisons, providing insights into how transitioning to sustainable energy solutions can significantly mitigate the carbon footprint of data center operations.

3.2 Data Collection

3.2.1 Data Collection on Electricity Consumption

To monitor electricity usage accurately, monthly readings were taken from strategically installed electricity meters within the data center. These meters play a vital role in providing detailed insights into energy consumption across different systems.

The data collection process encompasses the following elements:

Cooling Systems: Since cooling is one of the largest contributors to energy consumption, dedicated meters are used to track energy usage by chillers, air-handling units, and other cooling infrastructure. Seasonal fluctuations, particularly during hotter months, are closely monitored to evaluate their impact on total energy demand.

IT Operations: Electricity meters are integrated into server racks and storage units to measure the energy used by IT equipment, including servers, networking devices, and data storage systems. This ensures a clear understanding of the energy requirements for core operations.

Backup Systems: Power backup systems, such as uninterruptible power supplies (UPS) and batteries, are monitored to track their energy consumption under normal operations and during power disturbances or outages.

Other Systems: Additional energy usage from facility lighting, security systems, and other auxiliary systems is recorded. While these systems typically represent a smaller share of overall consumption, monitoring them provides a complete picture of the facility's energy needs.

3.2.2 Data Collection on Water Consumption

Water consumption data was collected through two main sources:

Municipal Water: Readings from the municipal water counter were taken to determine the volume of municipal water supplied to the data center. This measurement was help assess the facility's reliance on treated water sources for its operations.

Well Water: For the data center's cooling systems that utilize well water, readings were taken from the cooling system counters. These counters provided specific data on the volume of groundwater used, offering insights into the data center's use of alternative water sources for cooling purposes

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Energy Consumption in the Data Center

Electricity demand varied due to seasonal influences such as increased cooling requirements during the summer months. Data centers rely heavily on electricity for several critical operations, which mentioned in subsection of 3.2.1.

The electricity consumption data was then categorized by month to account for these variations and to develop a more accurate understanding of energy use throughout the year. When compared with İzmir's average monthly temperatures, a similar seasonal trend is observed. The measured electricity consumption values, along with the compared average temperatures, are presented in Table 4.1, which details the monthly consumption of electricity in kilowatt-hours (Turkish State Meteorological Service, 2024).

Table 4.1 Electricity Consumption in the Data Center

Electricity Consumption		
Month	**Average Temperature (°C)**	**Consumption (Kilowatt-hours/month)**
January	8.8	6,141,244.97
February	9.6	6,053,512.899
March	11.7	6,492,173.254
April	15.9	6,228,977.041
May	20.8	6,579,905.325
June	25.4	8,773,207.1
July	28.0	11,405,169.23
August	27.7	8,334,546.745
September	23.8	7,895,886.39

Table 4.1 Electricity Consumption in the Data Center

October	19.0	7,106,297.751
November	14.3	6,755,369.467
December	10.6	5,965,780.828
	TOTAL	**87,732,071.01**

In this selected data center, 87,732,071.01 kilowatt-hours (about 0.088 Terrawatt-hours) of energy is consumed per year. If it is assumed that there are approximately 11,800 data centers in the world (Statista, 2024), 880 TWh of energy is consumed per year for data centers in the world. However, it should be noted that energy consumption values would vary depending on the size of the data center. Li et al. (2025) reported that the International Energy Agency stated that data centers worldwide consumed 240-340 TWh of energy per year in 2022 and predicted that this consumption would double by 2026 (Li et al., 2025). Erdem and Ozdemir (2024) state that the market size of the data center sector will increase fivefold by 2030 (Erdem & Özdemir, 2024).

The table shows a higher consumption during the warmer months due to increased cooling needs, while lower consumption is observed during the colder months. This variation is critical for identifying potential areas for energy-saving improvements, particularly in the cooling systems. Optimizing cooling methods, such as leveraging free cooling, improving airflow management, and adopting more energy-efficient equipment, could significantly reduce electricity usage during high-demand periods.

4.1.1 Energy Consumption Reduction Options in the Data Center

Cooling systems account for a significant portion of energy consumption in data centers. To address this, climate-based cooling optimization, particularly through free cooling systems, has emerged as an innovative solution. Free cooling leverages outdoor air to cool data centers, reducing the reliance on traditional, energy-intensive cooling methods. This approach is especially effective in regions with cooler climates, where external temperature and humidity conditions can be used to maintain optimal operational environments.

Meta's Luleå Data Center in Sweden utilizes the region's naturally cold climate to implement a free cooling system. By directly channeling cold outside air into the data center, the facility minimizes the need for mechanical cooling. This method not only significantly reduces energy consumption but also enhances the sustainability of the data center. Additionally, the facility operates renewable energy, making it one of the most eco-friendly data centers in the world.

Studies have shown that optimizing cooling systems based on local climate conditions can reduce energy consumption by 23.5% to 60.8%. These substantial savings highlight the importance of integrating climate-based strategies into data center operations. By adapting cooling technologies to take advantage of local weather conditions, data centers can achieve higher energy efficiency and lower carbon emissions, contributing to global sustainability efforts (Silva-Llanca, et al. 2023).

Data centers generate a significant amount of waste heat during operations, which is often released into the environment. However, innovative waste heat recovery (WHR) systems can repurpose this heat for various applications, reducing energy waste and environmental impact. These systems capture and utilize the heat produced by servers, transforming it into a valuable resource for heating, energy production, or other processes.

The Equinix Paris 8 Data Center integrates waste heat recovery by channeling excess heat to a nearby district heating system. This setup supplies thermal energy to over 1,000 homes annually, showcasing how waste heat can benefit local communities while reducing reliance on conventional heating systems (Techzine, 2025).

Additionally, the study in a Shenyang-based data center, evaluates a high-efficiency cooling system integrated with WHR, comparing it to traditional systems. Centralised systems can reduce annual carbon emissions by 0.9%, but increase operating costs by 12.6%. In contrast, decentralised systems reduce emissions by 14.6% at a cost reduction of 3.5%. WHR systems have great potential to improve environmental

performance and economic viability, bridging the gap between energy efficiency and sustainability. (Ce Zhang et al., 2024)

WHR systems not only reduce the overall energy consumption of data centres, but also their carbon footprint. By recovering and reusing waste heat, data centres can significantly reduce their dependence on external energy sources and contribute to a circular energy economy (Yuan et al. 2023).

Another approach is stated green data centers, which are designed to minimize environmental impact by optimizing energy efficiency, integrating renewable energy sources, and employing innovative technologies. These facilities aim to reduce their carbon footprints while maintaining high performance, making them a cornerstone of sustainable digital infrastructure.

One of the most innovative examples of a green data center is Microsoft's Project Natick, which involves submerging data centers underwater. The tube-shaped data center, deployed off the coast of Scotland, operates entirely on renewable energy sourced from nearby wind and tidal resources. The cool underwater environment naturally reduces the need for energy-intensive cooling systems, significantly lowering operational energy costs and carbon emissions. Additionally, the sealed underwater environment protects the equipment from dust and oxygen-related corrosion, extending its lifespan and enhancing reliability (Microsoft, 2020).

4.2 Water Consumption in the Data Center

Data centers require significant amounts of water on-site, predominantly for their cooling operations. These systems typically include various components such as cooling towers, chillers, pumps, piping networks, heat exchangers, condensers, and computer room air handler (CRAH) units. Additionally, in larger facilities, certain computer room air conditioning (CRAC) units may also rely on water-based cooling methods.

Based on the data collection methods outlined in Section 3.2.2, water consumption in the data center is derived from two primary sources: municipal water and well water. When compared with İzmir's average monthly temperatures, a seasonal variation in water usage is observed. The annual total water consumption for the data center is 16,430 cubic meters. The distribution of water consumption between these sources is , along with the compared average temperatures, presented in Table 4.2. (Turkish State Meteorological Service, 2024)

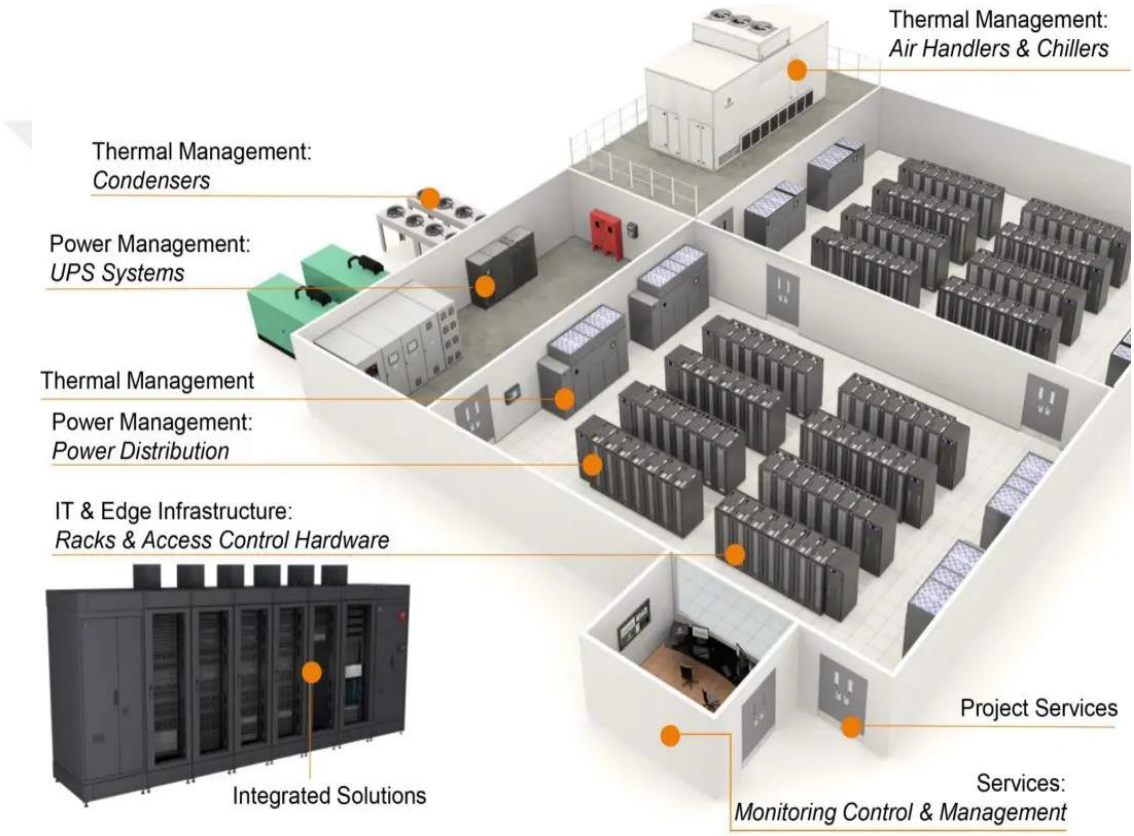

Figure 4.2 Typical data center layout of the cooling system (https://www.sisdistribution.com.hk/en/products.php?pid=58&id=51)

Table 4.2 Water Consumption in the Data Center

Month	**Average Temperature (°C)**	**Municipal (m^3/month)**	**Well (m^3/month)**	**Total (m^3/month)**
January	8.8	200	600	800
February	9.6	200	550	750
March	11.7	250	600	850
April	15.9	350	700	1,050
May	20.8	700	1,100	1,800
June	25.4	900	1,000	1,900
July	28.0	950	1,200	2,150
August	27.7	950	1,200	2,150
September	23.8	850	1,000	1,850
October	19.0	600	700	1,300
November	14.3	400	600	1,000
December	10.6	230	600	830
	TOTAL	**6,580**	**9,850**	**16,430**

16,430 m^3 uses an amount of water equivalent to the annual water consumption of approximately 225 people, assuming each person consumes 0.2 m^3/day on average (TUİK, 2020). When scaled globally, considering the presence of 10,800 data centers, the total water consumption becomes equivalent to meeting the annual water needs of approximately 2,500,000 people.

The textile sector was chosen as a benchmark due to its notoriously high water consumption. Although water consumption in the textile sector varies widely from region to region, the high-demand industry consumes up to 1 million liters of water per day (Samanta et al., 2019).

$$\text{Annual consumption} = (1*1{,}000{,}000/1{,}000)*365 = 365{,}000\ m^3/\text{year} \quad (4.1)$$

$$\text{Comparison rate} = 16{,}430/365{,}000*100 \cong 4.5 \quad (4.2)$$

Remarkably, a single data center's annual water usage can reach about 4.5% of that of a large textile factory, highlighting that even in comparison to industries traditionally known for intensive water use, data centers can pose a significant water demand. This underscores the importance of addressing water efficiency in data centers, given their growing presence and resource needs.

4.2.1 Water Consumption Reduction Options in the Data Center

The Aquasar system developed at Zurich is a pioneering example of hot water cooling in data centers. This system uses water at a temperature of 60°C to cool processors directly, eliminating the need for energy-intensive chillers. The heat removed is then reused to provide building heating, achieving a heat recovery efficiency of 80% (Zimmermann et al., 2012). This approach not only reduces water consumption but also optimizes energy use by integrating waste heat recovery into the system.

Studies have shown that absorption cooling systems have the potential to exploit low-quality waste heat in data centers. In these systems, waste heat is used to drive an absorption chiller, reducing reliance on traditional cooling methods and water-intensive chillers. By capturing waste heat, which can be as low as 70°C, data centers can significantly reduce their water usage and simultaneously lower their overall cooling energy requirements (Ebrahimi et al., 2014).

Additionally, Microsoft has introduced innovative zero-water cooling designs that consume no water, even under high ambient temperatures. By adopting chip-level cooling solutions, they achieve precise temperature control without relying on evaporative cooling, further reducing water consumption (Microsoft, 2024). Similarly, SkyCool Systems has developed radiative cooling panels that reject heat to the sky using a patented multilayer optical film, providing cooling with zero water usage (SkyCool Systems, 2020).

Another promising example is the use of treated wastewater or reclaimed water in data centers, as demonstrated by Facebook's New Mexico facility. This approach

significantly reduces potable water consumption while maintaining cooling efficiency (Ebrahimi et al., 2014). In regions with access to natural cooling resources, systems like Enwave's Deep Lake Water Cooling (DLWC) utilize the cold temperatures of large water bodies to cool data centers, cutting electricity use by 75% and eliminating water-intensive cooling towers (Enwave, 2024).

Finally, advances in dry cooling systems, which rely on air instead of water for heat dissipation, have been implemented by Amazon Web Services (AWS) in Oregon. These systems eliminate water use entirely in the cooling process, showcasing an effective solution in favorable climates (AWS, 2024).

By combining these technologies, data centers can achieve substantial reductions in water consumption, improve energy efficiency, and contribute to sustainable operational practices

4.3 Waste Production in the Data Center

Data centers produce a variety of waste streams. These wastes are primarily categorized into electronic waste (e-waste), cooling-related waste, packaging and general office waste, and hazardous waste, such as batteries or chemical residues from water treatment systems. The volume and types of waste generated depend on the size of the data center, its cooling methods, and operational practices. Table 4.3 shows the types of wastes and management methods generated in the selected data center.

Table 4.3 Waste production in the selected data center

Waste Type	**Source**	**Estimated Annual Quantity (kg)**	**Disposal/Management Method**
Electronic Waste (e-waste)	Obsolete servers, storage devices, and cables	5,000 kg	Recycled via certified e-waste recyclers
Plastic Waste	Packaging materials	1,000 kg	Sent to recycling facilities
Paper/Cardboard Waste	Office operations, packaging	800 kg	Sent to recycling facilities
Wastewater Treatment Residue	Residue from reverse osmosis (RO) system	1,000 kg	Sent to specialized hazardous waste recyclers
Hazardous Waste	Contaminated waste, oil filter, top tube	4,200 kg	Sent to specialized hazardous waste recyclers
Metal Scrap	Old racks, frames, and components	3,400 kg	Sent to recycling facilities

4.3.1 Waste Production Reduction Options in the Data Center

Reducing waste generated by data centers is essential to meet sustainability targets and minimize environmental impact. Implementing effective strategies can decrease waste production, enhance recycling efficiency, and support a circular economy approach.

One of the most effective ways to reduce e-waste in data centers is by implementing automated e-waste recycling technologies. Companies like Apple have pioneered robotic disassembly systems such as Liam and Daisy, which efficiently recover valuable materials from old devices, reducing landfill waste (Apple, 2023). Similarly, Dell's Closed Loop recycling initiative processes used electronics, ensuring that materials are recovered and reused in new devices (Dell Technologies, 2023). These advancements allow data centers to minimize their environmental footprint by optimizing material recovery.

Another critical approach is establishing secure and efficient asset disposition programs. Given the frequent upgrade cycles in data centers, a significant amount of electronic waste comes from decommissioned servers, storage devices, and networking equipment. Partnering with specialized recycling firms such as TES-AMM, which utilizes automated disassembly and secure data destruction technologies, ensures that old hard drives and servers are recycled responsibly while maintaining data security (TES-AMM, 2023).

Encouraging circular economy practices through component reuse is another effective strategy. Data centers can significantly reduce e-waste by refurbishing and repurposing IT hardware. Organizations such as Exitcom Recycling in Türkiye and Vestel's sustainable manufacturing approach focus on extending the lifespan of electronic components by recovering materials from outdated equipment for reuse in new devices (Exitcom Recycling, 2023; Vestel, 2023). This not only minimizes raw material extraction but also reduces the energy required for manufacturing, supporting a more sustainable infrastructure.

In addition to implementing recycling technologies, data centers can deploy e-waste collection and recycling programs. Establishing designated drop-off points and structured collection initiatives for outdated IT assets can greatly increase recycling rates. In Türkiye, ELDAY and TÜBİSAD have developed nationwide e-waste collection campaigns, encouraging responsible disposal and ensuring that old electronic devices are processed in an environmentally friendly manner (ELDAY, 2023; TÜBİSAD, 2023).

To further incentivize proper recycling, consumer and enterprise e-waste buyback programs can be introduced. Initiatives such as EcoATM's device trade-in kiosks have successfully encouraged consumers to recycle their electronic devices in exchange for financial incentives (EcoATM, 2023). Data centers can adopt similar programs, offering credits or discounts to companies that return old servers and hardware for responsible recycling. This approach promotes greater participation in recycling efforts and reduces overall waste generation.

To further enhance sustainability efforts and minimize the environmental footprint of data centers, it is crucial to adopt targeted waste reduction strategies. These strategies encompass various aspects of waste management, including the efficient handling of electronic waste, minimizing packaging materials, and optimizing resource utilization. The following sections outline key approaches to achieving a more sustainable and circular waste management system in data centers.

4.3.1.1 Strategies for Reducing Electronic Waste

Prolonging Equipment Life: Extend the use of IT equipment by performing regular maintenance, upgrading components, and using modular designs for ease of repair.

Adopting Virtual Technologies: Use virtualization and cloud computing to reduce dependency on physical hardware.

Supplier Take-Back Services: Collaborate with suppliers offering programs to return or recycle old equipment in an environmentally responsible manner.

Circular Economy Solutions: The speed of hardware development leads to a high rate of obsolescence. It turns working hardware into waste. Sending obsolete hardware to firms or countries that need it helps create a circular economy.

4.3.1.2 Reducing Packaging Waste

Eco-Friendly Packaging: Source equipment from vendors that utilize recyclable or biodegradable packaging materials.

Reusing Packaging Materials: Establish systems to reuse packaging for future shipments where possible.

Bulk Shipments: Consolidate deliveries to minimize the overall use of packaging.

4.3.1.3 Managing Waste from Cooling Systems

Modern Cooling Technologies: Switch to efficient cooling methods, such as liquid or closed-loop cooling, to decrease waste production from cooling processes.

4.3.1.4 Handling Hazardous Waste Responsibly

Battery Recycling: Use longer-lasting, rechargeable batteries for UPS systems and ensure proper recycling through certified facilities.

Optimized Chemical Use: Replace conventional water treatment chemicals with eco-friendly alternatives to minimize hazardous residues.

4.3.1.5 Minimizing General Office Waste

Paper-Free Systems: Transition to digital document handling and communication to cut down on paper usage.

Composting Organic Waste: Install composting units for biodegradable waste from employee areas.

Enhanced Recycling Programs: Provide clearly labeled recycling bins for items like paper, plastics, and metals to increase participation.

By applying these practices, the data center can significantly cut waste output; enhance resource efficiency, and lower operational costs. These measures also contribute to meeting environmental regulations and improving the facility's sustainability profile, aligning with global best practices

4.4 Other Suggestions

Effective data center management prioritizes energy efficiency, water conservation, and waste reduction. Incorporating green building designs and energy-efficient equipment is essential for achieving sustainable infrastructure (Manganelli et al., 2021). Strategic planning for green data centers involves considering critical factors such as infrastructure, green technologies, and business continuity, while adhering to sustainability standards that balance environmental, economic, and corporate goals (Siddik et al., 2021).

Technological and social discussions emphasize the need for energy-efficient operations, waste recovery systems, and climate-conscious digitization strategies to integrate data centers with power systems in a sustainable manner (Wang & Tang, 2022). Techniques for improving data center sustainability include the adoption of advanced cooling solutions, efficient use of natural resources, automation, low-power electronics, and equipment designed to operate at higher thermal limits (Ahwazi et al., 2021).

Moreover, hybrid cloud systems can significantly enhance sustainability by optimizing energy use in storage systems through methods such as data compression, deduplication, tiered storage, and integrating renewable energy sources (Murino et al., 2023).

The environmental footprint of data centers can be reduced by strategically locating them in areas with minimal water stress and by leveraging renewable energy sources to power those (Seddiki et al., 2021).

Virtual machine migration among cloud data centers based on renewable energy availability can improve energy consumption and maintain quality of service (Fatima & Ehsan, 2023).

Green data center approaches include assessing environmental impacts, identifying and mitigating CO_2 emission factors, and implementing performance metrics for sustainability (Raut et al., 2023).

Energy management strategies in sustainable data centers within smart grids involve integrating renewable energies and addressing challenges such as energy demand coordination and cyber-attacks (Austen & Subroto, 2023).

As we advance, the imperative for sustainable data center management becomes increasingly clear. The convergence of innovative technologies, strategic planning, and sustainability practices heralds a new era of environmentally responsible data centers. These efforts not only contribute to the reduction of the digital infrastructure's carbon footprint but also pave the way for a more sustainable and resilient future in the digital age. Through collaborative efforts across the industry, academia, and regulatory bodies, sustainable data center management can achieve its full potential, ensuring that our digital expansion proceeds in harmony with our environmental stewardship goals.

4.5 Environmental Benefits of Sustainable Data Center Management

4.5.1 Carbon Footprint

Calculating the carbon footprint of the selected data center due to its electricity consumption is important to assess its environmental impact and identify potential sustainability improvements. For this purpose, the current carbon footprint of the data

center operating using the existing Turkish electricity grid was calculated. As a green data center, the carbon footprint was also calculated for the scenario where current energy consumption is provided only by renewable energy sources. An assessment was made of how the energy source affects the overall emissions of the data center, considering different energy mixes including solar, wind and other renewable sources. Solar and wind energy were chosen due to their widespread availability and increasing cost-effectiveness. Other renewable energy sources, such as hydropower and geothermal energy, were included because of their important contribution to Turkey's energy mix(Republic of Turkey Ministry of Energy and Natural Resources, 2025).

In the current scenario, the data center consumes a total of 87,732,071.01 kilowatt annually. The emission factor for Turkey’s electricity grid in 2022 is 0.7108 tons of 31 corbondioxide/megawatt-hours, reflecting the significant share of fossil fuels in the national energy mix (Republic of Turkey Ministry of Energy and Natural Resources, 2022). The first step in calculating the carbon footprint is converting the electricity consumption from kilowatt-hours to megawatt-hours:

Electricity Consumption = 1000 x 87,732,071.01=87,732.071 Megawatt-hours (4.3)

Multiplying the electricity consumption by the emission factor yields the total carbon footprint for the current scenario:

Carbondioxide Equivalent=87,732.071 × 0.7108 =62,360 tons of CO_2 (4.4)

In the green data center scenario, two types of renewable energy mixes are considered: solar and wind energy and other renewable sources such as hydropower or geothermal energy. The emission avoidance factor for solar and wind energy is 0.6261 tCO_2/MWh, while for other renewable energy sources, it is 0.5415 tCO_2/MWh.

For the solar and energy case, the carbon footprint avoidance is calculated as:

Carbondioxide Equivalent = 87,732.071 × 0.6261 = 54,929 tons of CO_2 (4.5)

For the other renewable energy case (hydroelectric, geothermal, biomass, and other non-solar, non-wind renewables), the carbon footprint avoidance is calculated as:

$$\text{Carbondioxide Equivalent}=87{,}732.071\times0.5415=47{,}507 \text{ tons of carbondioxide} \quad (4.6)$$

Comparing the results, it is clear that switching to renewable energy can significantly improve the data centre's carbon footprint avoidance (Figure 4.6). Specifically, the use of solar energy results in 87.4% of the original emissions avoided, resulting in a carbon footprint reduction of 54,929 tons of CO_2. Using other renewable energy sources results in a 76.2% reduction, reducing the carbon footprint to 47,507 tons of CO_2.

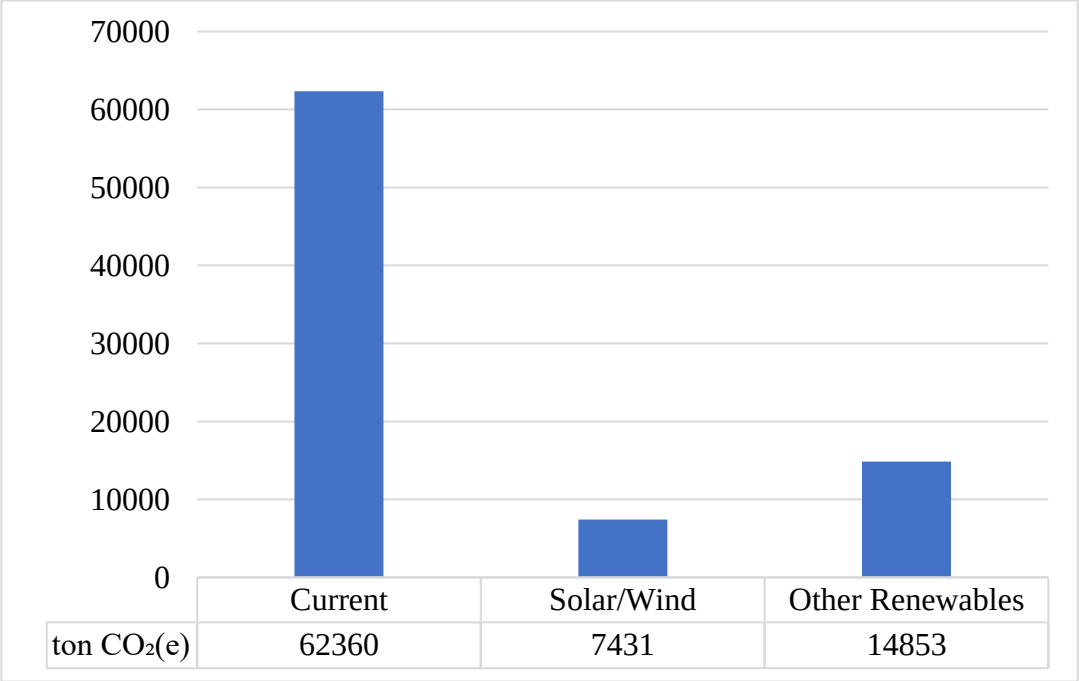

Figure 4.6 Carbon footprint comparison of different energy sources

These findings underscore the importance of renewable energy adoption in reducing the environmental impact of data centers. Switching to renewable energy sources, such as solar, wind, or hydropower, can substantially lower greenhouse gas emissions, helping data centers achieve their sustainability goals.

4.5.2 Water Consumption

The selected data center consumes 16,430 m³ of water annually, primarily for cooling systems and other operational needs. Implementing a reverse osmosis (RO) system with 50% efficiency offers a practical solution for reducing water consumption by enabling the recycling and reuse of wastewater. With 50% efficiency, the RO system can recover 8,215 m³ of treated water annually, which can be reused in the data center's cooling operations. Consequently, the data center's reliance on external water sources can be reduced by 50%, significantly lowering the burden on local water resources, and improving sustainability performance.

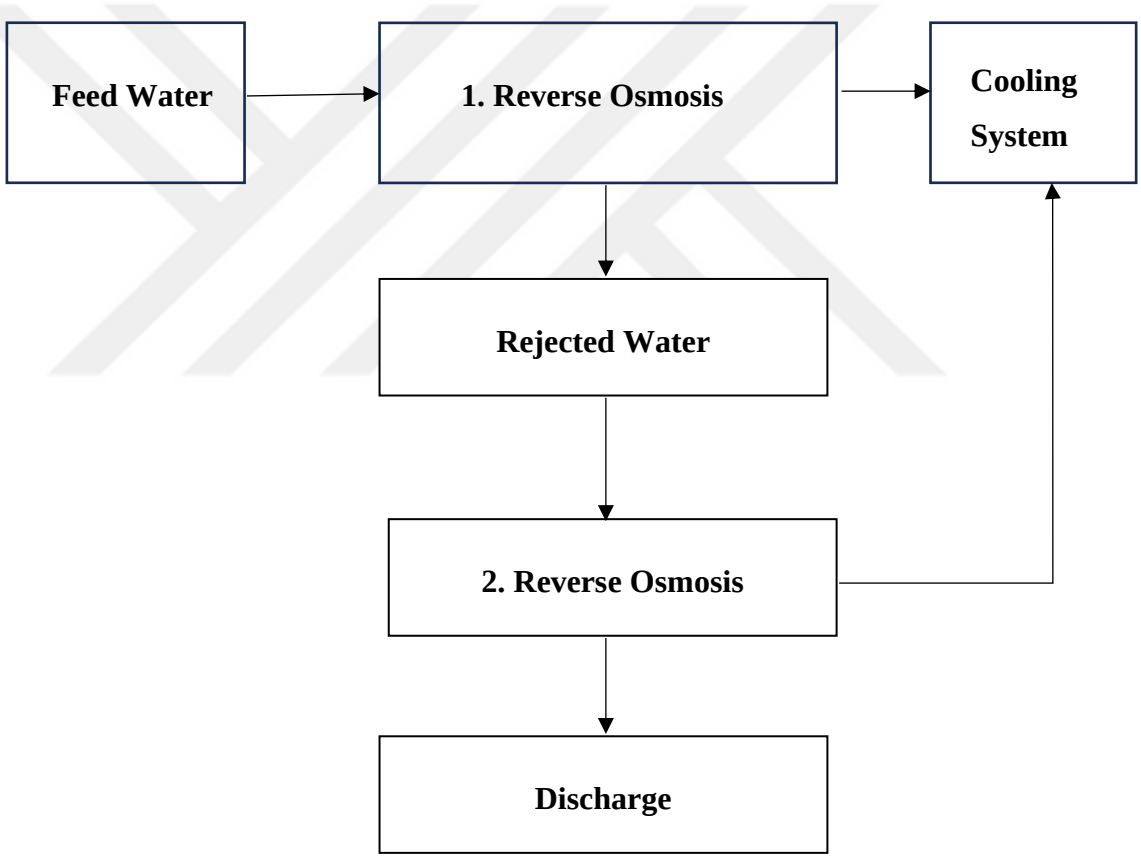

Figure 4.7 Recommended flowchart for water reuse in the cooling system

While the implementation of an RO system involves additional energy consumption costs and operational considerations, it presents a crucial step toward sustainable water management in data center operations, contributing to long-term environmental conservation and resource efficiency.

CHAPTER FIVE
CONCLUSION AND RECOMMENDATION

The findings of this thesis underscore the transformative effects of digitalization on climate change, revealing both its potential benefits and challenges. Digitalization offers unprecedented opportunities to optimize resource use, enhance efficiency, and minimize waste across various sectors. However, it also presents significant challenges, such as increased energy consumption, the generation of e-waste, and the potential for rebound effects that undermine environmental gains. This dual-edged nature of digital transformation necessitates a comprehensive and strategic approach to ensure that its benefits are maximized while mitigating adverse impacts on climate change.

The analysis conducted in this thesis emphasizes the need for sustainable practices in digital technology deployment. It also highlights the importance of life-cycle assessments and integrated sustainability strategies to address issues such as water and energy consumption, e-waste management, and carbon emissions. By fostering innovation, improving data-driven decision-making and encouraging collaboration between stakeholders, digitalization can better align with global environmental goals to reduce the impact of climate change. This thesis contributes to a growing understanding of how digital transformation intersects with ecological stewardship and underscores the importance of balancing technological progress with environmental responsibility.

To harness the full potential of digitalization while minimizing impacts on climate change, several strategic actions are recommended. First, industries must enhance data-driven decision-making by utilizing advanced analytics, artificial intelligence, and machine learning tools. These technologies can identify inefficiencies, optimize resource usage, and predict environmental impacts, enabling more informed and sustainable operations. Second, prioritizing sustainable design and operations is crucial. Adopting life-cycle thinking in digital technology development, such as integrating energy efficiency, water conservation, and circular economy principles,

will help reduce impacts on climate change. Encouraging the reuse, refurbishment, and recycling of digital equipment and materials further supports the transition to a circular economy, minimizing waste and conserving resources.

Investments in renewable energy are vital for powering digital infrastructure. Shifting from fossil fuels to renewable energy sources not only reduces carbon emissions but also enhances the resilience of digital systems. Additionally, fostering collaboration among governments, industries, and research institutions can drive the creation of policies and standards that support sustainable digitalization. Financial incentives for green technologies should also be considered to accelerate adoption.

A major focus should be on the development and promotion of green data centers. These facilities, designed with energy-efficient infrastructure and powered by renewable energy sources, significantly reduce carbon emissions, operational costs, and resource consumption. Green data centers often utilize innovative cooling technologies, waste heat recovery systems, and renewable energy integration to achieve higher sustainability standards. Encouraging industries to transition toward green data center solutions can foster a more environmentally responsible digital ecosystem. Policymakers and industry leaders should work together to provide financial and regulatory support for this transformation and ensure widespread adoption of green practices to reduce the impact on climate change.

Education and stakeholder engagement play a pivotal role in achieving sustainability goals. Awareness programs and training initiatives can empower employees, policymakers, and consumers to adopt environmentally responsible practices and technologies. Transparent methods for monitoring and reporting environmental metrics are essential for accountability. Regular evaluations ensure continuous improvement and alignment with sustainability objectives.

Lastly, promoting research and innovation in sustainable digital technologies is imperative. Efforts should focus on developing energy-efficient data centers, advanced cooling technologies, and low-impact digital devices. By encouraging innovation,

industries can stay ahead of environmental challenges and contribute to a more sustainable digital future.

By implementing these recommendations, industry and governments can balance technological advancements with environmental preservation, paving the way for a digital transformation that minimises the impact of global climate change.

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