A Circular and Sustainable Business Model: The "Qscale" Data Center Case

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Abstract

Data Centers, leading sectors of the digital economy, have a significant environmental impact. Their carbon footprint is a cause for concern. Since the existence of the IT sector depends on them, companies in the sector must plan strategies to impact less on the environment. Data center operators have identified the circular economy as a way to become sustainable. Until yesterday the orientation was to repair, reuse its servers and also recycle the heat to heat the buildings. Today, there are no studies on reusing waste heat from data centers for growing food. The general objective of the study is to provide support tools to data center companies to achieve greater diffusion of waste heat recovery projects and their related use in the agricultural sector. The article discusses how waste heat from data centers could be recovered and reused for the cultivation of agricultural products, illustrating the case of the “QScale” project from the perspective of the circular model; a technological solution characterized by the meeting between a modern and a traditional sector in which the innovation and digital nature of data centers are combined with the tradition of the agricultural sector.

Keywords: Sustainability, Environment, Business Model, Circular Economy, Data Center.

1. INTRODUCTION

Today, waste heat is considered by data center (DC) companies as a source of revenue. It represents a large untapped potential in the transformation of green energy. In the international data center technology market, a small share of operators is orienting their business model on the reuse of waste heat from their facilities, with the aim of optimizing it and being more virtuous from the point of view of environmental sustainability. The article is based on the assumption that the energy generated by data centers comes mainly from non-renewable sources (De Gaetano, 2025), and waste heat can be recovered and reused as a new resource. We therefore focus on the evaluation of circular economy models, viable on the heat emitted by data centers that, if not used, is discarded.

The contribution that the article makes to the literature on the environmental impacts of data centers is to describe a new approach in the path towards achieving the objectives of climate neutrality and environmental sustainability of data centers: the reuse of waste energy or heat in greenhouses, based on the new paradigm of the circular economy. Waste and waste are considered a potential value to be exploited, a value that is reborn thanks to the circular process. Many definitions have been given on the circular economy (CE). It represents a framework of solutions (Ellen Macarthur Foundation, 2020), which becomes a business model that seeks to solve major challenges and global problems (Chabowski et al., 2025). The problems it addresses are different; climate change, biodiversity loss, waste and environmental pollution perceived with growing interest by all governments, which are trying to implement more effective policies in promoting environmental sustainability and mitigating pollution (Aura & Scalera, 2024). The circular economy, presenting itself as the true pillar of the energy transition, leads us into a world where new business models are created, in which consumers themselves ask, inform themselves and want to understand how a product is built, transported, packaged, delivered, consumed and disposed of (Aura, 2022). Also understood as a system useful for reorganizing the flows of matter, information and energy, to improve resource efficiency through the reuse, regeneration and recycling of materials (Puntillo et al., 2021). A circular economy has the potential to lead to sustainable development, decoupling economic growth from the negative consequences of resource depletion and environmental degradation (Murray et al., 2017; Babbitt et al., 2018; Hofmann, 2019). Policy makers and scholars are questioning how to use excess heat from data centers, considered the least desirable form of energy, as it is difficult to distribute and use (Terenius et al., 2023), in order to achieve carbon neutrality by 2030 as part of the European Green Deal. The introduction of a circular economy model, and therefore the sustainability of data centers, is a highly debated aspect by the European Commission, which is seeking solutions and interventions aimed at integrating the principles of the circular economy into cloud computing and data centers. Currently, everything that represents information and communication technologies plays a key role in promoting sustainability (Core et al., 2024).

For example, data centers produce waste heat, which becomes waste; since the new paradigm of the circular economy requires us to reduce and eliminate waste, it is necessary to understand how to manage excess heat according to the application of a circular economy model that is sustainable towards the environment. Specifically, the contents of this article describe the benefits and advantages that could arise from the use of waste heat from data centers, creating a circular model. The use of excess heat has already been implemented by some data centers for the decarbonization of operations, foreseeing its reuse in heating and district heating systems. However, building heating is not the only innovative solution for the recycling of thermal waste generated by data centers.

The use of waste heat is closely linked to the concept of circular economy (Murray et al., 2017) and based on this approach, the article presents a little-explored opportunity: the capture of waste heat from data centers and its reuse to fuel the cultivation of agricultural products in greenhouses (Meschini et al., 2025). In this sense, the broader social impact of the use of waste heat that becomes a new resource is highlighted. In this sense, data center structures, in addition to consuming significant amounts of energy, will also perform a secondary function: food production in greenhouses. The new approach is therefore rooted in the circular economy model, a sustainable solution to reduce energy consumption, recovered heat waste and environmental impact. To demonstrate the relationship between waste heat recovery and the circular economy model, a real ongoing project is described: the project of the Canadian company Qscale. The work uses a methodology, based first on a literature review and then on a case study, which is useful when you want to delve into the dynamics in which a specific experience develops. It is a sustainable model that uses new technologies to recover waste heat in order to produce food at reduced costs and with zero environmental impact, starting from a resource that would otherwise be wasted. The Canadian company QScale, based in Quebec, has been operating since 2024 and aims to make its data centers more environmentally sustainable; The study describes it as a candidate to become a sustainable model for other companies in the sector to follow . In addition to representing an innovative solution in the agricultural sector, QScale's data center could in the future generate other innovative ways to transform waste heat. For example, tons of heating energy could be recycled to heat swimming pool water, for fish farms, for the production of industrial insects (Siddiqui et al., 2024) or to produce wood pellets. Today, the need to recover excess heat puts data center companies in line with the objectives of decarbonization and sustainability.

The environmental impact of technologies and in particular of data centers is a sensitive issue, at the heart of the double transition launched by the EU: the green one and the digital one. Data centers, reproduce both the heart and the nervous system of the digital economy and represent the information backbone of an increasingly digitalized world (Masanet et al., 2020); they have simply become indispensable following the digitalization of the economy and its new uses. As structures used to host IT systems and associated components, more energy-intensive (Lee, 2013), like all industrial structures, they consume energy and produce heat. It is necessary to assume environmental and social responsibility also in the storage of data managed by data centers, which must be energy efficient and meet strict requirements for hazardous substances.

Since the high demand for data use contributes directly to the climate crisis, today the most advanced technologies cannot ignore an evolution compatible with environmental protection (Aura, 2021). As structures that store, process and manage data, data centers become the place where the needs of digitalization and climate change collide perfectly, because they are corporate realities consisting of structures known for excessive electricity consumption and heavy CO2 emissions into the environment, equal to approximately 900 billion kilograms (Pearce, 2018), similar to those emitted by the global aviation industry (Air Transport Action Group 2020). Their carbon footprint is increasing, so it is necessary to find solutions based on the recovery of waste typical of the circular economy. Reconciling digitalization and sustainability in data centers is essential, given their significant impact in terms of energy consumption and emissions into the environment. Knowing the electricity consumption of global data centers provides a useful point of reference to test claims about the CO2 implications of data center services (Energy innovation, 2020). European data centers are very energy-intensive and their operation generates heat. Some consume as much as a large city with about 100,000 inhabitants. Much of that energy could be reused and there are various solutions currently being considered, some already implemented; Many companies from the North to the South of the world are changing their strategies to limit energy consumption and CO2 emissions into the environment, in order to reach the Net Zero objective. An analysis conducted by the European Commission (2018) reveals that “the energy consumption of data centers in the EU was 76.8 TWh. This is expected to increase to 98.52 TWh by 2030, an increase of 28%”. These data show that data centers need to become more energy efficient and this is one of the priorities of Agenda 2030. In 2019, the European Commission had presented some regulations to indicate the technical standards to be followed to reduce the environmental impact of DCs. Companies and governments in recent times, especially in America, have sought solutions and adopted measures to make data centers more efficient and less energy-intensive. In a previous analysis by Sovacool et al. (2022), the use of waste heat from data centers in the Nordic countries was studied, concluding that a holistic strategy is needed. This effort has been implemented to reduce the stress on the electricity grids that power data centers. However, there is a new approach that has been poorly analyzed and studied: how to exploit data center waste heat for agricultural production.

This paper contributes to the literature on this new scenario, where data centers may soon have a new secondary function: contributing to the cultivation of food. Ultimately, the paper will provide recommendations and practical advice for companies, which will support more sustainable data center operations, for the benefit of all. In fact, most companies are looking for advice on where to start. To date, there is no univocal definition of the concept, but several can be found, depending on the multiple sectors to which they can be applied. Since waste heat is not entirely recoverable today (Terenius et al., 2023), in addition to existing and proposed applications, the paper discusses a new application: use in agriculture. The paper discusses the concept of waste heat in data centers, highlighting its evolution and development in the literature. It is then demonstrated how it can be used within the new paradigm of the circular economy, to make it a resource to be reused and above all to achieve the objectives of reducing harmful emissions into the environment. This demonstration is possible with the analysis of the QScale case in which a new, little-used model for the reuse of waste heat in agriculture is illustrated. The conclusions of the article define how the uses of waste heat can be different and can favor the improvement of the entire electrical system if exploited in a complete and appropriate way, and what the implications of future applications may be. The strategic goal is for Qscale to become an international example of implementing circular economy principles at data center level.

2. LITERATURE REVIEW

In literature, the topic of data centers is addressed in various aspects, including the most relevant one, namely the environmental impact (Rong H. et al., 2016; Shuja et al., 2016; Corbett, 2018; Herman et al., 2018; Singh & El- Kassar, 2019; Kheybari et al., 2020; Lucivero, 2020); “Data center energy efficiency has gained critical importance in recent years due to its high economic, environmental and performance impact (Dayarathna et al, 2016). While ICT companies and data centers in particular play an important role in data management and storage, they will also play a key role in the journey towards climate neutrality (Bettiol et al., 2022). While data center sustainability is often focused on energy, the issue is much broader and should include without neglecting other aspects such as corporate social responsibility (CSR), circular economy and harmful substances. In the literature, there are studies that relate data center management to variables such as CSR (Choi & Park, 2022; Hassan & Adhikariparajuli, 2022; Channy & Sandhu, 2025) sustainable development (Carrol, 1979; 1999; Jamali, 2008; Cordeiro & Tewari, 2015; Freda, 2017; Calvo & Calvo, 2018;) and circular economy (Nassar, 2025). However, there are gaps in research on data centers and circular economy (Gorgan, 2024) as it is little discussed.

The study of the circular economy model in data centers is related to the recovery and reuse of waste heat. The literature discusses the problem of recycling and reusing waste heat, which has become a global problem. Data centers can be considered as real energy transformation devices. They consume energy, transform it into data, work and disperse 98% of electricity in the form of waste heat. In recent times, there has been a growing interest in the recovery of waste heat as a renewable source (Baur, 2022). Since the electricity produced by data centers is transformed into waste heat (Barroso et al., 2019) it is necessary to implement models for its recovery. As far back as 1972, Beall spoke in his writings about the reuse of waste heat (Hao et al., 2025; Huang et al., 2024).

Today, interest in these innovative methods is rapidly evolving, especially to meet the different needs of the many case studies to which they can be applied. Digital technologies located in the physical structures of data centers, represent a significant part of global energy consumption; these facilities are estimated to consume 1% of electricity globally (Masanet et al., 2020), and in the coming years, energy consumption will increase (Freitag et al., 2021); it is expected to triple or quadruple (Belkhir & Elmeligi, 2018). These percentages are expected to increase in the coming years due to the progress of the digital transition, therefore artificial intelligence (AI), the Internet of Things (IoT) and blockchain-based systems. It will therefore be important to try to implement new models, alternative to those already in use to recover excess heat produced. Waste heat recovery projects, although cutting-edge for large companies, have a huge optimization potential, but their implementation rate is still low. In recent years, the environmental impact of data centers has been discussed (Bilal, 2014; Schulz, 2009), both in academic and business environments; data center operators should pay more attention to the use of renewable energy and the exploitation of waste heat (Zhang & Yang, 2021; Meschini et al., 2025).

Liesa et al., in 2020, studied the recovery of waste heat from low-quality buildings and its valuable reuse as thermal input for greenhouses and vice versa, in order to improve the sustainability of the combined system. Publications and studies in this direction are growing and are interested in this innovative phenomenon. Corporate ICT through data centers is responsible for an increasingly significant amount of carbon dioxide emissions, consequently contributing significantly to the corporate carbon footprint.

The debate is heated in the literature (Güğül et al., 2023); For example, “sustainability certification for the entire process as a whole: from demolition of the old data center site to reuse of energy resources” is being studied (Impresa City, 2023). Many works often concern renewable energy in data centers and their consumption. “Traditional data centers consume huge amounts of electricity generated from fossil fuels, which increases the carbon footprint in the environment” (Mandal et al., 2022). Based on the indications contained in the US Energy Act enacted in 2021, which aims to make data centers more energy efficient, the company QScale has created a new project powered by 99.5% renewable sources. This data center reuses the waste heat produced to grow agricultural products. With this approach, the areas of waste heat reuse are diverse: from heating (Wahlroos et al., 2018; Koronen et al., 2020; Oltmanns et al., 2020) of homes and businesses, to agricultural crops that few have evaluated.

In addition, waste heat can be used to offset heating costs (Haywood et al., 2012). Through these methods, a “green digital ecosystem” could be created that will allow companies of any size to adopt a concrete and sustainable approach. Unfortunately, as already widely announced, few describe the waste heat of data centers (Terenius et al., 2023), especially its reuse in agriculture (Meschini et al. 2025) and for food crops (Falk et al., 2025). In this sense, a new business model could emerge that uses waste heat to grow agricultural products, powering greenhouses. Waste heat is similar to renewable energy because it is carbon neutral and in some federal states there is already a heat planning requirement. Nyberg, 2022 shows in his studies that in a California data center powered by an energy mix consisting of an average dependence of 40% on fossil fuels across the state, the reuse of waste heat is not planned. This excess waste heat is then lost if it is not recovered and reused. There are many examples of data centers that collaborate with neighboring companies to transform waste heat into reusable energy. In the study by Montagud-Montalvá, (2023) on the recovery of waste heat from a data center on the university campus of the Politècnica de València on the Mediterranean coast of Spain, it was shown that waste heat can be used to heat buildings on the campus. Most research on waste heat reuse therefore focuses on the building efficiency sector. In recent months, data centers have come under the spotlight for their enormous water waste; they use huge amounts of water to keep servers cool, using different methods (Pallardi, 2023). Additionally, data centers in the Nordic countries, including QTS, Digital Realty, and Equinix, reuse excess heat from cooling operations to provide affordable heat to nearby homes (Fisher, 2023). The most current topic in data center research is environmental sustainability and social concerns, where the holistic, social, and technical aspects are assessed (Terenius et al., 2023). Their rapid development increases energy demand and jeopardises the progress made towards achieving climate goals (Monsalves et al., 2023). Studies focus more on the technical side of the phenomenon (Siriwardana et al., 2013; Oró, 2015), on the evaluation of energy savings and the search for indicators to measure the efficiency of energy use in data centers (Zhang et al., 2022) or on the green development of data centers (Li, 2019; Li et al., 2023). In response to political and governmental pressure on energy efficiency and carbon footprint reduction, some companies have experimented with waste heat strategies with the aim of increasing energy efficiency in their operations (Juhola et al., 2024). Energy conversion in data centers represents a new and crucial aspect to achieve environmental sustainability goals in data centers (Jones & Fleischer, 2014). An overview of the literature shows that most of the articles highlight the characteristics of data centers, listing research gaps and future directions. There is discussion about the development of new criteria for cloud infrastructures, which include best practices for data center sustainability, setting the standard for transparent and more sustainable digital assets. From an economic point of view, the study by Shuja et al. (2016) shows that waste heat generated by electronic components can be used in absorption cooling systems to offset data center cooling costs. It remains to be presented in the literature how waste heat can be used and reintroduced for the cultivation of agri-food products. This aspect may be assessed in a few years, thanks to the analyses conducted on the new case study QScale, the subject of our analysis.

3. THE METHODOLOGY

In order to facilitate the understanding of the observed elements and the consequent reflections set out in the following paragraphs, it is necessary to present the methodology used in the research work. The investigation framework (method) adopted assumes a two-level approach. In the first part, a systematic review of the literature was adopted. This review paid particular attention to those scientific contributions that have explored the environmental impact of data centers and the valorization of waste heat in agriculture, in promoting environmental sustainability strategies based on the new paradigm of the circular economy. The second part aimed to delve deeper into the object of study through the analysis of the QScale data center and all the documents found through social media, website and network. The result of the systematic analysis of the literature, however, led to little theoretical evidence on this aspect. While recognizing the undoubted advantage of the narrative review in providing general knowledge on the research topic analyzed, it was preferred to adopt a systematic review of the literature, in order to carry out a review based on all the writings published in the last 5 years, (2020, 2021, 2022, 2023, 2024 and the first months of 2025) on the specific research questions:

- RQ1: How many studies have analyzed the “data center” dimension in the definition of the “circular economy” model in the last 5 years?
- RQ2: How many studies have analyzed the “data center” dimension in the definition of “circular model” and “waste heat” adding the keyword “agriculture” in the last 5 years?
- RQ3 How many studies have analyzed the “data center” dimension in the definition

of “circular model” adding the words “waste heat” and “agriculture” in the last 5 years?

- RQ4: Which topics have been explored in depth and which ones need further exploration? To this end, the articles were identified using the search keywords (“data center” and “circular economy” and “waste heat” and “agriculture”) in the database of scientific articles and publications of Web of Science because it is considered more reliable, as it includes only peer-reviewed scientific publications and allows detailed citation analysis and the calculation of the H-index.

The first level of investigation involved a review of articles obtained using the keywords regarding “data center” and “circular “economy” in the last 5 years and those of very recent publication (first months of 2025), which allowed to reconstruct the general aspects and the evolution of the functions attributable to it. Subsequently, the topic “waste heat” was added, always searching for the same time period; finally the topic “agriculture”. The analysis then focused on the scientific works considered most congenial for the purposes of the areas investigated. In particular, this first line of analysis allowed to reconstruct a theoretical framework of reference. In addition to identifying multiple interpretations of the increasingly multifaceted role of data centers, it was considered appropriate to narrow the field to the in-depth study of those studies that focused on the strategies and advantages that can derive from the presence of models for the recovery of waste heat strongly oriented to the paradigm of the circular economy. All this is analyzed and studied in a logic of shared creation of environmental value.

The second level of research in the work was conducted through the analysis of a case study . The study of a single case (Yin, 2017), highlights the characteristics and nature of the specific case, providing a greater understanding of the phenomenon. A qualitative approach widely used in business studies and which, due to its peculiarities, is necessary when one intends to delve into the dynamics in which a specific experience develops. The case study represents a research methodology that allows the phenomenon to be observed through the analysis of the context in which it is placed, thus managing to provide a very high level of understanding of the observed phenomenon and contributing to reducing the gap between theory and practice often highlighted by the literature in the field of business studies (Chiucchi, 2014). The case study, with its inclination to reconcile theory and context (Welch et al., 2022), therefore proves to be an effective strategy in terms of design and data quality control. The sources used to collect the various elements define the methodological framework used for the analysis of the case study that will be illustrated later in the research. Table 1 illustrates the methodological framework on the information and the type of data expected both in the first phase of the research and in the second when the case study will be illustrated.

Type of information	**Data present in the cited database. Data present on the online site of the Data Center under study**
Sources	Scientific publications on waste heat recovery in data centers that have a circular economy model approach. Online articles. Public and institutional documents. Official sites. Social platforms.
Aspects analyzed	Circular Economy Model in Data Centers Waste heat recovery in data centers that approach the circular economy

TABLE 1: Methodological framework. Source: own elaboration.

4. REVIEW RESULTS

The results of the review conducted are shown in Table 2. Using the words “data center” and “circular economy” on WoS, 168 articles were identified initially in the years 2020-2025. Subsequently, the search was refined by inserting the topic of “waste heat” and 10 articles remained in the last 5 years. Finally, the word “agriculture” was inserted, which resulted in only one result. In total, only one article was analyzed because it is the only one that arises from the search when the element “agriculture” is introduced, and therefore contains the four key topics to carry out a literature review relating to the field of investigation.

Review decision flow	
Selected Science Direct papers on *“data center”* and *“circular economy”.*	168
Selected Science Direct papers on *“data center”* and *“circular economy”* and *“waste heat”.*	10
Selected Science Direct papers on *“data center”* and *“circular economy” and “waste heat” and “agriculture”.*	1

TABLE 2: Decision flow. Source: own elaboration.

The analysis of the articles evaluated in the last 5 years, has produced the following result: there is little attention to the dimension of waste heat recovery in data centers, oriented to a circular approach, when the word agriculture is added. The literature regarding waste heat management technology and its secondary market opportunities, are oriented towards other aspects and above all, on the reuse of heat in waste-to-energy plants (Leary et al., 2025). In the articles that investigate the binomial data center and circular economy there is greater attention; when the topic “waste heat” is added the number of articles decreases because it becomes 10, until it becomes 1 when the term “agriculture" is added. Below are the answers to the research questions:

- RQ1: How many studies have analyzed the “data center” dimension in the definition of the “circular economy” model in the last 5 years ?

AQ1: The studies that have analyzed the “data center” dimension in the definition of “circular economy” model in the last 5 years are 168. Most of them offer an analysis relating to waste heat recovery and reuse in the district heating sector. Some articles are discarded because they deal with other topics, similar at first, but different in content; for example, the article by Manso et al., (2025) is discarded because it deals with issues relating to the Mass Spectrometry Data Center (MSDC) for the creation of CE models that are not the subject of the paper. Another article that is discarded is that of Frost et al., (2021) because even if it appears in the research, it is not relevant for the purposes of our investigation as it investigates the environmental impacts of a circular recovery process for rare earth magnets of hard drives. Articles that actually address the issues related to RQ1 are evaluated (Paiho et al., 2021; Leary et al., 2025; Wang et al., 2025). The field of investigation is then narrowed by inserting the keyword “waste heat”, which allows us to answer the second search question.

- RQ2: How many studies have analyzed the “data center” dimension in the definition of “circular model” adding the words “waste heat” in the last 5 years?

AQ2: The results obtained from the analysis of the articles confirm that together with the study of the “waste heat” dimension the number of articles decreases a lot. Specifically Wang et al.,(2025) in their article state that the recovery of waste heat from data centers offers a promising path towards a circular economy. The authors realize a circular economy by coupling a data center and a renewable energy system, directly using the waste heat of the data center but applying it to a biomass system. In the study by Leary et al., (2025), the authors highlight a truth that in the paper following the review appears clear: in the engineering and energy literature, topics such as the use of waste heat from processes such as data centers and the production of energy from raw materials for CO_2 emissions artificial photosynthesis, are strongly increasing; they are little discussed in the economic one. From their research an important aspect emerges: considering the recovery of waste heat from DCs as a real market of secondary waste, which, through a policy of promotion of residues, allows to transform such waste through artificial photosynthesis, and obtain many social and environmental advantages and reduction of marginal costs on waste disposal.

- RQ3 How many studies have analyzed the “data center” dimension in the definition of “circular model” and “waste heat” adding the keyword “agriculture” in the last 5 years?

AQ3: Agriculture as a possible practice and innovative approach, becomes a new method involved in the development and operation of data centers that produce waste heat. Unfortunately, the only article found on Wos by Paiho et al, (2021) analyzes the implementation of circular business models from a holistic perspective within smart cities, evaluating how an urban district can aim for circularity with solutions in the fields of transport, energy and food. In the paper, there is minimal mention of waste heat recovery on possible data center structures, and also of urban or hydroponic agriculture thanks to waste heat recovery.

- RQ4: Which topics have been explored in depth and which ones need further exploration?

AQ4: the most in-depth aspects concern the reuse of waste heat from DC in district heating as an element closely linked to the circular economy because it allows the use of renewable or recovered heat sources, reducing energy waste and emissions. Instead, this new approach should be explored and analyzed: reuse in the food or agricultural sector, together with the possibility of reducing the costs for their construction and management. Another issue not addressed is the adequate consideration of the related environmental costs (Rangone, 2025). Furthermore, of the articles analyzed, only one is relevant in the field of economic studies, while most concern the engineering sphere.

5. DATA CENTERS AND WASTE HEAT REUSE: AN OVERVIEW OF THE PROBLEM

A data center is typically a warehouse-like building that houses hundreds of servers that store, process, and transmit large amounts of data. It plays the role of a technological enabler for the digitalization of companies. During their operation, a lot of heat is produced, which, at the end of the process, is used to heat the buildings adjacent to the data center or is dispersed. Unfortunately, the dispersion of the excess heat produced is an emerging problem especially for issues related to environmental impacts, therefore the reduction of carbon emissions (Hao et al., 2025). The growing interest in artificial intelligence will bring more powerful servers to many data center environments, which will release a lot of excess heat. This, instead of being dispersed, can be used, reused, and recycled for different purposes, including agriculture, as described in the QScale project that will be analyzed. Data centers around the world can vary in size; some are relatively large and consist of thousands of servers running 24 hours a day. Their management requires high costs that could be reduced by recovering and reusing waste heat. Such facilities typically consume enormous amounts of electricity, producing a lot of heat. As shown in Figure 1, the United States is home to the largest number of data centers.

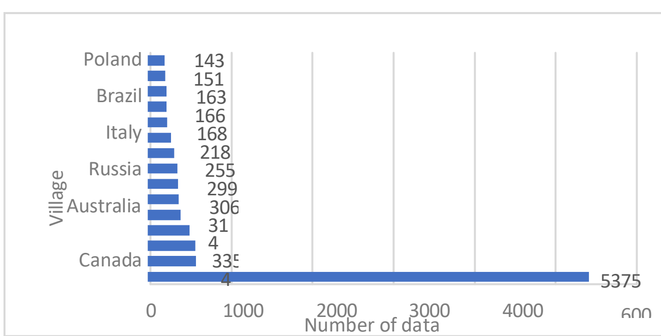

FIGURE 1: Number of Data Centers in the world as of 2023. Source: own elaboration.

As of September 2023, the United States reported 5,375 data centers, the highest number in the world, according to data collected by Statista (a global data and business intelligence platform). Another 522 were located in Germany, while 517 were in the United Kingdom. Other countries such as China and Canada follow, ranking well in terms of the number of facilities. Further down the list are countries such as Brazil, India, and Poland. Many companies operating in the data center industry could help shape this developing sector, from the increasing adoption of the cloud, to the rise of artificial intelligence (AI) and the Internet of Things (IoT), to changing security and sustainability needs. In particular, emerging trends for data center companies can be summarized as: in Table 3.

Trend Data Center	What is it for?
Reuse of waste heat.	- Improving energy efficiency; - reduction of district heating costs; - reduction of environmental costs.
Investing in sustainable development.	- Creating value in local communities.
Develop new cooling techniques.	- Improved PUE energy utilization effectiveness.

TABLE 3: Data center trends and benefits. Source: own elaboration.

Given that waste heat is seen as a source of revenue by DC companies, there are numerous examples of data centers partnering with companies in the surrounding areas to turn waste heat into usable energy. Unfortunately, only a handful of companies are responsible for the majority of global data center energy use. Consider corporate giants like Amazon, Microsoft, Google, Alibaba, Facebook, and Apple, who power their facilities with renewable energy to reduce their carbon footprint.

Other companies, however, believe in the model of reusing waste heat in the context of the circular economy. Some examples are IBM, based in Switzerland, which uses waste heat from data centers to heat a local swimming pool; Yandex and Academica data centers in Finland share waste heat with local residents, who use it, reducing the use of energy from non-renewable sources and reducing CO2 emissions. Today, the topic of the “green” data center, designed for minimal environmental impact, is inevitably growing in interest and centrality and many companies in the sector are interested in it. Currently, numerous definitions of “data centers” have emerged. Data centers are large-scale mission-critical IT infrastructures that operate 24 hours a day (Tareq et al, 2023), without data centers, it would be the end of digital. Its origins date back to around the 1940s, when the first computer systems such as the Electronic Numerical Integrator and Computer (ENIAC) began to emerge. Until recently, this system was simply called CED, Data Processing Center. Interest in these IT tools is starting to mature, so much so that companies and other organizations are rapidly using them to organize, process, store and distribute large amounts of data, relying significantly on the applications, services and data contained in a data center, making it a focal point and a critical resource for daily operations. The data center represents the beating heart of the digital economy and digital transformation: there is no type of company today that does not use a data center to manage its assets and resources. Without data centers there would be no videoconferencing, e-commerce, apps, streaming or even home banking. Since data centers have positive and negative externalities, it is necessary to recover and reuse waste heat:

- Among the positive aspects of data centers is the possibility of automating various business processes and flows, focusing precious time and resources on more important and core activities for the company’s business, with a significant reduction in workload.
- Data centers also have downsides, concomitant disadvantages, and unintended or harmful consequences: they can consume too much energy or generate too many carbon emissions. Although they are not the most energy-hungry of all the players in the digital ecosystem, it is true that their operation requires significant energy consumption,

which is not neutral for the environment. Fortunately, there are solutions to reduce their environmental impact.

In line with the concepts of circular economy, much of this energy can be reused (Terenius et al., 2023). Reuse can occur in different ways: heating buildings, dehydrating raw materials, producing electricity and storing energy. Although much of the literature discusses these different alternative methods of reuse, unfortunately very few analyze the scenario of reuse in agriculture. The research fits into this almost unexplored gap in the literature, discussing the recovery of waste heat in the agricultural field by exploiting the fundamental principle of the circular economy. The basis of the circular economy is the sustainable exploitation of resources. Extract, produce, consume and reproduce: this is the new economic model to aim for: a circular economy that imitates natural cycles by transforming waste, in which products are designed to be reused, regenerated and recycled creating new value. It focuses on reducing environmental impact, containing greenhouse gas emissions, circularity of processes and reducing the exploitation of resources, characteristics such as connectivity, control and improvement of performance. Through these three pillars we get the keys to open the doors to innovation and sustainability. With waste heat recovery, it will be possible to improve the environmental sustainability of data centers. It will create a truly sustainable and competitive digital ecosystem. As both a vital driver of economic growth and a source of environmental damage, we must ensure that large data centers are operated sustainably (Zhang & Yang, 2021) by providing waste heat recovery.

5.1 Reuse of waste heat in agriculture: proposed application of the QScale model

Based on what has been said above, an alternative solution for waste heat recovery could be its application in the agricultural sector, by powering greenhouses. Agriculture, the primary sector par excellence, is now facing new challenges, ranging from climate change to the scarcity of natural resources. The concept of agriculture as something traditional must be rethought in a modern way; agriculture has always been synonymous with innovation, because new transformations are introduced every year. To overcome these difficulties, it is necessary to adopt innovative solutions that make it more efficient and sustainable. Digital technologies are in fact changing food production models. It is not just a matter of facilitating the harvesting of agricultural products with machines equipped with intelligent software. In addition to the components that will make cultivation techniques increasingly precise, there are other directions in which research is moving. In particular, in this context, the QScale project presents itself as a cutting-edge solution for the agriculture of the future, because it combines artificial intelligence, innovation, circular economy, high-capacity IT servers, clean energy, greenhouse production and food autonomy (agritecture.com). Today, based on the QScale model, data centers will represent a great resource for the agricultural sector in the coming years. Companies are combining data centers with greenhouses, capturing the heat emitted by the computing hardware and reusing it to grow indoors. Agriculture, often considered the future of food production, is also energy-intensive, so the heat resulting from waste produced by data centers finds the right application if used to provide energy to agricultural crops. Agriculture therefore becomes one of the large sectors that can be managed through the heat of data centers. The agricultural sector is in the ideal position to exploit digital technologies and at the same time contribute to the production of renewable energy without producing emissions. QScale is in fact the only model in the world that recovers waste heat to contribute to agricultural production. The unique partnership between data centers and greenhouses signals a potential change in the future of agriculture. Data centers will be considered from a new perspective. In fact, data center technology combined with agriculture can reduce costs and simplify processes. The business model of the company QScale, based on environmental sustainability in line with the objectives of the Agenda 2030, allows a series of economic and environmental benefits when applied to the agricultural sector. This connotation makes the model developed by the company take on the conceptual nature of a DCsS or a behavior model in organizations specialized in adapting to sustainability demands (Ortiz-Avram et al., 2023), which helps the environment by introducing green innovation in production processes (Wong, 2013). The QScale model is a model of sustainable, multi-stakeholder behavior in which outcomes (e.g., green innovation) or relational structures (e.g., multi-stakeholder collaboration) suggest that all are components of the DCsS (Ortiz-Avram et al., 2023).

A data center is defined as sustainable when it is designed to efficiently drive energy trends, reducing and optimizing consumption in a green and energy-saving perspective, allowing for the recovery of waste heat in a circular economy perspective. Since data centers produce enormous amounts of heat, in the cold climate of Quebec, greenhouses could use a little more waste heat, which can be reused to help grow food throughout the year in the most efficient way possible. If you consider not only the management of the energy flow, but also all the ecosystems that coexist in a facility, you speak of a sustainable data center.

Based on the circular economy model, the practical benefits that can be derived from the recovery of waste heat from the DC QScale and its reuse in agriculture are multiple; these are social, environmental and economic benefits. The recovery of waste heat would in fact allow data center companies to increase their energy efficiency, thus reducing the environmental and climate-altering impact and improving competitiveness and energy security for the entire community in which the company is located. Table 4 summarizes some of them:

Environmental benefits	Social benefits	Economic benefits
• Recovery of waste heat that is transformed from waste into use. • State-of-the-art facilities powered by renewable energy.	• Food self-sufficiency of the province where the data center is located. • Artificial intelligence that automates physically demanding jobs.	• Reduction of energy supply costs. • Energy saving • Energy efficiency in systems

TABLE 4: QScale Benefits for Data Centers. Source: Own elaboration.

Benefits include reducing procurement costs; recovering waste heat from waste into a new resource; increasing food self-sufficiency in the province where the data center is located (with a potential 400 hectares of greenhouses for the first of several campuses in use alone); operating large-scale, state-of-the-art facilities powered by clean energy; using artificial intelligence to automate physically demanding work; and specializing in AI innovation.

Sustainability is at the heart of QScale's mission, which therefore aims to recycle part of the heat coming from data centers, to represent a great victory for the environment and for the company that carries out this project. Sustainability, circular economy, closed carbon cycle (Cogswell, 2023), are three principles present in the QScale project for data centers, which includes among its objectives the recovery of waste heat produced and its reuse in agriculture. Not only the efficiency of buildings through the recovery of waste heat, but also the supply of energy to agricultural greenhouses. QScale's approach combines renewable energy and heat recovery, to meet the growing need for technological infrastructures, while minimizing the environmental impact (opencompute). In the next paragraph the article describes the QScale data center project, as a model that contributes to reducing environmental impact and climate change by considering the reuse of waste heat in a different way, or applying it to the feeding of agricultural crops, with the aim of achieving sustainability goals.

6. "QSCALE" PROJECT: TECHNICAL ASPECTS

QScale is a Canadian-based data center provider that launched in 2021 with the start of construction of its QO1 campus. Construction of the second building began in September 2022 (datacenterdynamics.com). The data center has been operational since 2024 and is spread across a colocation facility located in Canada, in the Québec City area. Its frameworks are designed for high-density compute, artificial intelligence, and machine learning workloads. Its business model is focused on sustainability and energy efficiency. The facility is powered by 142 MW of nearly 100% renewable energy and includes a waste heat recovery system (QScale.com). The facility, as a state-of-the-art, large-scale hosting facility powered by clean energy, produces heat that is then reused. It seems to be perfectly in line with the circular economy model. Reusing waste heat from its facilities makes data centers sustainable. Specifically, QScale is building a 130-acre data center campus in Lévis, Quebec, where it will use heat from the servers to grow over 80,000 tons of produce per year (corporateknights.com); the heat released by QScale's servers will be recovered to heat adjacent agricultural greenhouses. As part of the QScale project, a heat exchange relationship is being created between the data center and the greenhouses. In practice, the heat emitted by the IT hardware is captured and then reused for indoor or indoor farming. Indoor farming is envisioned as an alternative method for the future of food production, as it is very energy-intensive. Being able to recycle some of the heat from data centers could be a major boon for both data centers and the agricultural industry.

The company, founded in 2018, specializes in the design, construction, management and operation of high-density data centers with a focus on sustainability (corporateknights). The Lévis campus of the QScale project will be powered by 99.5% renewable sources (thanks to Quebec's large-scale hydroelectric network). The waste heat recovery methods will make energy use more circular, moving ever closer to a business model closely linked to the new paradigm of the circular economy. The company will also be able to grow agricultural products in greenhouses. The QScale project aims to develop technologies that allow the production of a fair amount of vegetables, with an estimated possibility of producing 2,800 tons of small fruits and 80,000 tons of tomatoes per year; starting from the recovery of waste heat from the data center, the importance of artificial intelligence, energy efficiency and sustainability is highlighted in pursuing the objectives of the new paradigm of the circular economy, which allows waste to be transformed into a resource to be reused in the production cycle. The tools used by QScale, as part of the ongoing experimentation at the "Q01" campus, will allow not only to recover and reuse next-generation thermal energy for various initiatives, including greenhouses, but also to use high-quality and energy-efficient infrastructures for HPC, minimizing costs and waste. This is a sustainable model that can be replicated in other types of data centers that until now have recovered and used waste heat only for efficiency and heating of adjacent buildings. As illustrated in Figure 2, QScale facilities recover and use waste heat from high-performance servers by storing it in liquid-filled tubes.

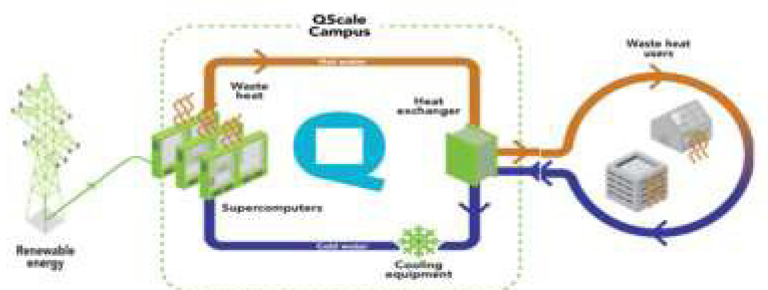

FIGURE 2: Recovery of waste heat from a Qscale Campus. Source: opencompute.org.

The heated liquid then passes through a heat exchanger, which will help move energy from the plants to the greenhouses. QScale systems are powered almost 100% by clean and renewable energy; a large part is powered by hydroelectric energy (opencompute.org). The QScale data center therefore represents a prototype on which to test a new model. Subsequently, the project team, in all its components, will be able to present itself as a reality capable of developing customized proposals based on the possible requests of diversified users. QScale is an innovative project also because it intends to integrate renewable energy, waste heat recovery and agricultural cultivation, considering flexibility, connectivity and control in a logic of open innovation and incremental approach (implementing parts of technologies and parts of solutions at any time) and above all with zero environmental impact. This is a significant innovation, because it is based on the low-cost application of the principles of the circular economy to the technological and agricultural sectors, which allows the achievement of social, environmental and production objectives: a technological solution "appropriate" to the international context of data centers, characterized by the necessary meeting between a modern and a traditional sector; the innovation and digital nature of data centers merge with the tradition of the agricultural sector. In Canada, specifically in Quebec, HPE (Hewlett Packard Enterprise) is the main tenant of the QScale QO1 campus. In the mission of the QScale project, this agreement demonstrates the desire to create cutting-edge and large-scale hosting facilities powered by clean energy, therefore oriented towards environmental sustainability; production on the campus is in fact based on the use of “almost” 100% renewable energy. The Q01 campus combines HPC hosting and office space, with plans for 8 data centers and up to 96 megawatts of capacity. (www.datacenterfrontier).

The QScale project essentially translates into three main steps:

- it will be operated with 99.5% renewable energy sources (thanks to Quebec’s powerful hydroelectric network);
- a more circular use of energy thanks to the waste heat recovery system;
- Growing a fair amount of vegetables in the adjacent greenhouses.

These are the essential objectives of the project: to promote innovative green design capabilities that will enable QScale The Lévis facility will not only provide a substantial digital infrastructure, but will also promote the government’s agricultural and sustainability objectives. A continuous link is therefore established between the principles of the circular economy and the creation of added value through waste heat recovery. This translates into the possibility of enhancing and sustainably growing Québec to become one of the world’s leading markets for data centers characterized by a green vision. With regard to the theme of environmental sustainability, the QScale model enhances the economic dimension especially in reference to effective corporate management based on compliance with the highest CSR standards. In the social dimension, great importance is given to the health and safety of employees and their professional and personal growth, while the development of climate strategies and eco-efficient operational management are among the aspects that contribute most to the environmental dimension. In this direction, the use of the QScale design model could provide a valid example for the various data centers present in Canada and beyond, in identifying the best path to achieve excellent levels of environmental sustainability.

7. CONCLUSION AND DISCUSSION

The study presented, through the analysis of the QScale case, provides suggestions to data center companies that must be very careful about the environment. It suggests that companies in the sector critically analyze their processes, in order to identify potential waste heat flows and gather ideas regarding possible heat recovery interventions. Large companies today build data centers to enable significant transactions and data management. These are companies that span many sectors: healthcare, transportation, etc. Equipping oneself with a data center means investing, incurring many costs. Until now, the excess heat provided by data centers had been reused for district heating services (Tervo et al., 2025). Since data centers produce a lot of energy and waste heat, one could (as happens in the case study analyzed) think of exploiting this excess heat to provide support for the cultivation of agricultural and food products. In this way, waste becomes a new resource, helping to reduce environmental impacts, and at the same time excess heat is used to diversify investments in agri- food crops, to make a profit. In the QScale project, therefore, attention and interest in the topic of heat recovery to be reused for the cultivation of agricultural products in greenhouses emerges. Waste heat is no longer waste, but is transformed into a new resource, and based on the circular model it is rethought as an element that provides new utility. New value is created from something that had been considered waste. Waste heat is considered by companies to be a source of income for data centers, in fact, excess heat is used to power the greenhouses that are part of the QScale campus.

Data centers are now fundamental infrastructures for the territory, with significant impacts for the entire digital supply chain and for citizens. A data center in the territory represents a technological enabler for the provision of services and solutions to support the digitalization of companies in the country. In recent years, the market has registered a growing interest, with a consequent significant increase in investments and the opening of new infrastructures around the world. Unfortunately, most data centers have not provided methods for waste heat recovery. In recent times, companies are evaluating the idea of reusing waste heat also for heating swimming pool water, for fish farms, for the production of insects for industrial purposes (Siddiqui et al., 2024) or to produce wood pellets. This idea is supported by the fact that waste heat recovery is among the various frontier experiments in the field of industrial process efficiency. A challenging path that, also through greater awareness of stakeholders, could become a determining factor for achieving energy recovery and reconversion objectives, as well as an opportunity for our country, from an economic and environmental point of view. In this study, the general objective was to provide support tools to data center companies to achieve a greater diffusion of heat recovery projects for uses other than those related to heating buildings, filling the gap that currently does not allow to make the most of this significant reserve of sustainable energy and therefore effectively contribute to the European objectives of energy security, sustainability and decarbonization . The only data center that has been designed for the recovery of waste heat and its reuse in areas other than heating buildings is QScale. The QScale data center model provides for the recovery and reuse of waste heat for the cultivation of agricultural products in greenhouses powered by excess heat. Therefore, according to this approach, heat is no longer considered a waste, but a resource. In the context of the circular economy paradigm, heat therefore participates in this cycle in which, once produced, it is reused, creating new value. The QScale data center heat recovery system has been operational at the Lévis campus since early 2024. Unfortunately, it will take time to quantify the economic benefits due to the lack of data related to the short time in use of the data center . The industrial symbiosis between the QScale data center and the adjacent agricultural greenhouses offers the potential to provide year-round growing conditions for food production in the context of server technology, as well as mitigating the environmental impact. The company says that part of its mission is to set an example for the industry so that other companies follow its example. The project is ambitious and forward-looking, and therefore aims to create a truly intelligent system, a combination of different technological components, at the service of the user and their needs. Server technologies can also contribute substantially to the process of making workspaces more efficient, with consequent benefits in terms of environmental protection. When building a new data center or renovating an old one, it is advisable to use locally sourced materials with low embodied carbon content, such as limestone instead of concrete. It is also important to calculate greenhouse gas emissions, monitor progress towards climate goals, and address carbon capture and sequestration. It would be good practice to understand how resources are used in each data center and what impact they have on the environment. Unfortunately, as Rangoni (2025) says in his recent study, “the enthusiasm for AI applications that have enabled, among other things, very important advances in environmental protection has not traditionally been accompanied by adequate consideration of the related environmental costs”.

By the end of this article, we have realized that data centers have an unexplored potential to offer enormous energy benefits. However, the challenges are: where to start, what are the next steps and how to accelerate towards the approaches of the new circular economy paradigm. Current political strategies, especially European ones, are pushing the productive fabric towards the implementation of circular economy models. These models reduce, to the point of eliminating them, the environmental impact, creating added value, eliminating waste and scraps as much as possible (Aura, 2021). The Circular Economy Action Plan, which is part of the European Green Deal, transmitted by the European Commission on 11 March 2020, contains a series of initiatives whose overall objective is to achieve climate neutrality in Europe by 2050. Trying to reduce the environmental impact of “massive” infrastructures such as data centers can make a difference today. The productive fabric of the future is therefore part of an intelligent and sustainable ecosystem, in which the implementation of data centers becomes fundamental, such as QScale, which anticipate in their business models an enabling technology that is revolutionizing the new industrial model, because it will have to be oriented towards the paradigm of the circular economy while respecting the environment. By developing projects such as QScale, through the use of new ecological technologies for heating, or for the production of food through the recovery of waste heat, attention to sustainability is promoted and enhanced. Data centers such as QScale that use a circular approach thanks to the recovery of waste heat can be considered the new tool for the green and digital transition of the technological industry, so desired by Europe and the rest of the world.

8. REFERENCES

Alawneh, T. A., Jarajreh, M. M., Alkasassbeh, J. S., & Sharadqh, A. A. (2023). High-Performance and Power-Saving Mechanism for Page Activations Based on Full Independent DRAM Sub-Arrays in Multi-Core Systems. *IEEE Access, 11,* 79801-79822.

Aura, C., & Scalera, F. (2024). Italian and Albanian energy market: two countries compared. The new REC model in energy transition. *international journal of business management and economic research, 15* (2), 2350-2364.

Aura, C. (2022). Circular Economy and Energy Transition: New Challenges for SMEs. FrancoAngeli. Milan.

Aura, C. (2021). Digital twin an aid to sustainability: "the samba" Case. *European Proceedings of Social and Behavioral Sciences* .

Babbitt, C. W., Gaustad, G., Fisher, A., Chen, W. Q., & Liu, G. (2018). Closing the loop on circular economy research: From theory to practice and back again. *Resources, Conservation and Recycling, 135,* 1-2.

Baur, F., Hoffmann, P., Noll, F., & Wern, B. (2022). Climaneutrale Wärmeversorgung der Zukunft - was kann und muss Bioenergie listen? doi:10.18453/rosdok_id00003615.

Bawden, T. (2016). Global warming: Data centers to consume three times as much energy in next decade, experts warn. *The Independent, 23,* 276.

Beall Jr, S. W. (1972). *USES OF WASTE HEAT* (No. CONF-720415-1). Oak Ridge National

Lab.(ORNL), Oak Ridge, TN (United States).

Belkhir, L., & Elmeligi, A. (2018). Assessing ICT global emissions footprint: Trends to 2040 & recommendations. *Journal of cleaner production, 177,* 448-463.

Bettiol M., Cerana L., Di Maria E. (2022). The environmental impact of data centers: approaches and challenges for sustainable development. On Agendadigitale.eu.

Bilal, K., Malik, S.U.R., Khalid, O., Hameed, A., Alvarez, E., Wijaysekara, V., ... & Khan, S.U. (2014). A taxonomy and survey on green data center networks. *Future Generation Computer Systems, 36,* 189-208. Doi: https://doi.org/10.1016/j.future.2013.07.006

Calvo, N., & Calvo, F. (2018). Corporate social responsibility and multiple agency theory: A case study of internal stakeholder engagement. *Corporate Social Responsibility and Environmental Management, 25* (6), 1223-1230. https://doi.org/10.1002/csr.1633.

Carroll, A. B. (1979). A three-dimensional conceptual model of corporate performance. *Academy of management reviews, 4* (4), 497-505.

Carroll, A. B. (1999). *Corporate social responsibility. Evolution of a definitional construct. Busienss & Society, 38 (3), 268–295* .

Chabowski, B. R., Gabrielsson, P., Hult, G. T. M., & Morgeson III, F. V. (2025). Sustainable international business model innovations for a globalizing circular economy: a review and synthesis, integrative framework, and opportunities for future research. *Journal of International Business Studies, 56* (3), 383-402. https://doi.org/10.1057/s41267-023-00652-9.

Channi, H. K., & Sandhu, R. (2025). Energy-Efficient Data Center Design. In *Digital Sustainability* (pp. 175-203). CRC Press.

Chiucchi, M. S., Giuliani, M., & Marasca, S. (2014). The design, implementation and use of intellectual capital measurements: a case study. *Management Control: 2, 2014,* 143-168.

Choi, H. Y., & Park, J. (2022). Do data-driven CSR initiatives improve CSR performance? The importance of big data analytics capability. *Technological Forecasting and Social Change, 182,* 121802.

Cogswell C., (2023). How to close the carbon loop with CO2 conversion. Elsevier.

Corbett, C. J. (2018). How sustainable is big data? Production and Operations Management, 27(9), 1685-1695. https://doi.org/10.1111/poms.12837.

Cordeiro, J. J., & Tewari, M. (2015). Firm characteristics, industry context, and investor reactions to environmental CSR: A stakeholder theory approach. *Journal of business ethics, 130,* 833-849. https://doi.org/10.1007/s10551-014-2115-x.

Core, GIAN, Antonucci, G., Venditti, M., & Gitto, A. (2024). Digital Transformation and Sustainability in Cooperatives Enterprises: A Literature Review. *International journal of business research management, 15* (2), 43-62.

Dayarathna, M., Wen, Y., & Fan, R. (2015). Data center energy consumption modeling: A survey. *IEEE Communications surveys & tutorials, 18* (1), 732-794. doi: 10.1109/COMST.2015.2481183. De Gaetano, L. (2025). The Do Not Significant Harm (DNSH) Principle and the Environmental Costs of Artificial Intelligence. *BioLaw Journal-Rivista di BioDiritto,* (1), 571-590.

Energy Innovation Report. Accessed at https://www.energystrategy.it/, September 30, 2020. Ebrahimi, K., Jones, G. F., & Fleischer, A. S. (2014). A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities. *Renewable and sustainable energy reviews*, *31*, 622-638. https://doi.org/10.1016/j.rser.2013.12.007.

Falk, S., Asgari, N., Pearce, J. M., & van Wynsberghe, A. (2025). The Potential of Data Center Waste Heat Recovery for Greenhouse Food Production in the US: Ramifications for Sustainable AI. *Available at SSRN 5170348*.

Fisher S., (2023). Data centers use cooling to heat homes. On Green.it. https://www.datacenterknowledge.com/green-it.

Freda, M. (2017). The Influence of Self-Regulation and Stakeholder Theories on Corporate Social Responsibility (CSR). *International Journal of Multicultural and Multireligious Understanding, 4* (3), 29-34. Doi: http://dx.doi.org/10.18415/ijmmu.

Freitag, C., Berners-Lee, M., Widdicks, K., Knowles, B., Blair, G.S., & Friday, A. (2021). The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations. *Patterns*, *2* (9).

Gorgan, A. V. (2024). *Towards sustainable data centers: An analytical model of circular economy* (Master's thesis, University of Twente).

Güğül, G. N., Gökçül, F., & Eicker, U. (2023). Sustainability analysis of zero energy consumption data centers with free cooling, waste heat reuse and renewable energy systems: A feasibility study. *Energy, 262,* 125495. https://doi.org/10.1016/j.energy.2022.125495.

Hao, Y., Zhou, H., Tian, T., Zhang, W., Zhou, X., Shen, Q., ... & Li, J. (2025). Data centers waste heat recovery technologies: Review and evaluation. *Applied Energy, 384,* 125489. https://doi.org/10.1016/j.apenergy.2025.125489.

Hao, Y., Zhou, H., Tian, T., Zhang, W., Zhou, X., Shen, Q., ... & Li, J. (2025). Data centers waste heat recovery technologies: Review and evaluation. *Applied Energy, 384,* 125489.

https://doi.org/10.1016/j.apenergy.2025.125489.

Haywood, A., Sherbeck, J., Phelan, P., Varsamopoulos, G., & Gupta, S. K. (2012). Thermodynamic feasibility of harvesting data center waste heat to drive an absorption chiller. *Energy Conversion and Management, 58,* 26-34. https://doi.org/10.1016/j.enconman.2011.12.017.

Herman, J., Herman, H., Mathews, M. J., & Vosloo, J. C. (2018). Using big data for insights into sustainable energy consumption in industrial and mining sectors. *Journal of Cleaner Production, 197,* 1352-1364. https://doi.org/10.1016/j.jclepro.2018.06.290.

Hofmann, F. (2019). Circular business models: business approach as driver or obstructer of sustainable transitions?. *Journal of Cleaner Production*, *224*, 361-374. Doi: https://doi.org/10.1016/j.jclepro.2019.03.115.

Huang, C., Shao, S., Wang, N., Guo, Y., & Wu, W. (2024). Performance analysis of compression-assisted absorption refrigeration-heating system for waste heat recovery of liquid-cooling data center. *Energy, 305*, 132325.

Jamali, D. (2008). A stakeholder approach to corporate social responsibility: A fresh perspective into theory and practice. J *ournal of business ethics*, *82*, 213-231. Doi: https://doi.org/10.1007/s10551-007-9572-4.

Koronen, C., Åhman, M., & Nilsson, L. J. (2020). Data centers in future European energy systems energy efficiency, integration and policy. *Energy efficiency*, *13* (1), 129-144. Doi: 10.1007/s12053-019-09833-8.

Kheybari, S., Davoodi Monfared, M., Farazmand, H., & Rezaei, J. (2020). Sustainable location selection of data centers: developing a multi-criteria set-covering decision-making methodology. *International journal of information technology & decision making*, *19* (03), 741-773. Doi: https://doi.org/10.1142/S0219622020500157

Li, M., & Porter, A. L. (2019). Can nanogenerators contribute to the global greening data centres? *Nano energy, 60,* 235-246. Doi: https://doi.org/10.1016/j.nanoen.2019.03.046

Mandal, R., Banerjee, S., Islam, M. B., Chatterjee, P., & Biswas, U. (2022). QoS and energy efficiency using green cloud computing. In *Intelligent Internet of Things for Healthcare and Industry* (pp. 287-305). Cham: Springer International Publishing. Doi: https://doi.org/10.1007/978-3-030-81473-1_14.

Masanet, E., Shehabi, A., Lei, N., Smith, S., & Koomey, J. (2020). Recalibrating global data center energy-use estimates. *Science, 367* (6481), 984-986.

Meschini, S., Tagliabue, L.C., Di Giuda, G.M., Aldinucci, M., Gasbarri, P., & Accardo, D. (2025, March). Sustainable-HPC: toward Digital Twin for active management of self-cooled data centers with Renewable Energy Sources and waste heat recovery. In *2025 33rd Euromicro International Conference on Parallel, Distributed, and Network-Based Processing (PDP)* (pp. 471-477).

Montagud-Montalva, C., Navarro-Peris, E., Gomez-Navarro, T., Masip-Sanchis, X., & Prades-Gil, C. (2023). Recovery of waste heat from data centers for decarbonisation of university campuses in a Mediterranean climate. *Energy Conversion and Management 290,* 117212. https://doi.org/10.1016/j.enconman.2023.117212 .

Monsalves, J. J., Bergaentzlé, C., & Keles, D. (2023). Impacts of flexible-cooling and waste-heat recovery from data centers on energy systems: A Danish case study. *Energy, 281,* 128112. Doi: https://doi.org/10.1016/j.energy.2023.128112.

Muñoz-Liesa, J., Royapoor, M., López-Capel, E., Cuerva, E., Rufí-Salís, M., Gassó-Domingo, S., & Josa, A. (2020). Quantifying energy symbiosis of building-integrated agriculture in a mediterranean rooftop greenhouse. *Renewable energy*, *156*, 696-709. https://doi.org/10.1016/j.renene.2020.04.098.

Murray, A., Skene, K., & Haynes, K. (2017). The circular economy: an interdisciplinary exploration of the concept and application in a global context. *Journal of business ethics, 140,* 369-380. doi : 10.1007/s10551-015-2693-2.

Oró, E., Depoorter, V., Garcia, A., & Salom, J. (2015). Energy efficiency and renewable energy integration in data centres. Strategies and modeling review. *Renewable and Sustainable Energy Reviews, 42,* 429-445. https://doi.org/10.1016/j.rser.2014.10.035.

Juhola, S., Laurila, A. G., Groundstroem, F., & Klein, J. (2024). Climate risks to the renewable energy sector: Assessment and adaptation within energy companies. *Business Strategy and the Environment, 33* (3), 1906-1919.

Leary, N., Zunino, M., & Wagner, J. (2025). The marginal abatement cost function with secondary waste markets. *Ecological Economics, 228,* 108445.

Li G., Zixuan Sun, Qingqin Wang, Shuai Wang, Kailiang Huang, Naini Zhao, Yanqiang Di, Xudong Li, G., Sun, Z., Wang, Q., Wang, S., Huang, K., Zhao, N., ... & Zhu, Z. (2023). China's green data center development: Policies and carbon reduction technology path. *Environmental Research*, *23*, 116248. https://doi.org/10.1016/j.envres.2023.116248.

Lucivero, F. (2020). Big data, big waste? A reflection on the environmental sustainability of big data initiatives. *Science and engineering ethics*, *26* (2), 1009-1030.

Möbius, C., Dargie, W., & Schill, A. (2013). Power consumption estimation models for processors, virtual machines, and servers. *IEEE Transactions on Parallel and Distributed Systems*, *25* (6), 1600-1614. Doi: 10.1109/TPDS.2013.183.

Nassar, D. (2025). *A Holistic Approach to Addressing Environmental Sustainability in Data Centers* (Doctoral dissertation, University of East London).

Nyberg, D., Ferns, G., Vachhani, S., & Wright, C. (2022). Climate change, business, and society: Building relevance in time and space. *Business & Society, 61* (5), 1322-1352. https://doi.org/10.1177/00076503221077452.

Oltmanns, J., Sauerwein, D., Dammel, F., Stephan, P., & Kuhn, C. (2020). Potential for waste heat utilization of hot - water - cooled data centers: A case study. *Energy Science & Engineering, 8* (5), 1793-1810. doi : 10.1002/ese3.633.

Ortiz - Avram, D., Ovcharova, N., & Engelmann, A. (2024). Dynamic capabilities for sustainability: Toward a typology based on dimensions of sustainability - oriented innovation and stakeholder integration. *Business Strategy and the Environment*, *33* (4), 2969-3004. https://doi.org/10.1002/bse.3630.

Paiho, S., Wessberg, N., Pippuri-Mäkeläinen, J., Mäki, E., Sokka, L., Parviainen, T., & Laurikko, J. (2021). Creating a Circular City–An analysis of potential transportation, energy and food solutions in a case district. *Sustainable Cities and Society*, *64*, 102529.

Pallardi R., (2023). How can data centers reduce water consumption and improve efficiency? Informationweek. www.datacenterknowledge.com

Pearce, F. (2018). Energy hogs: can world's huge data centers be made more efficient. *Yale Environment, 360* (3).

Rangone, N. (2025). Artificial Intelligence, Environmental Protection and European Regulation. *BioLaw Journal*, (1), 529-548.

Rong, H., Zhang, H., Xiao, S., Li, C., & Hu, C. (2016). Optimizing energy consumption for data centers. *Renewable and Sustainable Energy Reviews, 58,* 674-691.

Schulz, G. (2016). *The green and virtual data center* . CRC Press. ISBN 0367386003.

Singh, S. K., & El-Kassar, A. N. (2019). Role of big data analytics in developing sustainable capabilities. *Journal of cleaner production, 213,* 1264-1273.

Sovacool, B. K., Upham, P., & Monyei, C. G. (2022). The "whole systems" energy sustainability of digitalization: Humanizing the community risks and benefits of Nordic datacenter development. *Energy Research & Social Science, 88,* 102493. doi: 10.1016/j.erss.2022.102493.

Terenius, P., Garraghan, P., & Harper, R. (2023). A material social view on data center waste heat: Novel uses and metrics. *Frontiers in Sustainability*, *3,* 1008583.

Oró, E., Depoorter, V., Pflugradt, N., & Salom, J. (2015). Overview of direct air free cooling and thermal energy storage potential energy savings in data centres. *Applied thermal engineering*, *85*, 100-110. https://doi.org/10.1016/j.applthermaleng.2015.03.001.

Puntillo, P., Gulluscio, C., Huisingh, D., & Veltri, S. (2021). Reevaluating waste as a resource under a circular economy approach from a system perspective: Findings from a case study. *Business Strategy and the Environment, 30* (2), 968-984. https://doi.org/10.1002/bse.2664.

Siddiqui, S. A., Elsheikh, W., Ucak, İ., Hasan, M., Perlita, Z. C., & Yudhistira, B. (2024). Replacement of soy by mealworms for livestock feed-A comparative review between soy and mealworms considering environmental aspects. *Environment, Development and Sustainability,* 1-44.

Siriwardana, J., Jayasekara, S., & Halgamuge, S. K. (2013). Potential of air-side economizers for data center cooling: A case study for key Australian cities. *Applied Energy, 104,* 207-219. https://doi.org/10.1016/j.apenergy.2012.10.046.

Shuja, J., Gani, A., Shamshirband, S., Ahmad, R. W., & Bilal, K. (2016). Sustainable cloud data centers: a survey of enabling techniques and technologies. *Renewable and Sustainable Energy Reviews, 62,* 195-214.

Tervo, S., Syri, S., & Hiltunen, P. (2025). Reducing district heating carbon dioxide emissions with data center waste heat–Region perspective. *Renewable and Sustainable Energy Reviews, 208,* 114992.

Wahlroos, M., Pärssinen, M., Rinne, S., Syri, S., & Manner, J. (2018). Future views on waste heat utilization–Case of data centers in Northern Europe. *Renewable and Sustainable Energy Reviews*, *82*, 1749-1764. doi : 10.1016/j.rser.2017.10.058.

Simón-Manso, Y., Erisman, E. P., Mak, T. D., Burke, M. C., Zuber, A., Yang, X., ... & Stein, S. E. (2025). NIST Mass Spectral Libraries in the Context of the Circular Economy of Plastics. *Journal of the American Society for Mass Spectrometry*.

Wang, P., Pan, L., He, G., Li, G., Song, J., Zhou, M., & Wang, J. (2025). Constructing a Biomass-Data Center Nexus for Circular Economy-based Energy Systems Integration. *IEEE Open Access Journal of Power and Energy* . doi: 10.1109/OAJPE.2025.3567739.

Welch, C., Paavilainen-Mäntymäki, E., Piekkari, R., & Plakoyiannaki, E. (2022). Reconciling theory and context: How the case study can set a new agenda for international business research. *Journal of International Business Studies, 53* (1), 4-26. https://doi.org/10.1057/s41267-021-00484-5

Wong, C. W. (2013). Leveraging environmental information integration to enable environmental management capability and performance. *Journal of Supply Chain Management, 49* (2), 114-136. https://doi.org/10.1111/jscm.12005.

Yin, R. K. (2017). Case Study Research and Applications: Design and Methods. Thousand Oaks, CA: SAGE Publications.

Yu, W., Hassan, A., & Adhikariparajuli, M. (2022). How did Amazon achieve CSR and some sustainable development goals (SDGs)—climate change, circular economy, water resources and employee rights during COVID-19? *Journal of Risk and Financial Management, 15* (8), 364. doi: 10.3390/jrfm15080364.

Zhang, Q., & Yang, S. (2021). Evaluating the sustainability of big data centers using the analytic network process and fuzzy TOPSIS. *Environmental Science and Pollution Research, 28,* 17913-17927. Doi: https://doi.org/10.1007/s11356-020-11443-2.

Zhang, Y., & Liu, J. (2022). Prediction of overall energy consumption of data centers in different locations. *Sensors, 22* (10), 3704.. https://doi.org/10.3390/s22103704. https://ec.europa.eu/commission/presscorner/detail/en/qanda_22_6229.

https://energyinnovation.org/2020/03/17/how-much-energy-do-data-centers-really-use. [Last retrieved: May 5, 2025].

https://www.corporateknights.com/?s=Qscale. [Last retrieved: May 5, 2025].

https://www.datacenterdynamics.com/it/. [Last retrieved: May 5, 2025].

https://www-datacenterfrontier-com.translate.goog/cooling/article/33004853/aligned-investe-in-quebec-hpc-specialist-qscale?_x_tr_sl=en&_x_tr_tl=en&_x_tr_hl=en&_x_tr_pto=sc. [Last retrieved: May 5, 2025].

https://www.ellenmacarthurfoundation.org/. [Last retrieved: May 5, 2025].

https://www.fasken.com/. [Last retrieved: May 5, 2025].

https://www.impresacity.it/news/28496/i-dolori-del-giovane-data-center-italiano.html. [Last retrieved: May 5, 2025].

https://www.science.org/doi/abs/10.1126/science.aba3758. [Last retrieved: May 5, 2025].

https://digital-strategy.ec.europa.eu/en/library/energy-efficient-cloud-computing-technologies-and-policies-eco-friendly-cloud-market. [Last retrieved: May 5, 2025].

https://www.statista.com/statistics/1228433/data-centers-worldwide-by-country/. [Last retrieved: May 5, 2025].