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Utilising Data Centres' Side Streams – A Waste Heat Case Study

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Abstract: This article investigates the different challenges and phases of building an ecosystem to utilise data centre waste heat. Data centres consume an increasing amount of energy, and currently, in many cases, excess heat is not utilised beyond heating the data centre property. The research examines how a circular economy can be integrated into the operations of a data centre's waste heat business ecosystem and how a business ecosystem based on utilising waste heat from a data centre should be built. The research is based on a literature review, interviews with experts and stakeholders in the case ecosystem and a survey. Based on the research, a concept for a business ecosystem based on the utilisation of waste heat from a pre-existing data centre perspective is modelled, and the concept outlines things to be considered when building such an ecosystem. Key findings were the challenges, opportunities and prerequisites of developing a data centre waste heat ecosystem and the roadmap of constructing one.

Keywords: business ecosystem; circular economy; data centre; side streams; value chains

1 INTRODUCTION

The world's economy still relies heavily on a linear business model lacking built-in mechanisms for reuse or recycling, which is not sustainable in the long run because of environmental degradation and resource depletion [1]. A linear economy is based on material consumption, where the resources are used to make products, and after use, they become waste [2]. The endless use of limited resources is affecting nature, and the circular economy is thought to be one solution to these environmental challenges [3, 4]. The circular economy is a model in which as few resources as possible are used, and these resources are then reused to prolong their life cycle. At the same time, waste generation decreases [5]. The purpose of the circular economy is to avoid creating waste by using it as a resource in other processes [6].

The EU directive [7] states that data centres with a combined rated power above 1 MW are required to repurpose their waste heat for heating or other energy recovery uses, except when doing so is not technically or economically viable. This approach supports a circular economy and helps decrease reliance on fossil fuels. Yet currently, it is common for data centres to not utilise the waste heat in any way [8]. The amount of data and internet usage is increasing rapidly; thus, the number of new data centres worldwide is growing [9, 10]. Furthermore, data centres are vast consumers of electricity, estimated to be up to 1.5% of the global energy demand [11]. Because of this, the environmental effect of the data centres' operations is significant and should be considered [10].

This study aims to create a concept for utilising waste heat from a data centre in a business ecosystem. Typically, 40% of a data centre's energy consumption is attributed to cooling [10]. This means that the northern parts of Europe and other countries with colder climates are propitious locations for building data centres because of the reduced amount of cooling required. Data centres also create business opportunities and employment in sparsely populated areas, which in the case of Nordic countries have a lot of renewable energy and a reliable infrastructure required by the data centres. The research goals were as follows: To determine where data centres' waste heat could be utilised and what affects the creation of the business ecosystem, as well as to publish the information for operators.

These goals were condensed into the following research questions:

RQ1. What are the challenges and opportunities of utilising data centre waste heat?

RQ2. What are the main steps in creating a business ecosystem for the utilisation of data centre waste heat?

In addressing these questions, a comprehensive understanding was obtained regarding the factors involved in integrating sustainable development, particularly the circular economy, into business practices. Additionally, insights were gained on how to utilise waste heat generated by data centres and how these concepts are realised within a business ecosystem for waste heat. The concept was developed from the perspective of an existing data centre, indicating that it cannot be directly applied in all aspects when constructing a new data centre waste heat business ecosystem, but it includes considerations that should be taken into account.

2 LITERATURE REVIEW

2.1 Side Streams

The European Parliament and Council's Waste Framework Directive [12] defines how to protect the environment and people's well-being by preventing waste and transitioning to a circular economy. The directive presents a five-step waste hierarchy that defines the order of priority for actions to prevent the generation of waste based on waste management legislation. The five steps are waste prevention, preparation for reuse, recycling, recovery and disposal. In nature, no waste is produced, but everything serves as a resource for other processes [3]. For that reason, in a value chain based on a circular economy, side streams arising from processes are recovered and utilised to increase value according to the waste hierarchy [13].

A large amount of potentially reusable waste and side streams remain unutilised. Industrial side streams include everything that results from production processes, except for the main product [14]. By further processing and combining side streams of different industries, new products can be created [15] and new sources of income can be found [14]. A company's sustainable development efforts should be integrated into its value chain through a life cycle approach to products, which includes increasing the use of recycled materials in product design, reducing energy consumption in production and properly managing hazardous waste after the materials' useful life [16].

Industrial symbiosis refers to a group of companies (for example, clusters or supply chains) where the sharing of resources promotes the efficiency of several stakeholders, either by reducing, for example, energy use and costs, or by offering waste (side streams) from one company's process as a contribution to the value creation process of another company [13]. In industrial symbiosis, companies utilise each other's waste and resources in their operations [2]. Generally, the development of products manufactured through industrial symbiosis encourages material recycling and reduces resource consumption and waste generation [15].

2.2 Data Centres

Because of the digitised society, data centres have become a critical part of the infrastructure [17]. To meet the growing needs of the internet and cloud computing, the number and size of data centres have increased in recent years [9, 10]. Data centres are constantly growing larger, becoming more complex and using a lot of electricity due to the increased demand for data storage and computing power [18].

Data centre equipment is generally divided into IT equipment and support equipment [17]. IT devices include servers, storage devices and communication networks, which directly affect the main functions of the data centre, such as data storage, processing and transferring. Support equipment usually consists of the cooling system and electrical infrastructure as well as lighting and equipment related to safety and other support functions [17].

The substantial energy consumption and associated costs of data centres primarily stem from the electrical demands of servers and cooling systems in addition to lighting, power distribution and other auxiliary operations [19–22]. Many data centre companies also consume excessive energy to ensure high reliability for their clients, resulting in low utilisation rates of IT systems [23]. In other words, although servers and storage devices have become increasingly energy-efficient during active use, they operate at full capacity for only a limited time [17].

2.3 Energy Efficiency in Data Centres

A data centre is an environment where precisely defined temperatures and cooling needs for information technology, such as servers and computers, are controlled and maintained [24]. Nearly all the electricity used in a data centre ultimately becomes heat, which must be extracted to maintain proper operation [17]. Maintaining a suitable temperature is important, as IT equipment can be damaged or stop working at too high a temperature or due to rapid temperature fluctuations [9].

Data centres consume a significant amount of energy, which leads to CO_2 emissions, and the energy consumption of servers and computers in data centres is constantly increasing [21]. Consequently, energy consumption and environmental impacts have developed into significant challenges in the design and operation of data centres [19], particularly the high energy consumption of cooling systems [10]. As current equipment increasingly generates heat loss, the efficiency and management of energy use play a crucial role in system design [21]. Additionally, indoor thermal conditions significantly impact the electricity consumption of air-conditioning systems [9].

According to the IEA [11], data centres account for approximately 1%–1.5% of global electricity use and, together with data transmission networks, 0.6% of global greenhouse emissions. Companies are increasingly aware of the negative effects of their operations on the environment and the need to reduce them [25]. Therefore, attention has also shifted towards the high energy consumption of data centres [9, 18, 21], pressuring them to reduce their carbon footprint.

Energy efficiency refers to solutions in which technology is used for the same functions with less energy [21]. Energy efficiency metrics can be used to evaluate data centre performance and find opportunities to reduce electricity use [9]. The high energy consumption and costs of data centres are mainly due to the electricity demand of the servers and the cooling system as well as lighting, electricity distribution and other support functions [19, 21]. Many data centre companies also use an excessive amount of energy to ensure high reliability for their customers, resulting in a low utilisation rate of IT systems [23].

2.4 Waste Heat

Data centres produce a significant amount of waste heat, typically quite low-grade, and it can be utilised in various applications [26]. Low heat can be raised in an economically profitable way; for example, with the help of heat pumps, it can be reused in a process that requires higher heat. Utilising waste heat can improve the energy efficiency of data centres by eliminating the need for chillers [18]. The temperature of waste heat depends on the cooling techniques used by the data centre [17].

With the help of heat pumps, waste heat can be used as a source of district heat [18]. For example, in Mäntsälä, an ecosystem has been built around the local data centre, where the waste heat is utilised in the municipality's district heating network [27, 28]. Stockholm City's district heating network also receives green energy by using waste heat from data centres. The ecosystem's vision is that no heat would be wasted in the data centre industry. Waste heat is therefore seen as a valuable resource, and its usage is part of an environmental act [29].

Waste heat can also be used for drying or heating in industrial processes [17]. Other examples of uses are greenhouses and fish farming. The Agriport A7 business ecosystem area is located near Amsterdam, where waste heat from the data centre is used in the operation of greenhouses [30]. According to Yuan et al. [31], the most efficient way to utilise waste heat is as a heating supply for nearby buildings.

3 RESEARCH METHODOLOGY
3.1 Research Process and Method

This study was carried out using a qualitative research method to increase understanding of the data centre industry and to form an understanding of issues that must be considered when creating a business ecosystem based on the utilisation of data centre waste heat. The empirical research included semi-structured interviews with experts and stakeholders in the case business ecosystem. Experts were interviewed to gain a deeper understanding of the industry.

The first interviewee was a data centre industry expert, and the second interviewee was a regional policy expert. The research was continued by interviewing the representatives of the companies in the case business ecosystem. The case business ecosystem companies are presented in Tab. 1. The data collected from the interviews were analysed using thematic analysis. Additional information about the data centre business ecosystems was gathered by sending a questionnaire to the following groups of stakeholders: 24 data centre companies, 72 potential user companies and 83 cities and municipalities. In total, 25 replies were received, making the combined response rate 14%. The questionnaires were intentionally kept concise and short to enable responses to be quick and easy. Most of the questions were multiple choice; for some, it was possible to select several different answer options, and some questions could be answered openly by writing a response. The answer options for the multiple-choice questions were 'yes', 'no' and 'I don't know'. The questionnaires were created using the Webropol tool, and a link to the surveys was sent to different target groups via email. The low number of responses can partly be explained by the fact that the recipients did not belong to the appropriate target group in terms of survey content. However, everyone who started the survey completed it, which suggests that the questions were not too difficult.

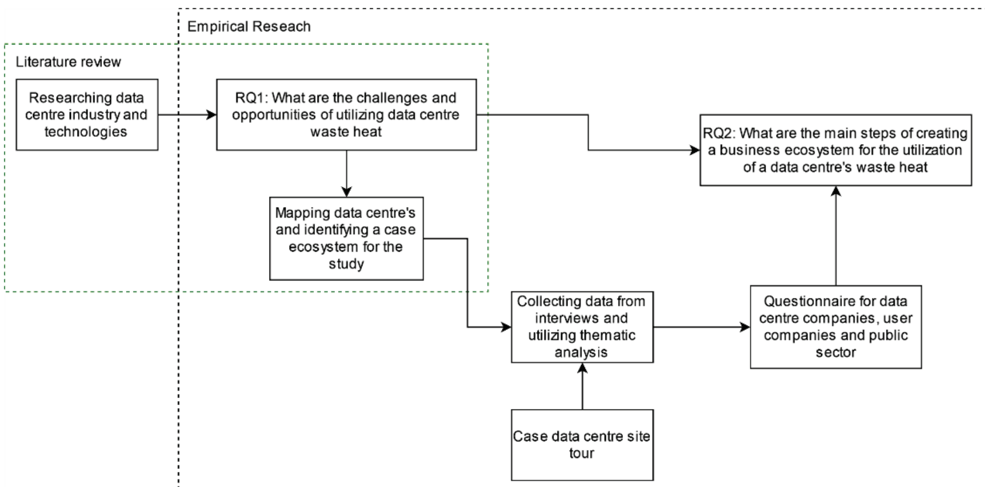

Figure 1 Research process

Table 1 Case ecosystem main players

Company	Description
A	Data centre company
B	District heating company
C	Material drying company

According to Flick [32], qualitative research focuses on collecting, interpreting and understanding qualitative data. Qualitative research can include many different interview formats, the most common of which is the semi-structured interview. Semi-structured interviews are flexible and allows the researcher to explore topics spontaneously during the interview [33]. Expert interviews can be used for various purposes, such as research data collection or familiarisation with a new field, to obtain a thematic structure and hypothesis for the researched topic [32]. According to Braun and Clarke [34], thematic analysis is a flexible analysis that is used to identify, analyse and finally report themes found in the data. Braun and Clarke [34] defined six steps for thematic analysis: familiarise yourself with the data you have collected, generate initial codes, find themes, review themes, define and name themes and produce a report.

3.2 Thematical Analysis

After coding the data from the case business ecosystem stakeholder interviews, the codes were divided into suitable themes and the themes were named descriptively. The themes and codes are presented in Tab. 2.

Table 2 Themes of thematical analysis

Theme	Codes
The business for waste heat utilisation	Ecosystem's stakeholders
	Roles in the ecosystem
	Legislation
Circular economy in the business ecosystem	Circular economy practices
	Environmental impacts
Lucrativeness of the business ecosystem	Profitability
	Quality of waste heat
	Challenges
	Benefits

3.2.1 Main Players of the Business Ecosystem for Waste Heat Utilisation

When creating a business model, all stakeholders of the ecosystem must be determined. In addition to the data centre and the user of waste heat (local heat or district heat), the business ecosystem's stakeholders can include a city or municipality. The role of the city or municipality can be, for example, landowner or financier. From Company C's point of view, a significant factor affecting lucrativeness is also finding a customer in the data centre area who has material to be dried.

Company A's role in the business ecosystem would be mainly to be a passive donor of waste heat. According to them, they do not currently utilise waste or any heat recovering solutions, and see that the current electricity tax reduction for data centres has been designed with large operators in mind and therefore does not benefit smaller data centres. Company B, on the other hand, would operate and decide by itself when it is worth using waste heat in the district heating network and, if necessary, use some other heat source. In the case of Company C, the use of waste heat would depend on the model implemented in the project. One possibility would be to build a testing or pilot site that Company C itself or their customer would use independently, in which case the utilisation of waste heat would be irregular but still predictable.

Company B stated the following: 'Both the economic and environmental benefits of waste heat utilization are significant. Support through legislation can also be used to motivate district heating companies to make use of waste heat'. The attractiveness is increased by electricity tax reduction and constantly tightening regulations on fossil fuel use. From Company A's point of view, electricity tax reduction benefits larger data centres more than their operations.

3.2.2 Lucrativeness of the Case Business Ecosystem

Every stakeholder in the case project emphasised the impact of the profitability of the ecosystem on its lucrativeness. It was agreed that environmental benefits bring added value after financial benefits. In each company, however, the impact of environmental benefits on improving the company's image was identified.

Company A produces waste heat continuously around the clock and throughout the year. The amount of waste heat needed by both Companies B and C can vary at different times. The price of waste heat must be defined as appropriate and competitive for each party, and it must be predictable.

From Company A's point of view, building a business ecosystem for the utilisation of waste heat does not present significant challenges. From Company B's point of view, risks can arise from the operation of the heat pumps and whether they will last for at least the payback period of the investment. From Company C's point of view, the challenge of creating an ecosystem is the quality and quantity of waste heat, as the drying process requires a lot of thermal energy.

Company A would benefit financially from the sale of waste heat, as it would reduce cooling costs and be a new source of income. Companies B and C could also benefit financially from the ecosystem by gaining access to an affordable heat source. In addition, utilising emission-free waste heat could reduce the use of fossil fuels and thus increase the environmental friendliness of companies. Especially for Company B, the third significant benefit is improving the image of district heating through environmental friendliness.

4 RESULTS

4.1 Main Players of the Business Ecosystem

The concept was created based on the already existing data centre, which aims to collect and sell the waste heat in a business ecosystem and the corresponding literature. When building a business ecosystem, the stakeholders must be determined. The waste heat can be used in local or distant heating. Factors that fundamentally affect the choice of waste heat user are the location of the data centre and the amount and temperature of waste heat. In addition to the data centre and waste heat user, the city or municipality usually plays an important role as an enabler of the ecosystem. The roles of the stakeholders must also be determined because clear roles strengthen trust among stakeholders [35]. The identified prerequisites, challenges and opportunities of building a data centre waste heat business ecosystem are presented in Tab. 3.

Table 3 The prerequisites, challenges and opportunities of building a data centre waste heat business ecosystem

Prerequisites	Challenges	Opportunities
- Economic feasibility - Demand for waste heat - Stable and constant availability of waste heat - Desirable location of the data centre	- Payback of the investment - Predictability of electricity price development - Integration of waste heat recovery into the overall cooling system - Price and temperature of the waste heat - Balancing stakeholder requirements and responsibilities - Slow pace of zoning processes	- Reduction of cooling needs and costs - Reduction of burning more polluting sources for district heating, e.g. fossil fuels - Improvement of energy efficiency - Positive reputation - New source of income

Next, the rules, practices and business models for cooperation are determined. In addition, the contractual basis is agreed upon, which includes elements such as the price of the waste heat and it can be based, for example, on an open district principle. The challenges and benefits of the cooperation should also be recognised. The operations of the stakeholders should not be threatened because of the cooperation, and for example, the heat pumps must work at least for the payback time of the investment. The benefits of being part of the ecosystem can include cost savings, new incomes, energy efficiency improvements, reduction of emissions and improvement of the image of the companies.

The infrastructure for the ecosystem's operations must be planned. The infrastructure includes all the technology and equipment needed to recover and use the waste heat. These can include heat pumps and technology that is integrated into the data centre's cooling system. In addition, all required building and environmental permits must be applied for. Once the planning is done, the operation of the ecosystem can start. At this point, it must be confirmed that the recovery and usage of the waste heat are working efficiently. To ensure the sustainability of the ecosystem, operations must also be continuously improved. The concept of the business ecosystem and the relationships between its parts are presented in Fig. 2.

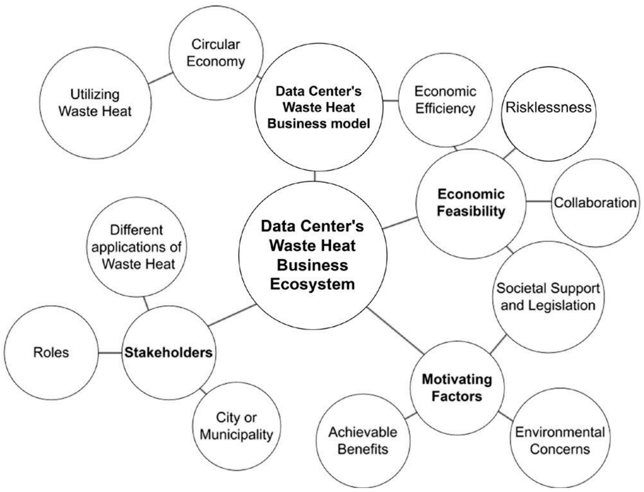

Figure 2 Business ecosystem based on utilising data centre's waste heat

The elements of the concept presented above offer the basis for building a business ecosystem where the data centre's waste heat is utilised. However, every project is unique, and the aspects of creating an ecosystem depend on the circumstances and stakeholders. When developing a business ecosystem, it is crucial to identify the stakeholders involved. Initially, the ecosystem area must have a user for the waste heat, either for the district or local heating. The city or municipality also plays a significant role as an enabler of the ecosystem. Additionally, the role of each stakeholder within the ecosystem must be defined clearly to enhance trust among stakeholders [35]. Generally, the data centre acts as a passive heat supplier while the waste heat user is the heat purchaser. The needs and relationships of the stakeholders are vital for value creation within the ecosystem. Belonging to the ecosystem emphasises cooperation, which requires transparency regarding the needs and expectations of each party. The compatibility of stakeholders' operations affects the ecosystem's functionality, and for the ecosystem to be sustainable, stakeholders must be committed to cooperation. The business ecosystem relies on sharing resources among stakeholders, where one company's waste is utilised in another company's value-creation process [13].

Next, a business model is established to define how costs, revenues and profits are generated from operations [36], and business models based on the circular economy have been developed to help companies transition to a circular economy. The development of the business model is influenced by the size of the entities involved, including the data centre and the waste heat user's heating needs. The utilisation of waste heat is based on a circular economy business model, which considers both economic value generation and environmental perspectives [37]. The circular economy is realised in the ecosystem by utilising the by-product of the data centre, namely waste heat. The profitability of an ecosystem primarily depends on its economic viability. Each stakeholder must benefit financially, which is facilitated by a well-structured contract and a competitive price for the waste heat. The contract can be based on principles such as bidirectional district heating or models defined by the energy authority. The economic benefit of using waste heat must cover all investment costs. A competitive price enables cost reductions for waste heat users and provides a new revenue stream for the data centre.

The safety and reliability of waste heat recovery and usage are essential for the ecosystem's profitability. The operational activities of the stakeholders must not be compromised; for example, heat pumps must function for the promised duration. Optimal utilisation of waste heat is continuous, but predictability in demand and pricing increases operational security. The suitability of waste heat usage must also consider specific applications. If necessary, the temperature of the waste heat can be increased using heat pumps to make it suitable for district heating. Local heating is the optimal option, as it avoids heat loss. Environmental concerns and the achievement of climate goals motivate the construction of an ecosystem. Circular economy principles can address sustainable development and climate goals [6]. Utilising waste heat can reduce emissions from combustion-based heat production. The growing energy demand and the desire to improve energy self-sufficiency also increase the viability of waste heat utilisation.

The international, national and private sectors all have significant roles in enabling sustainable development. Societal support can enhance the ecosystem's viability through legislation, such as potential reductions in electricity taxes, to encourage companies to utilise waste heat. An increasing number of European countries have either adopted, are currently adopting or have scheduled plans to phase out fossil fuel-based heating [38], making waste heat an ideal alternative heat source. Ecosystem operations can achieve environmental benefits through improved energy efficiency and reduced emissions. These environmental benefits can also enhance corporate image. However, one of the primary goals of participating in the ecosystem is economic gains, with environmental benefits as added value. According to the Ellen MacArthur Foundation [6], a circular economy can also lead to social benefits. Using waste heat can provide social benefits by supporting local communities, for example, by offering cheaper district heating to local residents.

4.2 Building a Data Centre Waste Heat Business Ecosystem

The starting point for the formation of a business ecosystem for waste heat involves the presence of an existing data centre generating waste heat that is not yet utilised. The formation of the ecosystem is significantly influenced by the location of the data centre [17], the quantity of waste heat produced and its temperature. The choice of waste heat user is influenced by the data centre's location, the amount of waste heat generated and its temperature. At this stage, it is necessary to determine the suitability of waste heat from the user's perspective. The process flow of building the data centre's waste heat business ecosystem is presented in Fig. 3 and is discussed in this section.

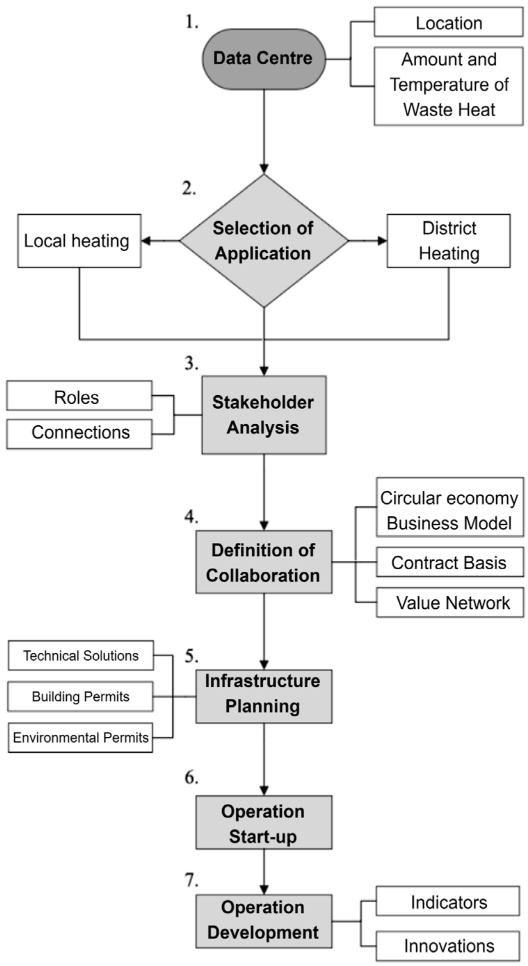

Figure 3 Building the main elements of the business ecosystem using the data centre's waste heat based on analysis

If there is vacant space around a data centre, local heating solutions, such as greenhouses, laundries or drying facilities for process industries, can be constructed. If the data centre is located in a residential area, the waste heat can be used to heat nearby buildings or streets. If the data centre is within a district heating network, the waste heat can be fed into it.

Next, the stakeholders of the ecosystem, their roles and their relationships are identified. Stakeholders include all parties who benefit from or influence the ecosystem's formation and development. These stakeholders include the data centre, the waste heat user, landowners, local residents and customers. Once the stakeholders are identified, their roles and responsibilities within the ecosystem are defined. In addition to clear roles that build trust among the ecosystem's stakeholders [35], establishing common rules are crucial for effective cooperation. According to Valkokari et al. [35], setting common rules can also enhance trust among the ecosystem's stakeholders. The needs and expectations of each actor must be understood, and interactions should be transparent. Additionally, the value network and business model of the ecosystem are defined, outlining how costs and revenues are structured within the ecosystem. Based on the business model, a contract framework is created that may follow principles such as bidirectional district heating or other existing contract templates. The framework specifies the price of the waste heat and other terms of utilisation. The price is determined based on investment and other costs, as well as the characteristics of the waste heat.

Once the business model and stakeholder needs are defined, the infrastructure of the ecosystem must be planned. This includes all necessary technologies and equipment for capturing and utilising waste heat, such as potential heat pumps and technology integrated into the data centre's cooling system. Additionally, the required environmental and building permits must be obtained. After the ecosystem's design is complete and all necessary infrastructure is built, operations can commence. At this stage, the operational activities of the ecosystem are initiated, ensuring efficient heat recovery and utilisation. To ensure the ecosystem's sustainability and continued operation, continuous development is necessary. According to Moore [39], the existence of a business ecosystem depends on its renewal in response to external changes, such as innovations or technologies. The ecosystem can be developed through activities such as operational optimisation and the creation of innovations. Development areas can be identified using various metrics, such as power usage effectiveness (PUE) and energy reuse factor (ERF), to measure the data centre's energy efficiency.

These phases provide a foundation for constructing a circular economy-based business ecosystem that utilises waste heat from data centres. However, it is important to note that every project is unique and that the phases of ecosystem development may vary depending on a project's conditions and different stakeholders. Additionally, the process of creating a new ecosystem inherently involves zoning and building permit processes.

4.3 Practical Implications

The concept of a business ecosystem based on the utilisation of waste heat was created at the general level from the point of view of an already existing data centre. The main pillars of the concept are the different options for the use of waste heat as well as the profitability, challenges and benefits of the ecosystem. Regarding the research questions, challenges for waste heat utilisation were detected to be payback of the investment, predictability of electricity price development, integration of the waste heat recovery into the overall cooling system, price and temperature of the waste heat, balancing stakeholder requirements and responsibilities and the slow pace of zoning processes. The opportunities detected were the reduction of cooling needs and costs, reduction of burning more polluting sources for district heating (e.g. fossil fuels), improvement of energy efficiency, positive reputation and a new source of income. The main steps of building a data centre ecosystem are the following: specifying the requirements of the data centre, selecting the application, conducting stakeholder and collaboration model analyses, planning the infrastructure, followed by the operation start-up and development.

Factors affecting profitability are the cost and earnings logic of the ecosystem's business model, value creation and the characteristics of waste heat. A separate business model must be built for each project, depending on the size, needs and contract basis of the operators, among other things. In particular, the size of the data centre and the amount of waste heat impact the business ecosystem that can be built around it.

The selection of the waste heat user is influenced, among other things, by the location of the data centre and the amount and quality of the waste heat. The users of waste heat can be roughly divided into local and district heating. The primary use is heating office premises in nearby areas. If enough waste heat is generated, it makes sense to use it, for example, in district heating or in heat-demanding processes such as local heating in the data centre area. Waste heat in district heating has been widely implemented, although this approach has been questioned in recent years due to energy losses in district heating pipelines. Thermal value is also influenced by other factors, such as soil conditions, infrastructure, insulation and the depth and construction of the district heating network.

Data centres would benefit economically from the ecosystem because it would serve as a new source of income, and customers would acquire a budget source of environmentally friendly heat. Currently, combustion based on biomass and other renewable energy sources is still profitable, but this will change in the near future. Therefore, the long-term sustainability of combustion-based energy production is poor. With the green transition, the first step is to abandon the burning of fossil fuels in favour of more environmentally friendly fuels and ultimately to reduce combustion altogether by utilising, among other things, the waste heat from data centres.

5 CONCLUSIONS

The purpose of this study was to create a concept for a business ecosystem that utilises the waste heat produced by a data centre in other companies' operations that require heat. One of the driving forces behind the promotion of waste heat utilisation in data centres is the requirements set by the EU directive on waste heat recovery [7]. The starting point of the concept is an already existing data centre creating waste heat around which a business ecosystem is planned.

When considering an ecosystem for data centre waste heat utilisation, key aspects include exploring different user options and assessing profitability, challenges and benefits. Factors affecting profitability include cost, value creation and quality of the waste heat. The business model should be tailored to each project based on the data centre's size and needs. Selecting a waste heat user depends on location. A specific business model defines costs, revenue and value creation, and clear contractual agreements are essential. Stakeholders in the ecosystem are identified, encompassing all factors influencing waste heat utilisation.

Key challenges in utilising waste heat from data centres include investment payback, electricity price uncertainty, technical integration, heat quality, stakeholder coordination and zoning delays. However, opportunities lie in reduced cooling costs, lower fossil fuel use in district heating, improved energy efficiency, enhanced reputation and new revenue streams. The formation of a business ecosystem for data centre waste heat recovery begins with assessing the location, quantity and temperature of available waste heat. Based on these, local or district heating are suitable applications. Key phases include identifying stakeholders and their roles, defining collaboration models and business contracts, planning infrastructure and obtaining permits and starting operations. Continuous development through monitoring, optimisation and innovation ensures the ecosystem remains sustainable and adaptive.

The research could be expanded by validating the results quantitatively and by repeating the study with a different ecosystem in hand. This research was based on a case study and results may vary based on the regional attributes and are also affected by the number of interviews and respondents. A similar concept could also be built from the perspective of a new data centre. In such a case, the same issues should be considered, but regional planning would represent a bigger factor. In addition, further studies could focus on how waste heat and other side streams can be utilised in larger-scale circular business ecosystems, such as in the steel industry. For example, an interesting and relevant question in this field is the decarbonisation of the steel industry, and one way of contributing to that could be by producing waste heat to produce biochar pellets to substitute fossil coal in electric arc furnaces.

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