

Article

# Carbon Handprint: Potential Climate Benefits of a Novel Liquid-Cooled Base Station with Waste Heat Reuse

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**Abstract:** The novel life cycle assessment (LCA)-based carbon handprint indicator represents a potential carbon footprint reduction that producers/products create for customers who use the(ir) product instead of a baseline product. The research question is how to consider a situation in which multiple customers use a product for different purposes to provide a carbon handprint quantification and the associated communication. The study further provides new insight into the greenhouse gas (GHG) emissions reduction potential within the mobile telecommunications and energy sectors. The carbon handprint of a novel Finnish liquid-cooled base station technology is quantified. The liquid-cooled base station provides a telecommunications service and waste heat that is recoverable through the cooling liquid for heating purposes. The baseline solutions are an air-cooled base station, and district and electrical heating. The liquid-cooled base station creates a carbon handprint, both through energy savings in telecommunications and additional waste heat reuse, replacing other energy production methods. A large-scale climate change mitigation potential through a liquid-cooled base station expansion could be significant. Different supply chain operators' contributions to the total carbon handprint could be terminologically distinguished in communications to emphasize their roles in a shared handprint. The handprint should be transparently communicated for each customer and function.

**Keywords:** handprint; carbon handprint; carbon footprint; life cycle assessment; LCA; base station; liquid cooling; waste heat reuse

## 1. Introduction

The consequences of climate change are increasingly concerning scientists and laypeople alike. The Intergovernmental Panel on Climate Change (IPCC) highlights the drastic consequences of limiting global warming merely to the common 2 °C target in comparison to pre-industrial levels, as opposed to 1.5 °C [1]. Regional and industrial greenhouse gas (GHG) emission reduction targets are exerting pressure on nations and companies to rethink production technologies and efficiency without compromising modern lifestyles. Industries have, for example, adopted science-based targets for reducing their GHG emissions to battle climate change [2].

A constructive mindset focusing on the environmental benefits of products has emerged to challenge a conventional mindset focusing on increasing efficiency by minimizing the negative

environmental impacts of products. For example, a climate change mitigation contribution represents an environmentally-beneficial product attribute. Dyllick and Rost consider a positive mindset to be a prerequisite for designing truly sustainable products [3]. Grönman et al. recently introduced the life cycle assessment (LCA)-based carbon handprint approach and indicator for the quantification and communication of potential climate benefits, which an organization can generate by providing products that reduce customers' carbon footprint when compared to a baseline situation [4]. The organization and its product, thus, achieve a carbon handprint if customers' carbon footprint is reduced [4]. The carbon handprint can be created through customers' carbon footprint reduction via a GHG emissions reduction in the producer's processes or customers' processes [4].

The quantification of a carbon handprint can be relatively straightforward for a product that is used for a specific purpose by one or more similar customers. In Grönman's et al. demonstration, renewable transportation fuel was utilized to provide transportation kilometers for moving people or goods by different users, such as consumers or logistic operators [4]. Thereby, a carbon handprint was created through the reduction of GHG emissions during the well-to-wheel life cycle of the renewable fuel in comparison to the baseline fuel mix, which contains ingredients of both fossil and renewable origin [4]. However, more complex cases exist.

The first aim of this study was to provide further insight into the carbon handprint approach and the use of a carbon handprint as a positive climate impact indicator through applying the approach to a novel liquid-cooled mobile radio network base station technology introduced by Nörtershäuser et al. [5] and recently implemented into use in Finland [6]. Unlike conventional air-cooled base stations, a liquid-cooled base station provides waste heat that is recoverable through the cooling liquid (water) for various heating purposes, in addition to providing mobile telecommunications services as its main purpose [5,7]. Liu et al. and Woodruff et al. have suggested that dispersed data centers be integrated into buildings that require heating [8,9]. These "data furnaces" [8] or environmentally opportunistic computing nodes [9] provide both the computing and required heating services directly at homes and office or apartment buildings. Through the case study demonstration, this study explores the question of how to consider a situation in which a product is simultaneously used for multiple different purposes by multiple different customers to provide a quantification and the associated communication of a carbon handprint.

Energy efficiency and the associated carbon footprint are major environmental concerns in mobile telecommunications infrastructures [10–12]. Although the energy efficiency of telecommunications networks has significantly improved over the past decade, the increasing demand of mobile data transmission could outweigh the achieved energy savings [13]. Base stations provide mobile telecommunications services by transmitting a radio signal and are responsible for the majority (nearly 60%) of the power consumption of a mobile telecommunications infrastructure [10] and the majority, reportedly over 80%, of the carbon footprint [14]. The European Commission is assessing the inclusion of base stations into its eco-design working plan [15], which implies a possible future EU-wide regulation concerning base station energy efficiency. The second aim of this study is to provide new insight into the GHG emission reduction potential within the rapidly growing mobile telecommunications sector and the energy sector through decentralized energy production using base stations.

The carbon handprint study of a liquid-cooled base station, previously summarized by Vatanen et al. [14], is discussed in detail in the following sections.

## 2. Materials and Methods

This study utilized the LCA-based carbon handprint approach that was first published by Grönman et al. [4] and further guided by Pajula et al. [16] and Vatanen et al. [17]. Figure 1 summarizes the four stages that contain ten key steps in determining the carbon handprint of a liquid-cooled base station in three scenarios. The next section describes the liquid-cooled base station technology,

and thereafter, each step and its implication to the liquid-cooled base station case is presented in the following sections.

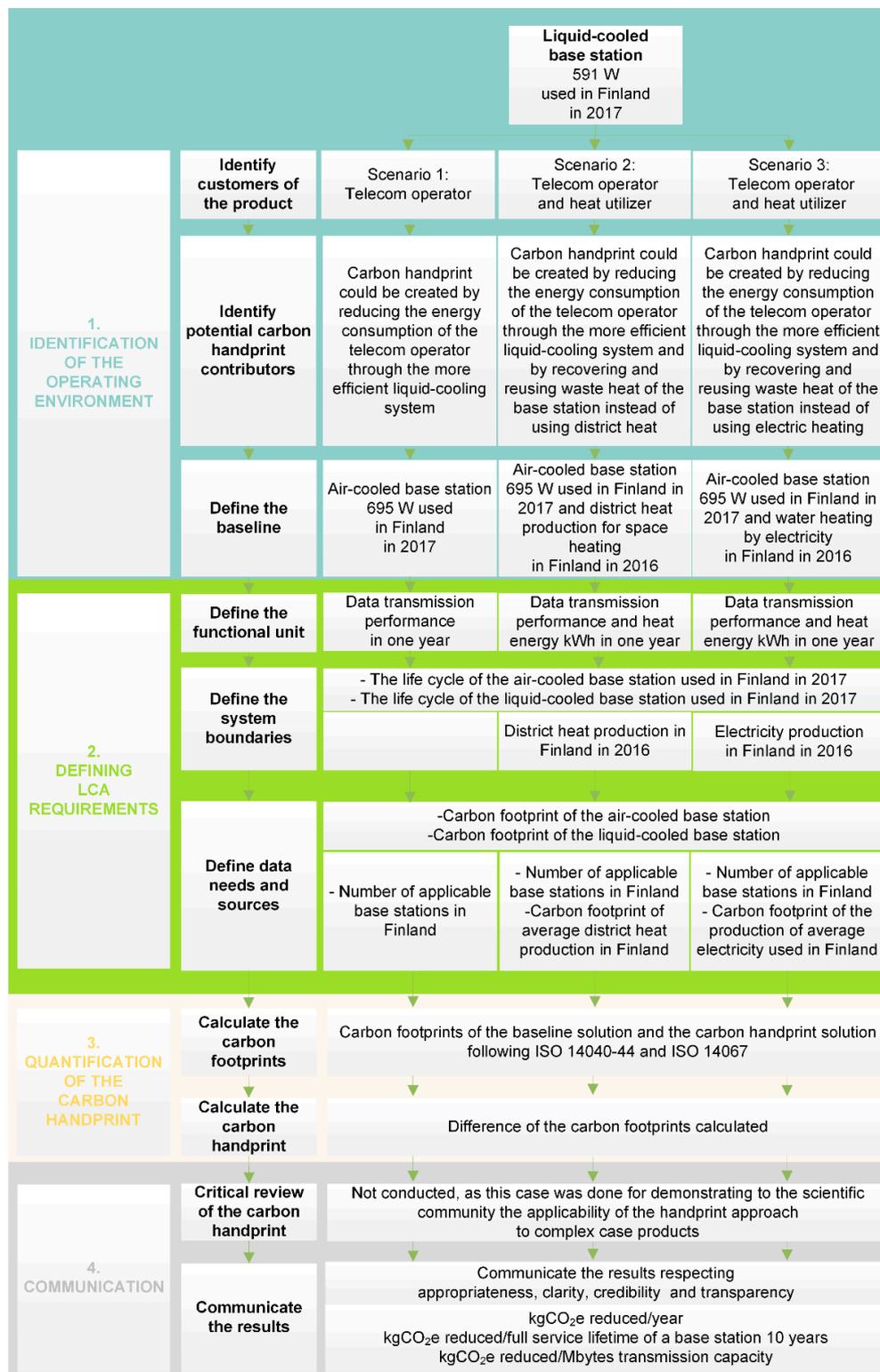


Figure 1. Stages and steps for determining the potential carbon handprint of the liquid-cooled base station [4,16,17]. LCA: life cycle assessment.

### 2.1. Description of the Proposed Handprint Solution Liquid-Cooled Base Station Technology

This section elaborates on the reasons for the selection of the potential handprint solution according to Grönman et al. [4]. Base stations provide mobile telecommunications services by transmitting radio signals and are responsible for the majority (nearly 60%) of the power consumption of the mobile telecommunications infrastructure [10] and the majority, reportedly over 80%, of the carbon footprint [14]. Typical base station components and layout are described, for example, in Han et al. [10]. Common solutions for reducing the energy consumption and carbon footprint of base stations include the use of renewable energy sources, improving the efficiency of the power amplifier and antennas, reorganization of the base station layout to minimize energy losses in cables between them [10], and deactivating parts of the hardware during low data-traffic volume [10,12].

According to the base station manufacturer Nokia, 20–30% of the energy consumption of a base station is converted to a radio signal and the remaining 70–80% is converted to waste heat [17], which requires heavy cooling equipment. The current practice is to use air for cooling base stations. However, Nörtershäuser et al. state that replacing air cooling with liquid cooling using water as a cooling agent saves energy [5]. In comparison to air-cooled base stations, heavy ventilation and air-conditioning are avoided [5]. The base station manufacturer estimates that if a base station's air ventilation system is replaced by a liquid cooling system, energy savings up to 15% can be achieved [17]. The manufacturer further states that liquid cooling increases product reliability and decreases the demand for maintenance by eliminating the need for exchanging air filters. The energy savings could reduce the carbon footprint of the base station and create a positive climate impact.

Typical limitations related to the air-cooling of electronic components are the low heat-carrying capacity of air and low heat-transfer rates between the surface of the components and the air [18]. These limitations can be evaded through liquid cooling, which consequently produces higher temperature waste heat [7,18]. Since liquid is a better heat transfer medium than air, liquid cooling provides an increased opportunity to utilize the waste heat [5], while avoiding the wasting of heat further benefits the climate. Wahlroos et al. reached a similar conclusion in a data center context [19]. Waste heat from data centers is already being systematically recovered and utilized, for example, for district heating in Finland [20]. Using liquid as a heat transfer medium further enables device miniaturization and an increase in power density [5]. In addition, liquid cooling helps reduce noise pollution in comparison to air cooling [6].

In this carbon handprint study, a small-sized liquid-cooled base station unit, the power consumption of which is 591 W, used in Finland in 2017, was selected as the potential handprint solution. According to the manufacturer, the power consumption of the base station equipment is typically 2–5 kW and can reach 10 kW. It was assumed that 80% (473 W) of the power consumption of the liquid-cooled base station (591 W) is converted to waste heat (4143 kWh/a) [17], which must be removed from the system and can be used for further heating purposes. According to the manufacturer, waste heat from the liquid-cooled base station is provided in a liquid form from the cooling system, has a volumetric flow of approximately 2 liters per minute, and a temperature between 50–60°C [17]. The liquid cooling agent used in the base station is water [5,7]. Additionally, some antifreeze and anti-corrosive agents may be added. The specific heat of water 4183 J/kg·°C was assumed as a sufficient approximation of the specific heat of the liquid cooling agent. In contrast, the specific heat of air is 1005 J/kg·°C at 20 °C [5].

### 2.2. Identification of the Operating Environment

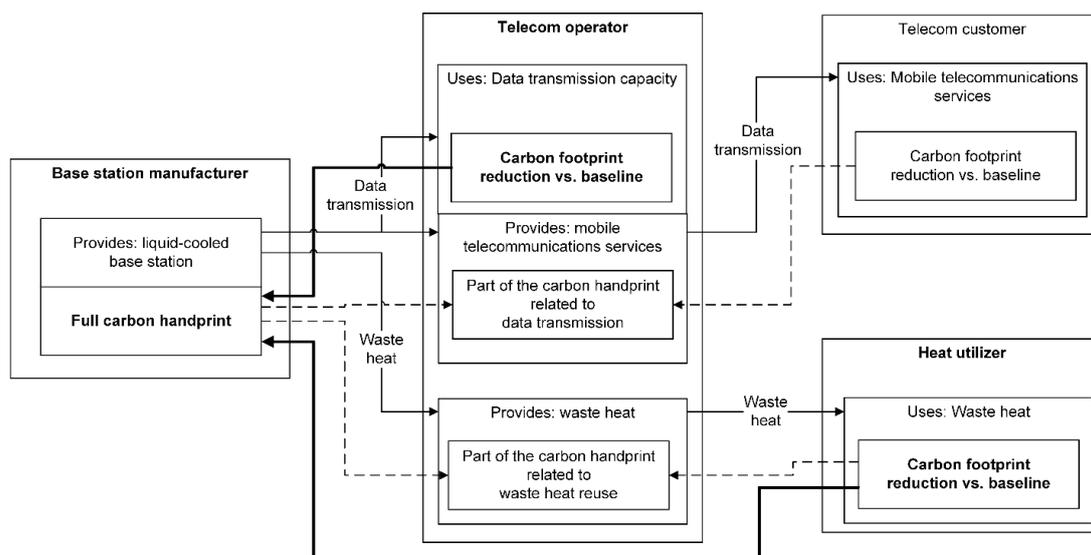
Identification of the operating environment is the core of the carbon handprint approach and distinguishes its special characteristics in the context of a LCA. In this stage, customers of the liquid-cooled base station are identified, a hypothesis is created for the mechanisms that potentially allow for a carbon footprint reduction when the liquid-cooled base station is used, and the baseline for the comparison of GHG emissions is defined.

### 2.2.1. Identification of Potential Customers and Contributors to Reduced GHG Emissions

Because a carbon handprint is only created when the carbon footprint of customers can be reduced, it is of key importance how the proposed handprint solution (in this case: liquid-cooled base station) is actually used and who the customers are [4]. Telecommunications network operators (hereafter: telecom operators) that use the data transmission/mobile telecommunications service represent the primary customers of both air-cooled and liquid-cooled base station manufacturers. In addition, the recoverable waste heat from liquid-cooled base stations can be utilized for multiple purposes. The telecom operator then decides whether they provide the waste heat to further customers. A minor share of the waste heat could be utilized for heating or cooling the base station site; however, the telecom operator will not need most of the waste heat for its own use, and the operator's own use is excluded from this study. Possible utilization of the waste heat by further customers potentially adds to the carbon handprint of the liquid-cooled base station.

Different combinations can be made of potential customers who use the mobile telecommunications service and waste heat. Therefore, in this theoretical case study, the handprint quantification was conducted for three scenarios that represent relevant customer combinations. In cases where the exact actual customers and uses are predetermined, the handprint quantification is more straightforward and does not require scenarios.

Figure 2 depicts customer relations related to the two uses of the liquid-cooled base station (data transmission for mobile telecommunications and heat production). This study considered the handprint that can be attributed to the liquid-cooled base station manufacturer and the liquid-cooled base station as a whole according to its realized uses, regardless of whether the user is a direct customer of the base station manufacturer or further down the supply chain. The telecom operator decides whether they provide the waste heat to further customers. Possible utilization of the waste heat by further customers potentially adds to the carbon handprint of the liquid-cooled base station. In other words, this study considered the full potential of a liquid-cooled base station's carbon handprint in the case of different uses. The full carbon handprint of the manufacturer, i.e., the telecom operator's carbon footprint reduction equals the carbon footprint reduction of all telecom customers because they use the same data transmission function of the base station.



**Figure 2.** Customers and uses of the liquid-cooled base station: The bold font shows the carbon handprint studied and the potentially reduced carbon footprints of customers that create the carbon handprint.

All three scenarios include telecom operators as the primary direct customers of the liquid-cooled base station manufacturer and the mobile telecommunications function of the base stations.

Additionally, two scenarios include potential waste heat utilizers as indirect customers. Each scenario described below further explains the potential contributing factors to reducing the GHG emissions for each customer combination.

In Scenario 1, the customer is a telecom operator. Scenario 1 does not consider waste heat recovery opportunities and simply quantifies the climate impacts of the primary function of a base station. The energy savings due to the use of liquid as a cooling agent instead of air could reduce the carbon footprint of the base station and create a carbon handprint for the base station manufacturer.

For establishing Scenarios 2 and 3, a variety of potential uses exists for the waste heat. The waste heat from liquid-cooled base stations is comparable to the waste heat from data centers in that both produce low-grade waste heat. Liquid-cooled data centers typically produce a heat output at 50–70 °C [18,21,22], and air-cooled data centers at 25–45 °C [18,21,23]. According to the base station manufacturer, the heat output of liquid-cooled base stations is typically at 50–60 °C [17]. Scientific literature suggests the following recovery options for the data center waste heat: space or water heating; cooling; and clean water production through desalination [21,22]; district heating; power plant co-location; direct or indirect power generation; and biomass processing [21].

Because radio base station antennas are typically installed on masts or on the roofs or walls of residential or public buildings [24], they are in close proximity to the heat demand and heating infrastructure. The heating of spaces and domestic water accounts for the majority of total energy consumption in residential buildings in Finland (238,533 TJ in 2016) at 68% and 15%, respectively. Space heating may be required throughout the year due to the climatic conditions, while relatively large fluctuations in heating demand occur depending on the season and daily temperatures. Space and water heating can, thus, be reasonably selected as potential applications for the waste heat from liquid-cooled base stations.

In Scenario 2, the customers are a telecom operator and a heat utilizer, which is an energy company or a building owner that uses the heat for space heating. The reduction of the telecom operator's energy consumption could create a carbon handprint, as in Scenario 1. The reuse of waste heat in space heating, replacing other heat energy produced in Finland while avoiding the wasting of heat, could further add to the carbon handprint.

In Scenario 3, the customers are a telecom operator and a heat utilizer, which is a building owner that uses the heat for heating domestic water. Reduction of the telecom operator's energy consumption and reuse of waste heat for water heating in the building that accommodates the base station, replacing other heat production for water heating purposes in Finland while avoiding the wasting of heat, could create a carbon handprint.

The energy company in Scenario 2 could be a local operator that receives the waste heat into a district heating network to provide heating services to its customers. In Finland, waste heat is the source of approximately 9% of district heat [25]. Local energy companies are introducing open district heating networks, to which various operators can sell their waste heat [26,27]. For example, the waste heat from Elisa, Ericsson, Tieto, and Yandex data centers is already widely utilized as an energy source for district heating in southern Finland [26,28]. The annual heat output of each of these data centers to district heating ranges from 10–20 GWh [26,28]. In comparison, the reusable annual heat output of the 591 W base station is of a few MWhs in magnitude.

The low temperature of heat recovered from air-cooled data centers, 25–45 °C according to different references, must be raised to at least 65–75 °C by using heat pumps to make the heat applicable in district heating networks [18,21,23], in which the temperature of the supply heating water is 65–115 °C depending on the weather [29]. In contrast, the waste heat from liquid-cooled data centers in the range 50–70 °C is more readily applicable for district heating purposes [18,21,22]. According to the manufacturer, the output heat temperature of liquid-cooled base stations is usually 50–60 °C [17], which makes the waste heat applicable for district heating. The base station manufacturer states that the waste heat can be fed into the return pipe of the district heating network, in which the water temperature is 40–60 °C [29]. This opportunity is similarly acknowledged for data centers [19].

An advantage of feeding the waste heat to the district heating network is a steadier heat demand than, for example, in direct space heating [18].

The owner of the building accommodating the base station could directly utilize the waste heat for heating spaces (Scenario 2) or domestic water (Scenario 3) in the building by acquiring the heat recovered from the base station. The owner could also acquire alternative heat energy when heating demand exceeds the base station's heat supply. As base stations are typically located on the roofs or walls of apartment buildings [24], the building owner could be a condominium.

### 2.2.2. Defining the Baseline Situations

In Scenario 1, in which the telecom operator is the sole customer, the baseline is a conventional air-cooled base station without energy reuse delivering the same function as the liquid-cooled base station in mobile telecommunications. The power consumption of the baseline air-cooled base station is 695 W, in contrast with the power consumption of 591 W of the liquid-cooled base station. It is assumed that both base stations were used in Finland in 2017.

In Scenario 2, in which the telecom operator and the heat utilizer are customers, the baseline situation includes two baseline products or services. The first was a conventional 695 W air-cooled base station without waste heat recovery, which delivers the same function as the 591 W liquid-cooled base station in providing mobile telecommunications in Finland in 2017. Second, Finnish district heating delivered the same amount of heat as the liquid-cooled base station for space heating.

District heating is the most common heating method in Finland [30], and therefore, a relevant baseline solution for the base station waste heat. District heating heats both spaces and water [31]. District heating provided 40% of the heating energy for residential, commercial, and public buildings in Finland in 2016 [32]. In residential buildings, district heating provided 31% of the space heating in Finland in 2016 (161,834 TJ), followed by wood (28%), electricity (23%), and several minor energy sources (heat pumps 10%, light fuel oil 7%, natural gas 1%, heavy fuel oil <1%, peat <1%, and coal <1%) [31]. The production efficiency of district heating was 91% in 2016 [33]. Approximately 75% of the district heating is produced through combined heat and power production (CHP) [34] and the remaining 25% solely as heat [30].

In Scenario 3, in which the telecom operator and the heat utilizer are customers, the baseline situation again includes two baseline products or services. The first was the conventional 695 W air-cooled base station without waste heat recovery, as in the other two scenarios. Second, electricity delivered the same amount of heat as the liquid-cooled base station for water heating.

Although district heating is the most common water heating method in Finland, electrical water heating was selected as the baseline in Scenario 3 to add versatility to the results for exemplary reasons. Electricity is a relevant energy source for water heating since, in the heating of domestic water in Finland in 2016 (35,861 TJ), district heating provided 53% of the required energy, followed by electricity, which provided 26% [31]. The remaining water heating energy demand was covered by several minor energy sources (heat pumps 8%, light fuel oil 7%, wood 5%, natural gas 1%, heavy fuel oil <1%, peat <1%, and coal <1%) [31].

### 2.3. Defining LCA Requirements

The carbon handprint approach is based on standardized life cycle assessment (ISO 14040-44 [35,36]) and carbon footprint (ISO 14067 [37]) methods [4]. In this stage, the features needed in an LCA assessment are defined. These include defining the functional unit, system boundaries, and data needs and sources.

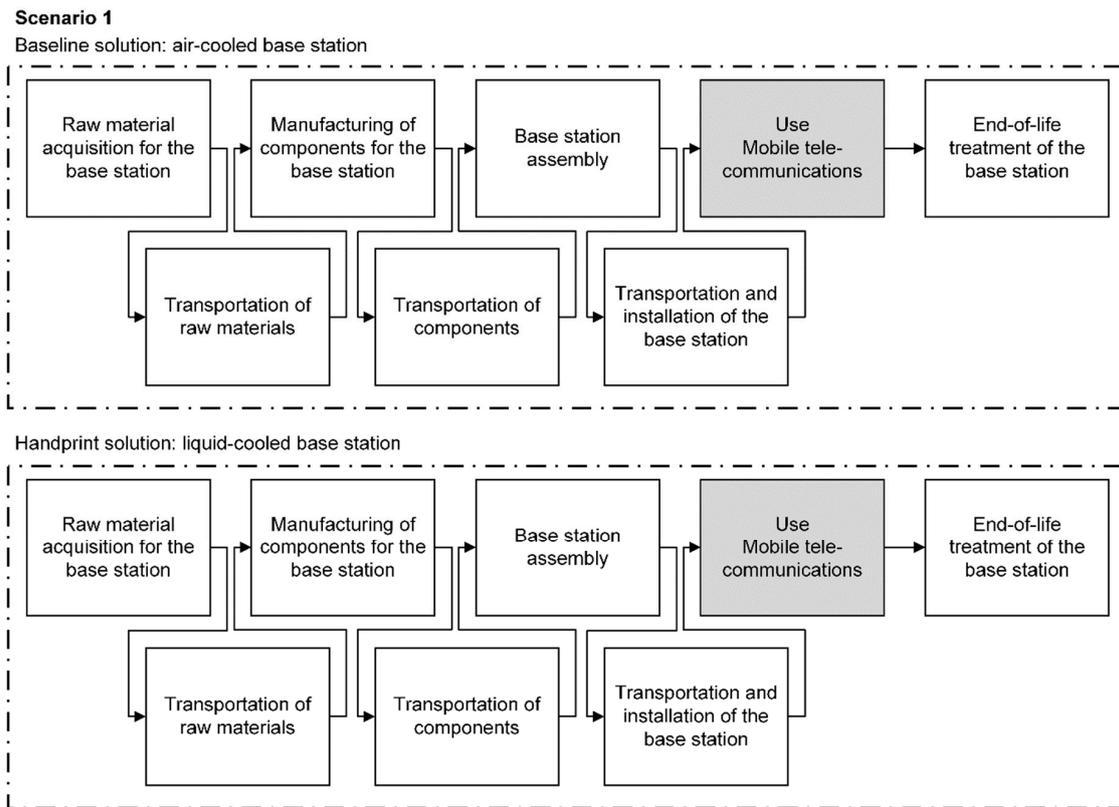
#### 2.3.1. Defining the Functional Units

The functional unit, which represents the mobile telecommunications function in all scenarios, was the data transmission performance of one base station in one year. The functional unit,

which represents heat in Scenarios 2 and 3, was the amount of heat energy in kWh recovered for reuse from one liquid-cooled base station in one year (4143 kWh/a).

### 2.3.2. Defining the System Boundaries

Figure 3 shows the system boundaries in Scenario 1. The cradle-to-grave life cycles of both base stations were considered. Raw materials and components of both base stations were included as close to 100% as possible, and no cut-off criteria were used. It was assumed that base stations were treated as waste electrical and electronic equipment at the end-of-life stage, whereas assuming recycling could have somewhat decreased the carbon footprint of both handprint and baseline solutions.

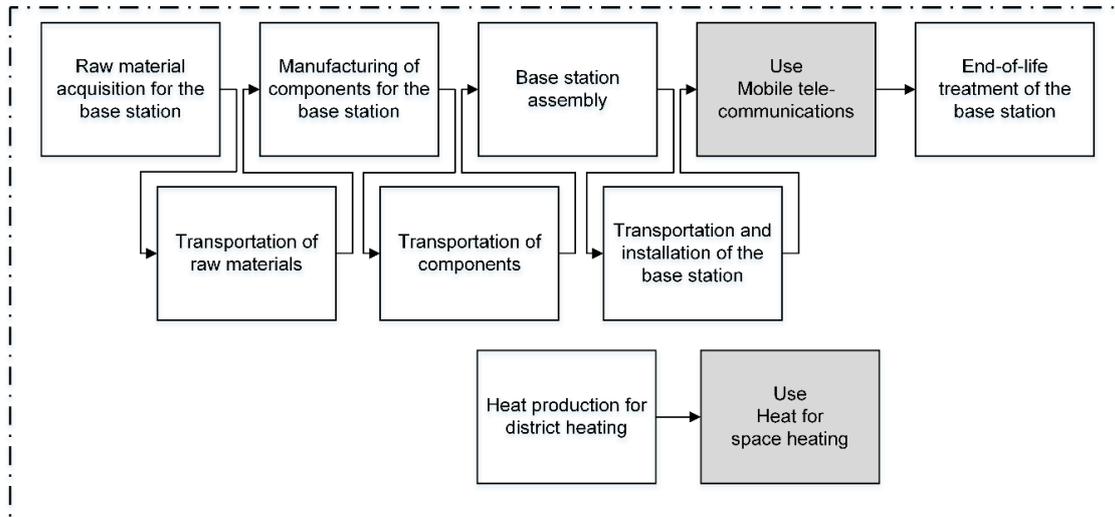


**Figure 3.** System boundaries in Scenario 1: The use stage is highlighted with grey to emphasize the base station user (customer), whose carbon footprint should be reduced to create a carbon handprint.

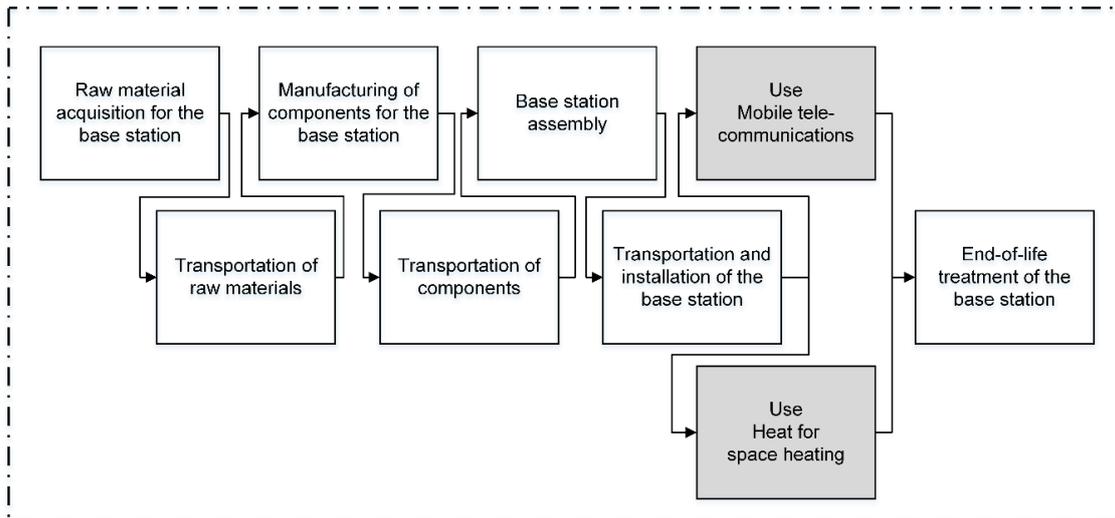
Figure 4 shows the system boundaries in Scenario 2. In the baseline situation, it was assumed that the waste heat from the air-cooled base station could not be recovered. Instead, the same amount of heat as recovered from the liquid-cooled base station (assumption: 80% of the power consumption, 473 W, 4143 kWh/a) must be produced by district heating. Raw material acquisition, fuel refining, and transportation were excluded and only the energy production for district heating (fuel combustion) stage was included. In the handprint solution, it was assumed that heat exchangers or heat pumps—required for reusing the recovered waste heat for district or space heating—were readily in place and their life cycles are not included in the carbon handprint quantification. The same assumptions concerning the system boundaries of the base stations in Scenario 1 applied in Scenario 2.

**Scenario 2**

Baseline solution: air-cooled base station plus district heating

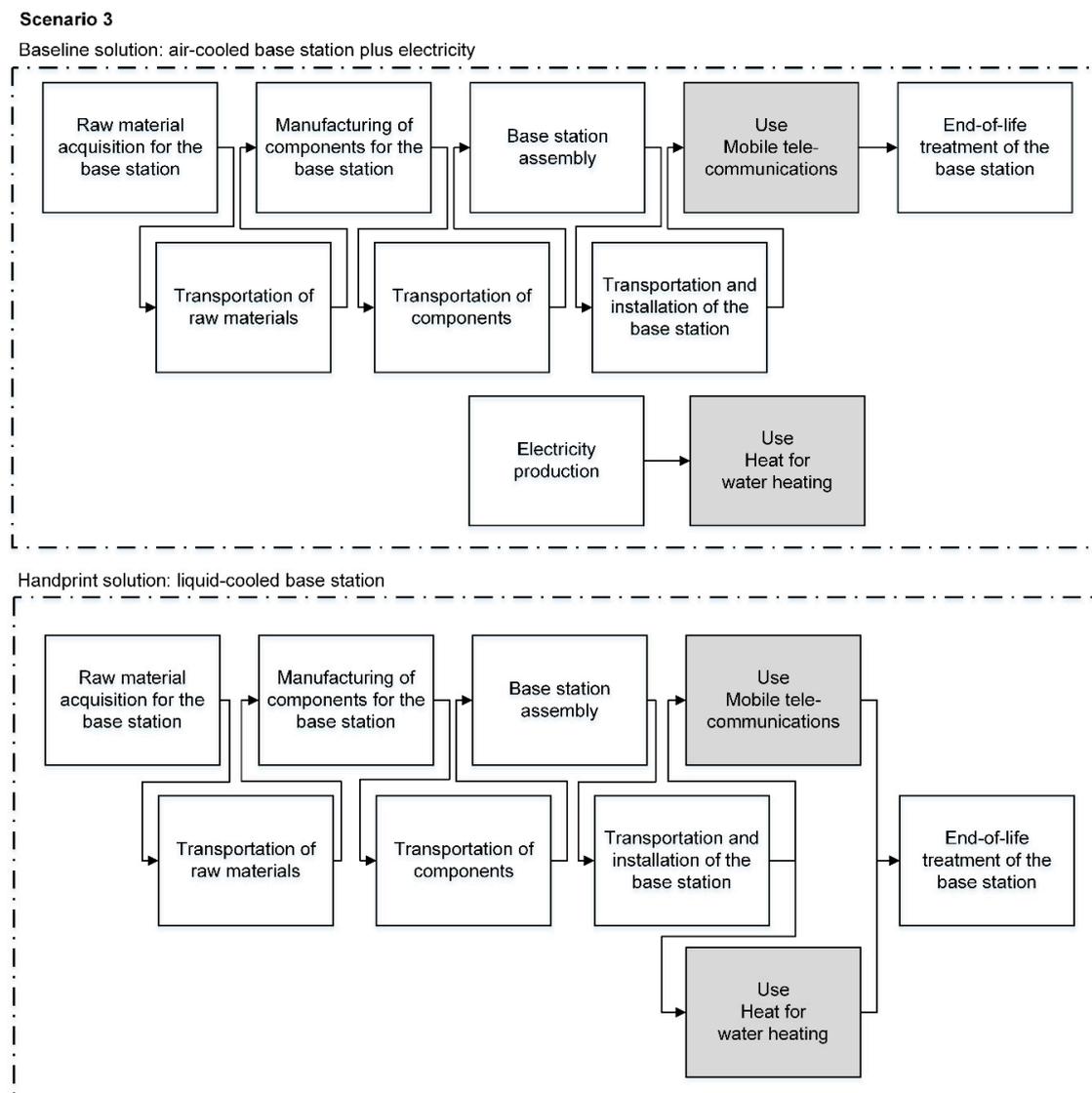


**Handprint solution: liquid-cooled base station**



**Figure 4.** System boundaries in Scenario 2: The use stage is highlighted with grey to emphasize the base station users (customers), whose carbon footprint should be reduced to create a carbon handprint.

Figure 5 shows the system boundaries in Scenario 3, in which the waste heat replaced electrical water heating, alongside the mobile telecommunications function. Otherwise, the system boundaries in Scenario 3 were based on the same assumptions as in Scenarios 1 and 2.



**Figure 5.** System boundaries in Scenario 3: The use stage is highlighted with grey to emphasize the base station users (customers), whose carbon footprint should be reduced to create a carbon handprint.

### 2.3.3. Defining Data Needs and Sources

Data used in carbon handprint quantification must be representative and accessible [4]. The geographical scope of the carbon handprint study was Finland, i.e., the liquid-cooled base station and its baseline products were utilized in Finnish conditions. The temporal scope of the study covered 2016–2017. It was assumed that the air-cooled and liquid-cooled base stations were used in 2017. District heating and electricity production data from 2016 was used.

In this study, actual customers were not specified, and instead, the three scenarios concentrated on potential customers. This choice required making assumptions and using average data, especially for the heat utilizers and production. However, telecom operators as a potential customer group are quite well-defined because three operators own a 99% market share in Finland [13].

Primary data was collected from air-cooled base stations that are applicable as a baseline for liquid-cooled base stations in 2017 and can be realistically replaced by liquid-cooled base stations. These are especially applicable for building sites, whereas waste heat recovery from masts is unfeasible. The base station manufacturer Nokia provided primary data on the base station technology. Part of the data cannot be disclosed due to competitive and confidentiality reasons.

LCA modeling was conducted in 2017 using GaBi software provided by Thinkstep, based in Stuttgart, Germany. GaBi and Ecoinvent databases were used as an additional data source in raw material and component manufacturing stages and for modeling transportation processes.

#### 2.4. Quantification of the Carbon Handprint

In this stage, the carbon footprint of the liquid-cooled base station and the baseline situation were calculated for each scenario. The carbon handprint was attributed for the liquid-cooled base station if it enabled a carbon footprint reduction for the customer against the baseline situation. In Scenario 1, the carbon footprints of the 591 W liquid-cooled base station and the 695 W air-cooled base station were quantified and compared to quantify the carbon handprint. Scenarios 2 and 3 required additional carbon footprint calculations for the waste heat, district heating, and electrical water heating. The summarized carbon footprint of the baseline air-cooled base station and heating solutions were compared with the carbon footprint of the liquid-cooled base station to determine the carbon handprint.

For the waste heat recovery in Scenarios 2 and 3, it was assumed that 80% (473 W) of the power consumption of the liquid-cooled base station (591 W) was converted to waste heat (4143 kWh/a) [17]. The telecom operator's waste heat utilization for heating or cooling of the base station site was not included in the calculation. All the recovered waste heat was assumed to be reused, regardless of possible seasonal, hourly, local, or other variations in heat demand related to, for example, the outdoor temperature, weather conditions, or the special characteristics of the heat user. Allocation was avoided by expanding the product system to include the waste heat, i.e., no GHG emissions were allocated to the waste heat because the heat was an unwanted and unavoidable by-product; optimization of heat production and recovery is not a design criterion for base stations and no base stations are primarily installed for heating purposes. Usually, the common three-step allocation procedure according to ISO 14044 [36] and ISO 14067 [37] is applicable in the handprint approach [4].

To determine the carbon footprints of district heating (Scenario 2) and electrical heating (Scenario 3), it was assumed that the same amount of heating must be produced by district and electrical heating as by the liquid-cooled base station (4143 kWh/a). Motiva determines and annually updates average CO<sub>2</sub> emission coefficients for district heating and electricity consumption in Finland [38]. The average CO<sub>2</sub> coefficients only include emissions from the combustion of fuels, while other life cycle stages are excluded [39]. Motiva's emissions coefficients were used for estimating the life cycle CO<sub>2</sub> emissions from the district heating production in Scenario 2 and electricity production in Scenario 3. The average CO<sub>2</sub> emission coefficient for district heating produced by CHP production, used in this study, was 188 kg<sub>CO<sub>2e</sub></sub>/MWh [38]. In Finland, 75% of district heating is produced by CHP [34], and thus, CHP is a valid assumption. The average CO<sub>2</sub> emission coefficient for district heating produced by CHP production is based on a three-year moving average from 2014–2016 [38,39]. During the reference period, wood fuels (30%), coal (21%), natural gas (16%), and peat (15%) were the most common fuels used in district heating production [40]. The coefficient is determined by allocating fuels and emissions of CHP production in relation to alternative acquisition methods of fuel consumption [41]. Condensing power for electricity and water boiler heating for heat are used as alternatives [41].

The average CO<sub>2</sub> emission coefficient for electricity used in the calculation, based on a five-year moving average in 2012–2016, was 164 kg<sub>CO<sub>2e</sub></sub>/MWh [38,39]. During the reference period, the most common energy sources in electricity generation were, on average, nuclear energy (34%), hydropower (24%), biomass fuels (16%), and coal (10%) [42].

#### 2.5. Communication

The final stage in the carbon handprint approach is communicating the results and, if required, performing a critical review [4]. A suitable unit must be selected for communicating the results, depending on the target audience and communication purpose [4]. The communication unit selected can be the functional unit or a more descriptive unit, which represents the emission reductions during

the life cycle of the base station [4]. Communications aspects of multi-purpose and multi-customer products are discussed further in Section 4.

### 3. Results

Figures 6–8 show a suggestion of how the carbon handprint results could be presented and further communicated in the three scenarios of this study, in accordance with the first research aim. As for communicating the multi-purpose products’ carbon handprint, in this study, the carbon handprint attributable to the liquid-cooled base station and its manufacturer is presented as a difference between the baseline and handprint solution’s carbon footprint. In Scenarios 2 and 3, the carbon footprints of the liquid-cooled base station’s two services are presented as an aggregated figure.

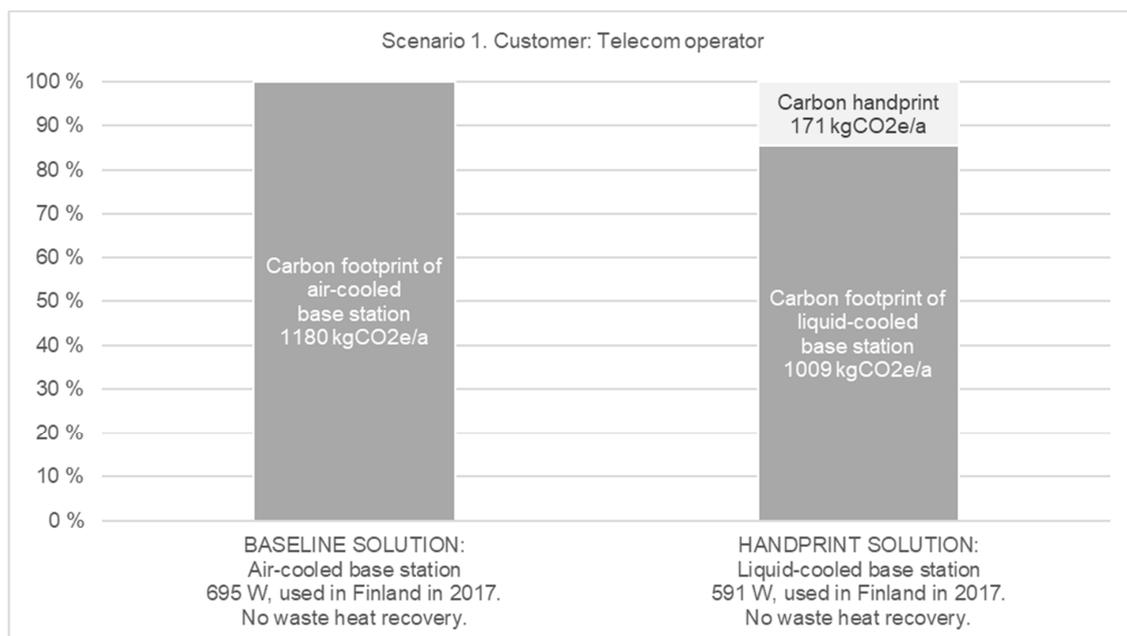


Figure 6. Carbon handprint in Scenario 1.

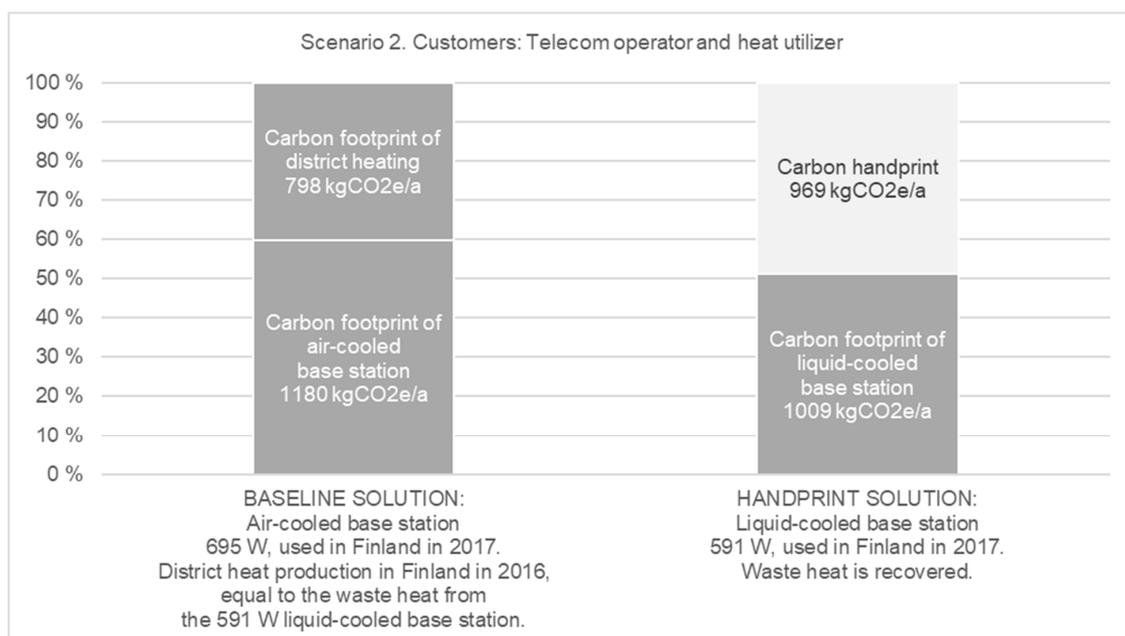


Figure 7. Carbon handprint in Scenario 2.

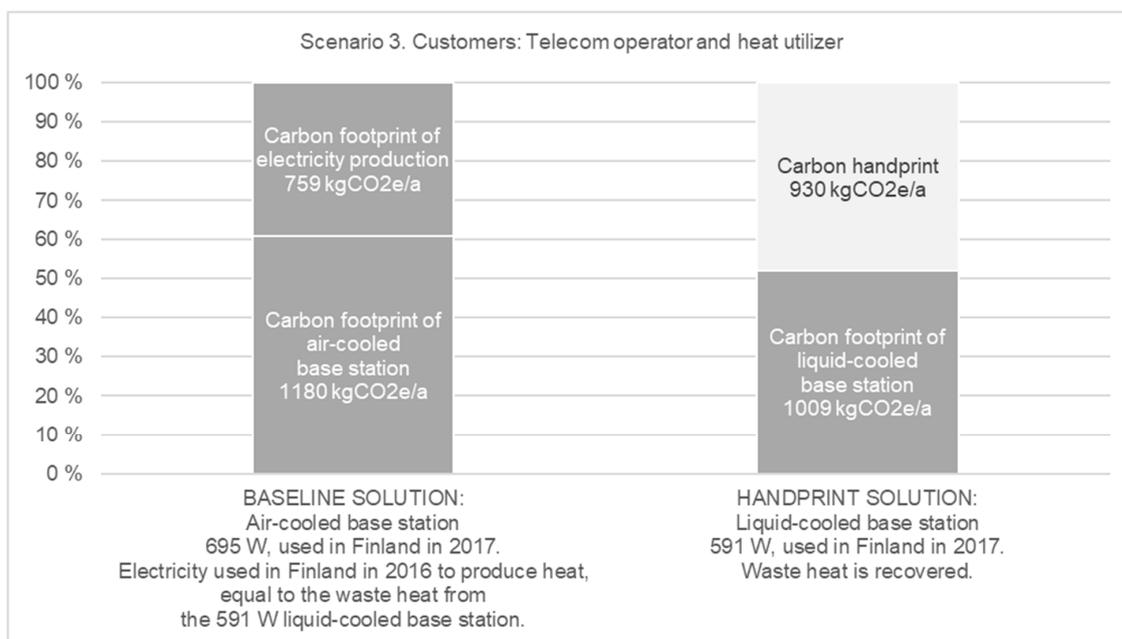


Figure 8. Carbon handprint in Scenario 3.

The carbon handprint in Scenario 1 was 171 kgCO<sub>2e</sub>/a. This 14.5% smaller carbon footprint of the handprint solution in comparison to the baseline solution was mainly due to a decrease in energy consumption in the base station use stage. In contrast, the difference in GHG emissions was marginal between the air-cooled and liquid-cooled base stations in the manufacturing and end-of-life stages. Figure 6 shows the carbon footprints of the baseline and handprint solution and carbon handprint in Scenario 1.

When waste heat recovery was included in the carbon handprint quantification, relevant for the second research aim, the carbon handprint in Scenario 2 was 969 kgCO<sub>2e</sub>/a. The liquid-cooled base station reduced the energy consumption of mobile telecommunications and the waste heat was reused for space heating, replacing Finnish district heating. The carbon handprint, thus, consisted of the 171 kgCO<sub>2e</sub>/a reduction plus the carbon footprint of district heating: 798 kgCO<sub>2e</sub>/a. The total reduction of carbon footprint was 49% when the handprint solution replaced the baseline solution. Figure 7 shows the carbon footprints of the baseline and handprint solutions and the carbon handprint in Scenario 2.

The carbon handprint in Scenario 3, which also included waste heat recovery relevant for the second research aim, was 930 kgCO<sub>2e</sub>/a. The liquid-cooled base station reduces the energy consumption of mobile telecommunications and the waste heat was reused for water heating, replacing electricity production in Finland. The carbon handprint, thus, consisted of the 171 kgCO<sub>2e</sub>/a reduction plus the carbon footprint of electricity production: 759 kgCO<sub>2e</sub>/a. The total reduction in the carbon footprint when the handprint solution replaced the baseline solution was 48%. Figure 8 shows the carbon footprints of the baseline and handprint solution and carbon handprint in Scenario 3.

#### 4. Discussion

To discuss the first research aim and the related methodological research question of this study regarding the carbon handprint quantification and communication of multi-purpose and multi-customer products, first, this study demonstrated that the carbon handprint approach was applicable to multi-purpose/customer products. Second, the demonstration was further comparable, applicable, and generalizable to such multifunctional products, which intentionally provide multiple simultaneous functions for customers as, for example, described in the International Reference Life Cycle Data System (ILCD) Handbook [43]. However, there are some challenges that should be further discussed and studied.

In this study, the telecommunications service was the main function of base stations, whereas waste heat from the liquid-cooled base station was an additional, unavoidable by-product. Therefore, the aggregation of telecommunications and heating carbon footprints in handprint communication, as in Figures 7 and 8 that address Scenarios 1 and 2, respectively, was justifiable. In contrast, if generalized to multifunctional products, which provide multiple hierarchically equal functions for multiple customers, the presentation and communication of the handprint results require more careful deliberation. It is possible that at least one function of a handprint solution performs similarly or worse than a baseline solution with regard to GHG emissions, i.e., it has a larger carbon footprint than the baseline solution of that specific function, even though the handprint solution would seem to create a carbon handprint as a whole. To establish clear handprint communications to different customers, we suggest distinguishing it function by function in terms of whether a carbon handprint is achieved or a larger carbon footprint created in comparison to each baseline. A true total carbon handprint is not created if any function of the handprint solution creates a larger carbon footprint than the baseline solution of that function.

The communication stage of the handprint approach comprises a critical review of the handprint, in accordance with the ISO 14040-44 instructions concerning comparative assertions [35,36] and the ISO 14026 instructions on footprint communication [44], and the definition of the unit for clear communication of the results [4,16]. This handprint study is limited in that the critical review was not conducted. However, this study mainly concerned the demonstration of the handprint approach to complex cases. These contributions were assumed to be of interest, predominantly to the scientific community and LCA practitioners. The carbon handprint results for this base station case are probably primarily applicable in the customer relationship between the base station manufacturer and its primary customer [16], the telecom operator, for comparing the climate benefits of liquid-cooled and air-cooled base stations, which are provided by the same manufacturer. Thus, the main competition probably occurs between the manufacturer's own products. A critical review is recommended if the liquid-cooled base station manufacturer is to further communicate the handprint it achieves when its product is utilized in those ways and creates the conditions specified in the scenarios, especially in consumer communications [17] and comparative assertions [35]. A few suggestions for the communication unit include kgCO<sub>2</sub>e reduced/year, kgCO<sub>2</sub>e reduced/full service lifetime of a base station over 10 years [10], or kgCO<sub>2</sub>e reduced/Mbytes transmission capacity.

This study did not allocate the carbon handprint between the supply chain operators, but instead assumed a shared handprint. In contrast, the International Council of Chemical Associations (ICCA) and World Business Council for Sustainable Development (WBCSD) distinguish different operators' share of the avoided emissions in a supply chain [45]. The telecom operator is responsible for the further realization of the handprint potential related to the waste heat reuse. The telecom operator should, thus, understand from communications from the manufacturer that only that part of the carbon handprint of the liquid-cooled base station related to the telecom operator's own use, i.e., providing mobile telecommunications, can reduce its own carbon footprint. Instead, if the waste heat is reused, the handprint potential related to the waste heat reuse that reduces the heat customer's carbon footprint is realized and becomes the telecom operator's handprint, shared with the liquid-cooled base station manufacturer. In the case of district heating, the realization of waste heat reuse is, however, subject to additional investment costs due to connecting to the district heating network [46]. Among the heat customers, energy companies could be interested in reducing their carbon footprint, and therefore, in carbon handprint communications from the upstream. In contrast, condominiums or consumers are more likely to value such communications less, having more interest in the service prices, which eventually determine the demand for the waste heat versus district or electrical heating. While numerically allocating a carbon handprint between the supply chain operators could be challenging or even unnecessary, as opposed to ICCA's and WBCSD's approach, different operators' contributions to total carbon handprint could be terminologically distinguished in communications to emphasize their roles in a shared handprint.

The second research aim of this study, concerning the carbon handprint and GHG emission reduction potential provided by the liquid-cooled base station technology within the mobile telecommunications and energy sectors, was also discussed. Because the handprint approach is by default linked to the operating environment in terms of the customers, the mechanisms that create the carbon handprint, and the baseline solutions, the current results are applicable in Finland in the case of average potential customers. As for a larger-scale regional climate change mitigation potential of liquid-cooled base station expansion, the three major telecom operators in Finland have multiple base stations at approximately 2000 building sites according to the base station manufacturer's estimate. If air-cooled base stations were exchanged for liquid-cooled base stations at 200 building sites per year, assuming three base stations were located at each site (typically, base stations of different telecom operators are located at the same site [47] or different generation network base stations are located at the same site), the potential carbon handprint exceeds 100,000 kg<sub>CO<sub>2</sub>e/a</sub> without waste heat reuse and 550,000 kg<sub>CO<sub>2</sub>e/a</sub> when waste heat is reused and replaces heat energy from district heating or produced from electricity. Similar climate benefits may be achievable from liquid-cooled base stations in the case of other customers and outside of Finland, and the global positive climate impact of a liquid-cooled base station expansion in the mobile telecommunications network could be significant. However, the study should be repeated in the local operating environment to verify the benefits. Future research could also cover other types of scenarios. For instance, examinations of Stirling engines for microgeneration [48], or organic Rankine cycle (ORC) [49] or thermoelectric generator [50], might be relevant for utilizing low-grade waste heat.

The carbon handprint results of the liquid-cooled base station include the following uncertainties. The actual fuels utilized for producing district heating or electricity used by the customer and replaced by the waste heat from the liquid-cooled base station affect the carbon handprint result. For example, the average CO<sub>2</sub> emission coefficient of district heating in Finland varies from 20 to 450 kg<sub>CO<sub>2</sub>/MWh</sub> depending on the location and on whether the district heating is produced by CHP or another heat production method [38]. This study used the coefficient value of 188 kg<sub>CO<sub>2</sub>/MWh</sub>. The raw material acquisition of fuels, fuel refining, and transportation stages related to district heating and electricity production were excluded from the baseline situations in Scenarios 2 and 3. Their inclusion, resulting in a larger baseline carbon footprint, would increase the carbon handprint of the liquid-cooled base station. In addition, heat demand and applications differ according to the local climate conditions, infrastructure, type of area (residential, industrial, etc.), and energy efficiency. Similarly, Zimmermann et al. state that the data center location is an important choice regarding the economic value of the waste heat due to location-specific differences [22]. In this study, all the recovered waste heat was assumed to be reused regardless of possible variations in heat demand. Especially, the need for space heating varies seasonally, and taking this into consideration would lower the carbon handprint achieved in Scenario 2. In contrast, the demand for hot domestic water, as in Scenario 3, could be assumed as more likely to be independent of the season. Furthermore, the current carbon handprint results do not include the carbon footprints of heat exchangers or heat pumps, which are required for reusing the waste heat produced by the liquid-cooled base station. Their inclusion would decrease the carbon handprint of the liquid-cooled base station. The waste heat recovery efficiency further affects the results, which are currently based on the assumption that all produced waste heat is recoverable, whereas, for example, Zimmermann et al. observed an 80% waste heat recovery rate in a hot water cooled data center [22].

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