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Expansion of Sewer, Water and District Heating Networks in Cold Climate Regions: An Integrated Sustainability Assessment

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Abstract: This study presents an integrated sustainability assessment of technical alternatives for water and heating services provision in suburban areas affected by a cold climate. Each alternative combines a drinking water supply, sewerage (gravity or low-pressure), pipe freeze protection (deep burial or shallow burial with heat tracing) and heating solution (district heating or geothermal heat pumps). An innovative freeze protection option was considered, in which low-temperature district heating (LTDH) is used to heat trace shallow sewer and water pipes. First, the performance of each alternative regarding seven sustainability criteria was evaluated on a projected residential area in Sweden using a systems analysis approach. A multi-criteria method was then applied to propose a sustainability ranking of the alternatives based on a set of weights obtained from local stakeholders. The alternative with a deep buried gravity sewer and geothermal heat pumps was found to have the highest sustainability score in the case study. In the sensitivity analysis, the integrated trench solution with a gravity sewer, innovative heat tracing and LTDH was found to potentially top the sustainability ranking if geothermal energy was used as the district heating source, or if the weight of the cost criterion increased from 24% to 64%. The study highlights the need for integrated decision-making between different utility providers as an integrated solution can represent sustainability gains.

Keywords: low pressure sewer; low temperature district heating; freeze protection; life cycle assessment; multi-criteria

1. Introduction

There are more than 450 million people worldwide living in cities and towns affected by a cold climate. In this paper, cold climate refers to group D in the Köppen-Geiger classification, characterised by at least one month averaging below 0 °C and at least one month averaging above 10 °C. Attractive cities in cold climates need to develop new urban settings in order to accommodate growing populations and tourists. Smaller towns with stable or decreasing populations may also need to build new urban areas to, for example, relocate populations threatened by the effects of climate change (e.g., erosion, rising sea levels) or by industrial activities (e.g., mining). With extensive heating period and frequent freezing temperatures, the choice of heating, water and sanitation systems is important to promote sustainable development in these new communities. Careful and informed decision-making is required, considering all sustainability aspects potentially impacted by the choice of system. Many cold climate cities worldwide have the following two practices in common: (a) the use of district heating (e.g., Moscow, Changchun, Stockholm, Helsinki); and (b) the use of frost protection measures for drinking water and sewer pipes (e.g., deep burial below local frost depth, insulated pipes, use of heated utilidor).

In Sweden, the large majority of newly built suburban areas are connected to existing water and sewer networks. Gravity sewers and drinking water pipes are commonly installed together below the local frost depth (1.1–2.5 m). This technique is simple, robust and energy-efficient, but requires large excavations, which lead to high installation costs and traffic disturbances during repair or replacement activities. The traditional alternative to deep buried gravity pipes is a low-pressure sewer (LPS) system. Sewer and drinking water pipes are insulated, heated with an electric cable and installed in a shallower trench. This technique can considerably reduce the need for excavation, but consumes electricity during winter for frost protection and generally requires having grinder pumps on all properties connected to the system.

For heat supply to buildings, most Swedish cities are equipped with district heating systems, representing a national market share of 55% [1]. When suburban areas are projected, district heating companies need to decide whether or not to expand their network to the new area. Increasing the company's customer base is usually perceived as environmentally friendly since the basic idea of district heating is "to use local fuel or heat resources that would otherwise be wasted" [2]. However, economic viability can be hard to achieve for district heating companies in new suburban areas due to the increased energy efficiency of buildings (i.e., lower heat demand) and uncertainties about future numbers of customers due to the concurrent heat pump market. One response to this challenge has been the development of low-temperature district heating (LTDH) solutions [3], which operate in the range 30–60 °C instead of 60–100 °C for traditional district heating systems, thereby reducing network heat losses. LTDH can also potentially reduce assembly costs thanks to simplified pipe fitting technologies, and comes with a broader vision to integrate renewable heat sources (e.g., geothermal, solar) into the district heating grid [3]. Examples of LTDH implementation can be found in cold climates, although they are limited to a few projects in Sweden and Canada [4]. An innovative technical solution for suburban areas was recently developed which aims at further reducing installation costs by laying LTDH, drinking water and sewer pipes in a single shallow trench. With this solution, a warm water pipe diverted from the district heating system is used to protect the other pipes from freezing. The solution has been implemented in Kiruna, northern Sweden, in a pilot project for nine single family homes, and its impact on drinking water and sewer temperatures is under evaluation [5].

As seen above, there are various available options concerning the expansion of heating and water service networks to new suburban areas in cold climates. Besides the common alternatives, other well-known unconventional solutions are sometimes chosen to meet specific economic or technical challenges. However, there is a lack of knowledge about the performance of these solutions in relation to each other from a broader sustainability perspective including environmental, social and health aspects. Sustainability studies on drinking water and sewer networks have mainly focused on the choice of pipe material [6] or rehabilitation technique [7], but not on sewer technology (gravity vs. low pressure) or freeze protection strategy (deep burial vs. shallow installation with insulation and heat tracing). Concerning residential heating systems, Kontu [8] used various sustainability criteria to compare alternatives for a suburban development, including district heating from biomass and individual heat pumps. Yet, similar studies that cover LTDH are not found in the literature. Moreover, the possibility of integrating LTDH, sewer and drinking water pipes in a single shallow trench [5] means that decisions concerning the expansion of district heating networks (no expansion, traditional expansion or LTDH expansion) influence the options available for expanding sewer and drinking water networks (possibility of shallow installation using LTDH for heat tracing or not). This calls for integrated sustainability assessments of the technical alternatives available to cold climate cities for expanding their utility networks, a topic that has not been addressed in previous studies.

Therefore, the objectives of this paper were (i) to compare different technical alternatives for sewer, water and district heating networks expansion according to a set of environmental, economic, social, technical and health & safety criteria; (ii) to rank these alternatives based on the priorities of a reference group; and (iii) to evaluate the sensitivity of the ranking and determine in which context (if any) the integrated shallow trench solution currently being tested in Kiruna [5] can support a more sustainable development of infrastructures in cold climate regions.

2. Materials and Methods

A systems analysis approach was used to compare different technical alternatives for heating and centralised water and sewerage services with regards to a set of evaluation criteria. The analysis was integrated in the sense that the system function was to provide heating, water and sewerage services to suburban residential units in a cold climate. A multi-criteria approach was then used to evaluate an overall sustainability score for each alternative, based on the results of the system analysis expressed criteria by criteria. The analysis was conducted on a representative case study, and a sensitivity analysis was carried out in relation to changes in stakeholder priorities, climate and urban contexts.

In this work, the reference (functional unit) used to compare the different system alternatives was the provision of drinking water, hot water, sewerage services, and space heating to one household throughout one year.

2.1. System Boundaries

Figure 1 summarises the different functions to be performed in order to provide heating, water and sewerage services to the residential units of a suburban area. The analysis presented in this paper was limited to the functions in bold in Figure 1; it covers heat production and heat transport to the residential area as well as the transport of heat, drinking water and sewage transport within the residential area. The functions excluded from the analysis would be performed in the same way independently of the alternative chosen for the new area (i.e., by increased use of the existing wastewater plant, drinking water production plant and pipe networks).

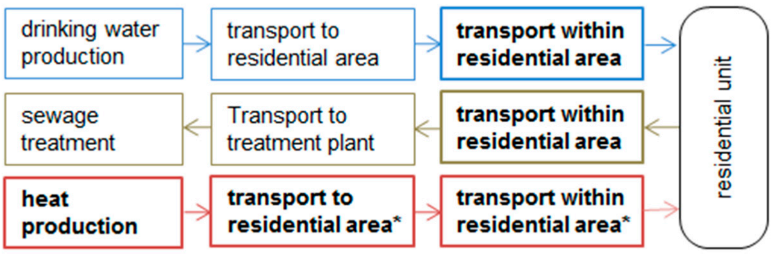

Figure 1. Functional decomposition and system boundaries. (*) applies only for alternatives with district heating.

2.2. Case Description

Repisvaara South II residential area in Gällivare, located in northern Sweden and with about 15,000 inhabitants, was selected as a case study for evaluating and ranking the different alternatives. Due to land subsidence caused by mining activities, a substantial part of the town (~3200 inhabitants) requires relocation before 2030 [9]. As part of the relocation project, a new residential development called Repisvaara South II is planned in a currently forested area 2 km south of the town centre. It consists of 7 multi-storey buildings of 20 apartments and 71 single family homes, for a total of 211 residential units (~420 inhabitants) (Figure 2).

The elevation in the area ranges from 390 m (Figure 1, A6) to 430 m (Figure 1, D2) above sea level and the geology consists of sand and sandy moraine covering the bedrock. The climate in Gällivare is sub-arctic (Dfc in Köppen-Geiger classification), with an annual average temperature of −1 °C [10] and an average temperature in January of −13 °C [11]. The frost-free depth for installation of water and sewer pipes reaches 2.4 m in the area. According to Swedish regulations [12], the energy use in single family homes and apartments in northern Sweden should not be higher than 130 kWh/m^2/year and 115 kWh/m^2/year, respectively. Annual heat demands (space heating + hot tap water) were calculated based on these values and considering a size of 130 m^2 for single family homes and 70 m^2 for apartments (Table 1). Daily water use in Sweden is, on average, 150 L per person for single family homes and 170 L per person for apartments [13]. These values were used to estimate the daily water consumption of residential units (Table 1) considering averages of 2.7 people per single family home and 1.6 people per apartment [9].

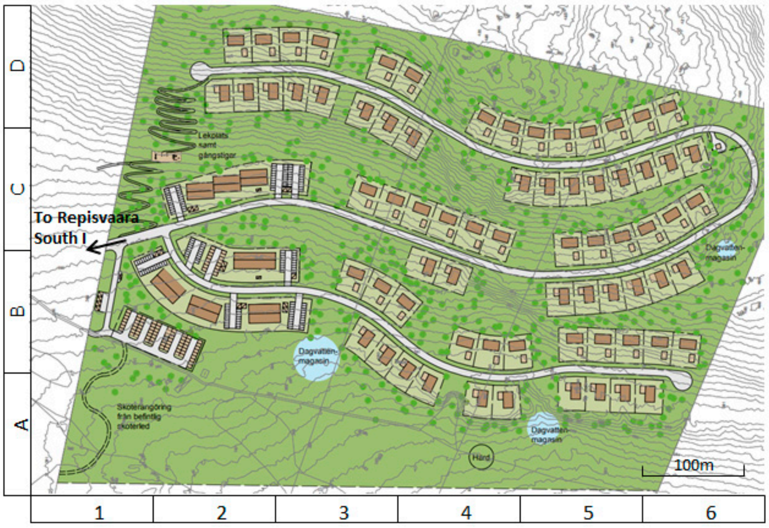

Figure 2. Map of Repisvaara South II residential area. Source: Gällivare municipality.

Table 1. Heat and water consumption of residential units considered in the study.

Residential Unit	Annual Heat Demand (kWh)	Daily Water Consumption (L)
Single family home	16,900	405
Apartment	8050	272

2.3. Alternatives

2.3.1. Choice of Alternatives

While drinking water distribution is systematically performed with pressurised networks, sewage can be transported to the existing network by using either a gravity sewer network or a low-pressure sewer (LPS) system. In both cases, the sewer and drinking water networks for a new development need to be protected against freezing. This can be done by laying the pipes below the local frost line or by insulating them and performing shallower installation. In the case of suburban areas in cold climate regions, freezing of shallow insulated pipes may occur due to low water/wastewater flows and negative soil temperatures [14]. Shallow insulated sewer/water pipes are therefore often equipped with an electrical or a warm water-based [5] heat tracing system. Concerning space heating and hot tap water, there are two alternatives: expansion of the municipal district heating network to the new area with a high- or low-temperature grid [3], or a local heat generation system for each property. For new constructions, air-to-air heat pumps and geothermal heat pumps are the most common alternatives to district heating in Sweden [15]. However, air-to-air heat pumps are less comparable due to lower thermal comfort in relation to district heating. In the present work, only geothermal heat pumps were selected as an alternative to district heating.

As this study was an integrated systems analysis, each alternative was a combination of a sewerage, freeze protection and heating solution. To reduce the number of evaluated alternatives from eighteen possible combinations to five, a selection method was applied based on technical factors, innovativeness, synergy level between water and heating systems and availability of data (see section A in the Supplementary Material).

2.3.2. Alternative 1: Gravity Sewer and High-Temperature District Heating

In Alternative 1, a gravity sewer system is used to connect the new residential units to the existing municipal sewer network. Drinking water is conveyed from the existing drinking water network (connection point in area B1, Figure 2) to the residential units through pressurised pipes in polyethylene (PE). Sewer and drinking water pipes are installed in the same trench below the frost depth (Figure 3a). Heat for space heating and hot tap water is produced by burning biomass and peat [16] at the combined heat and power plant of Gällivare and is conveyed to Repisvaara South II via the existing district heating network of the town. Within the residential development, heat is supplied to the houses through high temperature district heating pipes (90–60 °C). Each house is equipped with a district heating substation consisting mainly of two heat exchangers: one for the building's own heating system and the other for hot tap water production. The corresponding trench layout is presented in Figure 3b.

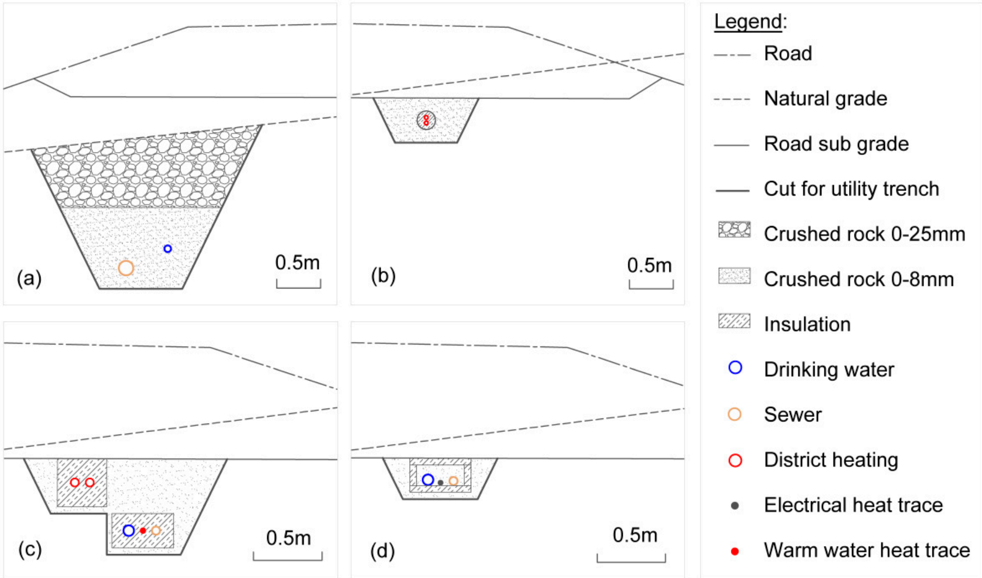

Figure 3. Trench layout under the main road in Repisvaara South II for (**a**) gravity sewer and drinking water (Alternatives 1 and 4); (**b**) high-temperature district heating (Alternative 1); (**c**) LTDH, drinking water and gravity or LPS sewer with warm water heat trace for freeze protection (Alternatives 2 and 3); (**d**) LPS sewer and drinking water with electrical heat trace for freeze protection (Alternative 5).

2.3.3. Alternative 2: Gravity Sewer and Low-Temperature District Heating

In Alternative 2, sewer and drinking water networks have the same shape and components as in Alternative 1. However, the two networks are installed 1.3 m below ground level in an utilidor made of expanded polystyrene (EPS) and protected from freezing by a warm water (20 to 25 °C) circulation pipe in cross-linked polyethylene (PEX). The heating system for the new development is an LTDH system (55–25 °C) [3]. District heating pipes are also in PEX and are placed in an EPS utilidor in the same shallow trench as the water-sewer utilidor (Figure 3c). The LTDH system includes a central heat exchanger installed in a house station built in area B1 (Figure 2). It transfers heat from the existing high-temperature network to the new low-temperature network. In the house station, part of the water returning from the low temperature network is diverted into the freeze protection pipe of the water-sewer utilidor. This integrated solution was implemented in a pilot project in Sweden in 2014 [5].

2.3.4. Alternative 3: Low-Pressure Sewer and Low-Temperature District Heating

The heating, drinking water and freeze protection systems for Alternative 3 are the same as in Alternative 2. Instead of using a gravity sewer system, sewage is conveyed from the residential units to the existing network (connection point in area B1, Figure 2) with an LPS system. Each single-family home and multi-storey building is equipped with a grinder pump station that discharges the sewage into a pressurised collection network made of small diameter PE pipes. The trench layout is the same as in Alternative 2 (Figure 3c).

2.3.5. Alternative 4: Gravity Sewer and Geothermal Heat Pumps

In Alternative 4, the sewer and drinking water systems are the same as in Alternative 1. Gravity sewer and drinking water pipes are installed in a common trench at a depth of 2.4 m for frost protection (Figure 3a). Instead of district heating, each single-family home and multi-storey building is equipped with its own geothermal heating system that includes a brine-to-water heat pump, vertical collectors and boreholes.

2.3.6. Alternative 5: Low-Pressure Sewer and Geothermal Heat Pumps

The heating system for Alternative 5 is the same as in Alternative 4 (geothermal heat pumps with vertical collectors). Sewage is conveyed from the residential units to the existing network (connection point in B1, Figure 2) with an LPS system as in Alternative 3. The LPS and drinking water pipes are co-located 1 m below the road surface in an extruded polystyrene (XPS) frost shield filled with sand and freeze protected with an electrical heat trace cable. The corresponding trench layout is presented in Figure 3d. The drinking water network is the same as in the other alternatives.

2.4. Sustainability Criteria

The system alternatives were compared using seven sustainability criteria (C1–C7) associated with measurable indicators and organised into five categories: environment, economy, social, health and safety, and technical. They were selected from the set of criteria defined by Hellström et al. [17] for assessing urban water systems. The selection was made by focusing on criteria commonly used in sustainability and environmental assessments of drinking water and sewage transport systems [6,18], as well as residential heating systems [8,19]. The criteria, indicators and methods used for their evaluation are described below.

2.4.1. Environment

C1. Energy efficiency. The exergy content of energy carriers [20] harvested from the environment in order to perform the system's function was used as an indicator of energy efficiency. In the present paper, this indicator is referred to as the cumulative exergy demand of energy carriers (CExDe), expressed in megajoules per functional unit. The motivation for using CExDe instead of cumulative energy demand [21,22] was to account for the difference in quality between geothermal energy (low-temperature heat) and the other primary energy sources (e.g., hydropower, nuclear, fossil, biomass, wind, solar) which can generate high-temperature heat or electricity.

C2. Climate preservation. The global warming potential (GWP) as defined by the international panel on climate change [23] was used as an indicator of climate preservation. In this paper, GWP is expressed in kilograms CO_2 equivalent emitted per functional unit.

C3. Material efficiency. The abiotic depletion potential of elements (non-fossil) resources as defined by van Oers et al. [24] was used as an indicator of the material efficiency criterion. The indicator is referred to as ADPE in this paper and is expressed in kilograms antimony equivalent extracted per functional unit.

The three environmental indicators were calculated for each alternative using a life cycle impact assessment (LCIA) approach [25]. The assessment covered the processes related to the production, transport, construction, maintenance and use phases of the elements composing the system (e.g., pipes, pipe insulation, pumps, heat pumps). Each alternative was decomposed into a list of system processes presented in the data article [16]. The environmental indicators I_j. (CExDe, GWP and ADPE) of each alternative were calculated using Equation (1), where i_{jk} are the environmental impacts of the system processes composing the alternative.

$$I_j = \frac{1}{N} \sum_k \frac{i_{jk} \times F_k}{T_k} \tag{1}$$

In Equation (1), F_k represents the output flows (e.g., length of pipe to be produced) of the system processes, and T_k represents their lifetimes. Values, data sources and calculation assumptions for i_{jk}, F_k and T_k are presented in Pericault et al. [16]. The total number of residential units serviced by the system, N, corresponded to 211 residential units in the case of Repisvaara South II.

2.4.2. Economy

C4. Affordability. The total cost per functional unit I_4 was used as an indicator of the affordability of each alternative, expressed in Euros per functional unit. I_4 includes the amortisation of investments, interest payments and Operation and Maintenance (O&M) costs related to the system, independently of who should pay these expenses (household, water utility or energy utility). It covers the cost of purchasing, transporting, installing, using and maintaining system components in the new residential area, as well as the marginal cost of using existing parts of the municipal infrastructures (sewer, drinking water, district heating networks and district heating plant).

The expenses related to each alternative were identified and corresponded to the groups of system processes used in the environmental impact assessment [16]. Equations (2) and (3) were used to calculate the total cost of each alternative.

$$I_4 = \frac{1}{N} \left(\sum_l \frac{P_l \times \tau_l}{T_l} + \sum_m U_m \times F_m \right) \tag{2}$$

$$\text{with } P_l = \frac{r \times V_l \times F_l}{1 - (1 - r)^{\tau_l}} \tag{3}$$

In Equation (3), V_l refers to investment costs per process group (e.g., cost per metre of installed pipe), F_l to the related output flows (e.g., length of pipe to be installed) and τ_l to amortisation periods for these investments (see Pericault et al. [16] for values and data sources). P_l are annuity payments and r is the annual interest rate. In this study, r was set to 4% which is common for long-term investment decisions in the Swedish water sector [26,27]. In Equation (2), T_l represents the lifetimes of investments (periods before re-investments are needed), U_m the yearly costs of O&M processes and F_m the related output flows (see Pericault et al. [16] for values and data sources).

2.4.3. Social

C5. User friendliness. The need for user engagement, measured in the number of actions to be performed yearly by the households in order to maintain the system (I_5), was used as an indicator of the user friendliness of each alternative. The following actions were considered: (a) organising a yearly check-up of the district heating sub-station; (b) organising a yearly check-up of the geothermal heat-pump; (c) monitoring the screen/warning lights of the geothermal heat pump and taking action if a fault appears; (d) monitoring the warning light of the LPS and calling the water utility if the light is red.

2.4.4. Health and Safety

C6. Safety for workers. The frequency of work accidents (accident/worker/year) that can be expected for each system alternative was used as the indicator (I_6) of the workers' safety criterion.

The average frequency of work accidents in the water and heat network construction sector in Sweden for the years 2012, 2013, 2015 and 2016 was calculated based on statistics from the Swedish Work Environment Authority [28]. This was used as the I_6 value for alternatives with traditional deep pipe installation (A1, A4). For the alternatives with shallow pipe installation (A2, A3, A5), the same procedure was used; however, accidents due to a person falling from a height, material collapse and material fall were excluded from the calculation.

2.4.5. Technical

C7. Reliability. This criterion was evaluated using two indicators. The first indicator I_{7a} represented anticipated failure rate of the sewer network expressed in failure/connection/year. For the gravity sewer option, the rate of blockages in main and lateral sewers in Gällivare between 2013 and 2015 was retrieved from the database of the Swedish water and wastewater association [29] and used as an estimate of I_{7a}. For the LPS option, the rate of failure of grinder pumps and pressurised pipes observed by Lindqvist et al. [30] in 29 Swedish municipalities between 1991 and 1998 was used as an estimate of I_{7a}. Please note that I_{7a} does not directly represent the failure rate as experienced by the users, since one blockage or one pipe failure can impact more than one household.

The second indicator I_{7a} represented the anticipated rate of failure of the heating system as experienced by the users (number of unmet heat demand events per household per year). For the geothermal heat pump option, the frequency of failures reported to insurance companies in Sweden between 2009 and 2011 was retrieved from Haglund Stignor et al. [31] and used as an estimate of I_{7b}. For the district heating options, I_{7b} was calculated based on the shape of the network and the failure rates reported by Åkerström [32] on pre-insulated pipes in Sweden. Details of these calculations are presented in section B of the Supplementary Material.

As infrastructure age can positively impact failure rates (due to deterioration), failure data from infrastructures of fairly similar aging levels (i.e., average asset age divided by assets lifetime) were used. For I_{7a}, the aging level was estimated to be 40% for the data source of the gravity sewer option [29], and 36% for the data source of the LPS option [30]. For I_{7b}, the average aging level of the heat pumps in [31] was estimated to be 32%, and 28% for the pre-insulated district heating pipes studied in [32].

2.5. Sustainability Assessment Method

2.5.1. Method Selection

Various methods of performing integrated sustainability assessments were organised by Lai et al. [33] into four main approaches: cost-benefit analysis (CBA), triple bottom line (TBL), integrated assessment (IA) and multi-criteria analysis (MCA). In this study, an MCA approach was employed, since it is well-suited to incorporating quantitative indicators together with stakeholders' perspectives. MCA methods have been used extensively to perform sustainability assessments on water and energy systems [34–36]. As defined by Rowley et al. [37], they can be grouped into two categories: compensatory (e.g., weighted sum model (WSM), analytical hierarchy process (AHP), TOPSIS) and non-compensatory methods (e.g., ELECTRE PROMETHEE). Despite being more distant from the concept of strong sustainability than non-compensatory methods [37], compensatory methods are simple, transparent and easily understandable, which makes them practical to communicate results to the public and engage stakeholders [38]. A recent literature review conducted by Diaz-Balteiro et al. [36] showed that AHP and WSM were the most frequently used methods in the field of multi-criteria sustainability assessment. In the present study, the WSM method was chosen because it allows the implementation of a direct rating procedure to elicit the importance of each criterion from decision makers. This offers more transparency than the AHP method, where criteria weights are derived from pairwise comparisons using an eigenvalue approach.

In the present study, normalisation of indicator values was done to calculate a weighted sum that is meaningful. The "smaller the better" ratio normalisation defined by Pollesch and Dale [39] was used (Section 2.5.2), which conserves proportionality and gives values in the range [0, 1].

2.5.2. Determination of Weights, Normalisation and Aggregation

Criteria weights were determined as follows. Firstly, a reference group of seven stakeholders from the town of Gällivare was gathered in a "budget allocation" workshop [40]. Three stakeholders were from the municipal water utility, one from the district heating company, one from the municipal urban planning unit and two from the main housing company of the town. After a presentation of the system boundaries, alternatives and criteria, the stakeholders were individually asked to distribute a budget of 100 points over the seven sustainability criteria. Later, a common discussion was held to try to reach a consensus concerning the budget allocation. However, no consensus could be reached. After the workshop, the average point distribution of each of the four sub-groups (water, energy, planning and housing) was calculated using the arithmetic mean. Next, the average point distribution of the entire reference group was obtained by taking the arithmetic mean of these four point distributions. Finally, the weight of each criterion (w_j) was obtained by dividing its number of points by 100.

The eight sustainability indicators were normalised using Equation (4).

$$I_j^* = 100 \times \frac{\min(I_j)}{I_j} \tag{4}$$

$\min(I_j)$ is the minimum of I_j over the five alternatives. For each alternative, the overall sustainability score S was then computed according to WSM (Equation (5)). Please note that for C1 to C6, normalised indicator values I_1^* to I_6^* were directly used as criteria scores, while for C7, the arithmetic mean of I_{7a}^* and I_{7b}^* was used.

$$S = \left(\sum_{j=1}^{6} w_j \, I_j^* \right) + w_7 \, \frac{(I_{7a}^* + I_{7b}^*)}{2} \tag{5}$$

The five alternatives were then ranked according to their S value.

2.6. Sensitivity Analysis

The sensitivity of the sustainability ranking to changes in criteria weights was evaluated according to the method developed by Triantaphyllou [41]. The basic principle of the method is to determine, for each criterion C_j, the minimum change in the weight w_j required to modify the ranking of the most preferred alternative. The sensitivity of the sustainability ranking to changes in several input parameters was also assessed. This was done manually by modifying parameter values in a step-wise manner until the ranking of the "top alternative" would change. The parameters assessed were: urban density, heat demand, failure rates for district heating and geothermal pumps, gravity sewer blockage rate, coefficient of performance (COP) of geothermal heat pumps, coal fraction of the electricity mix, biomass fraction of the district heating fuel mix, geothermal fraction of the LTDH fuel mix, lifespan of geothermal heat pumps, marginal costs of district heating, and electricity price. These parameters were selected for one of the following two reasons: (a) the parameter was believed to be uncertain and was related to one of the three indicators with the highest weight; or (b) the parameter represented a specific context (e.g., urban, climatic or geographic) of the case study. The parameter "coal fraction in electricity mix" corresponded to an interpolation coefficient between the environmental impacts of electricity in Sweden and in Poland [16]. For the parameter "geothermal fraction in LTDH mix", the environmental impacts calculated in Pericault at al. [16] and the cost provided by the European Geothermal Energy Council [42] for geothermal district heating were used.

3. Results

3.1. Environmental Indicators

The results of the life cycle impact assessment (LCIA) are presented in Figure 4. Alternatives featuring district heating (A1 to A3) showed a significantly higher CExDe and GWP than alternatives with heat pumps (A4 and A5). This trend was more pronounced for GWP. The opposite was observed for ADPE.

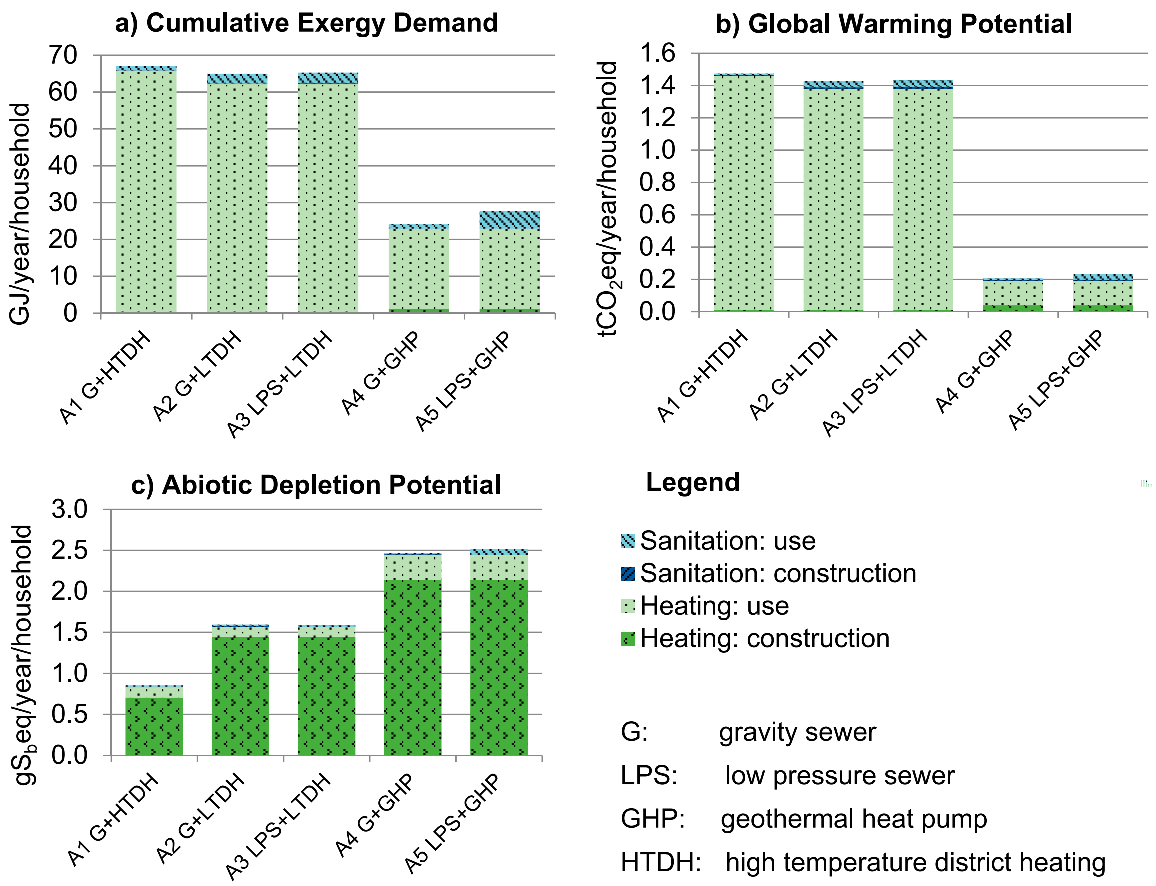

Figure 4. (**a**) CExDe, (**b**) GWP and (**c**) ADPE for the five studied alternatives on the case study of Repisvaara South II.

3.1.1. Cumulative Exergy Demand

CExDe was calculated for the five alternatives as an indicator of their energy efficiency (Figure 4a). A4 (gravity sewer and geothermal heat pump) had the lowest CExDe value with 24 GJ/household/year. A1 (gravity sewer and high temperature district heating) had the highest CExDe value with 67 GJ/household/year. The geothermal heat pumps were found to consume considerably less exergy than district heating options during the use phase of the system. This was because the heat pumps were considered to cover 75% of the heat demand of residential units with low temperature geothermal heat (7 °C) of negligible exergy content. The other 25% were considered to be covered with electricity produced in Sweden with a primary exergy factor of 2.1 MJ/MJ [16]. For the district heating option, 100% of the residential heat demand was assumed to be covered by the district heating plant of Gällivare with a primary exergy factor of 1.4 MJ/MJ [16]. Moreover, the use phase of the heating system had the largest contribution (78–98%) to CExDe for all the alternatives (Figure 4a), which explains the large differences between alternatives with district heating and those with geothermal heat pumps. The accumulated contribution to CExDe of heat losses from the district heating network and freeze protection of the water-sewer utilidor (A2 and A3) was low (9–12%). Consequently, the reductions of exergy use achieved with integrated trench solutions using LTDH (A2 and A3) were limited to only 3% in comparison with the separated solution featuring high temperature district heating (A1).

3.1.2. Global Warming Potential

Similar trends and relative contributions as for CExDe were found for the GWP indicator (Figure 4b). However, the gap between alternatives with district heating (A1 to A3) and those with geothermal heat pumps (A4 and A5) was even larger. On average, the GWP values for A1 to A3 were ~7 times higher than for A4 and A5. This was mainly due to the low carbon footprint of Swedish electricity (0.015 $kgCO_2eq$/MJ; mostly hydropower and nuclear), used to cover 25% of the residential heat demand in comparison with the carbon footprint of district heat in Gällivare (0.032 $kgCO_2eq$/MJ; mostly peat and wood chips), used to cover 100% of the residential heat demand.

3.1.3. Abiotic Depletion Potential of Elements

ADPE of each alternative was calculated as an indicator of the material efficiency criterion (Figure 4c). A5 (LPS and geothermal heat pump) was the least material efficient with an ADPE value of 2.5 gSbEq/household/year. A1 (gravity sewer and high temperature district heating) was the most material efficient with an ADPE value of 0.9 gSbEq/household/year (64% reduction from A5). Alternatives with low temperature (LT) district heating (A2 and A3) had ADPE values 77% higher than the option with high temperature (HT) district heating (A1) due to the extra heat exchanger and circulation pumps required for the HT-LT conversion [16]. Alternatives with geothermal heat pumps (A4 and A5) had ADPE values 178% higher than A1 due to the manufacturing of the heat pumps and the production of electricity for their operation [16].

3.2. Economic Indicator

The total cost of each alternative, expressed in €/year/household, is presented in Figure 5. A4 was the most expensive alternative (gravity sewer and geothermal heat pump) at ~910 €/year/household and the least expensive was A2 (gravity sewer and LTDH) with ~620 €/year/household (32% reduction). Please note that the cost figures do not represent what the household must pay yearly for water and heating services (see Sections 2.2 and 2.5.1).

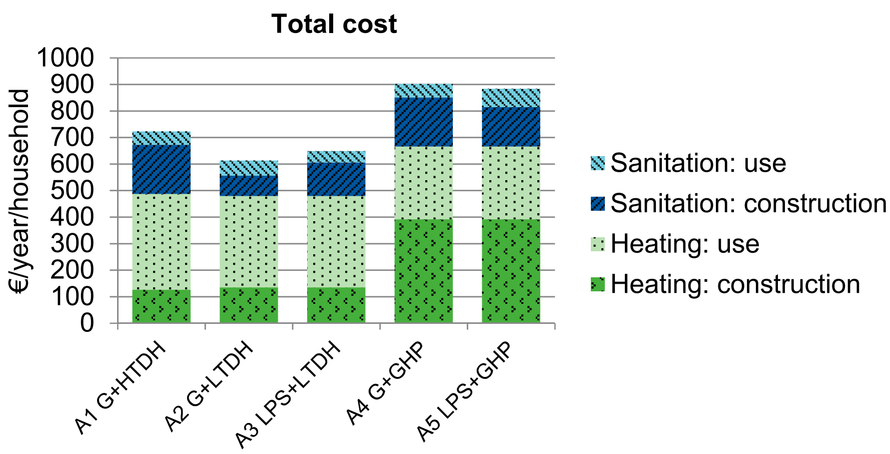

Figure 5. Total cost for construction and use of the five studied alternatives. G: gravity sewer; LPS: low pressure sewer; HTDH: high temperature district heating; GHP: geothermal heat pump.

Shallow, integrated trench solutions (A2 and A3) with LTDH and a heat traced water-sewer utilidor were cheaper than the other alternatives thanks to reduced installation costs for the sanitation system. A2 was cheaper than A3, since costs related to individual grinder pumps were avoided. Moreover, the topography in the area of this case study was favourable for the gravity sewer solution for which only one pumping station was required. Integration of sewer, drinking water and district heating pipes (A2) was found to reduce the total cost by 15% in comparison with the traditional separated approach (A1).

3.3. Social Indicator

The number of actions to be performed by the household was estimated for each alternative and used as an indicator of the user friendliness criterion. Indicator values are presented in Table 2. A5 with LPS and geothermal heat pump was the least user friendly with three actions to be performed by the household per year. This is the alternative with the most technology installed in the home of the tenants. The conventional alternative A1 with a gravity sewer and district heating was the most user friendly with only one action to be performed by the household per year.

Table 2. Indicator values of the user friendliness (I_5), workers' safety (I_6) and reliability criteria for the five studied alternatives. G: gravity sewer; LPS: low-pressure sewer; HTDH: high-temperature district heating; LTDH: low-temperature district heating; GHP: geothermal heat pump.

Indicator	Alternative				
	A1: G+HTDH	**A2: G+LTDH**	**A3: LPS+LTDH**	**A4: G+GHP**	**A5: LPS+GHP**
I_5: Number of actions to be performed by tenants	1 [a]	1 [a]	2 [a,d]	2 [b,c]	3 [b,c,d]
I_6: Work accident frequency [accident/worker/year]	0.016	0.012	0.012	0.016	0.012
I_{7a}: Failure rate-sewer [failure/year/connection]	0.03	0.03	0.11	0.03	0.11
I_{7b}: Failure rate-heating [failure/year/household]	0.16	0.21	0.21	0.02	0.02

[a] Organise a yearly check-up of the district heating sub-station; [b] Organise a yearly check-up of geothermal heat-pump; [c] Monitor the screen/warning lights of the geothermal heat pump and take action if a fault appears; [d] Monitor the warning light of the LPS and call the water utility if the light is red.

3.4. Health and Safety Indicator

The anticipated frequency of accidents in the water and heat networks construction sector was evaluated for each alternative as an indicator of the workers' safety criterion (Table 2). A2, A3 and A4 were found to have potential to reduce the frequency of work accidents by 25% by preventing accidents due to a person falling from a height, material collapse and/or material fall (e.g., trench collapse). These alternatives involve the excavation of shallow trenches not deeper than 1 m and therefore mitigate the risk of accident in comparison with trenches to frost-free depth (between 2.5 m and 4 m deep).

3.5. Technical Indicators

Failure rates for the sewer and heating system were evaluated as an indicator of the reliability criterion (Table 2). For the heating system, alternatives with geothermal heat pumps had the lowest failure rate with 0.02 failures/year/household. This is 8 to 10 times less than the failure rate found for alternatives with district heating. This difference originated mainly from the existing district heating network section of 2.5 km long connecting the newly built area to the town centre of Gällivare. Any failure on this section would affect all the households in the newly built area. The difference in failure rate between alternatives with high- (A1) and low-temperature (A2 and A3) district heating was due to the third pipe necessary for frost protection of the water-sewer utilidor in A2 and A3. For the sewer system, alternatives with a gravity sewer had the lowest failure rate with 0.03 failures/year/connection. This is less than a third of the failure rate found for alternatives with LPS. A3 (LPS and LTDH) had the highest failure rates for both the sewer and heating systems while A4 (gravity sewer and geothermal heat pump) had the lowest failure rates for both systems.

3.6. Scores, Weights and Overall Weighted Scores

The scores of the five alternatives with regard to the seven sustainability criteria are presented in Table 3. Since all indicators were of the "smaller the better" type, a score of 100 means the alternative had the lowest indicator value for the considered criteria, while a score of 50 means the alternative had an indicator value twice as high as the lowest indicator value.

Table 3. Performance matrix of the sustainability assessment problem, together with criteria weights and overall weighted scores. G: gravity sewer; LPS: low-pressure sewer; HTDH: high-temperature district heating; LTDH: low-temperature district heating; GHP: geothermal heat pump.

		Scores				
Criterion	**Weight**	**A1: G+HTDH**	**A2: G+LTDH**	**A3: LPS+LTDH**	**A4: G+GHP**	**A5: LPS+GHP**
C1. Energy efficiency	0.24	36	37	37	100	87
C2. Climate preservation	0.05	14	14	14	100	88
C3. Material efficiency	0.06	100	54	54	35	34
C4. Affordability	0.24	85	100	96	68	70
C5. User friendliness	0.06	100	100	50	50	33
C6. Safety for workers	0.06	75	100	100	75	100
C7. Reliability	0.29	56	55	18	100	63
Overall weighted score		**63**	**65**	**50**	**84**	**70**
Ranking		**4**	**3**	**5**	**1**	**2**

Criteria scores are also presented graphically using radar diagrams in section C of the Supplementary Material. The criteria weights, representing the priorities of the reference group, are also presented in Table 3. Details and intermediate steps concerning the calculation of these weights from the outcomes of the weighing workshop are presented in section D of the Supplementary Material. Reliability (29%), energy efficiency (24%) and affordability (24%) were the three most important criteria according to the reference group. The four other criteria were given nearly the same, relatively low, importance (5% to 6%). Table 3 also shows the overall weighted scores of the studied alternatives and the associated ranking. The upper boundary of the overall weighted score is 100 and corresponds to an alternative that would outperform all the other alternatives with regards to all criteria.

The highest overall weighted score of 84 was determined for the alternative combining geothermal heat pumps and a traditional gravity sewer (A4). A4 had the highest reliability, energy efficiency and climate preservation scores. A5, with LPS and geothermal heat pump, was ranked second with an overall weighted score of 70. The shallow integrated trench solution with LTDH and a gravity sewer (A2) was ranked third with an overall weighted score of 65. This alternative had the highest affordability, user friendliness and workers' safety scores. However, the difference in overall weighted score between A2 and A1 (deep buried gravity sewer and high temperature district heating) was limited to 2 points. A1 had the highest material efficiency score. Finally, the shallow integrated trench solution with LTDH and LPS (A3) was ranked fifth with an overall score of 50 points.

3.7. Sensitivity Analysis

3.7.1. Changes in Criteria Weights

As seen in Table 4, the stability of the top-ranked alternative (A4: gravity sewer and geothermal heat pump) in the face of changes in criteria weights was relatively high. Affordability was the most sensitive criterion and required a minimum increase of 249% in order to replace A4 by A2 (integrated shallow trench solution with a gravity sewer and LTDH) as the top-ranked alternative. This corresponds to a new weight value of 0.52 for the affordability criterion after re-normalisation (re-normalisation is to keep the sum of weights equal to unity). Material efficiency was the second most sensitive criterion, requiring an increase of 525% in order to replace A4 by A1 (traditional trench with a gravity sewer and high temperature district heating). This corresponds to a new weight value of 0.29 for the material efficiency criterion after re-normalisation.

Table 4. Stability of the top-ranked alternative (A4: G+GHP) with regards to changes in criteria weights. G: gravity sewer; LPS: low-pressure sewer; HTDH: high-temperature district heating; LTDH: low-temperature district heating; GHP: geothermal heat pump.

		Minimum Weight Variation to Replace Top-Ranked Alternative A4 (G+GHP) by Alternative:			
Criterion	**Weight**	**A1: G+HTDH**	**A2: G+LTDH**	**A3: LPS+LTDH**	**A5: LPS+GHP**
C1. Energy efficiency	0.24	-	-	-	-
C2. Climate preservation	0.05	-	-	-	-
C3. Material efficiency	0.06	+525%	+1635%	+2832%	-
C4. Affordability	0.24	+524%	+249%	+506%	+2714%
C5. User friendliness	0.06	+721%	+651%	-	-
C6. Safety for workers	0.06	-	+1368%	+2417%	+966%
C7. Reliability	0.29	-	-	-	-

3.7.2. Changes in Input Parameter Values

The sensitivity of the sustainability ranking to changes in selected input parameter values was low in this study. Replacing the top-ranked alternative by changing the input parameter values was either not possible or required significant changes. The coefficient of performance of the geothermal heat pumps was the most sensitive parameter and required division by 2.8 (−64%) in order to replace A4 (gravity sewer and geothermal heat pump) with A2 (gravity sewer and LTDH) as the top-ranked alternative. The blockage rate in the gravity sewer system was the second most sensitive parameter, requiring multiplication by 4.7 (+370%) in order to replace A4 with A5 (LPS and geothermal heat pump) as the top-ranked alternative. Considering the possibility of powering the local LTDH grid with both the existing district heating network (heat exchanger) and geothermal energy (large heat pump), it was found that the share of geothermal energy source had to reach 94% of the annual heat demand in order to replace A4 with A2 as the top-ranked alternative. For details, see section E in the Supplementary Material.

4. Discussion

4.1. Sustainability Indicators

To support sustainable development, it is paramount to develop and operationalise indicator sets that (i) address local and global challenges relevant to the decision-making context, (ii) can be estimated with reasonable accuracy, and (iii) avoid redundancy. In this study, indicators I_1 (CExDe) and I_2 (GWP) showed similar trends (Figure 4). However, they still address two separate environmental challenges: the efficient use of exergy harvested from the environment (I_1) and the reduction of greenhouse gases emissions (I_2). The use of I_2 only would mean that low carbon exergy resources (e.g., potential energy in dams, nuclear energy in uranium fuel) could be used inefficiently without negative impact on the sustainability ranking, while these resources can be useful for other purposes (e.g., electric cars). Other aspects were described by Klöpffer [43] and Frischknecht [44] in defence of cumulative energy demand as a relevant environmental indicator. The quantitative indicator I_6 (number of work accidents/1000 workers in the water and heat networks construction sector) was used in this study to evaluate the alternatives regarding workers' safety. This was possible thanks to detailed statistics on work accidents available in Sweden. In a context of low data availability on this issue, it may be more realistic to use a qualitative indicator of workers' safety for various utility trench alternatives. This could be, for example, an expert estimate of the risk of serious work accidents in relation to the most risky alternative (e.g., A2 is much less/less/equally risky for workers than A1).

4.2. Applicability

The results of the sustainability ranking and sensitivity analysis suggest that it is preferable (a) not to expand the district heating network to Repisvaara, (b) to incite property owners to install geothermal heat pumps, and (c) to expand the water and sewer network with a traditional gravity sewer and freeze protection by deep burial, according to the sustainability priority of the reference group: reliability, energy efficiency and affordability. However, in practice, the number of households that will choose a geothermal heat pump is uncertain. In Sweden, 62% of heat pumps installed in 2013 were air-to-air or air-to-water [15]. Some households will install an air heat pump, since it represents a lower investment. This will lower the average COP of the neighbourhood and in turn lower energy efficiency while increasing affordability. Hence, a large number of households choosing air heat pumps would influence the sustainability ranking found in the present study.

Although there is significant uncertainty concerning the reliability of each technical alternatives due to, e.g., influence of local conditions and incomplete data for new types of systems (e.g., LTDH), the sensitivity analysis showed that a drastic reduction in district heating pipe failure rate (÷20) or increase in gravity sewer blockage rate (×4.7) would be required to change the top-ranked alternative.

The use of a compensatory method means that criteria weights were representing trade-off relationships [37] at the criteria scores level. Also, the use of "smaller the better" ratio normalisation means that the "traded quantities", which were differences in scores, represented at the indicator level differences in relative reduction required to match the lowest indicator value. Before using the sustainability ranking to support or justify decision making, stakeholders should verify that the meaning of weights in the analysis is consistent with their initial intentions expressed during the weighing workshop. The WSM method implemented on a worksheet is transparent and therefore facilitates this process.

4.3. Generalisability

The criteria weights obtained in this study originated from a group of stakeholders from the town of Gällivare. Some common priorities can be expected for stakeholders in cities located in cold climate regions. For example, winter conditions can worsen the consequences of system failures, which may increase the perceived importance of reliability in these regions. On the other hand, the reference group in the present study attributed a weight of 5% to the climate preservation criterion. This is a remarkably low value, given the recognised threats of global warming [23] and the importance of climate preservation in recent European policy [45]. According to the sensitivity analysis (Table 4), increasing the weight of the climate preservation criterion would not change the top-ranked alternative A4. However, it would affect the sensitivity analysis on selected parameters (Section 3.7.2). In particular, the *coal fraction in electricity mix* and *biomass fraction in district heating mix* are two parameters directly connected to the relative performances of alternatives with heat pumps and those with district heating with regards to climate preservation. Variations in these two parameters did not change the top-ranked alternative in this study; however, this should be reconsidered if more importance were given to climate preservation.

In this study, alternatives with individual geothermal heat pumps showed low CExDe and GWP values in comparison with alternatives using district heating from combined heat power (Figure 4). At a national scale, the validity of this result requires that the increased electricity load caused by newly installed heat pumps can be covered by the current Swedish power grid or by new installed capacity that does not increase its primary exergy factor nor its carbon intensity. A4 (geothermal heat pumps and deep buried gravity sewer) was ranked first even when increasing urban density or heat demand per residential unit. However, the extraction of shallow geothermal energy in areas with high heat demand density can require large numbers of boreholes, decreasing the applicability of such systems due to lack of land availability. The topography was favourable to gravity sewers (only one pumping station needed) in the case study. The total cost of alternatives with a gravity sewer (A1, A2 and A4) would increase in flat areas (or those with unfavourable slope), potentially affecting the final sustainability ranking in favour of alternatives with LPS (A3 and A5) (not evaluated in the sensitivity analysis).

Other integrated studies of drinking water, sewer and heating systems were not found in the literature, but the results obtained here for non-integrated alternatives (A1, A4 and A5) can be compared to existing studies focused on sewer or heating systems. In a stochastic multi-criteria acceptability analysis, Kontu et al. [8] found that the most acceptable heating alternative for a new residential area in Finland was district heating from a Combined heat and power (CHP) plant using only biomass, while geothermal heat pumps were ranked second. This is not in line with the results of the present study, where alternatives with geothermal heat pumps (e.g., A4) had a better sustainability score than those with district heating (e.g., A1). This could be explained by various differences between the two studies. The work of Kontu et al. [8] was based on more indicators but did not include CExDe, which had a high weight in the present study and favoured geothermal heat pumps. Furthermore, the district heating fuel in the Finnish study was solely biomass [8] and the environmental impacts of fuel drying and transportation were not included, resulting in fewer climate impacts for district heating than geothermal heat pumps. The opposite was observed in the present study, as the district heating fuel mix was based not only on biomass but also peat, and the emissions from fuel drying and transport were included [16]. Moreover, district heating was assumed to be more reliable than geothermal heat pumps in Kontu et al. [8] while our estimates pointed in the other direction.

In the present study, the failure rate for the gravity sewer option (0.03 failure/connection/year) was lower than for the LPS option (0.11 failure/connection/year). When adapted to the density (number of connection/km of pipe) of Repisvaara South II network, the failure rates reported by Miszta-Kruk [46] show a similar but less pronounced trend with 0.29 and 0.48 failure/connection/year for the gravity and LPS systems, respectively.

4.4. Benefits of Utility Integration with Low-Temperature District Heating

A2 is an integrated solution where low temperature district heating (LTDH), gravity sewer and drinking water pipes are insulated with EPS and installed in a single shallow trench (Figure 3c). The main driver for developing and implementing this solution was to increase the viability of district heating projects in low heat density areas by decreasing investment costs [5]. In this study, the benefits of A2 were visible in total cost (−15%) and frequency of work accident (−25%) in comparison with the traditional separated solution A1. However, A2 offered a limited increase in overall weighted score in comparison with A1 (from 63 to 65), and both were outperformed by A4, featuring no district heating but individual heat pumps and a traditional water-sewer trench (score of 87). One benefit of A2 is the possibility offered by LTDH [3] to use renewable, low-temperature heat sources. The sensitivity analysis suggests this possibility should also be utilised for LTDH to be competitive with individual geothermal heat pumps. Indeed, A2 had the highest overall weighted score when more than 97% of the district heat demand was covered by a local geothermal heat pump. This was due to a reduction of CExDe, GWP and failure rate (local heat source decreases the reliance on the existing pipe network). Some potential benefits of A2 were not considered in this study, but would be worth evaluating. For example, the EPS insulation decreases heat losses from sewage to surrounding soil, which is beneficial for sewage heat recovery.

5. Conclusions

A comparative sustainability assessment of technical alternatives for sewer, water and district heating networks expansion in a cold climate was conducted on a case study considering the preferences of local stakeholders. Seven criteria were used, covering the environmental, economic, social, health and technical dimensions. The sensitivity of the sustainability ranking to changes in single criteria weights and selected input parameter values was evaluated. The main findings of the study are:

- The alternative with traditional deep-buried water services networks and geothermal heat pumps outranked the alternatives with LPS and/or district heating from biomass and peat. This result appeared robust to changes in criteria weights and input parameter values (e.g., urban density, lifespan of heat pumps, linear costs); however, the effects of changing more than one parameter/weight at a time were not investigated.
- The reliability criterion was given the highest weight (29%) by the stakeholders, but more research efforts on the relative reliability of district heating versus heat pumps and gravity versus LPS is needed, especially to model reliability as experienced by the households.
- The integration of LTDH, gravity sewer and drinking water pipes in a single shallow trench was shown to reduce total cost by 15% in comparison to traditional water service and district heating networks. This alternative would top the sustainability ranking if the district heating source was changed from biomass and peat to shallow geothermal energy (made possible by LTDH), or if the weight of the affordability criterion was raised from 24% to 65%.

As integrated solutions can represent sustainability gains depending on the local setting, it is relevant to adopt collaborative decision-making practices between water and district heating utilities concerning the expansion of their networks to new suburban areas.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/10/10/3743/s1, Figure S1: Criteria scores of the five studied alternatives. Scale from 0 (centre) to 100 (edge). Abbreviations: G: gravity sewer; LPS: Low pressure sewer; HTDH: high temperature district heating; LTDH: low temperature district heating; GHP: geothermal heat pump. Table S1: Criteria and overall scores of fourteen possible combinations of sewer, freeze protection and heating system. HTDH: high temperature district heating, LTDH: low temperature district heating, GHP: geothermal heat pumps. Table S2: Determination of weights for the sustainability assessment based on the point distributions obtained during the budget allocation workshop. Table S3: Stability of the top-ranked alternative (A4: gravity sewer and geothermal heat pump) with regard to changes in input parameters. Abbreviations: f.u: functional unit, DH: district heating, r.u: residential unit, co: connection, NP: not possible, GHP: geothermal heat pump, COP: coefficient of performance LTDH: low temperature district heating.

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