

Article

Environmental and Social Impacts of Renewable Energy-Driven Centralized Heating/Cooling Systems: A Comparison with Conventional Fossil Fuel-Based Systems

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Abstract

Heating and cooling (H&C) account for nearly half of the EU's energy consumption, with significant potential for decarbonization through renewable energy sources (RES) integrated in district heating and cooling (DHC) systems. This study evaluates the environmental and social impacts of RES-powered DHC solutions implemented in three European small-scale demo sites (Bucharest, Luleå, Córdoba) under the Horizon 2020 WEDISTRICT project. Using the Life Cycle Assessment (LCA) and Social Life Cycle Assessment (S-LCA) methodologies, the research compares baseline fossil-based energy scenarios with post-implementation renewable scenarios. Results reveal substantial greenhouse gas emission reductions (up to 67%) and positive environmental trade-offs, though increased mineral and metal resource use and site-specific impacts on water and land use highlight important sustainability challenges. Social assessments demonstrate improvements in gender parity, local employment, and occupational safety, yet reveal persistent issues in wage equity, union representation, and inclusion of vulnerable populations. The findings emphasize that while renewable DHC systems offer significant climate benefits, social sustainability requires tailored local strategies and robust governance to avoid exacerbating inequalities. This integrated environmental-social perspective underscores the need for holistic policies that balance technical innovation with equitable social outcomes to ensure truly sustainable energy transitions.

Keywords: district heating and cooling; life cycle assessment; social life cycle assessment; environmental and social impacts; climate change; renewable energy vs. fossil fuel; climate synergies and trade-offs



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1. Introduction

Heating and cooling (H&C) constitute around half of the European Union's (EU) energy consumption, from which the buildings (residential and commercial) and the industrial sector account for most of the heating demand [1]. Considering that by 2023 the share of renewable energy in this sector was still around 26%, decarbonized, redesigned, and sector-integrated H&C solutions could improve the EU's energy efficiency and effectively enable the transition away from fossil fuels [2].

In addition, with the adoption of the EU Climate Law in 2021, the EU aims to reduce greenhouse gas emissions by 55 percent compared to 1990 levels by 2030 and achieve climate neutrality by 2050 [1]. In this context, district heating and cooling (DHC) networks, which involve the centralized generation of heat/cold and its subsequent distribution to residences, businesses, and industry in a local area, will play a decisive role in the decarbonization of the H&C sector by enabling the integration of renewable and waste heat on a large and centralized scale [3].

After promoting DHC solutions through the EU strategy on heating and cooling [4] and the adopted directives on the promotion of the use of energy from renewable sources (RES) [5] and on energy efficiency [6], these systems have become widely implemented and extensively documented in scientific research as essential energy infrastructure for climate change mitigation [7]. However, the substantial decarbonization potential of DHC remains largely unexploited, as nearly 90% of the heat supplied is produced from fossil fuels, especially in China and Russia [8]. In the EU, around two-thirds of the DHC supply are still generated with fossil fuels and, as far as RES is concerned, bioenergy fuels (biomass, biofuels and renewable waste) constitute almost 88% of the renewable heat produced, followed by industrial excess heat (6%), heat pumps (4%), geothermal (2%) and solar thermal (0.5%) [9].

Thus, to achieve a greater decarbonization of DHC systems, it seems necessary to promote the so-called 4th and 5th generation DHC systems [10,11]. These systems include lower distribution temperatures, assembly-oriented components, use of cutting-edge managing technology and taking advantage of RES [12]. However, to the best of the authors' knowledge, few studies have applied the Life Cycle Assessment (LCA) methodology to assess the environmental impact of these DHC systems [13–16]. In fact, Marcher et al. [17] identified an important gap in the literature of studies reviewing and comparing LCA of strategies for decarbonizing DHC systems. These authors also highlighted the importance of following a standardized estimation methodology, such as LCA, in contrast to carbon footprint studies, for which many methods exist that are not always harmonized. Consistent with this, Gjoka et al. [18] stressed that the comprehensive environmental impact of DHC systems throughout their entire life cycle is still relatively unexplored and more information is needed not only about their operational efficiency and economic viability but also about the comprehensive evaluation of their full life cycle impacts. Tien et al. [19] also reported that LCA application to DHC systems remains fragmented due to the diversity of the different system scales, different geographical and technological contexts and different scopes, with LCA studies encompassing entire DHC networks and others focusing on specific components such as heat generation units or thermal energy storage [20,21].

Furthermore, the reduction in environmental impact from any energy generation system must not come at the cost of increasing social impacts. On this dimension, the existing literature on the Social Life Cycle Assessment (S-LCA) methodology remains particularly limited. Although there are pertinent sections in the literature applicable to DHC systems, a thorough, comprehensive S-LCA of such systems has yet to be documented [22–24].

Based on these premises, the European Union's Horizon 2020 research and innovation program funded the WEDISTRICT project (grant agreement N°857801). The main objective of WEDISTRICT was to study the impact of implementing local DHC systems powered by RES and waste heat, mostly from the point of view of climate change mitigation but also considering the social perspective. Within the project, a wide variety of renewable energy generation technologies were implemented in three locations across Europe, resulting in three small-scale demonstration projects (demo sites) implemented in Bucharest (Romania), Luleå (Sweden) and Córdoba (Spain).

This study aims to address the current gap regarding the integrated environmental and social assessment of the full implementation of RES-fed DHC systems. Beyond decarbonization evaluation, which was the fundamental objective of the WEDISTRICT project, this paper assesses various environmental impacts to gain a much more comprehensive understanding of the environmental impact associated with the energy solutions evaluated. To achieve all of this, as explained in Puentes Bejarano et al. [25] for Luleå, a comparative analysis was conducted for each demo site using LCA and S-LCA methodologies, according to ISO 14040:2006 [26] and the United Nations Environment program (UNEP) guidelines [27], respectively. While this study provides a comprehensive evaluation of the environmental and social impacts of RES-powered DHC systems, the economic dimension has been deliberately excluded. This decision responds to the heterogeneity and context-specificity of economic data across the three demo sites, which would have hindered a coherent comparative analysis. Furthermore, the aim of this study is to deepen the understanding of environmental and social performance, which are often underrepresented in integrated sustainability assessments of DHC systems. The analysis carried out contrasted the baseline scenario, characterizing the pre-implementation state in the WEDISTRICT project, with the WEDISTRICT scenario, depicting the post-implementation state after the deployment of the project's technologies based on RES.

2. Methodology

2.1. WEDISTRICT Project

The WEDISTRICT project, funded by the H2020 program of the European Commission, examined the combination of different renewables technologies (solar collectors, innovative thermal storage systems, advanced absorption chillers, biomass boiler, fuel cells and geothermal heat pumps) in three demo sites located in Luleå (Sweden), Cordoba (Spain) and Bucharest (Romania) to demonstrate their technical feasibility for the implementation of net-zero district heating and cooling (DHC). It showcased the application of renewable technologies to different climate zones in Europe, as well as different services: from a data center to a university campus, up to TRL7.

A myriad of technologies such as low NOx biomass boilers, Fresnel and parabolic trough solar collectors, innovative low-concentration thermal collectors (WESSUN), innovative thermal cooling systems (RACU) and absorption chillers, biogas fuel cells combined with immersed cooling for electronic racks and geothermal energy were implemented. As part of the implementation of the different technologies in the project, a Life Cycle Sustainability Analysis (LCSA) was developed to understand the three aspects of the sustainability analysis: Economic (Life Cycle Cost—LCC), Environmental (Life Cycle Analysis—LCA) and Social (Social Life Cycle Analysis—S-LCA). In this paper, we are focusing on advancing the discussion around LCA and S-LCA.

2.2. Case Studies: Demo Sites

This analysis compares the environmental and social performance of using RES against conventional energy sources for DHC energy generation. This research aims to verify if the environmental and social impacts of the current situation (baseline scenario) are reduced (or increased) after the implementation of the different technologies, when the energy demanded by the DHC systems proposed by the WEDISTRICT project is generated using renewable technologies.

To perform a proper analysis, this study compares two scenarios: (i) a baseline scenario, representing how the energy demand was covered at the beginning of the project and (ii) a WEDISTRICT scenario, which represents the situation once the renewable technologies selected by the project are implemented. Both scenarios were applied in three demo sites

to measure and demonstrate the performance of energy generation for DHC networks in terms of environmental and social sustainability.

2.2.1. Bucharest (Romania) Demo Site

This demo site is located on the campus of the National University of Science and Technology POLITEHNICA Bucharest (UNSTPB). In this campus, there was a building (known as target building, TB) whose heating demand was met with a 110 kW gas boiler (Keston C110 Gas Boiler, year of commissioning was 2005) and a 3 kW electric appliance for domestic hot water (DHW) production. For cooling, TB used three air conditioners running on electricity.

The WEDISTRICT project considered the combination of geothermal-photovoltaic hybridized technology to produce the required thermal and electrical energy using only renewable sources. This system ensures the proper heating and cooling of the TB, as well as covering its DHW and electricity demand. Figure 1 represents the complete demo-site block diagram of the technologies installed. The hybrid system is composed of a thermal subsystem, producing thermal energy using geothermal heat pumps, and an electrical subsystem, producing electrical energy using PV Panels.

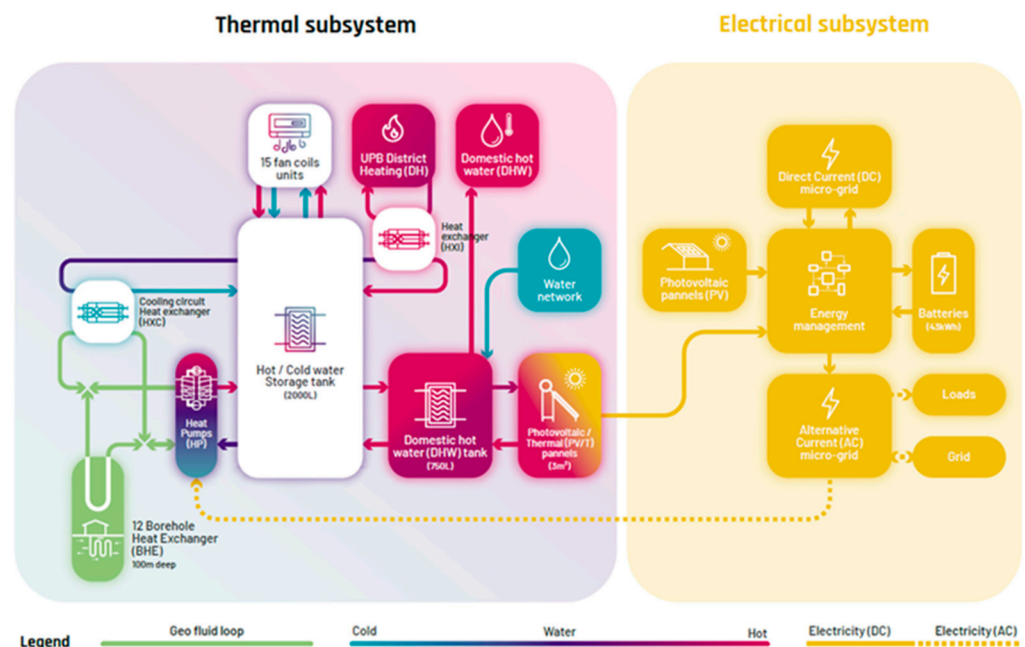


Figure 1. Bucharest demo-site process diagram.

2.2.2. Luleå (Sweden) Demo Site

The demo site is located within the Luleå Science Park in Sweden, home to the Research Institutes of Sweden (RISE). The science park thermal energy was covered by a district heating (DH) network, which provided energy from a cogeneration plant using recovered gases from a steel mill as fuel. These recovered gases are composed of 70% blast furnace gas, 20% converter gas (LD gas) and 10% coke gas.

The WEDISTRICT scenario is an innovative setup to harvest the excess heat from a RISE-owned data center (DC) with the integration of solid-oxide fuel cells (SOFCs) to cogenerate energy [25]. The DC excess heat is recovered by a liquid cooling technology and boosted to temperatures suitable for supplying it to the SOFC operation. The electricity produced by the SOFC is used to power the DC, and the thermal energy produced is used to feed the existing DH network.

Then, the technologies proposed combine two modules. The first one is the data center module (DC module) where the DC servers are immersed in a dielectric liquid for direct heat transfer by liquid cooling technology. The excess heat is transferred to preheat the incoming air into the second module, which is the solid-oxide fuel cell module (FC module), where nine biogas SOFCs are located. SOFC generates thermal and electrical energy. The thermal energy produced feeds the existing DH network. The electrical energy produced feeds 90% of the DC module consumption; the 10% left needed to operate is taken from the grid, according to the demo-site performance data. Figure 2 represents the demo-site process diagram of the technologies installed.

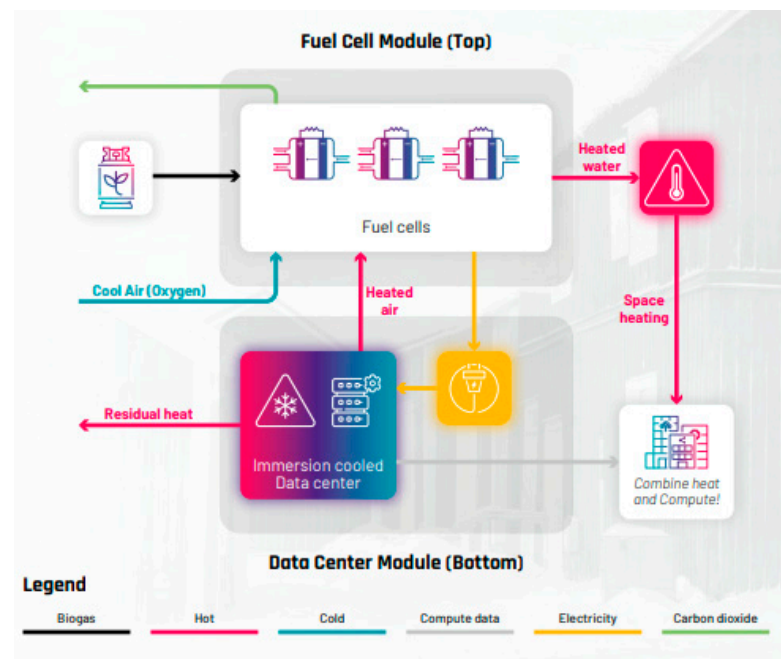


Figure 2. Luleå demo-site process diagram.

2.2.3. Córdoba (Spain) Demo Site

This demo site is located at the Rabanales Campus of the Universidad de Córdoba (UCO). Specifically, in the baseline scenario, the energy demand of two buildings (the changing rooms of Monte Cronos Sports stadium and the Da Vinci Building zones I, II and III) at the Rabales Campus was covered by a district heating (DH) network, which provided energy from six heat pumps and a gasoil boiler.

The WEDISTRICT demo site combines three different solar technologies to cover the heating demand of the Rabales Campus (Parabolic trough collector-PTC, Linear Fresnel collector-LFC, Tracking Concentrator with Fixed Tilt Collector-TC-FTC) and biomass boilers with improved air filters for reducing air pollutants (E-filter). For cooling, absorption chillers and a Renewable Air-Cooling Unit (RACU) prototype are used (Figure 3). Then, the technologies proposed by the project combine two modules. The first one is the thermal energy module, which consists of the previously mentioned concentration solar collectors and a thermal energy storage unit. It is important to highlight that the potential for solar energy is vast due to the amount of sunlight available in Spain. The direct normal sun irradiation in the middle of Spain is around 1980 kWh/m² year, which makes the concentrated solar technology a promising solution to cover the heating demand of buildings, as well as the cooling demand through absorption chillers. The second module consists of a high-efficiency, low-emissions biomass boiler to meet the energy demands of UCO.

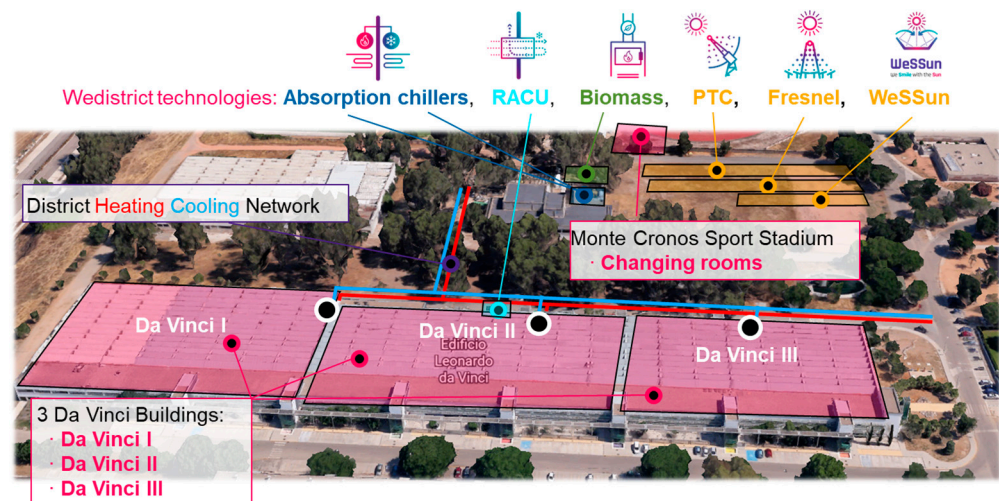


Figure 3. Córdoba demo-site process diagram.

2.3. Environmental Assessment: Life Cycle Assessment Methodology

Life cycle assessment (LCA) is an internationally standardized methodology according to ISO standards 14040 [26] and 14044 [28]. LCA helps to quantify the environmental pressures related to products, the environmental benefits, the trade-offs and areas for achieving improvements considering the full life cycle of the product. According to the ISO standard, the life cycle is defined as the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout all its consecutive and interlinked stages, from raw material acquisition to final disposal (or treatment) after use.

LCA studies are composed of four main phases:

1. Goal and scope definition: It includes the definition of the system boundaries, functional unit (FU) and level of detail of an LCA depending on the subject and the intended use of the study.
2. Life cycle inventory phase (LCI): It is the second phase of the LCA. It is an inventory of input/output data about the system being studied. It involves collecting the necessary data to meet the defined goals. In this step, a flow model of the system is built, usually a flowchart, showing the analyzed activities and the flows between them.
3. Life cycle impact assessment phase (LCIA): it transforms the data from inventory analysis into specific environmental impacts according to an LCIA method.
4. Life cycle interpretation: It is the final phase of the LCA, in which the results of an LCI or an LCIA, or both, are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition.

2.3.1. Goal and Scope

For this LCA, SimaPro 9.1.1.7 version and the Ecoinvent 3.6 database were used. The selected environmental impact assessment method was Environmental Footprint 3.0 (EF 3.0), as recommended by the European Union (EU Commission Recommendation, 2021/2279).

In this research, not all the environmental impact categories distinguished by the EF 3.0 method are considered. Eight of them are selected and prioritized to facilitate the interpretation of results considering the experts' opinion and according to the literature reviewed for energy generation systems [29–31]. These categories are climate change, photochemical ozone formation, acidification, eutrophication-terrestrial, land use, water use, resource use-fossils and resource use-minerals and metals.

The climate change impact category (carbon footprint, CF) is one of the greatest interests for WEDISTRICT project. Although special attention will be paid to this impact category, the other prioritized categories are also analyzed to understand the integrated environmental performance of the technologies assessed.

Functional Unit (FU).

The functional unit (FU) defined for this study is 1 kWh of energy delivered by the system, which serves as the basis for all comparisons.

System Boundaries.

The assessment follows a cradle-to-gate approach, covering processes from the extraction of raw materials up to the production of energy (i.e., the use phase of the installations). Detailed system descriptions for each demo site are provided in the following sections.

Assumptions and Limitations: The LCA relies on several assumptions and simplifications as outlined below:

- The end-of-life phase is excluded to maintain consistency with the scope and data availability for both environmental and social analyses.
- Transportation of equipment is not included; however, transport of raw materials is accounted for within the processes modeled using the Ecoinvent database.
- In cases of data gaps for specific equipment, background information from Ecoinvent and the relevant literature was used.
- To normalize all Life Cycle Inventory (LCI) data to the FU, annual energy production and the expected equipment lifetime were used as reference values.
- When needed, electrical and thermal energy outputs were weighted to express results as environmental impacts per total kWh of energy delivered.
- Avoided burdens are considered to present the results. The methodological approach of avoided burdens accounts for the environmental impacts that are prevented by substituting products or services generated within the evaluated demo site (such as additional electricity in some cases) for functionally equivalent alternatives (for example, electricity supplied by the regional distribution grid). In this way, the production of the substituted product or service is avoided, along with the environmental impacts associated with its life cycle [32].

2.3.2. Life Cycle Inventory (LCI)

The quantitative life cycle inventory data for each demo site are subject to confidentiality and therefore cannot be disclosed publicly.

Bucharest demo site

Table 1 summarizes the equipment used in the TB for energy generation before the project. Each scenario was divided into subsystems to facilitate the data collection and analysis of the results. All the subsystems were modeled with SimaPro.

Table 1. Bucharest demo-site equipment used for energy generation—baseline scenario.

SUBSYSTEM ANALYZED	ON-SITE EQUIPMENT
Heating	Natural gas boiler
Cooling	Air conditioners
DHW	Electric appliance

Details of the equipment acquired for the demo site construction and for the modeled processes in SimaPro are shown in Table 2.

Table 2. Bucharest demo-site equipment acquired—WEDISTRICK scenario.

SUBSYSTEM ANALYZED	DEMO-SITE EQUIPMENT
Thermal	Geothermal boreholes Heat exchangers Heat pumps Heating and cooling distribution network
Electrical	Photovoltaic (PV) roof-mounted panels Electrical distribution network
Photovoltaic-thermal (PV-T)	PV-T roof-mounted panels

In this phase, technical and budget sheets provided by UNSTPB (Universitatea Națională de Știință și Tehnologie Politehnica București) are used to list and characterize all the equipment included in the analysis. In addition, they provided detailed information on the mass, quantity and technical performance of the equipment.

All numerical inputs are normalized in terms of the FU using the energy production and energy delivered to the system in one year and the equipment lifetime.

Luleå demo site

To model the baseline scenario, background information from the Ecoinvent database was used. The type and share of each residual gas used in the cogeneration plant LuleKraft for DH production in Luleå, Sweden, were considered. Table 3 summarizes the equipment acquired for the demo site construction (WEDISTRICK scenario) and for the modeled processes in SimaPro.

Table 3. Luleå demo-site equipment acquired—WEDISTRICK scenario.

SUBSYSTEM ANALYZED	ON-SITE EQUIPMENT
DC module	Immersion cooled system Electronics
FC module	SOFC Biogas

In this phase, the technical data provided by RISE were used to identify and characterize all equipment included in the analysis for the WEDISTRICK scenario. All numerical inputs were normalized to the functional unit (FU) based on the annual energy production and delivery, as well as the expected equipment lifetime, following the same approach applied in the Bucharest demo site. As this is a newly built proof-of-concept demo site, the baseline scenario was defined to deliver the same amount of thermal energy injected into the secondary district heating (DH) network as in the WEDISTRICK scenario.

Córdoba demo site

To model the baseline scenario (Table 4), background information from the Ecoinvent database was used. The type of energy used in UCO, gasoil boiler and heat pumps, were considered. Table 5 summarizes the equipment acquired for the demo site construction and for the modeled processes in SimaPro (WEDISTRICK scenario).

Table 4. Córdoba demo-site equipment used for energy generation—baseline scenario.

SUBSYSTEM ANALYZED	ON-SITE EQUIPMENT
Heating	Heat Pumps Gasoil boiler
Cooling	Heat Pumps

Table 5. Córdoba demo-site equipment acquired—WEDISTRIC scenario.

SUBSYSTEM ANALYZED	ON-SITE EQUIPMENT
Heating System	PTC panels LFC panels TC-FTC panels Biomass boiler
Cooling System	Absorption chiller Cooling tower
	RACU
Thermal Storage Tank	Solar thermal storage tank ($1 \times 50,000$ L) Biomass boiler buffer tanks (2×5000 L)
Heat and Mass Exchangers	Da Vinci building substation Monte Cronos stadium substation

In this phase, technical information provided by UCO is used to list and characterize all the equipment included in the analysis for the WEDISTRIC scenario. All numerical inputs are normalized in terms of the FU using the energy production and energy delivered to the system in one year and the equipment lifetime, as it was performed in the previous demo sites.

2.4. Social Assessment: Social Life Cycle Assessment Methodology

From a broader definition, S-LCA is a methodology designed to assess the social impacts of products, services or processes throughout their life cycle, complementing traditional LCA, which focuses primarily on environmental concerns. In recent years, sustainability assessments have evolved to incorporate social and economic dimensions, providing a more comprehensive view of sustainability. S-LCA aims to examine the social implications of various activities within the life cycle of a product or service, extending the LCA framework by considering factors such as human rights, labor practices, community well-being, health and safety and socio-economic impacts [27,33]. It is worth mentioning that S-LCA's scope is wide-ranging and needs to be tailored based on the specific objectives of the assessment [27,34].

2.4.1. Goal and Scope

For the purposes of this S-LCA, the guidelines proposed by UNEP [27] were adopted as the primary methodological reference. Similarly to the environmental LCA, the same system boundaries were applied for the WEDISTRIC project scenario. Additionally, the baseline scenario was constructed using representative national and/or local data, reflecting the standard conditions prior to the project's implementation. Establishing this baseline is critical for enabling a meaningful comparison between the project's social impacts and the broader socio-economic context. This approach also facilitates a clearer understanding of the project's added social value. When specific data from the demo site was unavailable or not explicitly defined, national-level figures were used as a proxy to render pre-project conditions.

As mentioned in the UNEP/SETAC guidelines, due to their complex nature, most of the indicators are qualitative rather than quantitative. Therefore, 33 indicators within five main categories were allocated and are summarized as follows:

- Worker: Includes labor conditions, fair wages and worker health and safety.
- Local Community: Evaluates the impacts of a product or service on local communities, including issues related to community development and social equity.

- Society: Considers broader societal impacts, such as social justice, public health and economic development.
- Value Chain: Assesses the social conditions along the entire supply chain, identifying risks related to suppliers and sub-contractors.
- Consumer: Focuses on consumer rights, product safety and transparency in labeling and marketing.

These categories help in understanding the broader social consequences of products and services, contributing to ethical and sustainable decision-making. Through this analysis, key challenges and opportunities were identified, and it was possible to offer recommendations for advancing the integration of social considerations into decision-making processes on which the WEDISTRICT project is implemented.

2.4.2. Life Cycle Inventory (LCI)

Data for this analysis was obtained from both primary and secondary sources. Primary data was gathered directly at each demonstration site using a structured data collection tool. This dataset was divided into two categories: PRE and POST. The PRE data corresponds to information available prior to the implementation of the WEDISTRICT project at each demo site, while the POST data reflects conditions following the project's implementation. In addition, secondary data were compiled from national, regional and local government reports, relevant legislation, open-source databases, publications from private entities and other publicly accessible information available online. Table 6, previously introduced in Puentes Bejarano et al. [25], presents the different indicators included in the S-LCA.

The table of social categories, sub-categories and indicators has been maintained without modification to ensure consistency with internationally recognized frameworks for Social Life Cycle Assessment (S-LCA). According to the Guidelines for Social Life Cycle Assessment of Products and Organizations [27], a comprehensive S-LCA should address a broad range of social aspects across all stakeholder groups, including workers, local communities, society, consumers and value chain actors. The selected indicators in this table are directly aligned with these recommended categories and reflect established practices in recent S-LCA studies [25,35–37]. Altering this structure would compromise the methodological robustness and comparability of the results, potentially overlooking relevant social issues that are essential for a holistic sustainability assessment.

Moreover, due to the qualitative nature of the indicators used, it is important to acknowledge that most results do not yield numerical values readily comparable across different projects. As such, the analysis of indicators within the framework of S-LCA presents distinct challenges, primarily stemming from the reliance on subjective interpretations and perceptions. In contrast to quantitative data, which can be systematically measured and standardized, social indicators often depend on qualitative evaluations of complex societal phenomena, including human behavior, attitudes and social relationships.

To provide a comprehensive perspective on social performance across the three demo sites, the S-LCA results integrate the site-specific primary data with broader context from secondary sources. Local survey and observational data were complemented and interpreted alongside relevant national guidelines, regulatory frameworks and other publicly accessible records. The S-LCA results for all indicators were derived from data collected at each demo site through stakeholder surveys, project documentation and direct observations. To provide context and support interpretation, these local data were also compared with relevant national guidelines, regulatory frameworks and other publicly available records. This approach enables a comprehensive assessment of social performance, situating site-specific outcomes within broader national and regulatory benchmarks and highlighting both areas of improvement and potential challenges across the WEDISTRICT demo sites.

Table 6. Main categories, sub-categories and indicators used in the collection tool for all the demo sites. Source: Repurposed from Puentes Bejarano et al. [25].

CATEGORY	SUB-CATEGORY	INDICATOR
Worker	Freedom of association and collective bargaining	• Presence of unions • Total number of affiliates
	Child labor	• Presence of child labor
	Fair salary	• Wage inequality • Average annual wage in the sector • Payment • Compensation for overtime • Lowest paid worker
	Equal opportunities	• Employment of people with special needs • Men to women employability • Gender equality • Career development
	Health and safety	• Education, training and other programs • Lost time per injury • Policies concerning health and safety • Sick-leave days • Accidents
Local community	Local employment	• Local employment in the project • Workers residing in the local community
	Safe and healthy living conditions	• Environmental certifications • Impacts by activities of the company • Initiatives for improvement • Transparency on issues
Society	Product utility	• Relevance of the product to satisfy needs • Affordability of technologies
	Commitments to sustainability	• Agreements on sustainability issues • Public reporting
	Corruption	• Legal issues
Value chain	Fair competition	• Legal actions on anti-competitive issues
Consumers	Health	• Damages caused by the product
	Quality	• Quality labels • Access to clear information

3. Results

3.1. Life Cycle Assessment

3.1.1. Bucharest Demo Site

Table 7 presents the results for both the baseline and WEDISTRIC scenarios, while Figure 4 illustrates these results in relative terms, with the baseline scenario normalized to 100%. Comparing the WEDISTRIC scenario against the baseline reveals three distinct trends. The first trend shows environmental improvement in the categories of climate

change and fossil resource use. The second trend indicates higher environmental impacts in the WEDISTRIC scenario for photochemical ozone formation, water use, land use and mineral and metal resource use. The third trend, observed for terrestrial eutrophication and acidification, shows similar impacts in both scenarios, suggesting that these results are inconclusive and require careful interpretation.

Table 7. Environmental impact results include the avoided burden—Bucharest demo site.

Impact Category	Units (/kwh)	Baseline	WEDISTRIC	WEDISTRIC + Avoided Burden
Climate change	kg CO ₂ eq	2.29×10^{-1}	7.65×10^{-2}	-2.67×10^{-2}
Photochemical ozone formation	kg NMVOC eq	1.99×10^{-4}	2.78×10^{-4}	5.16×10^{-5}
Acidification	mol H ⁺ eq	2.66×10^{-4}	3.33×10^{-4}	-4.16×10^{-4}
Eutrophication, terrestrial	mol N eq	5.73×10^{-4}	6.30×10^{-4}	-1.44×10^{-4}
Land use	Pt	1.76×10^{-1}	1.50×10^0	9.40×10^{-1}
Water use	m ³ depriv.	5.68×10^{-3}	3.81×10^{-2}	6.50×10^{-3}
Resource use, fossils	MJ	3.71×10^0	8.01×10^{-1}	-1.13×10^0
Resource use, minerals and metals	kg Sb eq	1.82×10^{-7}	1.14×10^{-5}	1.06×10^{-5}

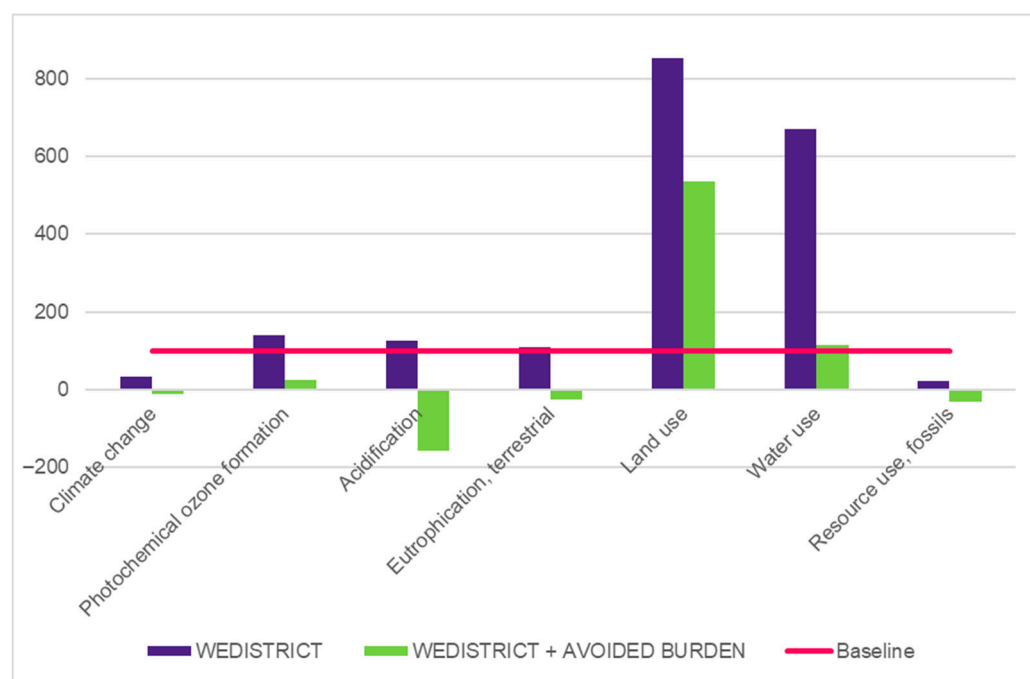


Figure 4. Bucharest demo site environmental results (baseline scenario = 100%).

Specifically, for climate change, the LCA results indicate that the carbon footprint is 0.23 kg CO₂ eq/kWh for the baseline scenario and 0.07 kg CO₂ eq/kWh for the WEDISTRIC scenario, representing a 67% reduction. This improvement is mainly due to the substitution of natural gas with alternative energy sources in the energy production phase for the thermal boiler (TB).

However, when reviewing the other prioritized environmental impact categories, the WEDISTRIC scenario impacts are mostly higher. The main reason for this increase is attributed to the inclusion of the electrical subsystem in the analysis, specifically the impacts associated with the manufacturing and the raw materials acquisition processes for the monocrystalline silicon wafers used to produce the PV panels. Furthermore, as mentioned in the limitations, detailed data were taken directly from UNSTPB to build

the WEDISTRICK scenario model in SimaPro, unlike the baseline scenario that was built mainly with secondary and less detailed data, which could also influence the results.

Nevertheless, the electrical energy that is being generated with the WEDISTRICK scenario technologies is partly consumed by the heat pumps of the geothermal system, and the surplus energy is sent and distributed for internal consumption in the UNSTPB, avoiding the current electricity consumption from the Romanian grid, which is highly dominated by fossil fuel sources (71% by 2020). This surplus energy is considered an avoided burden, as outlined in the Goal and Scope Definition chapter, since part of the conventional energy generation is replaced by the renewable one [32].

When the avoided burden is introduced in the assessment, the results show an evident improvement for the WEDISTRICK scenario. In terms of climate change, the LCA results show that for each surplus kWh generated, 0.10 kg CO₂ eq is avoided, leading to a global carbon footprint of -0.03 kg CO₂ eq/kWh for this scenario. In addition, lower contributions to the other environmental impact categories are obtained, except for the resource use-minerals and metals and land use environmental impact categories. For these latter impact categories, as mentioned before, the contributions are related to the raw materials acquisition and the manufacturing stage of the PV panels, mainly related to the monocrystalline silicon (single-Si) used. Different studies [38–40] have shown that the production of PV panels is a critical process (both in terms of raw material acquisition and the manufacturing process) because different chemical compounds that cause negative effects on the environment are often released.

3.1.2. Luleå Demo Site

Table 8 shows the environmental impact results, and Figure 5 represents them graphically (it also shows the results in relative terms, where the baseline scenario results are equal to 100%). As in the Bucharest demo site, the comparison of the WEDISTRICK scenario against the baseline in Luleå reveals three divergent trends in environmental impact. An optimizing trend is evident for impact categories, including climate change, photochemical ozone formation and terrestrial eutrophication. In contrast, the WEDISTRICK scenario exhibits higher environmental impacts concerning water consumption, fossil resource depletion and mineral/metal resource consumption. A third neutral trend indicates comparable environmental impacts for acidification and land use in both scenarios, rendering these particular results non-conclusive and necessitating meticulous analysis and interpretation.

Table 8. Environmental impact results including the avoided burden—Luleå demo site scenarios.

Impact Category	Units (/kWh)	Baseline	WEDISTRICK	WEDISTRICK + Avoided Burden
Climate change	kg CO ₂ eq	1.23×10^{-1}	6.44×10^{-2}	-1.46×10^{-1}
Photochemical ozone formation	kg NMVOC eq	5.57×10^{-4}	2.33×10^{-4}	-6.52×10^{-4}
Acidification	mol H ⁺ eq	4.95×10^{-4}	5.73×10^{-4}	-8.17×10^{-4}
Eutrophication, terrestrial	mol N eq	1.05×10^{-3}	7.63×10^{-4}	-3.37×10^{-3}
Land use	Pt	1.75×10^0	1.85×10^0	-2.29×10^1
Water use	m ³ depriv.	8.64×10^{-3}	2.31×10^0	1.80×10^0
Resource use, fossils	MJ	1.07×10^0	1.91×10^0	-2.07×10^1
Resource use, minerals and metals	kg Sb eq	1.06×10^{-6}	3.93×10^{-6}	-5.84×10^{-7}



Figure 5. Luleå demo site environmental results (baseline scenario = 100%).

For the climate change impact category, the results indicate that the carbon footprint for the baseline and WEDISTRICK scenarios are 0.12 kg CO₂ eq/kWh and 0.06 kg CO₂ eq/kWh, respectively, representing a 48% reduction in the WEDISTRICK scenario. It is important to note that, even though the baseline scenario already represents a relatively sustainable solution, promoting industrial symbiosis and circular economy principles by recovering gases from the steel mill, the WEDISTRICK scenario achieves further improvements across the entire life cycle through the innovative technologies implemented by the project. Previous research [41–44] confirms that the use of renewable sources, such as biogas in biogas-fed solid oxide fuel cells (SOFCs), significantly reduces the carbon footprint compared to conventional energy generation systems.

However, for other impact categories, namely water use, resource use (fossils), resource use (minerals and metals), land use and acidification, the WEDISTRICK scenario exhibits higher environmental impacts. These increases are primarily associated with the use phase of the energy-generation equipment. Specifically, the higher impacts in resource use (fossils) and land use are linked to the small fraction of electricity sourced from Sweden's national grid to operate the district heating module. Similar findings were reported by Pasciucco et al. [41], who identified electricity consumption as the main contributor to abiotic depletion (fossil fuels) in three of the four scenarios modeled in their study.

The elevated impacts in water use, resource use (minerals and metals) and acidification are attributable to the biogas consumed in the fuel cell module. In particular, the biogas production phase involves substantial water consumption during anaerobic digestion [45] and the use of chemical inputs, such as sulfuric acid and cobalt, included in the background database for biogas stabilization [46]. These results highlight that while renewable energy systems substantially reduce greenhouse gas emissions, they may also introduce trade-offs in other environmental impact categories that must be carefully managed.

It is important to note that a portion of the district heating (DH) module self-consumes the electricity generated by the fuel cell (FC) module to operate and supply energy to the DH network. This internal consumption reduces reliance on the national grid by approximately 90%, thereby mitigating the substantial environmental impacts associated with grid electricity production.

As a result, the avoided impacts, represented by negative values in the assessment, exceed the direct impacts in seven out of eight prioritized environmental categories. This demonstrates that the WEDISTRICK scenario is environmentally advantageous even when compared to the circular and resource-efficient baseline scenario. These findings underscore the importance of combining renewable fuels with innovative energy generation technologies to achieve sustainable solutions in the energy sector. Similar approaches, incorporating avoided burdens into comparative LCA assessments of energy generation technologies, have been reported in previous studies [41,47,48], which present results consistent with those observed in this analysis.

Specifically, for climate change, including the avoided burdens, the LCA results indicate that 0.21 kg CO₂ eq are avoided for each kWh of electricity self-consumed within the DH module, resulting in a net carbon footprint of −0.15 kg CO₂ eq/kWh for the WEDISTRICK scenario. Conversely, for water use, the elevated impacts of the WEDISTRICK scenario remain primarily associated with water consumption during biogas production [45,49]. This identified hotspot highlights the need to evaluate a broad range of environmental impact categories and supports informed decision-making regarding potential technological improvements. Addressing such hotspots is essential for advancing a truly sustainable energy value chain that balances decarbonization with the minimization of other environmental burdens.

3.1.3. Córdoba Demo Site

Table 9 and Figure 6 show the environmental impact results of the baseline and the WEDISTRICK scenarios.

Table 9. Environmental impact—Córdoba demo site scenarios.

Impact Category	Units (/kWh)	Baseline	WEDISTRICK
Climate change	kg CO ₂ eq	7.79×10^{-2}	2.90×10^{-2}
Photochemical ozone formation	kg NMVOC eq	1.21×10^{-4}	1.31×10^{-4}
Acidification	mol H ⁺ eq	1.82×10^{-4}	1.74×10^{-4}
Eutrophication, terrestrial	mol N eq	3.99×10^{-4}	4.52×10^{-4}
Land use	Pt	7.90×10^{-1}	2.62×10^0
Water use	m ³ depriv.	1.27×10^{-1}	3.63×10^{-2}
Resource use, fossils	MJ	2.21×10^0	6.90×10^{-1}
Resource use, minerals and metals	kg Sb eq	9.16×10^{-7}	3.82×10^{-6}

When comparing the WEDISTRICK against the baseline scenario for the Córdoba demo site, the results present interesting results. It is possible to identify that, when compared to the baseline, the WEDISTRICK scenario represents a large improvement in the long run regarding climate change, water use and resource use (fossils) impacts.

Regarding climate change, the baseline result is approximately three times larger than the WEDISTRICK result. This indicates that the WEDISTRICK system emits far fewer greenhouse gases per FU compared to the baseline system, meaning it is considerably more climate friendly. The decrease in emissions per kWh (from 0.078 to 0.029 kg CO₂ eq/kWh delivered to the system) shows that WEDISTRICK integrates more energy-efficient processes, cleaner energy sources or renewable solutions. These findings capture the cumulative climate impact of each system across their entire life cycle, emphasizing the environmental advantages of the WEDISTRICK approach.

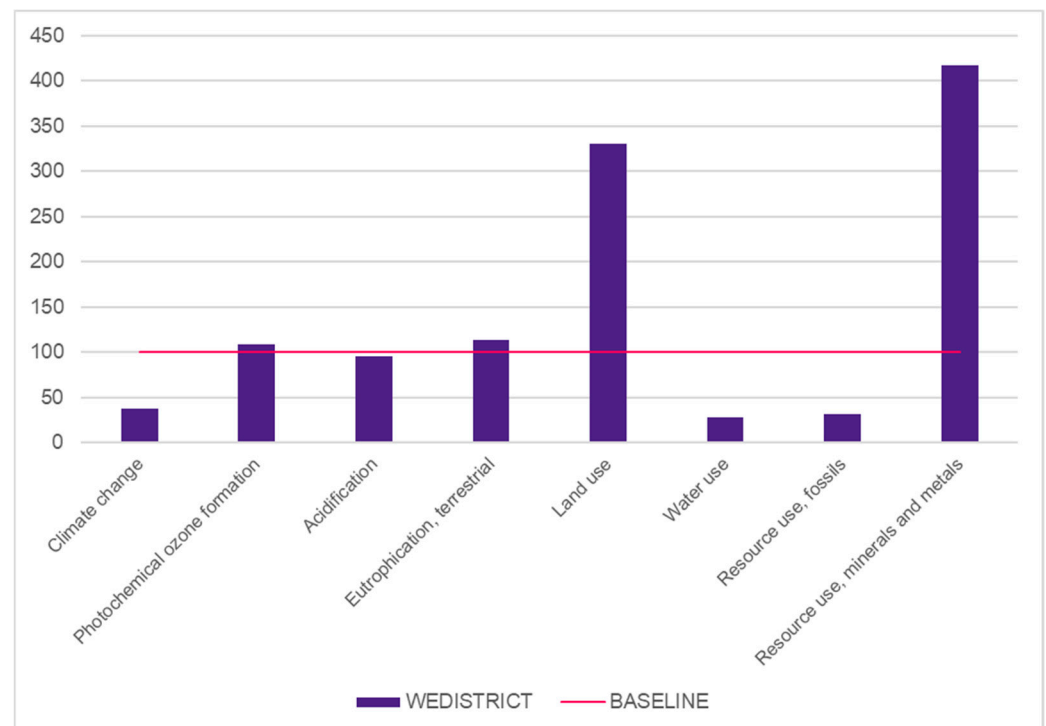


Figure 6. Córdoba demo site environmental results (baseline scenario = 100%).

Solar panels are favored due to their significantly lower greenhouse gas emissions over their operational life. Although the production of solar panels does involve the release of some greenhouse gases, particularly during the mining, manufacturing and transportation processes, these emissions are quickly offset once the panels start generating electricity. Over the considered lifespan of the system, its CF is minimal compared to the emissions from electricity generation consumed in the demo site (according to Spanish electricity mix) and the impact due to the gasoil boiler, which must burn fuel throughout its operational life (81 and 19% of the total impact, respectively). By harnessing solar energy, the dependency on fossil fuels is reduced, and the life cycle climate change impacts associated with energy generation significantly diminished.

In the WEDISTRICK scenario, more than 50% of the impact on climate change is due to the consumption of electricity from the grid and, therefore, generated in accordance with the Spanish electricity mix.

Regarding water use, the baseline value is approximately 3.5 times larger than the WEDISTRICK result. Water use is a critical environmental factor, particularly in regions facing water scarcity like Córdoba, where prolonged droughts and rising temperatures linked to climate change are increasing. The region's agricultural reliance further strains limited water resources, posing challenges for its sustainable management. The substantial reduction in water demand in the WEDISTRICK system means it not only has a lower environmental impact in terms of energy production but also conserves an essential natural resource, making it a more sustainable option overall.

Finally, reflecting the resource use (fossils), the baseline value is roughly 3.2 times larger than the WEDISTRICK result. By integrating renewable energy technologies, WEDISTRICK minimizes non-renewable resources consumption, unlike the baseline, which involves fossil fuel demands. WEDISTRICK's focus on reducing fossil fuel consumption aligns with global sustainability goals by decreasing reliance on finite, polluting energy sources.

On the negative impacts of implementing the WEDISTRIC project, it was identified that resource use (minerals and metals) consumes 4.2 times the minerals and metals when compared to the baseline scenario. This higher consumption reflects the use of renewable energy technologies which require metals like copper, aluminum and lithium, as well as other critical materials for construction and energy transport and storage. The main contributions to this total impact in the WEDISTRIC scenario are due to the LFC and TC-FTC panels. The extraction and processing of the materials used in these panels can have environmental consequences, such as habitat destruction, energy-intensive mining operations and waste generation, which must be carefully managed to ensure sustainability. While WEDISTRIC uses more minerals and metals, there is potential to offset this impact through circular economy practices. Many of the materials used in renewable technologies can be recycled at the end of their life cycle, reducing the need for virgin material extraction and mitigating the overall resource use impact. This will be key for the project at the end of its life cycle and should be carefully considered over time.

Additionally, land use takes into account the entire life cycle of the solar panels and the biomass boiler, considering the material extraction, their production process and, even, the implementation of the systems on the demo site. These values are 3.3 times larger than the baseline scenario, as can be seen in Figure 6; it is important to understand that these still have an impact which needs to be paid attention to, as higher land consumption can lead to deforestation, habitat loss and reduced biodiversity. Biomass plays a very relevant role in the magnitude of this impact in this scenario.

The results presented in Tables 8–10 are derived from a comprehensive Life Cycle Assessment (LCA) conducted according to ISO 14040/44 standards [26,28]. All numerical values for both the baseline and WEDISTRIC scenarios are provided, allowing for full verification and interpretation. The LCA was performed using consistent system boundaries, functional units and impact assessment methods across scenarios, ensuring that differences in results directly reflect the environmental performance of the assessed systems. By presenting both absolute and relative values, the tables enable clear comparison between the baseline and WEDISTRIC scenarios, highlighting improvements, trade-offs and areas where impacts remain similar.

Table 10. Summary table of social impacts across demo sites.

Area	Luleå	Córdoba	Bucharest
Wage trend	↓ Below national average	↓ Below national average	↓ Below national average
Gender equity	↑ Leading in female employment	↑ Improved, still below management parity	↑ Improved occupation equity
Special needs employment vs. National average	↓ From 7% to 5%	↑ From 0% to 10%	↓ From 18% to 0%
Union presence	Maintained at 75%	No presence	No presence
Local hiring	↑ Up to 92%	↑ Up to 95%	↑ Up to 100%
Accidents	None reported	None reported	None reported
Transparency	Maintained high	↑ Improved from low baseline	Maintained high
Fair competition	Stable	↑ Perceived improvement	↑ Perceived improvement

Note: The upward arrows (↑) mean an improvement compared to the baseline. Likewise, the downward arrows (↓) mean a retrogression compared to the baseline.

3.2. Social Life Cycle Assessment

This section presents a comparative and comprehensive analysis of the social performance of the three WEDISTRICT demo sites, based on key social indicators tracked before and after the implementation of the project. The indicators are interpreted relative to their respective national baselines to identify patterns of improvement, similarity or decline. While each site is shaped by its national socio-economic context, several common threads emerge in terms of gender equality, worker safety, community integration and transparency. The analysis reveals heterogeneous impacts, exposing both areas of good practice and structural contradictions that challenge assumptions of social sustainability in the context of energy system transitions.

The findings are grouped in different areas of social impacts and summarized in Table 10.

For social indicators, data were collected through a stakeholder survey administered to employees, suppliers and local community representatives at each demo site. While the full survey instrument is not included in this manuscript due to intellectual property considerations, it was designed to capture a wide range of perspectives, providing nuanced insights into social performance. To contextualize the findings, local survey results were compared with relevant national-level indicators, such as the Gender Equality Index for Spain [50], data on union presence in Sweden [51] and information on disability inclusion in Romania [52]. This approach situates the demo-site results within broader national benchmarks, highlighting both site-specific outcomes and trends that reflect wider socio-economic patterns. The results per grouped area are discussed in the following sections.

Employment quality and economic compensation

A consistent pattern across all three demo sites is the relative underperformance of average annual wages post-WEDISTRICT, in most cases falling below both the national average and the site's own pre-implementation baseline. In Luleå, a slight wage decline was observed, while in Córdoba the drop was more significant, despite the site's overall improvements in other areas. Bucharest showed the steepest regression, with wage levels decreasing after project implementation, even from an already low baseline. This divergence between project implementation and economic benefit raises concerns about the long-term viability of the social component of sustainability transitions. While cost-efficiency and environmental innovation are central to such projects, declining wages suggest a disconnect between sustainability and equitable economic development. These trends may be explained by a shift toward temporary or subcontracted labor and merit further scrutiny regarding labor policy alignment.

Inclusion of vulnerable populations

The inclusion of people with special needs represents a pivotal indicator of equity. Results across the three sites were mixed. Córdoba made marked progress by increasing participation from 0% to 10%, demonstrating intentional inclusion efforts. Conversely, Luleå and Bucharest saw declines in this area, most notably in Bucharest, where inclusion dropped from 18% pre-project to 0% post-implementation. These outcomes suggest persistent systemic barriers to inclusivity in employment practices, even within socially ambitious frameworks. The lack of structured incentives or requirements for integrating vulnerable populations undermines the equity potential of renewable energy initiatives, particularly in countries with weaker labor protections.

Gender representation and executive roles

The gender dimension emerged as a relative success story. All three demo sites improved gender parity, in general, workforce composition. Luleå achieved particularly notable outcomes, with a reversal in the men-to-women employment ratio and greater female representation in executive positions. Córdoba and Bucharest also improved,

although the pace of change was slower, and executive-level parity remains a challenge. These results reinforce the potential for well-designed infrastructure projects to drive progress on gender equality. However, these achievements should be interpreted with caution: overemphasis on gender indicators without parallel improvements in wage equity, inclusivity and unionization may obscure other forms of inequality.

Unionization and collective labor rights

Union presence and collective bargaining were areas of significant concern. Both Córdoba and Bucharest saw a complete absence of union affiliation post-WEDISTRIC, despite having active union participation at baseline. In contrast, Luleå retained strong union representation, reflecting Sweden's robust labor framework. This erosion of labor representation in two of the three sites raises critical questions about the nature of employment under the project. It may indicate increased use of short-term contracts or deliberate avoidance of unionized labor. The absence of collective representation undermines workers' ability to negotiate fair wages, safe conditions and equitable treatment, all of which are cornerstones of social sustainability.

Occupational health and safety

Positive developments were evident in occupational safety across all sites. Reported accident rates fell to zero in Luleå, Córdoba and Bucharest, suggesting improvements in workplace safety protocols and training. This could also reflect the high proportion of locally hired workers, particularly in Córdoba and Bucharest, who may be more familiar with the site environment and expectations. However, these findings should be treated cautiously due to potential underreporting or limited duration of employment contracts. Without third-party verification or formal reporting structures, it is difficult to confirm the robustness of these results. Nevertheless, the trends suggest a move in the right direction regarding health and safety practices.

Transparency and governance

Transparency in social and environmental reporting improved or remained strong across all demo sites, a testament to the project's commitment to openness. All sites reported active dissemination of information and labeling related to sustainability performance. Regarding fair competition, Córdoba and Bucharest both recorded a perceived improvement in this indicator post-WEDISTRIC, contrasting with Luleå, which maintained its initial levels of already having these practices in place. These results point to identifying and battling possible irregularities in procurement processes or perceived favoritism, especially in countries where anti-corruption frameworks are weaker, which speaks volumes of the project's impact, promoting not only environmental justice, but building public trust through positive social changes.

4. Discussion

The application of the LCA methodology has revealed that the technological solutions based on renewable energy implemented at each of the demo sites help reduce the impact on climate change. In the case of the Bucharest demo site, the reduction in climate change impact is 67%, even reaching negative carbon footprint values when the avoided environmental burden is also considered. This burden is avoided due to the additional electricity generated, which is fed into the national grid and would replace electricity generation according to Romania's national energy mix. A similar situation occurs in Luleå. The climate change impact is reduced by approximately 50%, and when the avoided burdens from the use of surplus electricity are considered, the carbon footprint becomes negative. Finally, in the case of Córdoba, the reduction in climate change impact is 63%, with no avoided burdens in this case.

The substantial reductions in environmental impact under the avoided burden approach observed in two of the demo sites analyzed depend on the electricity generated by the demo site itself and on the type of electricity generation it displaces. Thus, if the grid electricity mix is dominated by fossil fuel sources, the avoided environmental burden on climate change will be greater than if the mix is dominated by renewable energies, as highlighted in [32].

Beyond the impact on climate change, the analysis reveals that this type of solution also contributes to reducing (or at least not significantly increasing) several other environmental impacts, including acidification, fossil resource use, tropospheric ozone formation or terrestrial eutrophication. However, trade-offs are evident in certain impact categories. Notably, land use impacts increase significantly with the renewable solutions proposed in the Bucharest and Córdoba demo sites, primarily due to biomass and solar energy infrastructure. Likewise, water resource use may also increase considerably, as shown in the results from the Luleå demo site, due to biogas production processes.

A particularly critical concern is the increased use of mineral and metal resources, where the implementation of renewable solutions can lead to several-fold increase in demand, as observed in the results from Córdoba and Bucharest (and in the case of Luleå, when avoided burdens are not considered). These findings highlight the importance of taking comprehensive life cycle perspective when designing and evaluating decarbonization strategies to ensure that environmental burdens are not simply shifted from one impact category to another.

The S-LCA method has proven invaluable in tracking and quantifying social impacts across the WEDISTRICT demo sites, offering detailed insights into gender equity, local employment, health and safety and transparency. Very palpable is the shift in the men-to-women occupation ratio, and the rise in women's representation in executive roles exemplifies the project's strides toward gender equality, a critical goal in the construction and urban development sectors. Likewise, the noticeable increase in local employment underscores the success of localization strategies that anchor the economic benefits of the project in the surrounding community, fostering stronger connections between workers and their work environments. The project also demonstrated a significant commitment to health and safety, reflected in the zero accidents and the absence of legal actions related to the demo sites, which strengthens its reputation for responsible governance.

However, while S-LCA has revealed these significant positive outcomes, it has also highlighted a central tension within the WEDISTRICT initiative. Progress in gender equity, occupational safety and transparency is clear, but these gains are not always evenly distributed across all demo sites. For example, despite improvements in gender balance in the workplace, disparities persist, particularly in the number of women in executive positions and compensation structures. Particularly concerning are the weakening of labor protections and the exclusion of vulnerable groups in Bucharest and Luleå. These outcomes challenge the assumption that green infrastructure is inherently socially beneficial. In contrast, Córdoba demonstrates that targeted efforts, such as improving local hiring, boosting inclusion of people with special needs and increasing safety, can yield meaningful improvements, although this did not translate into better wages or unionization. These results indicate that while some social benefits have been realized, other social rights and protections, such as fair wages and union representation, are sometimes sidelined in favor of achieving short-term goals, suggesting a need for a more balanced, holistic approach to social sustainability.

The findings also raise broader questions about the methodological frameworks guiding S-LCA, such as the following: Can a project truly be labeled socially sustainable if it reduces employment benefits and silences collective labor voices, even as it promotes

decarbonization? And are improvements in gender ratios and local hiring sufficient to offset the erosion of economic and governance standards?

Current approaches may insufficiently capture informal labor dynamics, subcontracting practices and governance weaknesses, especially in countries with under-resourced monitoring institutions. These contradictions suggest that green infrastructure projects, no matter how well-intentioned, require vigilant social oversight and structured accountability mechanisms.

This underscores the dual value of S-LCA, as it serves not only as a tool for recognizing positive changes but also as a critical lens for spotting areas that require further improvement and deeper reflection, ensuring that the project's benefits are shared equitably across all dimensions of social well-being.

Nonetheless, does promoting decarbonization improve local communities? Many indicators are dependent on the social structure where projects are developed, and a single project alone cannot change systemic structures. Thus, labor safety, hiring practices and even gender balance policies are subject to local regulations. In any case, local energy projects may be a seed for advancing the social development of local communities, fixing wealth, employment and opportunities.

5. Conclusions

The WEDISTRICT project demonstrates that renewable energy technologies can deliver significant environmental benefits in district heating and domestic hot water systems. Across the three demo sites, greenhouse gas emissions were substantially reduced, particularly when considering avoided burdens from displaced energy production, such as grid-supplied electricity (derived from fossil fuels, in some cases). These results confirm that integrating renewable energy sources into centralized energy generation can contribute meaningfully to decarbonization goals and provide additional environmental co-benefits when properly implemented.

Although the results are derived from small-scale demo sites and cannot be directly generalized to all renewable energy-powered district heating installations, they provide valuable evidence of the potential of localized interventions to advance broader sustainability objectives. A life cycle perspective proved critical in capturing the full spectrum of environmental impacts. While greenhouse gas reductions were substantial, the assessment also revealed trade-offs, particularly in the consumption of mineral and metal resources, which carry environmental and social implications. Maximizing equipment lifetimes, promoting repair and reuse strategies, advancing material recovery and recycling and integrating circular economy principles are therefore essential to ensure renewable energy systems deliver comprehensive and sustainable benefits.

The United Nations' 2024 Global Resources Outlook report [53] warns that global material extraction has tripled over the last 50 years and is expected to grow by 60% by 2060 compared to 2020. The depletion rate of these resources is particularly high, raising serious concerns about the long-term sustainability of the global economy.

The analysis of material flows highlights the strategic importance of critical resources such as aluminum, copper, lithium, cobalt and rare earth elements, which are integral to renewable energy technologies. The European Union's European Critical Raw Materials Act further underscores the need for secure, sustainable and resilient supply chains. Aligning renewable energy deployment with circular economy strategies through the recovery of metals from solar panels, batteries, geothermal facilities and infrastructure supports both resource efficiency and environmental sustainability while reducing dependency on virgin materials. These practices ensure that renewable energy systems not only decarbonize

energy supply but also contribute to broader sustainability objectives, including the efficient use of natural resources and resilience in supply chains.

For the renewable energies implemented in the demo sites, it is crucial to maximize equipment lifetime and recover as many materials as possible at end-of-life. Key recovery targets include (1) metallic silicon, aluminum and glass from solar panels; (2) lithium, cobalt and nickel from batteries; (3) steel and alloys of titanium, nickel, copper, chromium, manganese and molybdenum from geothermal facilities; and (4) steel and copper from pipelines, supports and electrical or data connections used across technologies. Advancing recovery, reuse and recycling techniques will therefore be essential, as this remains an area with considerable potential for technical progress.

The advancement of these techniques will support the achievement of circular economy objectives and strategies by promoting resource efficiency and ensuring that materials are retained within productive systems and, by extension, the wider economy, for the longest possible time.

The social assessment indicates that impacts of renewable district heating systems vary significantly depending on local context and project design. Initiatives that incorporate active stakeholder engagement, inclusive hiring and transparent governance tend to generate stronger social values. Conversely, projects driven primarily by market logic without robust governance or labor protections risk reinforcing existing inequalities. Across the demo sites, positive outcomes were observed in gender inclusion, local community engagement and transparency in decision-making, demonstrating that social policies can produce measurable improvements. At the same time, challenges, including wage disparities, limited union representation and underrepresentation of marginalized groups, highlight the need for a holistic approach that integrates structural considerations, labor rights and inclusive practices into project design and implementation.

These findings emphasize that technical innovation alone is insufficient to achieve sustainable urban energy transitions. While renewable energy systems can substantially reduce environmental impacts, achieving lasting sustainability requires concurrent attention to social equity, governance and stakeholder participation. Future projects should integrate social and environmental considerations into core planning frameworks, supported by robust data collection, monitoring and feedback mechanisms. This integrated approach ensures that renewable energy systems deliver benefits that are both environmentally and socially meaningful.

The interaction between environmental and social performance further underscores the value of integrated assessment. Decisions regarding technology selection, system design and operational practices influence both resource efficiency and social outcomes. For example, circular economy practices can simultaneously reduce environmental impacts and generate local economic opportunities through jobs in recycling, maintenance and repair. Transparent communication and stakeholder engagement enhance social acceptance, trust and collaboration, illustrating how multi-dimensional approaches can create synergies between environmental and social objectives.

From a policy and practice perspective, the WEDISTRICT findings offer actionable insights for decision-makers, planners and practitioners. Environmental performance metrics, including life cycle emissions and resource use, inform the design and optimization of future district heating systems, while social indicators provide guidance on promoting equity, inclusivity and community engagement. Combining quantitative life cycle assessment data with qualitative social analysis establishes a robust evidence base for informed decision-making, guiding the development of policies and regulations that incentivize sustainable and socially responsible energy projects.

The WEDISTRICT experience also highlights considerations for replication and scaling. While demo sites are localized, the methodological framework, lessons learned and integrated assessment approach can inform broader applications across regions. Scaling renewable energy systems requires attention to context-specific environmental and social conditions, optimization of material flows and the adoption of circular strategies. The WEDISTRICT approach, combining life cycle assessment with stakeholder engagement and national benchmark comparisons, offers a replicable model for evaluating and improving sustainability outcomes in future projects.

Finally, the project underscores the importance of continuous innovation, policy support and multi-stakeholder collaboration. To fully realize the potential of renewable energy systems, stakeholders must implement technically robust solutions while embedding social safeguards, governance structures and inclusive practices. Achieving resilient, equitable and circular energy systems requires collaboration among policymakers, industry, communities and researchers. Lessons from WEDISTRICT highlight that sustainable urban energy transitions are dynamic processes requiring integrated strategies, long-term commitment and adaptive management.

Overall, the WEDISTRICT project provides a comprehensive assessment of environmental and social dimensions of renewable district heating systems. By combining quantitative life cycle assessment results with qualitative social analysis and contextual benchmarking, the project demonstrates the value of integrated sustainability assessment for informing policy, guiding implementation and supporting replication of renewable energy solutions. The findings highlight that meaningful decarbonization can be achieved while promoting resource efficiency, circularity and social equity, but only if projects are designed with attention to both technical performance and socio-economic context. These insights offer a robust foundation for shaping energy policy, guiding sustainable infrastructure investments and advancing the broader goals of urban sustainability and climate mitigation.

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