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Environmental and Social Life Cycle Assessment of Data Centre Heat Recovery Technologies Combined with Fuel Cells for Energy Generation

Camila Andrea Puentes Bejarano [1], Javier Pérez Rodríguez [1,*], Juan Manuel de Andrés Almeida [1], David Hidalgo-Carvajal [2], Jonas Gustaffson [3], Jon Summers [3] and Alberto Abánades [4]

1 Chemical and Environmental Engineering Department, Universidad Politécnica de Madrid, 28006 Madrid, Spain; camila.puentes@alumnos.upm.es (C.A.P.B.); juanmanuel.deandres@upm.es (J.M.d.A.A.)
2 Department of Organization Engineering, Business Administration and Statistics, Universidad Politécnica de Madrid, 28006 Madrid, Spain; david.hidalgo.carvajal@upm.es
3 Research Institutes of Sweden, 431 53 Luleå, Sweden; jonas.gustafsson@ri.se (J.G.); jon.summers@ri.se (J.S.)
4 Energy Engineering Department, Universidad Politécnica de Madrid, 28006 Madrid, Spain; alberto.abanades@upm.es
* Correspondence: javier.perezr@upm.es

Abstract: The energy sector is essential in the transition to a more sustainable future, and renewable energies will play a key role in achieving this. It is also a sector in which the circular economy presents an opportunity for the utilisation of other resources and residual energy flows. This study examines the environmental and social performance of innovative energy technologies (which contribute to the circularity of resources) implemented in a demonstrator site in Luleå (Sweden). The demo-site collected excess heat from a data centre to cogenerate energy, combining the waste heat with fuel cells that use biogas derived from waste, meeting part of its electrical demand and supplying thermal energy to an existing district heating network. Following a cradle-to-gate approach, an environmental and a social life cycle assessment were developed to compare two scenarios: a baseline scenario reflecting current energy supply methods and the WEDISTRICT scenario, which considers the application of different renewable and circular technologies. The findings indicate that transitioning to renewable energy sources significantly reduces environmental impacts in seven of the eight assessed impact categories. Specifically, the study showed a 48% reduction in climate change impact per kWh generated. Additionally, the WEDISTRICT scenario, accounting for avoided burdens, prevented 0.21 kg CO_2 eq per kWh auto-consumed. From the social perspective, the WEDISTRICT scenario demonstrated improvement in employment conditions within the worker and local community categories, product satisfaction within the society category, and fair competition within the value chain category. Projects like WEDISTRICT demonstrate the circularity options of the energy sector, the utilisation of resources and residual energy flows, and that these lead to environmental and social improvements throughout the entire life cycle, not just during the operation phase.

Keywords: data centre; heat recovery; energy efficiency; SOFC; biogas; LCA; S-LCA; sustainability; district heating

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1. Introduction

Nowadays, countries' sustainability agendas are becoming more relevant within the different economic sectors' efforts to move toward more environmentally and socially responsible value chains. The energy sector, besides being one of the most important sectors for the proper development of society, presents challenges and opportunities to develop initiatives toward innovative and cleaner technologies to meet society's energy needs. Promoting sustainable development and tackling climate change have become intertwined aspects of energy planning, analysis, and policy making. To make the sector more sustainable, an effort must be made to fulfil the demand reasonably and reliably by consuming the fewest resources from nature, promoting ecosystems and human health, and minimising the negative environmental consequences [1].

In 2020 the energy consumption in the European Union (EU) was determined by five main sectors: transport (29.2%), households (27.9%), industry (25.6%), services (13.8%), and others (3.6%). Within households, the primary activities that consume energy are space heating (62.8%), water heating (15.1%), lighting and appliances (14.5%), cooking (6.1%), space cooling (0.4%), and other end-uses (1.0%) [2]. Since space and water heating are relevant contributors to European energy consumption, there is a special focus on developing cleaner technologies to provide energy and comfort for society [3]. In addition, the recent Energy Efficiency Directive (EED) adopted in September 2023 sets a new binding target of reducing the EU's energy consumption by 11.7% by 2030 (Directive (EU) 2023/1791). The directive identifies the Information and Communication Technology (ICT) sector as a sector of increasing importance in this context. In 2018, data centres accounted for 2.7% of the electricity demand in 2018 in the EU and will reach at least 3.2% by 2030 if development continues on the current trajectory [4].

When talking about energy efficiency, both the value chains of district heating (DH) networks and data centres (DCs) must be considered. A DH network involves generating heat in a centralised location and then distributing it through a network of insulated pipes to residences, businesses, and industries in a local area. The thermal energy is transported as low-pressure steam, hot water, and hot air, and it is usually categorised into three groupings: heating, cooling, and heating and cooling [5].

The environmental impacts associated with these value chains stem mainly from the share of fossil fuels used as the main source of energy (about 90% of total heat production, referring to DH value chains) [6] and the high levels of electrical energy needed to operate DCs. Nevertheless, a comprehensive understanding of environmental impacts throughout the value chain of these energy systems is important to detect environmental stresses at different stages and identify strategies for improvement without burden shifting [7].

The Life Cycle Assessment (LCA) and Social Life Cycle Assessment (S-LCA) methodologies provide a framework for assessing the potential environmental and social impacts of products or services throughout their whole life cycle, according to the ISO 14040:2006 and UNEP/SETAC 2013 guidelines, respectively. This research will focus on using LCA and S-LCA as a tool to analyse the environmental and social impacts related to an innovative set-up demonstrator combining waste heat recovery from DC technologies with biogas-fed solid-oxide fuel cells (SOFC) for energy generation. The demonstrator was built in Luleå (Sweden) as part of the WEDISTRICT project, which is funded by the European Union's Horizon 2020 research and innovation programme under Grant Agreement N°857801. In the project, renewable energy generation technologies are implemented in four locations across Europe, forming four demonstration projects. One of these locations, and therefore one of these demonstration projects, is Luleå. For this demonstrator, the situation before the implementation carried out in the WEDISTRICT project (baseline scenario) was compared with the situation after the implementation of the proposed technologies in the WEDISTRICT project (WEDISTRICT scenario). This paper aims to compare these two different scenarios (baseline and WEDISTRICT) to determine the environmental and social impacts of generating energy by replacing conventional energy sources with innovative and renewable solutions.

LCAs of DH networks and energy systems have been developed [8–10] stating that DH systems using the integration of renewable sources to generate energy could potentially minimise environmental impacts in comparison to conventional sources. Thus, the importance of DH systems in carbon footprint emissions reduction is discussed in these studies. For DC systems, the studies are mainly related to solutions for increasing the energy and resource efficiency within these systems [11,12], rather that the integration of technologies for energy generation and their environmental impacts. Therefore, it is important to highlight the added value of the WEDISTRICT project and this study compared to the other studies previously carried out. This study investigated the integration of DC waste heat recovery technologies with renewable fuels for DH energy generation needs.

Additionally, incorporating circular economy principles into the energy sector is essential to promoting resource efficiency, reducing waste, and minimising environmental impacts, thus reducing dependency on finite natural resources [13]. For DH and DC, integrating circular approaches such as waste heat recovery, renewable energy sources, and energy-efficient technologies can significantly lower their environmental footprint. In the context of the WEDISTRICT project, the integration of waste heat recovery from DC with biogas-fed SOFC is a prime example of applying circular economy principles. By capturing and reusing waste energy, this system minimizes resource use while providing reliable, sustainable energy solutions. Applying LCA and S-LCA helps assess the potential benefits and challenges of such technologies, ensuring a holistic approach to sustainability that addresses both environmental and social impacts. Circular economy initiatives in this sector not only contribute to reducing emissions and resource consumption but also enhance system resilience and align with broader sustainability goals [14].

Although a few studies have been previously developed to present an LCA analysis for DH [15–17], to the best of the authors' knowledge, only one other research study (by Chiavetta et al. [18]) presents results for an LCA focused in Energy Renewable Systems for Heating and Cooling, which is not exactly the same case but is close enough from the environmental perspective. From the social perspective, the literature around the application of S-LCA methodology is still scarce. For example, Lenzo et al. [19] presents the application of S-LCA to a textile product made in Italy, evaluating the social benefits and impacts on local communities and workers. Mirabella et al. [20] covers various aspects of LCA applied to urban systems, including social aspects, providing a broader context for urban sustainability assessments. Finally, Zhai et al. [21] discuss the environmental and social impacts of ground source heat pumps for heating and cooling. As can be seen, these documents present sections which could be relevant if applied into DH systems, but to the best of the authors' knowledge, there is no document in the academic body of literature presenting an S-LCA under the DH context.

The LCA and S-LCA results presented here provide a comprehensive analysis and highlight the main favourable and critical environmental and social impacts of the technologies proposed. Thus, project partners, policymakers, and the project's stakeholders will be able to identify the good actions that have been taken and the drawbacks to be improved while satisfying the energy needs of society.

If a reduction in environmental impact is demonstrated, it must not come at the cost of increasing social impacts. Therefore, addressing these two pillars of the sustainability jointly is necessary, which constitutes the primary contribution of this research.

2. Methodology

2.1. Case Study and System Boundaries

The DH network analysed is a brand-new facility built inside the Luleå Science Park (Luleå, Sweden) where the RISE (Research Institutes of Sweden) offices are located. The thermal energy demand of the science park is currently and entirely covered by a DH network (installed before the implementation of WEDISTRICT technologies), which provides energy from a cogeneration plant using recovered gasses from a steel mill as fuel. The composition of these recovered gasses is: 70% blast furnace gas, 20% converter gas (also known as LD gas), and 10% coke oven gas [22]. It is important to mention that the electricity produced by the cogeneration plant is sent to the electricity grid. The DH only receives thermal energy, so this electricity was not considered in the LCA. This situation represents the baseline scenario (pre-WEDISTRICT situation), and the flowchart is schematised in Figure 1. The energy inputs are the electricity to the DC and the recovered gasses to the DH.

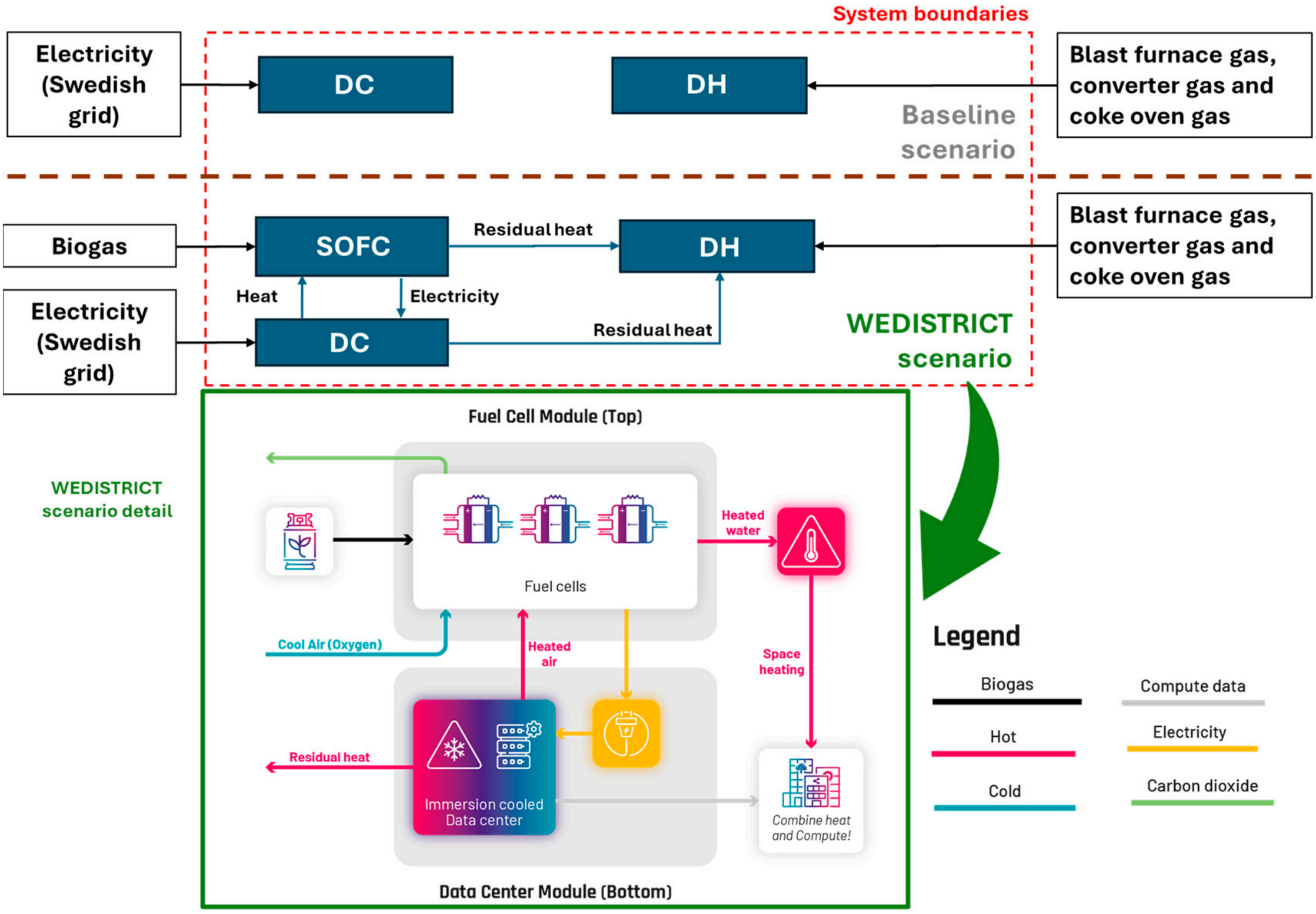

Figure 1. Technologies implemented in the Luleå demonstrator. System boundaries definition of baseline and WEDISTRICT scenario.

Within the WEDISTRICT project, a pilot-scale demonstrator was designed from a heat recovery perspective. The system combined a DC immersion cooling system (ICS) for heat recovery (also called the DC module) alongside 9 biogas-fed SOFCs (also called the SOFC module) to generate energy. The system had two major heat sources, the servers inside the ICS and the SOFC, and one source of electricity, the SOFC. The demonstrator delivered heat to the secondary heat network of the building where the demonstrator was connected as well as electricity to the DC. It operated for 6 months, then it was decommissioned.

Immersion cooling means that the servers were fully immersed in a non-conductive fluid (a dielectric coolant). The heat generated in the microelectronics on board the servers was transferred to the dielectric coolant and then to the water circuit by an immersed liquid-to-liquid heat exchanger inside the ICS. The heat captured in the DC module was transferred to two cooling coils (dry coolers). One of the coils was used to pre-heat the incoming air to the SOFC module, the secondary coil was used to reject excess heat (expected only during summertime). The purpose of pre-heating the air supply to the SOFC module was to increase the thermal efficiency of the SOFC units, which were connected to the secondary network of the building's existing DH network. Inside the SOFC module, the 9 biogas-fed SOFCs were located. The SOFCs generated thermal and electrical energy. The thermal energy produced fed the existing DH network. The electrical energy produced fed 90% of the DC module's electrical consumption. The 10% left needed for operation was taken from the grid.

This configuration is called the WEDISTRICT scenario, representing the situation once the technologies proposed by the project for energy generation were implemented. The flowchart and the system boundaries of the WEDISTRICT scenario are also shown in Figure 1. The main equipment acquired for the implementation of WEDISTRICT technologies is shown in Table 1 (The Supplementary Material includes a detailed list of the inventory of the WEDISTRICT scenario). The energy inputs are the electricity to the DC (a lower amount than in the baseline scenario, since the DC demand is partially met by the electricity generated in the SOFC), biogas to the SOFC, and the residual gas to the DH (a slightly lower amount than the baseline scenario due to the use of residual heat).

Table 1. WEDISTRICT scenario main equipment acquired.

Subsystem Analysed	On-Site Equipment
DC module	Immersion cooled system electronics
SOFC module	9 SOFC Biogas input

2.2. LCA and S-LCA Goal and Scope Definition

This study aimed to verify that the technologies proposed by the project improved the environmental and social performance in comparison to the current situation (applying the LCA and S-LCA, respectively, over the baseline and the WEDISTRICT scenario). The functional unit defined and used as a basis for comparison was the production of 1 kilowatt-hour of thermal energy (1 kWh_t) per energy produced. This assessment considers a cradle-to-gate approach, which includes processes from raw materials acquisition to the energy produced. For the LCA, the software used to perform the assessment was SimaPro 9.1.1.7, with Eco Invent 3.6 as the background database. For the S-LCA, data were collected from primary and secondary sources, following the guidelines developed by UNEP/SETAC [23–25] and supplemented with the recommendations made in ISO 26000 [26,27].

2.3. LCA Methodology

2.3.1. Life Cycle Inventory (LCI)

In this phase, the technical information provided by RISE was used to list and characterise all of the equipment included in the analysis for the WEDISTRICT scenario. Foreground information was facilitated by RISE according to conversations with the equipment providers as well as previous research reports developed by RISE in collaboration with other universities. All numerical inputs were normalised in terms of the functional unit (FU) using the energy production in one year and the equipment's lifetime. For the baseline scenario, the composition of the recovered gasses described in Section 2.1 was used to assess the impacts of 1 kWh_t generated. For the WEDISTRICT scenario, Table 1 shows the information used to model the scenario and Table 2 shows the annual energy production after the technologies' installation. A detailed inventory of the WEDISTRICT scenario is shown in Tables S1 and S2 of Supplementary Material.

Table 2. WEDISTRICT scenario energy production.

Energy Production	Annual Production	Unit
Thermal energy	15,600	kWh_t/year
Electricity	78,785	kWh_e/year

2.3.2. Life Cycle Impact Assessment (LCIA)

The LCIA methodology used was the Environmental Footprint (EF 3.0) impact assessment method, as recommended by the European Commission 'Commission Recommendation (EU) 2021/2279' [28]. The main environmental impact category considered was climate change, considering the interests of the project partners and the approach of WEDISTRICT. Moreover, academic literature from various disciplines and applications considers climate change as the key element to be analysed during an LCA [29–38]. Nevertheless, the results regarding seven other impact categories were also considered, as these are deemed of deep interest: photochemical ozone formation [39–41], acidification [42,43], eutrophication–terrestrial [44,45], land use [46–48], water use [49–51], resource use–fossils [52,53], and resource use–minerals and metals [54,55].

2.4. S-LCA Methodology

System Boundaries

The S-LCA includes the same boundaries in the analysis for the WEDISTRICT scenario. Contrarily to the environmental LCA, an S-LCA identifies the importance of defining a baseline scenario which uses average national and/or local data as a standard for comparison before project implementation [56,57]. Moreover, this approach links social indicators and impacts to a product [58] and/or a process [59], which is the specific case here. Therefore, in the research here presented, the baseline scenario includes average national and/or local data relevant to the case, and it is assumed to be the standard for the company before implementing any project and measuring its social impacts. Understanding this is paramount, as it allows researchers to compare the specific impacts related to the project versus the national reality [60,61].

For this case, and in alignment with other studies [62–64], the results after implementation of the project (POST) were compared to the situation prior its implementation (PRE), as well as to the local and/or national indicators.

While some studies mainly focus on just one of the five main categories of an S-LCA (i.e., workers [65], local community [66], society [67], supply chain [68], consumers [69]), this research intends to provide a general overview of all categories at once. For this, within the five main categories, a total of 13 sub-categories and 33 indicators (presented in Table 3 below) were analysed for PRE and POST scenarios.

Table 3. Number of indicators per category for S-LCA.

Category	Sub-Category	Indicator
Worker	Freedom of association and collective bargaining	* Presence of unions * Total number of affiliates
	Child Labour	* Presence of child labour
	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 programmes * Lost time per injuries * Policies concerning health and safety * Sick-leave days * Accidents

Table 3. *Cont.*

Category	Sub-Category	Indicator
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	* Damage caused by the product
	Quality	* Quality labels * Access to clear information

Data were collected from primary and secondary sources. Primary data was collected directly within the Luleå demo-site through a collection tool, being split into PRE (information available before implementation) and POST (information collected after implementation), following similar approaches by Fan et al. [70] and Ekener et al. [62]. As secondary data, Sweden's national information was collected from government (national, regional, and local) reports, legislation, open-source data, reports from private companies, and other public information available online.

3. Results and Disccussion

3.1. LCA Results

Table 4 presents the environmental impact results of the baseline and the WEDISTRICT scenarios, respectively. Figure 2 represents the results graphically in relative terms, where the baseline scenario results are equal to 100.

Table 4. Environmental impact–baseline and WEDISTRICT scenarios results.

Environmental Impact Category (Acronym)	Units (/kWh$_t$)	Baseline	WEDISTRICT
Climate change (CC)	kg CO_2 eq	1.23×10^{-1}	6.44×10^{-2}
Photochemical ozone formation (POF)	kg NMVOC eq	5.57×10^{-4}	2.33×10^{-4}
Acidification (AC)	mol H^+ eq	4.95×10^{-4}	5.73×10^{-4}
Eutrophication, terrestrial (EUT)	mol N eq	1.05×10^{-3}	7.63×10^{-4}
Land use (LU)	Pt	1.75×10^{0}	1.85×10^{0}
Water use (WU)	m^3 depriv.	8.64×10^{-3}	2.31×10^{0}
Resource use, fossils (RUF)	MJ	1.07×10^{0}	1.91×10^{0}
Resource use, minerals and metals (RUM)	kg Sb eq	1.06×10^{-6}	3.93×10^{-6}

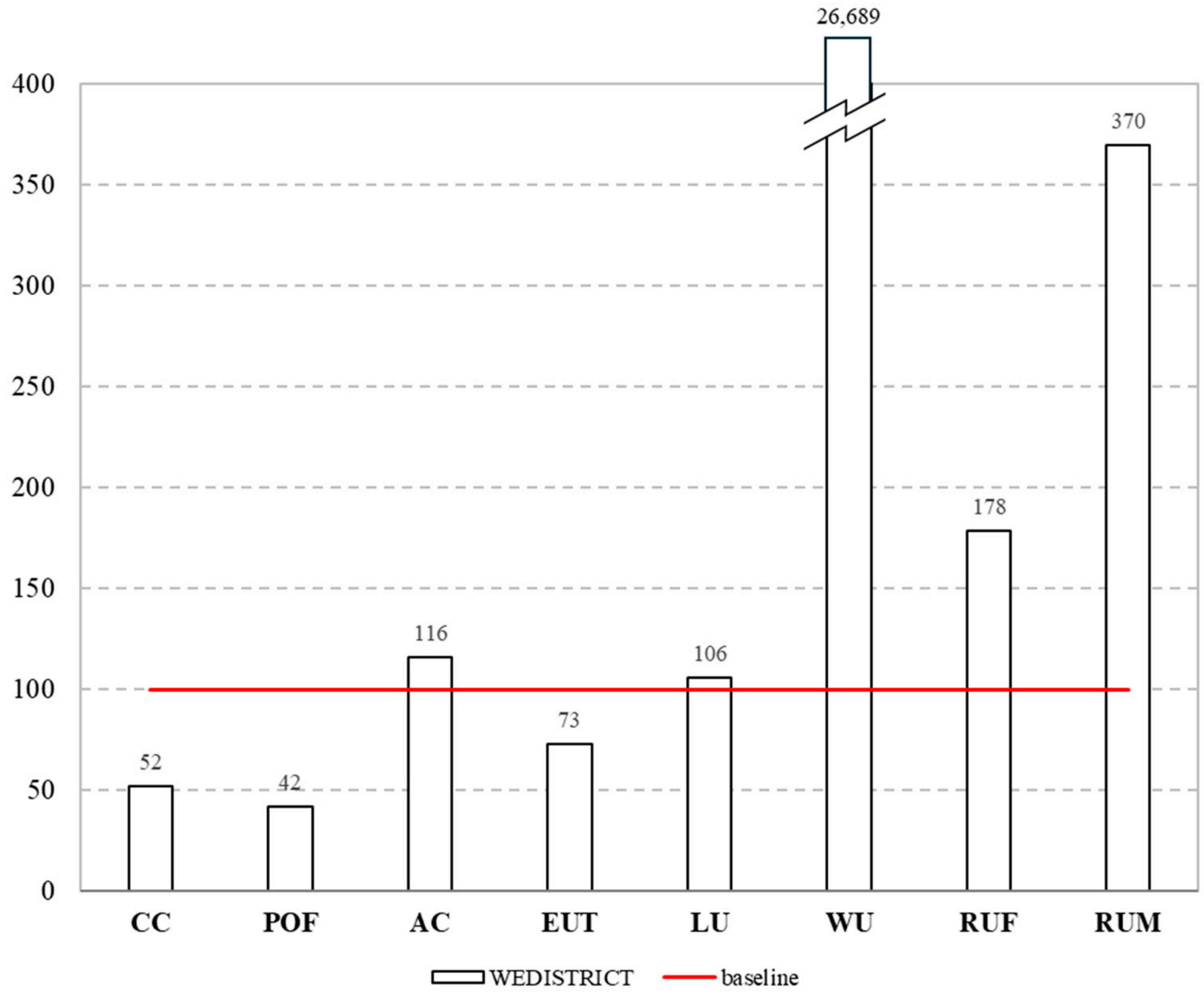

Figure 2. Environmental impact results comparing the baseline scenario against the WEDISTRICT scenario (the baseline scenario impacts are equal to 100).

When comparing the WEDISTRICT against the baseline scenario, the results present three different trends. One trend of improvement was associated with the environmental impact categories of climate change, photochemical ozone formation, and eutrophication–terrestrial. A second trend, for water use, resource use–fossils, and resources use–minerals and metals, revealed the environmental impacts associated with the WEDISTRICT scenario to be higher than those of the baseline. Finally, a third trend indicated that the environmental impacts regarding acidification and land use are relatively similar for both scenarios, so the results are not conclusive and require careful analysis and interpretation.

For climate change, the LCA results show that the impact for the baseline and the WEDISTRICT scenarios are 0.12 and 0.06 kg CO_2 eq/kWh_t, respectively. Thus, the WEDISTRICT scenario has 48% less impact than the baseline scenario. It is important to highlight that even though the baseline situation is already a good solution in terms of sustainability (it promotes an industrial symbiosis and a circular economy solution since it recovers the gases from the steel mill), the WEDISTRICT scenario still shows improvement in environmental behaviour when transitioning to the innovative situation proposed by the project. Previous research has shown [71–74] that the use of renewable sources such as biogas to generate energy, specifically in biogas-fed SOFCs, minimises the impact in terms of climate change compared to conventional sources of energy generation.

However, for water use, resource use–fossils, resource use–minerals and metals, land use and acidification, the WEDISTRICT scenario presents higher environmental impacts. For these impact categories, the impacts are mainly associated with the use phase of the equipment, when it is used to generate energy. For the resource use-fossils and land use categories, the impacts are attributable to the small percentage of electricity that is taken from Sweden's nationwide electrical grid to power the DC module. Similar results were obtained by Pasciucco et al. [71], in which electricity consumption was the main contributor to abiotic depletion (fossil fuels) potential in three out of four scenarios modelled within their study. For the water use, resource use–minerals and metals, and acidification categories, the impacts are associated with the biogas consumed in the SOFC module. Specifically, the impacts are attributable to the biogas production phase, in which large volumes of water are used during the anaerobic digestion process to obtain the biogas and the background database inputs that considers materials such as sulfuric acid and cobalt for biogas stabilisation. Similar results were reported by Tian et al. [75] and Pobeheim et al. [76], respectively.

Nevertheless, it is important to highlight that the DC module is auto-consuming the electricity generated by the SOFC module to operate and generate energy for the DH network. Therefore, in the WEDISTRICT scenario, 90% of the baseline consumption of electricity from the national grid is being avoided. This avoided burden should be considered when comparing these scenarios; thus Table 5 presents the results when the avoided burden is included in the WEDISTRICT scenario and Figure 3 shows the results graphically, again considering the baseline scenario results equal to 100%.

Table 5. Environmental impact results including the avoided burden.

Environmental Impact Category	Units (/kWh$_t$)	Baseline	WEDISTRICT	WEDISTRICT + Avoided Burden
CC	kg CO_2 eq	1.23×10^{-1}	6.44×10^{-2}	-1.46×10^{-1}
POF	kg NMVOC eq	5.57×10^{-4}	2.33×10^{-4}	-6.52×10^{-4}
AC	mol H+ eq	4.95×10^{-4}	5.73×10^{-4}	-8.17×10^{-4}
EUT	mol N eq	1.05×10^{-3}	7.63×10^{-4}	-3.37×10^{-3}
LU	Pt	1.75×10^{0}	1.85×10^{0}	-2.29×10^{1}
WU	m^3 depriv.	8.64×10^{-3}	2.31×10^{0}	1.80×10^{0}
RUF	MJ	1.07×10^{0}	1.91×10^{0}	-2.07×10^{1}
RUM	kg Sb eq	1.06×10^{-6}	3.93×10^{-6}	-5.84×10^{-7}

Figure 3 shows how the avoided impacts are higher (negative values) than the direct impacts in seven out of eight impact categories prioritised thanks to the reduction of the amount of electricity consumed from the national grid. Hence, the WEDISTRICT scenario is more environmentally beneficial than even the circular solution of the technologies presented in the baseline scenario, confirming the importance of implementing the use of renewable fuels combined with innovative technologies for energy generation as a sustainable solution in the market. Different studies [72,77,78] have included avoided burdens within the assessments performed for the comparison of different technologies for energy generation, presenting similar results to this study.

In terms of climate change, including the avoided burden, the LCA results show that 0.21 kg CO_2 eq are avoided for each kWh auto-consumed, leading to a global carbon footprint of -0.15 kg CO_2 eq/kWh for the WEDISTRICT scenario. For the water use impact category, as was mentioned before, the high contributions of the WEDISTRICT scenario are related to the water needed in the biogas production stage [75,79]. Identifying this hotspot enables decision-makers to understand other environmental categories to consider upgrading for future technologies and to decide whether the whole value chain of the energy sector wants to transition to a completely sustainable value chain.

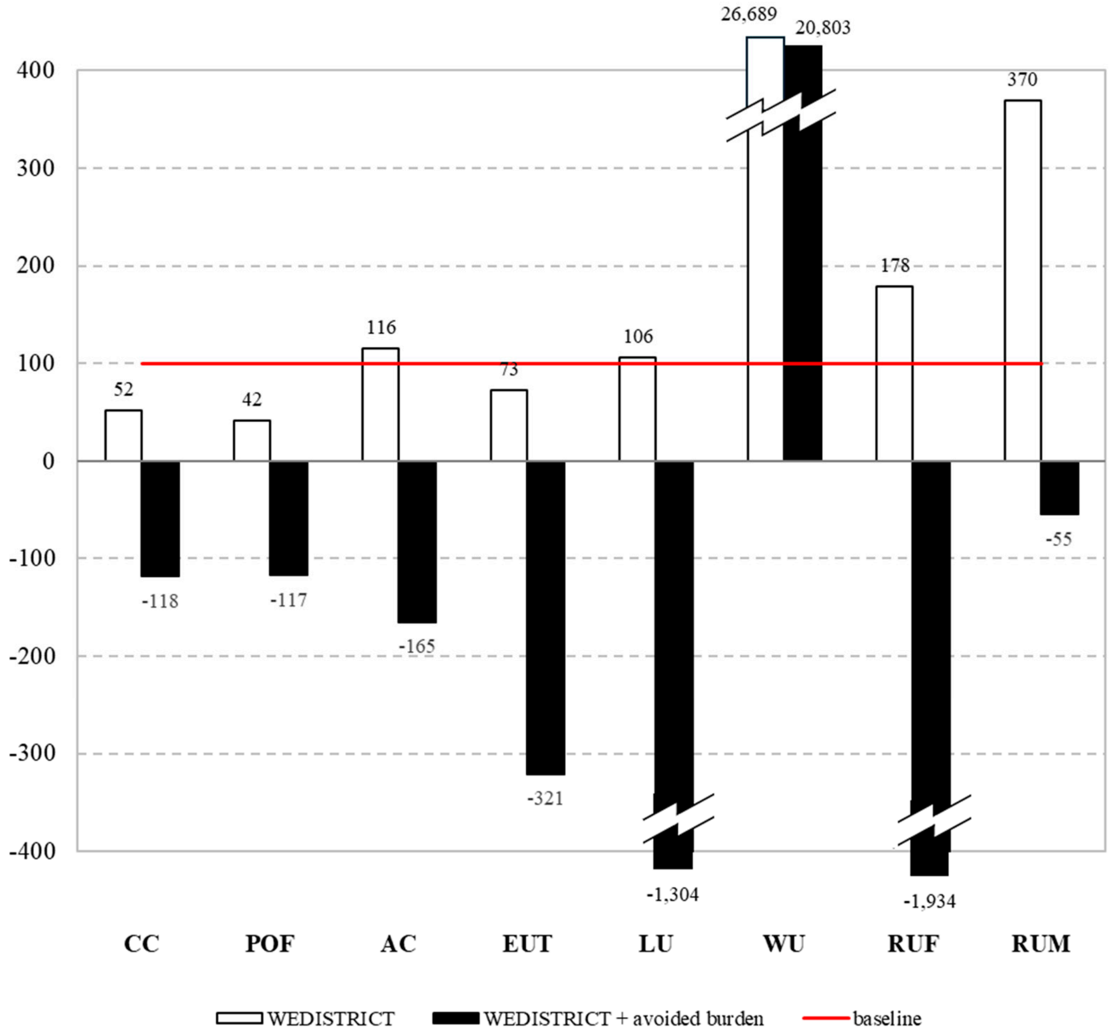

Figure 3. Environmental impact results comparing the baseline scenario against the WEDISTRICT scenario and the WEDISTRICT scenario with the avoided burdens included (the baseline scenario impacts are equal to 100).

3.2. S-LCA Results

As mentioned in Section 2.4, data were collected through a self-reported collection tool developed in Excel to allow the organisation to compare the results after project implementation (POST) with the previous situation prior to its implementation (PRE) [58] and with the local and/or national level to identify opportunities for further improvement [80,81]. The collection tool was structured as a comprehensive questionnaire aimed at capturing social impacts divided into key sections, each focused on specific stakeholder groups (i.e., workers, local communities, consumers, value chain actors, and society) and for each group, there was a set of questions aligned with the relevant social indicators. Likewise, data from the national and/or local level were collected from Swedish government reports (e.g., Directive 94/33/EC, Working Hours Act (1982:673), National Inventory Report by UNFCCC, NORDEFCO annual report, among others), European reports (e.g., EU National Report Sweden, EU Employment, Social Affairs & Inclusion, EU Country Reports on Human Rights Practices: Sweden, and others) and other industry and NGO reports (e.g., European Employment Services, the Baker McKenzie report on Global Sustainable Buildings, the Transparency International Corruption Report, EARTH.org–Sustainability index, and others) with highly relevant data for the study. Although RISE's small number of employees could generate uncertainties due to limited data, these were mitigated by benchmarking all of the indicators against nationwide social indicators, thus reducing variability and allowing comparability between the local and the national contexts.

After conducting the S-LCA at the demo-site, it was found that after the implementation of the project, 20 out of the 33 indicators presented no change compared to the situation prior to the project implementation, i.e., the baseline scenario. The changes on the remaining 13 indicators for the Luleå demonstrator are summarized in Table 6 below.

Table 6. Relevant results per indicators for S-LCA.

Impact Category	Units	Baseline	WEDISTRICT	
Workers ***(directly involved in WEDISTRICT boundaries)***				
Men to women occupation ratio in the company	Ratio	1.15	0.40	↑
Men to women executive managers ratio	Ratio	1.1	0.5	↑
Total number of affiliates	% (people in union/total)	68	75	↑
Wage inequality (average salary compared to managers salary)	% (average salary/managers salary)	46	50	↑
Lowest paid worker	€	24,194	25,000	↑
Average annual wage in the sector	€	60,750	50,000	↓
Employment rates of people with special needs with respect to the total employed people	%	52	0	↓
Sick-leave days	#/year/employee	14	N/A	
Accident ratio per employee	accidents/year/1000 workers	2.6	Unknown	
Local community				
Percentage of workers who reside in the local community	%	72	90	↑
Environmental certifications	Yes/No	Yes	No	↓
Society				
Relevance of the product to the satisfaction of basic needs	Yes/No	No	Yes	↑
Legal actions during the assessment period	Yes/No	Yes	No	↑
Value chain				
Legal actions during the reporting period	Yes/No	Yes	No	↑
Consumers *(people in general using the facilities of the target building)*				
Access to objective information	Yes/No	No	Yes	↑

Legend:

- N/A: not available
- ↑: a better performance of WEDISTRICT scenario
- ↓: a worse perfomance of WEDISTRICT scenario

Within the different categories, it was found that implementing the WEDISTRICT project resulted in a large improvement on the ratio of male to female employability, showing a larger percentage of women over men in the work environment, as can be seen with the first and second indicators. This is good improvement for women's employability, but we should be careful not to go completely in the opposite direction. It is worth mentioning that the considerable improvement in women's employment in Sweden can also be attributed to a combination of progressive social policies, economic factors, and cultural attitudes toward gender equality. These improvements highlight Sweden and the demonstrator's commitment to creating an equitable and sustainable workforce, serving as a model of integrating social sustainability into economic development.

Additionally, the percentage of people who were members of unions being larger than the national level demonstrates the openness to freedom of association resulting from the project's implementation. This can also be linked to the next two indicators, which show no large inequalities regarding wages from managerial positions to the lowest paid employee, which makes it possible to ensure tangible benefits and employee satisfaction.

Unfortunately, the average wage within the project is lower than the average median for professionals in similar fields. This could be an opportunity to improve working conditions. Likewise, other compensation indicators important to workers (i.e., sick-leave days and accident ratios) require attention. This coincides with the findings by Neugebauer et al. [82] on the pursuit of fair wages and compensation for workers. Additionally, it is recommended that the Luleå demonstrator tracks any accidents during the development of its activities as an important tool to improve safety conditions in the workplace.

Regarding employability in Sweden, it should be acknowledged that the country has significantly improved its employment rates after the COVID-19 crisis. Furthermore, the employment rates of people with special needs are an important social indicator in Sweden, yet challenges persist in ensuring equitable employment for people with disabilities. In this context, the percentage of people with special needs involved in the Luleå demonstrator is abnormally low compared to the national level, which presents itself as an opportunity. This agrees with the findings by Dreyer et al. [83] and Lindkvist & Ekener [84], which highlight the employability of and opportunities for people with special needs.

Regarding the local impact of the project, it is remarkable that 90% of workers come from the local community, which has a direct impact on local society through the development of local initiatives. Additionally, it must be highlighted that the project has proven that fair competition is possible and that it is possible to generate processes and projects that are not tainted by corruption scandals. This matches the findings by Arcese et al. [85] regarding the importance of fair competition to improving the overall conditions along the supply chain. It is also important to remark that after the implementation of the technology, the needs for cooling and heating were better covered, thus satisfying the needs of the users, even though the technology had not been environmentally certified at the time of the implementation, as can be seen in the Table 6. Finally, transparency—showing the project's findings and outcomes—has made our findings clear to the general population, which shows that the project intends to clearly mention all processes and impacts.

4. Conclusions

In the present study, an LCA and an S-LCA were performed to compare two DH energy generation scenarios located in Luleå (Sweden) as part of the WEDISTRICT project financed by the European Union. When compared, the results revealed that the technologies proposed by the project for thermal energy generation minimises environmental impacts in seven out of the eight impact categories evaluated and prioritised (climate change, photochemical ozone formation, acidification, terrestrial eutrophication, land use, resource use–fossils, and resource use–minerals and metals). For the water use environmental category, the impact of the WEDISTRICT scenario is higher than that of the baseline scenario, which is mainly attributable to the production phase of the biogas used to feed the SOFC module.

From the social perspective, while significant progress has been made in ten indicators after the implementation of the Luleå demonstrator, some challenges related to data availability, methodological integration, and stakeholder engagement persist. These pose additional challenges: to ensure inclusion for vulnerable groups, close the gender pay gap, reduce rural-urban disparities, and manage complex supply chains. Understanding these dynamics is key for different stakeholders to enhance social sustainability across various sectors.

The results obtained from the LCA and S-LCA for this DH allow us to draw some conclusions things regarding the value chains of current energy systems. From the environmental point of view, the results for climate change show a clear improvement when fossil fuel sources are replaced by renewable sources for energy generation. This indicates that efforts to meet the objectives of global agendas such as the European Green Deal can be achieved through the scalability of these technologies in operational environments. However, it is important to highlight that the LCA methodology allows the identification of potential impacts throughout the different life cycles of the energy service at critical points. Thus, the study concludes that the raw materials used for the production of renewable sources currently causes greater environmental impacts on water use than conventional systems. Therefore, the challenge for governments and organisations is to promote initiatives so that renewable technologies can advance to the point of achieving a balance between being competitive and being holistically better for the environment. These initiatives could contribute to meet the comprehensive set of actions to ensure the EU's access to a secure, diversified, affordable, and sustainable supply of critical raw materials and energy.

Additionally, integrating circular economy principles into energy systems could further enhance sustainability by promoting the reuse and recycling of resources throughout the entire value chain. The incorporation of waste heat recovery from data centres and the use of biogas-fed SOFC technologies exemplifies the shift towards a more resource-efficient and closed-loop system. Furthermore, adopting circular strategies can help mitigate the negative impacts identified in both the environmental and social assessments, contributing to long-term sustainability goals.

In conclusion, demonstration projects such as WEDISTRICT show the reduction of environmental and social impacts that can be achieved by implementing renewable and innovative technologies for DH and electrical networks in the EU. As technologies are scaled up, better results will be achieved in mitigating negative impacts and gradually upgrading the energy systems and their value chains in a sustainable way.

Limitations and Assumptions

The limited availability and reliability of social data from secondhand (i.e., government and NEO reports and additional grey literature) pose significant challenges to conducting comprehensive S-LCA assessments. Although this study has studied the most up-to-date information contained in government reports, as mentioned in Section 3.2, it should be taken into account that these results could be biased, as they lack an independent reviewer to assess their reliability [86]. Despite the limitations of the S-LCA, the use of macro-level indicators is crucial, especially when assessing social impacts where micro-level data is either lacking or difficult to standardise. Indicators such as national employment rates, income inequality, and access to essential services (education, healthcare) provide measurable and comparable data that offer a broad perspective on social conditions. These macro-level indicators serve as important benchmarks for understanding larger systemic social issues and can guide decision-makers in addressing the most critical challenges. When used alongside micro-level indicators—such as the working conditions at specific facilities or individual human rights violations—macro-level data add context and depth to the analysis.

Additionally, assessing social impacts involves subjective judgements from different stakeholders' perspectives. Although there have been some improvements in developing data collection and analysis methods that provide more quantitative outputs [87], these studies are still nascent. Future research should take an approach that includes quantitative analysis to understand the impact under a 'common' numerical perspective.

Furthermore, it should be pointed out that social systems are complex and interconnected, which implies that plenty of stakeholders are involved. Thus, the information from different parties could overlap and create more confusion rather than clarity (imperfect information) or can provide insufficient information about the overall system (incomplete information) [88].

End-of-life processes were not addressed in this research due to the lack of information within the project in this phase. Given the project's nature, any analysis would be completely theoretical and it is outside the scope of the timeframe in which the study took place. However, its inclusion may be the subject of future research, including an economic assessment using a life cycle costing (LCC) methodology to consider a complete study from a wholly sustainable perspective.

Finally, it must be highlighted that while challenges exist, ongoing efforts to standardise methodologies, improve data quality, and foster interdisciplinary collaboration are promising.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en17184745/s1. Table S1. WEDISTRICT scenario: detailed life cycle inventory of material inputs; Table S2. WEDISTRICT scenario: energy generation and consumption.

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