# LIFE CYCLE ASSESSMENT METHODOLOGY APPLICATION FOR ENERGY GENERATION ALTERNATIVES IN DISTRICT HEATING AND COOLING NETWORKS: A CASE STUDY FOR BUCHAREST

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## ABSTRACT

District heating and cooling (DHC) networks in buildings account for about 28% of the European Union's total energy consumption (90% coming from fossil fuels). This study aims to compare the environmental performance of using different technology alternatives to cover the energy demand of a DHC network located in Bucharest (Romania). Specifically, the application of renewable energies (geothermal and solar photovoltaic) is compared against conventional energy sources (natural gas and electricity supplied by the Romanian power grid). This research is part of the WEDISTRICT project, funded by the European Union's *Horizon 2020* research and innovation programme.

An attributional life cycle assessment (LCA) from a cradle-to-gate approach was developed to compare two scenarios. A baseline scenario (DHC network powered by conventional energy) and a WEDISTRICT scenario (powered by renewable technologies replacing the conventional sources used). The scenarios were modelled in SimaPro 9.1.1.7 software, using the Eco Invent 3.6 database and Environmental Footprint 3.0 as the environmental impact assessment method. The functional unit was 1 kWh of energy generated. The avoided burdens associated with the WEDISTRICT scenario were also considered.

The results revealed that transitioning to renewable sources for DHC networks minimizes impacts in six out of eight prioritised categories (climate change, photochemical ozone formation, acidification, terrestrial eutrophication, water use, and fossil resource use). For land use and resource use-minerals and metals categories, the impacts of the WEDISTRICT scenario are greater due to the contributions attributed to acquiring raw materials for the photovoltaic panels manufacture and the manufacturing process itself. Regarding the climate change category, the LCA results show that by implementing the renewable technologies proposed within the project, there is a 67% decrease for each kWh generated in this impact category. In addition, if the avoided burden by the surplus electricity generated and distributed is considered, replacing electricity from Romanian grid, the WEDISTRICT scenario has a total impact of -0.03 kg $CO_2$ eq/kWh.

Demonstrative projects such as WEDISTRICT show the environmental impact reduction that can be achieved by implementing renewable technologies for DHC networks in the European Union and gradually decarbonizing energy systems and their value chains.

**Key Words**: LCA, sustainability, DHC, energy, renewable energy, geothermal, photovoltaic, environmental impacts, SimaPro.

## 1 INTRODUCTION

The energy sector plays a vital role in the sustainable development of countries as they are associated with environmental, social, and economic concerns including climate change, energy security, and

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increasing energy costs. 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 minimizing the negative environmental consequences (Rashid & Majed, 2023). Promoting sustainable development and tackling climate change have become intertwined aspects of energy planning, analysis, and policy making. In 2020 the energy consumption in the 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%) (Eurostat, 2022). Being space and water heating relevant contributors within the European energy consumption, it has a special focus on developing cleaner technologies to provide energy and comfort for society. Energy accounts for two-thirds of global greenhouse gas emissions, so the energy sector is a central player in efforts to reduce emissions and mitigate climate change (IEA, 2023).

Recently, district heating (DH) and district heating and cooling (DHC) systems (depending on whether they satisfy only heating or heating and cooling needs), have seen increasing dynamism, particularly in Europe, where they have gained greater policy support since 2022. The environmental impacts associated with DHC networks stem mainly from the share of fossil fuels used as main source of energy (about 90% of total heat production) (IEA, 2023). Nevertheless, a comprehensive understanding of environmental impacts throughout the value chain of energy systems is important to detect environmental stresses at different stages and identify strategies for improvement without burden shifting (Hellweg & Canals, 2014). These diagnoses are the first step to propose and implement actions to mitigate the impacts related to activities carried out directly or indirectly by the organizations.

Life Cycle Assessment (LCA) methodology provides a framework for assessing the potential environmental impacts of products/services throughout their whole life cycle. Promoting life cycle thinking enables the possibility for organisations to generate value in a more comprehensive and sustainable way. In LCA, potential environmental impacts associated with the life cycle of a product/service are assessed based on a life cycle inventory (LCI), which includes relevant environmental input/output data compiled for the system associated with the product/service in question. The comprehensive scope of LCA is useful in avoiding problem-shifting from one life cycle phase to another, from one region to another, or from one environmental problem to another (Turconi *et al*., 2013).

This research will focus on using LCA as a tool to analyse the environmental impacts related to a DHC system located in Bucharest (Romania) that is part of the WEDISTRICT project (https://www.wedistrict.eu/). The research aims to compare two different DHC scenarios (pre and post WEDISTRICT) to determine the environmental impact of generating energy by replacing conventional energy sources (natural gas and electricity supplied by the national grid) with renewable sources (geothermal and solar) with the goal of reducing its carbon footprint at affordable costs.

The LCA results provide a comprehensive analysis and highlight the process stages associated with the main environmental impacts. Thus, project partners, policymakers, and the project's stakeholders will be able to identify solutions on how to mitigate the DHC environmental impacts while satisfying the energy needs of society.

# 2 METHODOLOGY

## 2.1 Case Study

The DHC network analysed is located at the Universitatea Națională de Știință și Tehnologie Politehnica București (UNSTPB), partners of the WEDISTRICT project. The campus heat demand is assured by a combined heat and power (CHP) plant, a primary thermal network, a secondary thermal network, and 9 thermal substations. The project selected as a "target building" the DHC network that

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provides energy to the Renewable Energy Sources Laboratory building which was heat-fed by one of the thermal substations. The building is located at the end of the secondary thermal network; therefore, the thermal comfort conditions may not always be ensured. For this reason, the building covered the heat demand with a natural gas boiler (110 kW) until December 2019 when it failed. For the domestic hot water (DHW) a 3kW electric appliance was installed to prepare hot water at the point of consumption. The cooling demand of the building was covered with 3 conventional air conditioning systems 3.44 kW each.

Hence, the renewable technologies proposed by the project were designed expecting to cover and ensure the thermal comfort conditions of the building. A hybrid geothermal-photovoltaic network containing 3 subsystems was implemented: a thermal, an electrical, and photovoltaic-thermal (PV-T) subsystem. **Table 1** describes the details of the main equipment of each subsystem.

**Table 1.** WEDISTRICT project – main equipment

| Subsystem | Equipment | Details |
|---|---|---|
| Thermal | 12 deep boreholes | • 100m deep approximately<br>• Closed circuit<br>• U-profile double tube |
| | 2 ground-source heat pumps (master and slave) | Master:<br>• Rated heating output: 42.3 kW<br>• Cooling capacity: 33.6 kW<br>Slave:<br>• Rated heating output: 20.5 kW<br>• Cooling capacity: 16.4 kW |
| | 1 buffer storage tank | Capacity: 2000 litres |
| | 1 domestic hot water (DHW) preparation tank | Capacity: 750 litres |
| | 2 heat exchangers | Heat exchanger heating cycle:<br>• Capacity: 64kW<br>Heat exchanger cooling cycle:<br>• Capacity: 78kW |
| Electrical | 192 roof-mounted photovoltaic (PV) panel modules | • Type: monocrystalline<br>• Total power installed: 66 $kW_p$ |
| | 16 storage batteries | Type: $LiFePO_4$ battery, intelligent with integrated battery management system (BMS) |
| PV-T | 2 roof-mounted PV-T panel modules | • Number of cells: 60<br>• Total surface collector: 1.55 $m^2$ |

In this study, a LCA comparing two scenarios is defined to measure and analyse the environmental performance of energy generation for this DHC network. A baseline scenario representing how the energy demand was covered at the beginning of the project (pre-WEDISTRICT situation), and a WEDISTRICT scenario representing the situation once the renewable technologies proposed by the project were implemented.

## 2.2 LCA

2.2.1 Goal and scope definition. As previously mentioned, the study intends to compare the environmental performance of using renewable energies (geothermal and solar photovoltaic) against conventional energy sources (natural gas and conventional electricity sources) for DHC energy generation. The functional unit (FU) defined and used as a basis for comparison is the production of 1 kWh of energy. The assessment considers a cradle-to-gate approach, which includes processes from raw materials acquisition to the energy produced. The LCA software used is SimaPro 9.1.1.7, with Eco Invent 3.6 as the background database.

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The technologies and equipment considered within the baseline and WEDISTRICT scenarios are described in **Table 2** and **Table 3** respectively. Each scenario is divided into subsystems to facilitate the process modelling and the interpretation of results.

**Table 2.** Bucharest equipment used for energy generation – Baseline scenario.

| SUBSYSTEM ANALYSED | ON-SITE EQUIPMENT |
|---|---|
| HEATING | Natural gas boiler |
| COOLING | Conventional air conditioning system |
| DHW | Electric appliance |

**Table 3.** Bucharest equipment acquired - WEDISTRICT scenario.

| SUBSYSTEM ANALYSED | DEMO-SITE EQUIPMENT |
|---|---|
| THERMAL | Geothermal boreholes<br>Heat exchangers<br>Heat pumps<br>Storage tanks<br>Heating and cooling distribution network |
| ELECTRICAL | Roof-mounted PV panels<br>Storage batteries<br>Electrical distribution network |
| PV-T | Roof-mounted PV-T panels |

2.2.2 Limitations and assumptions. For the LCA, it was necessary to make the following simplifications and assumptions:

- To relate and normalize all the information collected in the life cycle inventory (LCI) to the functional unit, the energy production in a whole year is taken as a reference as well as the equipment lifetime.
- A weighting of electrical and thermal energy is made to present the results in units of environmental impact per total kWh of energy produced.
- For equipment data gaps, Eco Invent 3.6 databases and literature were used as background information.
- Transportation of equipment is not included. Raw materials transportation is included within the processes modelled using Eco Invent 3.6.

2.2.3 Life cycle inventory (LCI). In this phase, technical and budget sheets provided by the project and from UNSTPB are used to list and characterise all the equipment included in the analysis. In addition, they provided detailed information on the mass, quantity, and technical performance of the equipment. Primary sources for data collection were also documents published by the project itself. When assumptions were required, data collected in the inventory was also taken from the Eco Invent 3.6 database. All numerical inputs were normalised in terms of the FU, using the energy production in one year and the equipment lifetime. **Table 4** and **Table 5** present the energy production of each scenario based on the data provided and the simulation of the UNSTPB building within the WEDISTRICT project (ACCIONA S.A., 2020).

**Table 4**. Baseline scenario energy production.

| Subsystem | Annual energy production | Unit |
|---|---|---|
| HEATING | 127705 | $kWh_t$ / year |
| COOLING | 13285 | $kWh_t$ / year |
| DHW | 625 | $kWh_t$ / year |

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**Table 5.** WEDISTRICT scenario energy production.

| Subsystem | Annual energy production | Unit |
|---|---|---|
| THERMAL | 93730 | $kWh_t$ / year |
| ELECTRICAL | 68749 | $kWh_e$ / year |
| PV-T | 4245 | $kWh_t$ / year |
|  | 808 | $kWh_e$ / year |

2.2.4 Life cycle impact assessment (LCIA). The LCIA methodology used is the Environmental Footprint (EF 3.0) impact assessment method (Commission Recommendation (EU), 2021/2279). The main environmental impact category considered is climate change considering the interests of the project partners and the approach of WEDISTRICT. Nevertheless, the results regarding other seven impact categories (photochemical ozone formation, acidification, eutrophication-terrestrial, land use, water use, resource use-fossils, and resource use-minerals and metals) are also considered. **Table 6** gathers the list of impact categories analysed and the characterization factors of each one.

**Table 6**. Impact categories prioritised and analysed within the study.

| Impact category | Unit | Characterization factor |
|---|---|---|
| Climate change (CC) | kg $CO_2$ eq[1] | Radiative forcing as Global Warming Potential (GWP100). |
| Photochemical ozone formation (POF) | kg NMVOC eq[2] | Photochemical ozone creation potential (POCP): Expression of the potential contribution to photochemical ozone formation. |
| Acidification (AC) | mol H+ eq[3] | Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit. |
| Eutrophication, terrestrial (EUT) | mol N eq[4] | Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area, to which eutrophying substances deposit. |
| Land use (LU) | Pt | Soil quality index. |
| Water use (WU) | $m^3$ depriv. | User deprivation potential (deprivation-weighted water consumption). |
| Resource use, fossils (RUF) | MJ | Abiotic resource depletion fossil fuels (ADP-fossil); based on lower heating value. |
| Resource use, minerals and metals (RUM) | kg Sb eq[5] | Abiotic resource depletion (ADP ultimate reserve). |

# 3 RESULTS AND DISCUSSION

**Table 7** and **Table 8** present the results obtained for the baseline and WEDISTRICT scenarios, respectively. The results detail the values for the prioritised environmental impact categories for the

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[1] Kilograms of carbon dioxide equivalent.

[2] Kilograms of Non-Methane Volatile Organic Compounds equivalent.

[3] Moles of hydron equivalent.

[4] Moles of nitrogen equivalent.

[5] Kilograms of antimony equivalent.

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subsystems within each scenario, as well as the total weighted result to compare both scenarios, as shown in **Figure 1**.

**Table 7**. Environmental impact per unit of FU – Bucharest baseline scenario.

| Impact category | Units (/kWh) | Baseline subsystem | | | Baseline scenario weighted |
|---|---|---|---|---|---|
| | | Heating | Cooling | DHW | |
| CC | kg $CO_2$ eq | 2.37E-01 | 1.34E-01 | 4.99E-01 | 2.29E-01 |
| POF | kg NMVOC eq | 1.85E-04 | 2.91E-04 | 1.10E-03 | 1.99E-04 |
| AC | mol H+ eq | 1.81E-04 | 9.64E-04 | 3.62E-03 | 2.66E-04 |
| EUT | mol N eq | 5.14E-04 | 9.94E-04 | 3.74E-03 | 5.73E-04 |
| LU | Pt | 1.10E-01 | 7.24E-01 | 2.73E+00 | 1.76E-01 |
| WU | $m^3$ depriv. | 1.56E-03 | 4.06E-02 | 1.53E-01 | 5.68E-03 |
| RUF | MJ | 3.79E+00 | 2.49E+00 | 9.35E+00 | 3.71E+00 |
| RUM | kg Sb eq | 6.96E-08 | 1.13E-06 | 4.34E-06 | 1.82E-07 |

**Table 8.** Environmental impact per unit of FU – Bucharest WEDISTRICT scenario.

| Impact category | Units (/kWh) | WEDISTRICT subsystem | | | WEDISTRICT scenario weighted |
|---|---|---|---|---|---|
| | | Thermal | Electrical | PV-T | |
| CC | kg $CO_2$ eq | 4.14E-02 | 1.74E-01 | 1.83E-02 | 7.65E-02 |
| POF | kg NMVOC eq | 1.25E-04 | 6.97E-04 | 7.89E-05 | 2.78E-04 |
| AC | mol H+ eq | 1.99E-04 | 1.34E-03 | 1.83E-04 | 3.33E-04 |
| EUT | mol N eq | 4.60E-04 | 2.14E-03 | 2.54E-04 | 6.30E-04 |
| LU | Pt | 9.01E-01 | 6.02E+00 | 9.17E-01 | 1.50E+00 |
| WU | $m^3$ depriv. | 5.51E-03 | 1.25E-01 | 1.19E-02 | 3.81E-02 |
| RUF | MJ | 2.71E-01 | 2.24E+00 | 2.32E-01 | 8.01E-01 |
| RUM | kg Sb eq | 5.03E-06 | 2.90E-05 | 3.08E-06 | 1.14E-05 |

**Figure 1** shows the results in relative terms, where the baseline scenario results are equal to 100%. The results present three different trends when comparing the WEDISTRICT against the baseline scenario. One trend of improvement associated with the environmental impact categories of climate change and resource use-fossils. A second trend for photochemical ozone formation, water use, land use, and resource use-mineral and metals, where the environmental impacts associated with the WEDISTRICT scenario are higher. Finally, a third trend, indicates that the environmental impacts regarding eutrophication-terrestrial, and acidification are similar for both scenarios, so the results are inconclusive and require careful analysis and interpretation.

For climate change, the LCA results show that the carbon footprint impact for the baseline and the WEDISTRICT scenarios are 0.23 kg $CO_2$ eq/kWh and 0.07 kg $CO_2$ eq/kWh respectively. Thus, the WEDISTRICT scenario has 67% less impact than the baseline scenario. This is mainly attributed to the substitution of natural gas as a heating source in the energy production phase. As previously found (Hosseini *et al*., 2022; Kabayo *et al*., 2019; Atilgan & Azapagic, 2016), when transitioning to renewable sources of energy generation, the environmental impacts associated with carbon footprint decreases, enabling projects and organizations interested in achieving the decarbonization objectives proposed by governments, to gradually meet the transition to a zero-carbon energy production.

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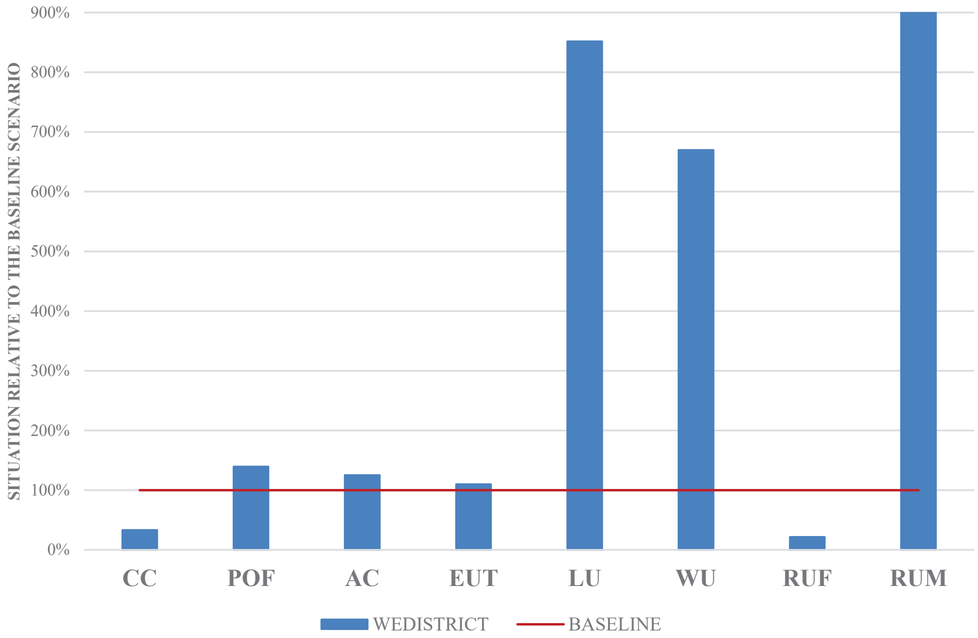

**Figure 1.** Bucharest environmental results (baseline scenario = 100%).

However, when reviewing the other prioritised environmental impact categories, the WEDISTRICT 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, detailed data was taken directly from UNSTPB to build the WEDISTRICT scenario model in SimaPro, unlike the baseline scenario, which was built mainly with secondary and less detailed data, which could also influence the results.

Stamford *et al*. (2012); Gibon *et al*. (2017) and Kabayo *et al*. (2019) discuss how the manufacturing stage of the monocrystalline silicon used for single-Si photovoltaic panels for solar energy production has major contributions to these environmental impact categories when comparing the results against other energy supply options, having similar results as the present study. Moreover, different studies (Chen *et al*., 2016; Lamnatou *et al*., 2017; 2019) 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.
Therefore, the importance of understanding the processes contributing more to environmental impacts from an integrated point of view (not only focusing on the environmental impacts associated with the use phase), allows decision-makers to determine hotspots where improvements for achieving sustainable value chains may be proposed.

Nevertheless, the electrical energy that is being generated with the WEDISTRICT scenario technologies is partly consumed by the heat pumps of the geothermal system. 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 since part of the conventional energy generation is replaced by the renewable one (Pérez *et al*., 2018). **Table 9** shows the results for the WEDISTRICT scenario when the avoided burden is included, and **Figure 2** and **Figure 3** illustrate graphically the results.

When the avoided burden is introduced in the assessment, the results show an evident improvement for the WEDISTRICT scenario. In terms of climate change, the LCA results show that for each surplus kWh generated, 0.10 kg $CO_2$ eq are avoided, leading to a global carbon footprint of -0.03 kg $CO_2$ eq/kWh

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for this scenario. Besides, 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 it was mentioned before, the most relevant contributions to total impact are related to the raw materials acquisition and the manufacturing stage of the PV panels, mainly related to the monocrystalline silicon used. Regarding the land use impact category, land occupation is not considered within this impact since the PV panels are roof-mounted as described in **Table 1**.

**Table 9.** Environmental impact results including the avoided burden- Bucharest.

| Impact category | Units (/kWh) | Baseline | WEDISTRICT | WEDISTRICT + avoided burden |
|---|---|---|---|---|
| CC | kg $CO_2$ eq | 2.29E-01 | 7.65E-02 | -2.67E-02 |
| POF | kg NMVOC eq | 1.99E-04 | 2.78E-04 | 5.16E-05 |
| AC | mol H+ eq | 2.66E-04 | 3.33E-04 | -4.16E-04 |
| EUT | mol N eq | 5.73E-04 | 6.30E-04 | -1.44E-04 |
| LU | Pt | 1.76E-01 | 1.50E+00 | 9.40E-01 |
| WU | $m^3$ depriv. | 5.68E-03 | 3.81E-02 | 6.50E-03 |
| RUF | MJ | 3.71E+00 | 8.01E-01 | -1.13E+00 |
| RUM | kg Sb eq | 1.82E-07 | 1.14E-05 | 1.06E-05 |

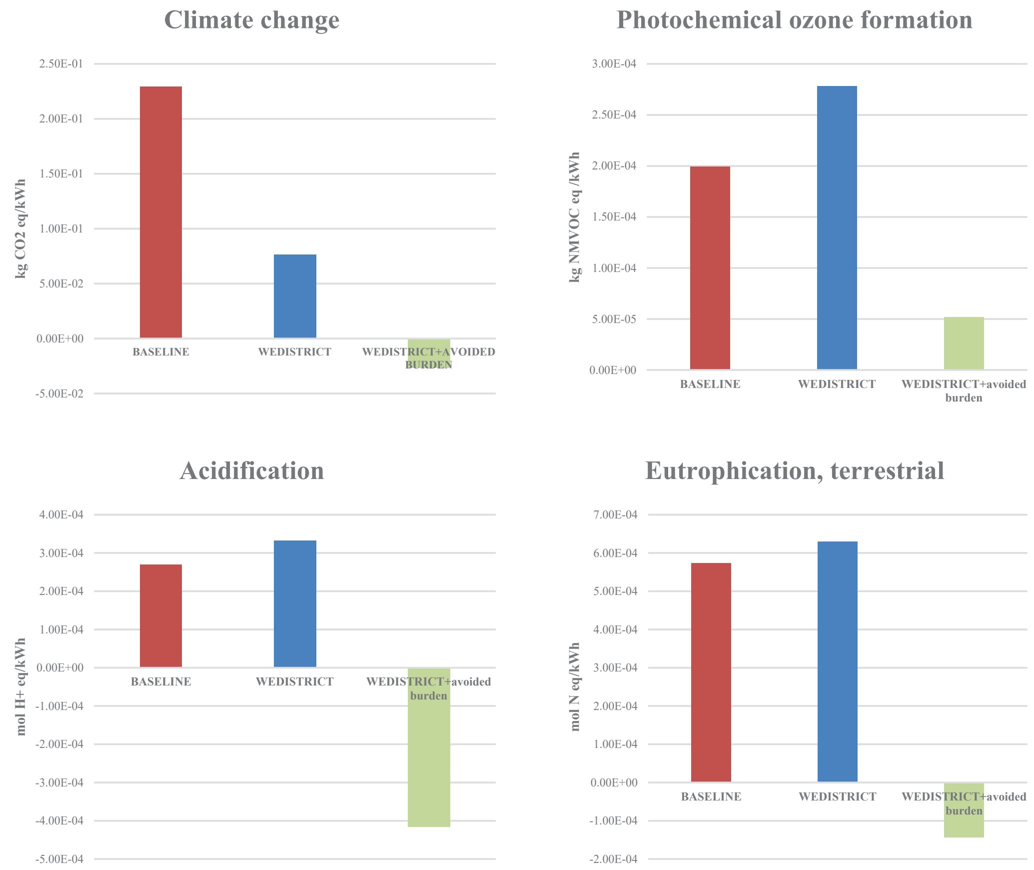

**Figure 2.** Environmental impacts: climate change, photochemical ozone formation, acidification, eutrophication-terrestrial with avoided burden.

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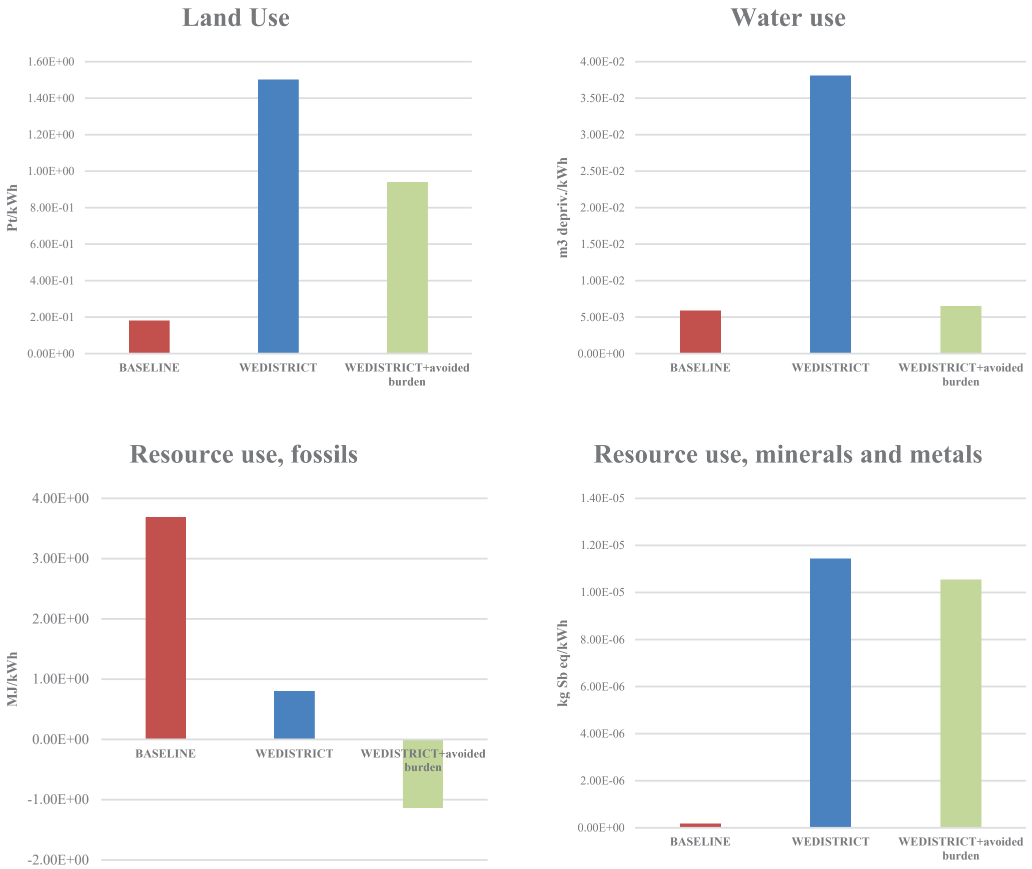

**Figure 3.** Environmental impacts: land use, water use, resource use fossils, resource use minerals and metals with avoided burden.

## 4 CONCLUSIONS

In the present study, a LCA has been applied to compare two energy generation scenarios within a DHC network located in Bucharest (Romania) as part of the WEDISTRICT project financed by the Horizon 2020 research and innovation programme of the European Union. The first scenario (baseline) uses conventional energy sources (natural gas and electricity from the Romanian grid) for energy generation. The second one is a renewable scenario composed of geothermal, solar photovoltaic, and photovoltaic-thermal technologies for thermal and electric energy generation (WEDISTRICT scenario). When comparing both scenarios, the results revealed that the transition to renewable sources for this DHC network minimizes environmental impacts in six out of eight impact categories evaluated and prioritised (climate change, photochemical ozone formation, acidification, terrestrial eutrophication, water use, and fossil resource use). For land use and resource use-minerals and metals categories, the impacts of the WEDISTRICT scenario are greater than those of the baseline scenario.

For carbon footprint, the LCA shows that for the baseline scenario and the WEDISTRICT scenario, the results are 0.23 kg $CO_2$ eq/kWh and 0.07 kg $CO_2$ eq/kWh respectively. This demonstrates a 67% decrease in this environmental impact for each kWh generated. In addition, by including in the WEDISTRICT scenario the results of the avoided burden by the surplus electricity generated and

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distributed for UNSTPB's internal use, for each surplus kWh generated, 0.10 kg $CO_2$ eq are avoided, leading to a global carbon footprint of -0.03 kg $CO_2$ eq/kWh.

However, for the environmental impact categories resources use-mineral and metals and land use, the impacts of the WEDISTRICT scenario are higher. This is mainly attributed to the acquisition of raw materials to produce the PV panels and the manufacturing process itself. This shows that, by analysing energy generation systems from a life cycle perspective, critical points are revealed, beyond the impacts related to climate change. In this way, it will be possible to promote more comprehensive sustainability initiatives for the energy systems value chains. It is recommended for future research to conduct sensitivity analyses between different types of renewable technologies to understand if by including fewer intensive processes in the manufacturing stages, projects could have more favourable results for these impact categories.

End-of-life processes should be considered when performing an LCA for the technologies assessed within this project to obtain more comprehensive results. This stage has not been addressed in this research because the system boundaries should maintain coherent results when combining them with the system boundaries of the life cycle sustainability assessment (including social and economic issues) on going within the project. However, its inclusion may be the subject of future research.

In conclusion, demonstration projects such as WEDISTRICT show the reduction of the environmental impacts that can be achieved by implementing renewable technologies for DHC networks in the EU. As technologies are scaled up, better results will be achieved in mitigating environmental impacts and gradually decarbonizing the energy systems and their value chains.

## REFERENCES

ACCIONA S.A. (2020). Pre-assessment of demo-sites. WEDISTRICT Deliverable 6.1: p. 44-77.

Atilgan, B., & Azapagic, A. (2016). An integrated life cycle sustainability assessment of electricity generation in Turkey. Energy Policy, 93, 168-186. https://doi.org/10.1016/j.enpol.2016.02.055.

Chen, W., Hong, J., Yuan, X., & Liu, J. (2016). Environmental impact assessment of monocrystalline silicon solar photovoltaic cell production: A case study in China. Journal of Cleaner Production, 112, 1025-1032. https://doi.org/10.1016/j.jclepro.2015.08.024.

Commission Recommendation (EU) 2021/2279 of the European Parliament and of the Council of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations (OJ L 471/1, 30.12.2021). http://data.europa.eu/eli/reco/2021/2279/oj.

Eurostat. (2022). Energy consumption in households. Retrieved June 6, 2023, from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households#Energy_products_used_in_the_residential_sector.

Gibon, T., Arvesen, A., & Hertwich, E. G. (2017). Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options. Renewable and Sustainable Energy Reviews, 76, 1283-1290. https://doi.org/10.1016/j.rser.2017.03.078.

Hosseini, S. M., Aslani, A., & Kasaeian, A. (2022). Energy, water, and environmental impacts assessment of electricity generation in Iran. Sustainable Energy Technologies and Assessments, 52, 102193. https://doi.org/10.1016/j.seta.2022.102193.

IEA. (2023). *Energy System*. Retrieved January 9, 2024, from District Heating: https://www.iea.org/energy-system/buildings/district-heating.

IEA. (2023). International Energy Agency. Retrieved June 6, 2023, from Climate change: https://www.iea.org/topics/climate-change.

Hellweg, S., & Canals, L. (2014). Emerging approaches, challenges and opportunities in life cycle assessment. Science. https://doi.org/1248361.

https://doi.org/10.52202/077185-0140

Kabayo, J., Marques, P., Garcia, R., & Freire, F. (2019). Life-cycle sustainability assessment of key electricity generation systems in Portugal. Energy, 176, 131-142. https://doi.org/10.1016/j.energy.2019.03.166.

Lamnatou, C., & Chemisana, D. (2017). Photovoltaic/thermal (PVT) systems: A review with emphasis on environmental issues. Renewable Energy, 105, 270-287. https://doi.org/10.1016/j.renene.2016.12.009.

Lamnatou, C., Smyth, M., & Chemisana, D. (2019). Building-Integrated Photovoltaic/Thermal (BIPVT): LCA of a façade-integrated prototype and issues about human health, ecosystems, resources. Science of The Total Environment, 660, 1576-1592. https://doi.org/10.1016/j.scitotenv.2018.12.461.

Pérez, J., De Andrés, J. M., Lumbreras, J., & Rodríguez, E. (2018). Evaluating carbon footprint of municipal solid waste treatment: Methodological proposal and application to a case study. Journal of Cleaner Production, 205, 419-431. https://doi.org/10.1016/j.jclepro.2018.09.103.

Rashid, E., & Majed, N. (2023). Integrated life cycle sustainability assessment of the electricity generation sector in Bangladesh: Towards sustainable electricity generation. Energy Reports, 10, 3993-4012. https://doi.org/10.1016/j.egyr.2023.10.041.

Stamford, L., & Azapagic, A. (2012). Life cycle sustainability assessment of electricity options for the UK. International Journal of Energy Research, 36(14), 1263-1290. https://doi.org/10.1002/er.2962.

Turconi, R., Boldrin, A., & Astrup, T. (2013). Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renewable and Sustainable Energy Reviews, 28, 555-565. https://doi.org/10.1016/j.rser.2013.08.013.

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