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Environmental Impact of Enhanced Geothermal Systems with Supercritical Carbon Dioxide: A Comparative Life Cycle Analysis of Polish and Norwegian Cases

Magdalena Strojny [1,*], Paweł Gładysz [1], Trond Andresen [2], Leszek Pająk [3], Magdalena Starczewska [3] and Anna Sowiżdżał [3]

[1] Faculty of Energy and Fuels, AGH University of Krakow, 30-059 Kraków, Poland; pawel.gladysz@agh.edu.pl
[2] SINTEF Energy Research, 7034 Trondheim, Norway; trond.andresen@sintef.no
[3] Faculty of Geology, Geophysics and Environmental Protection, AGH University of Krakow, 30-059 Kraków, Poland; pajakl@agh.edu.pl (L.P.); msobczy@agh.edu.pl (M.S.); ansow@agh.edu.pl (A.S.)
* Correspondence: mstrojny@agh.edu.pl

Abstract: Low-carbon electricity and heat production is essential for keeping the decarbonization targets and climate mitigation goals. Thus, an accurate understanding of the potential environmental impacts constitutes a key aspect not only for the reduction in greenhouse gas emissions but also for other environmental categories. Life cycle assessment allows us to conduct an overall evaluation of a given process or system through its whole lifetime across various environmental indicators. This study focused on construction, operation and maintenance, and end-of-life phases, which were analyzed based on the ReCiPe 2016 method. Within this work, authors assessed the environmental performance of one of the renewable energy sources—Enhanced Geothermal Systems, which utilize supercritical carbon dioxide as a working fluid to produce electricity and heat. Heat for the process is extracted from hot, dry rocks, typically located at depths of approximately 4–5 km, and requires appropriate stimulation to enable fluid flow. Consequently, drilling and site preparation entail significant energy and material inputs. This stage, based on conducted calculations, exhibits the highest global warming potential, with values between 5.2 and 30.1 $kgCO_2eq/MWh_{el}$, corresponding to approximately 65%, 86%, and 94% in terms of overall impacts for ecosystems, human health, and resources categories, respectively. Moreover, the study authors compared the EGS impacts for the Polish and Norwegian conditions. Obtained results indicated that due to much higher electricity output from the Norwegian plant, which is sited offshore, the environmental influence remains the lowest, at a level of 11.9 $kgCO_2eq/MWh_{el}$. Polish cases range between 38.7 and 54.1 $kgCO_2eq/MWh_{el}$ of global warming potential in terms of electricity production. Regarding power generation only, the impacts in the case of the Norwegian facility are two to five times lower than for the installation in the Polish conditions.

Keywords: enhanced geothermal systems; supercritical carbon dioxide cycles; life cycle assessment; geothermal energy; environmental performance

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1. Introduction

Supercritical fluids constitute an attractive alternative to be fed as working fluids into power cycles. They are especially considered as substitutes in modern power plants or as fluids for Organic Rankine Cycles (ORCs) and Brayton cycles. In recent years, researchers have captured notable interest in supercritical carbon dioxide (sCO_2), examining and exploring its prospects and features [1]. By virtue of its physical or chemical properties, it may be utilized as a suitable candidate for systems which deploy nuclear energy, waste heat recovery, or concentrated solar power. The advantages of those systems stem from high power density leading to a small plant footprint, high efficiency of conversion, and technical applicability with different heat sources [2].

The supercritical state of CO_2 can be easily reached because of its low critical parameters: (i) temperature of 304.13 K and (ii) pressure of 7.38 MPa. Therefore, sCO_2 can be a viable solution for implementation in various installations. However, research faces a few obstacles that may slow the development rate down. The authors of study [3] point out the lack of system design and methodology for steady/transient operation analysis, lack of comprehensive understanding of its conversion and energy transfer mechanisms, as well as some technical barriers for turbomachinery. Nonetheless, further investigation and experiments should solve those problems by adapting the characteristics of the heat source to reach higher efficiency, as well as optimizing key components' design and system operation [3].

One of the technologies in which there is growing interest, and which deploys sCO_2, is Enhanced Geothermal Systems (EGSs). EGSs are unconventional systems that use techniques that unlock high geothermal potential by creating channels in hot, dry rock (HDR). These bedrocks are characterized by low porosity, low permeability, and low to medium enthalpy [4]. This, after appropriate treatment and stimulation, allows fluid to circulate through the rock, become heated, and then be used to generate electricity or heat at a topside power plant. Around thirty EGS projects are currently either under development or in operation worldwide, with a total installed capacity of about 12 MW [5]. Of these, five are in routine operation and fourteen are currently capable of producing power. Nevertheless, EGS projects have not yet reached large-scale commercial operation due to a number of obstacles that need to be overcome. In article [5], authors underlined aspects which may cause an impediment to rapid EGS deployment, some of the points mentioned are as follows:

- Lack of adequate and efficient HDR artificial fracture management technology in EGS development, which may lead to isolated, disproportionately large artificial fractures, fluid circulation short circuits, early thermal breakthrough, and, consequently, inefficient heat recovery.
- The processes of EGS formation and heat recovery are influenced by a number of variables, including water–rock interaction, seepage, heat transmission, medium deformation, and several others. It is yet unknown how multi-scale and multi-field coupling patterns and mechanisms influence geothermal reservoirs.
- Pressure drops during the lifting process in EGS producers can result in fluid flashing, which modifies the well's flow and heat transfer properties and limits the extraction of hot fluid efficiently.

Typically, EGS installations use water as a circulating working fluid, but Brown et al. [6] suggested that supercritical CO_2 may also be a suitable substance, with environmental benefits. The comparison between sCO_2 and water properties indicates carbon dioxide offers benefits in terms of flow ease in geothermal wells due to lower viscosity and density. Because of the higher compressibility of sCO_2, greater mass flows are required for system circulation and heat extraction from the source [7]. However, this aspect also benefits the CO_2 potential sequestration rate in the geological reservoir, which may amount to approximately 5–8% and may be considered as a favorable option [8]. The only pilot project that attempted to deploy sCO_2 was the Ogachi Project (1989–2002), located in Japan [9]. The project was terminated due to financial reasons. Despite that, some key flow and borehole tests were carried out and the results may be used for future research [10]. Therefore, currently, there is no sCO_2-EGS project operating and, thus, the available data are limited. This is one of the key challenges in conducting analysis for sCO_2-EGS installations. Research efforts should focus on gathering comprehensive data to accurately assess the overall performance of these systems. Nevertheless, with the development of more sCO_2 cycles and the decrease in costs associated with preparation of the EGS site and wells, sCO_2-EGS may constitute a viable option and an alternative to conventional CO_2 utilization and storage methods within the chain of Carbon Capture, Utilization and Storage (CCUS) technologies.

Since EGS units have gained more attention, there have been several studies conducted in the field of overall energy efficiency and energy performance of Enhanced Geothermal

Systems using sCO_2 as a working fluid. In [11], the authors examine the overall potential to deploy such installations in Polish conditions. The work [12] focusses on utilization of captured CO_2 from a coal plant to extract heat accumulated in a geological reservoir in an ORC unit for further electricity production. The authors of [13] follow up the concept of EGSs in various configurations to examine which have the best performance. This indicates that much of an investigation in the field of EGS units was carried out, but especially from energetic and economic perspectives.

Nevertheless, one of the most relevant aspects of all renewable energy sources (RES) lies in their environmental influence. Due to their independence from fossil fuels, RES, during their operation phase, have an inconsiderable impact on the environment, which underlines the significance of the construction and end-of-life phases of such systems within their lifetime [14]. To examine and quantify the environmental impact of a product, process, or whole unit, the life cycle assessment (LCA) methodology is applied. It allows for the determination of all of the flows coming in and out of a system and, therefore, characterizes the impacts in different environmental categories. LCA also enables us to compare different systems with respect to their environmental factors and influence. In terms of geothermal sources, there are dedicated guidelines prepared in the framework of GEOENVI EU H2020 Project which refer to LCA standards for preparing such an assessment [15]. However, current efforts are mainly directed towards conventional water-based units, including EGSs. Frank et al. [16] proposed a study associated with sCO_2 geothermal power production, although it does not refer to Enhanced Geothermal Systems and focusses more on global warming potential (GWP) through greenhouse gas emissions and energy consumption without placing distinction on system phases and other environmental impact categories. Frick et al. [17] proposed an LCA study of geothermal binary power plants with different configurations, showing that the environmental impacts are associated with geological conditions at a specific site. Nonetheless, this work was mainly dedicated to analysis of only three environmental effects: global warming, acidification, and eutrophication based on SO_2- and $PO^3{}_4$-equivalent emissions without further normalization or weighting steps. Lacirignola and Blanc [18] also examined EGSs' environmental performance but used five impact categories including seismicity risk and considered ten scenarios. Mentioned studies focused on impact assessment of water-based systems mainly with an ORC loop; in relation to that, there is a research gap in terms of other working fluids, especially sCO_2, which may be climate beneficial, and different unit configurations.

In virtue of this, previous studies have focused predominantly on the energetic and economic aspects of EGS units, leaving a gap in the understanding of their environmental impact. The novelty and importance of this work lie in its emphasis on assessing the environmental influence of sCO_2-EGS units, a critical aspect when analyzing one of the RES. The use of life cycle assessment methodology becomes crucial in this context, allowing for an extensive evaluation of the environmental footprint throughout the life cycle of EGS installations. Although there are existing guidelines for conducting a LCA for conventional water-based geothermal units, there is a lack of comprehensive research on alternative working fluids such as sCO_2 and their associated environmental impacts. The significance of this work is underlined by its potential to provide insights into the environmental performance of EGS units, considering disparate plant configurations and different site localizations including countries with high- and low-emission economies.

2. Life Cycle Analysis

For most renewable energy sources, the crucial aspect with regard to greenhouse gas emissions and other environmental influences lies in their infrastructure, indicating the impacts correlated with the extraction of raw materials, the energy mix used for the production of equipment, the fuels used for site preparation, transportation methods, and other factors related to manufacturing and construction [19]. Therefore, it is essential to provide a comprehensive assessment of the system throughout its life.

2.1. Goal and Scope

The main objective of this LCA is to examine the environmental impact of the EGS unit which uses supercritical CO_2 as a working fluid at two locations: Poland (Gorzów Block) and Norway (Åre formation). In both localizations, heat from high-temperature bedrock is extracted in order to be utilized in a topside power plant.

In the Polish case, two configurations were assessed (Table 1): (i) first one is dedicated to combined electricity and heat generation within the direct sCO_2 cycle and (ii) second one involves only power production via indirect sCO_2 cycle including ORC. The direct sCO_2 cycle is based on direct sCO_2 expansion in a dedicated turbine after which, once cooled, it can be injected back into the reservoir. This variant requires less equipment in the topside plant. The Norway case involved one configuration similar to Polish case 2, however, Åre formation is located in the North Sea, thus, additional distance between shore and site was included within the assessment. Moreover, due to offshore siting of Norway unit, it was assumed that the plant itself is located at sea floor. Nevertheless, since EGSs also constitute a potential CO_2 storage site in geological reservoir, additional pipelines for CO_2 supply were excluded from the boundaries of the evaluation.

Table 1. Analyzed cases description.

Case	Localization	Description
Case 1	Poland, Gorzów Block	Combined heat and power with direct sCO_2 cycle
Case 2	Poland, Gorzów Block	Power generation only with indirect sCO_2 cycle with ORC
Case 3	Norway, Åre formation (at sea floor)	Power generation only with indirect sCO_2 cycle with ORC

Figure 1 presents the system boundaries assumed for this work.

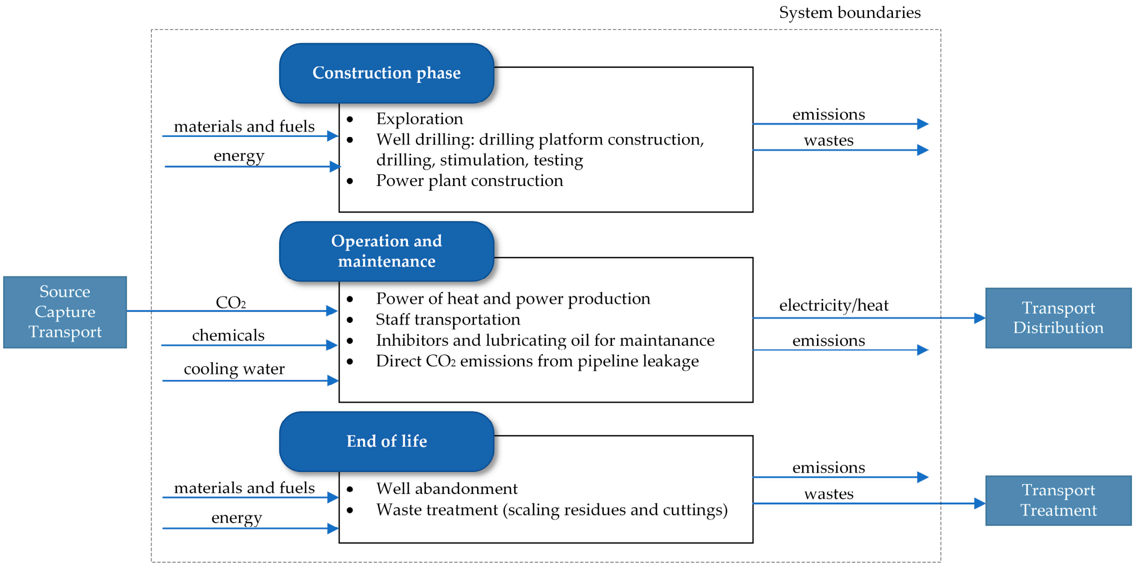

Figure 1. sCO_2-EGS plant life phases with system boundaries.

Project lifetime was set as 33 years. This value refers to the duration of site preparation (2 years), activity of the plant (30 years), and its dismantling (1 year). Surface power equipment lifetime in GEOENVI guidelines is recommended to be set to 30 years and is used to calculate total electricity or electricity and heat production except for specific equipment. The functional unit for this LCA was set as 1 MWh_{el} of net electricity produced from sCO_2-EGS unit.

ISO 14044 states that, if possible, process allocation should be avoided. Nonetheless, because of multi-functionality of Case 2, for combined heat and power unit in the allocation, shame has to be introduced on the basis of output products. For ratio of the net electricity production to the net heat generation higher than 75%, the allocation should refer to energy type of output products. In this case, the substitution approach (ISO, 14044) [20] recommend using the EU natural gas process for the heat process and the country-specific electricity mix for the electricity process is used. When the ratio is lower than 75%, the exergy allocation should be used. For systems with dominant heat generation, the allocation should be based on exergy or Primary Energy Saving (PES) [15]. Within this study, due to dominant heat generation in Case 2, exergy allocation was assessed as a base scenario. The total exergy produced constitutes of work and heat exergy contributors. The work output refers to electricity generated in dedicated sCO_2 turbine, whereas the heat exergy was calculated involving quantity and quality of available heat, based on average mean temperature difference calculation of heat exergy included. Nonetheless, obtained results were also compared in the following parts with other allocation approaches such as physical and economic. Physical allocation relates to division of inputs and outputs based on physical relationships between the products such as mass or energy while economic allocation refers to division on basis of economic revenue of the products.

2.2. Life Cycle Inventory

Primary data on EGS input and output flows were calculated and adapted from the GEOENVI guidelines [21], based on information related to the Gorzów Block [22,23] and the Åre formation [24] as well as mathematical modelling of both reservoirs. Furthermore, further data related to the performance of plants during their operational phase were obtained on the basis of simulation of the designed structural models of geological reservoirs and simulations of the topside systems conducted in the dedicated engineering software IPSEpro 8.0. The key parameters were aggregated in Table 2. Polish cases were simulated with nominal mass flow of 100 kg/s while in the Norwegian case the minimal, optimal value for efficient operation was established to be 200 kg/s, thus, the obtained results are much higher in terms of the power output. Moreover, only in Case 1 was the additional heat supply for district heating system considered, therefore, production in direct sCO_2 cycle is almost 3 times lower than in binary cycle.

Table 2. Key parameters regarding sCO_2-EGS performance evaluation.

Parameter	Case 1, Poland Direct sCO_2 Cycle	Case 2, Poland Indirect sCO_2 Cycle with ORC	Case 3, Norway Indirect sCO_2 Cycle with ORC
Gross power, MW_e	0.8	2.1	13.0
Gross electricity production, MWh_e	175,844.3	451,058.1	2,877,695.7
Electricity own consumption, MWh_e	55,609.1	81,818.0	299,708.7
Net electricity production, MWh_e	120,235.1	369,240.1	2,577,987.0
Heat production, MWh_{th}	2,219,119.1	n/a	n/a
Heat exergy supply, MWh_{ex}	396,692.8	n/a	n/a

Secondary data such as electricity or material production inventory were retrieved from the Ecoinvent database version 3.10. Furthermore, regionalization is a relevant part of the assessment as it influences the adaptation of electricity mixes, as well as other industrial processes associated with fuels, materials, and performance indicators, which are characterized by local conditions [25], and it should also be modelled within the evaluation. Thus, Polish and Norwegian mixes regarding materials and other resources were considered, if possible, when no suitable processes where available; average EU or global data were taken into account.

In [16], it is shown that differences in piping equipment and well materials for water and sCO_2 working fluids will have an insubstantial effect on the final results in terms of plant construction. Since there is a lack of data on detailed material information of the sCO_2 equipment and bearing in mind the fact mentioned above, within this work the authors adopt the GEOENVI general guidelines [21] for a water-based Enhanced Geothermal System. Further assumptions for LCA of sCO_2 are presented in Table 3.

Table 3. Main assumptions regarding sCO_2-EGS LCA study for both locations.

Parameter	Unit	Value
Number of injection wells	-	1
Number of production wells	-	1
Drilling platform size	m^3	20,000
Operating hours	hours	7884 (90% of year)
Average distance for material transportation	km	300
Average distance for staff transportation onshore	km	50
Staff working days	days	250
Fraction of CO_2 released from pipeline leakage	%	0.01

Further assumptions included:

- The distance between shore and installation at Åre formation was set as 230 km, travelled by diesel freight transport.
- Transport of the materials used in the different processes is undertaken by a 16–32 metric ton lorry of category EURO4.
- Sea water cooling in Norway case.
- Well length: 4200 m for Gorzów Block and 4450 m for Åre formation.
- ORC unit modelled based on the Ecoinvent process with correction to the actual power.
- R134A as a working fluid in ORC in Polish case and butane in Norwegian case.
- Working fluid mass flow in reference variants was set as 100 kg/s for Polish cases and 200 kg/s in Norwegian case (lower mass flow for this case would be insufficient for viable unit operation).
- Testing using carbon dioxide was conducted only in Polish cases.

2.2.1. Construction Phase

Geophysical exploration is a step in the construction stage that precedes well drilling. For this purpose, seismic investigation is typically conducted and constitutes an essential step in reservoir forecasting. The amount of diesel used in the assessment was chosen to represent the energy required for the seismic vibrators to operate. Essentially, this phase involves well drilling, so the energy, chemicals, and materials required for drilling, although the process also includes building the platform and retention basins, reservoir hydraulic stimulation, and well testing. The amount of CO_2 compressed to the geological structure was included in the last stage, including the possible leakage from pipes. Furthermore, authors examined the materials used for the construction of the topside plant building and the necessary equipment.

2.2.2. Operation and Maintenance Phase

This phase includes the production of energy, routine maintenance tasks (such as the use of chemicals and inhibitors as well as lubricating oil for installation maintenance), and transportation of the staff to the plant during work hours. Furthermore, it is expected that some CO_2 would leak from the pipelines during this time, and it was also taken into account. The electricity generated by the EGS unit is directly utilized to power pumps and other equipment.

Due to the absence of a possibility of heat utilization, in the Norway case only power generation was established. Furthermore, in the base case, it was assumed that the electricity generated from the EGS would cover the needs of the nearby oil drilling platform or should be connected to the local offshore wind grid to avoid placing the additional cables connecting the shore with the installation.

2.2.3. End-of-Life Phase

In the last stage of installation life, the decommissioning and dismantling of power plant structures as well as machinery equipment recycling were excluded from calculation. Nevertheless, this phase does include the well abandonment, so the amount of energy and cement that would be consumed in this operation. In this phase, the shut-down processes of the wells, as well as the handling and disposal of the wastes produced during construction and operation, were also considered.

2.3. Life Cycle Impact Assessment

The normalization and weighting procedures of the LCA are optional, but they are required to create a single score indicator. Single score metrics facilitate easier communication of complex environmental information and comparison between different products or processes. However, it is crucial to recognize that the choice of impact categories, normalization and weighting methods, and other assumptions can influence the resulting single score and should be carefully considered when interpreting LCA results. Thus, it is advisable to use benchmarking amongst various impact assessment techniques to ensure that the main categories are fairly represented and to increase the single score evaluation's dependability [14]. Within this work, the single score environmental impact of each component of the system was calculated using ReCiPe 2016 (H), which corresponds to the assessment of the impact of the hierarchist viewpoint using a weighting and normalization set: Europe ReCiPe (H) [26].

3. Results

Within this work, Polish and Norwegian cases were assessed using SimaPro software with the Ecoinvent 3.10 database. This allowed us to evaluate the sCO_2-EGS environmental influence for midpoint and endpoint ReCiPe categories.

3.1. Case 1—Combined Heat and Power with Direct sCO_2 Cycle

The calculations for the first case were conducted including exergy allocation for power and heat generation. The presented results are related to 1 MWh of electricity generated considering additional heat production from the installation. The graph in Figure 2 shows the share of the environmental impact of each phase during the life cycle of a given system from Case 1, which was performed for Polish conditions in Gorzów Block. The construction stage is dominant within the obtained impacts, although the operation and maintenance phase is characterized by the substantial impact in global warming categories due to CO_2 pipeline leakages which were taken into account in the evaluation. The end-of-life stage involves low-level radioactive wastes treatment; thus, it influences the ionizing radiation impact category the most.

Considering normalization procedure, the highest impact value of 0.97 was received for the human carcinogenic toxicity category; again, the construction phase accounted for around 96% of it. The lowest impacts were recorded for mineral resource scarcity and marine eutrophication, as well as for stratospheric ozone depletion. Moreover, to evaluate the LCA results for different mass flows of a working fluid in an EGS installation, three variants were compared. The graph in Figure 3 presents the results. Because of the different units and values of each impact category within the ReCiPe Characterization method, a variant with the highest impact achieves 100%, whereas the remaining ones are recalculated to match the percentage scale.

Due to much lower electricity production, with the same amount of energy and materials covering the demand for construction and end-of-life phases, an EGS installation with the lowest mass flow analyzed—50 kg/s—has the highest environmental impact. Carbon dioxide mass flows of 100 kg/s and 150 kg/s demonstrate similar results with a slightly lower impact for the unit with higher mass flow.

For Case 1, product allocation plays a relevant role within the assessment. The reference variant involved exergy allocation, which was named within the GEOENVI guidelines [15]. The authors evaluated the sCO_2-EGS installation with heat and electricity production with physical and economic allocation to show the difference between adopted approaches. For these calculations, 160 EUR/MWh was assumed as an electricity price and 28 EUR/GJ as a heat price. The summary of the particular share of the products is presented in Table 4.

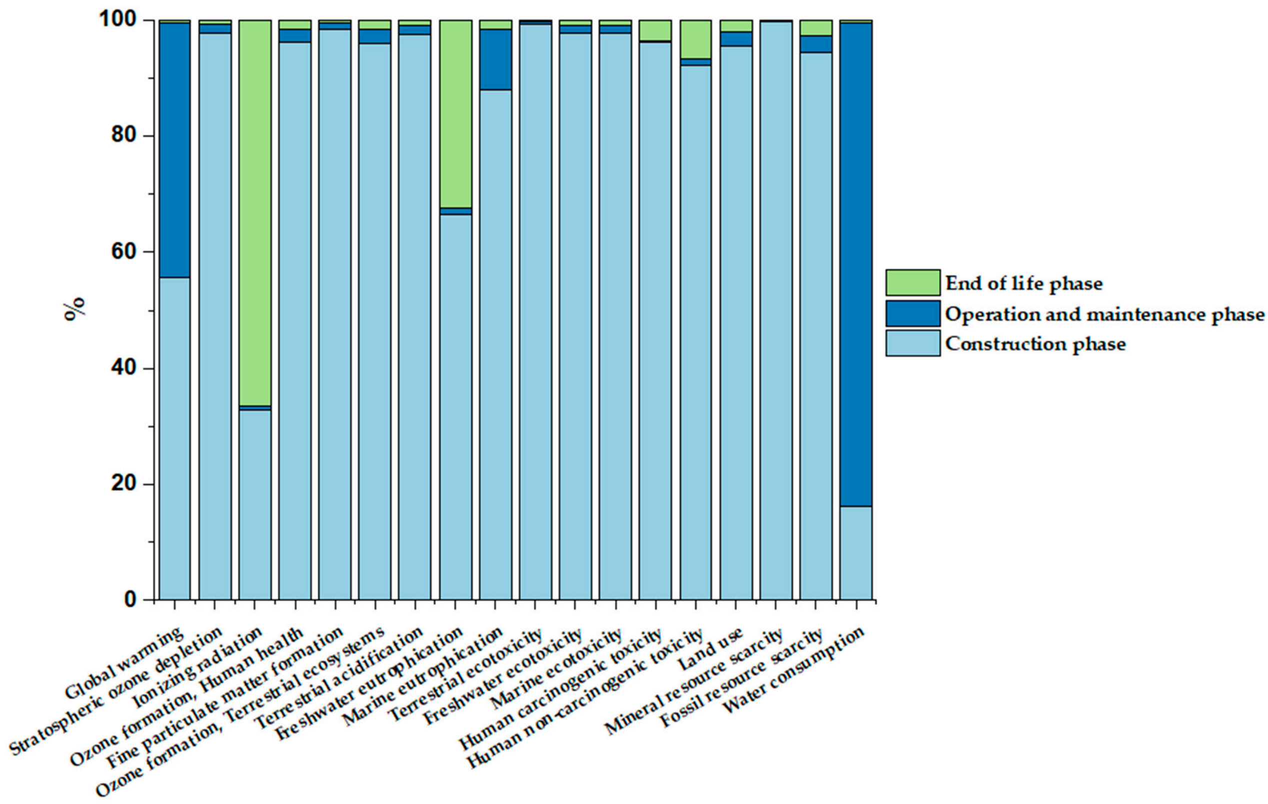

Figure 2. LCA results for Case 1 with exergy allocation for electricity production, ReCiPe 2016, midpoint (H), and characterization.

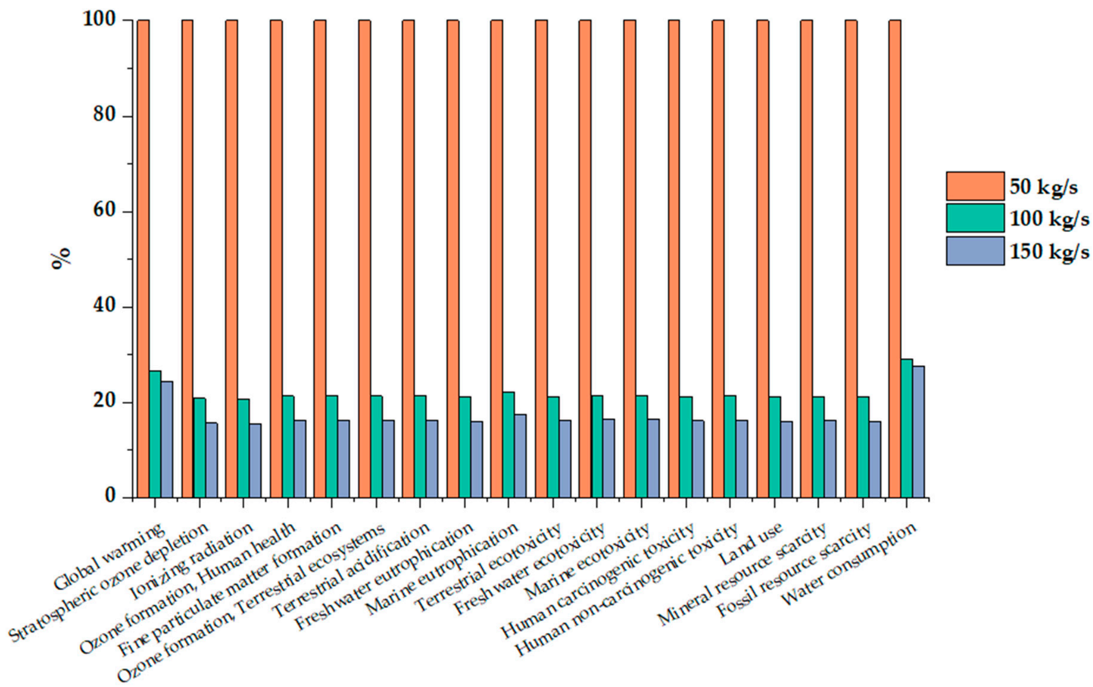

Figure 3. LCA results for different mass flows for Case 1 with exergy allocation for electricity production, ReCiPe 2016, midpoint (H), and characterization.

The allocation within this work was assigned to electricity production. The obtained results (Figure 4) indicate significant differences between the values of environmental impacts. The recommended exergy scheme allocates the exergy of the primary energy source to the outputs (electricity and heat) based on their exergy content. Since exergy allocation reflects the quality of outputs, the obtained values for this method indicate the highest impacts compared to the remaining schemes. This points out the inherent complexities of analyzed an energy system and more comprehensive approach. In the base case with exergy allocation, the sCO_2-EGS global warming potential totaled 38.7 $kgCO_2eq$, whereas this value amounts to 13.2 and 8.6 $kgCO_2eq$ for physical and economic allocation, respectively. This shows that the obtained values for the reference scenario were 66% and 78% higher.

Table 4. Summary for different allocation schemes.

Allocation Scheme	Heat Product	Electricity Product
Exergy	76.8%	23.2%
Physical energy	94.9%	5.1%
Economic	92.1%	7.9%

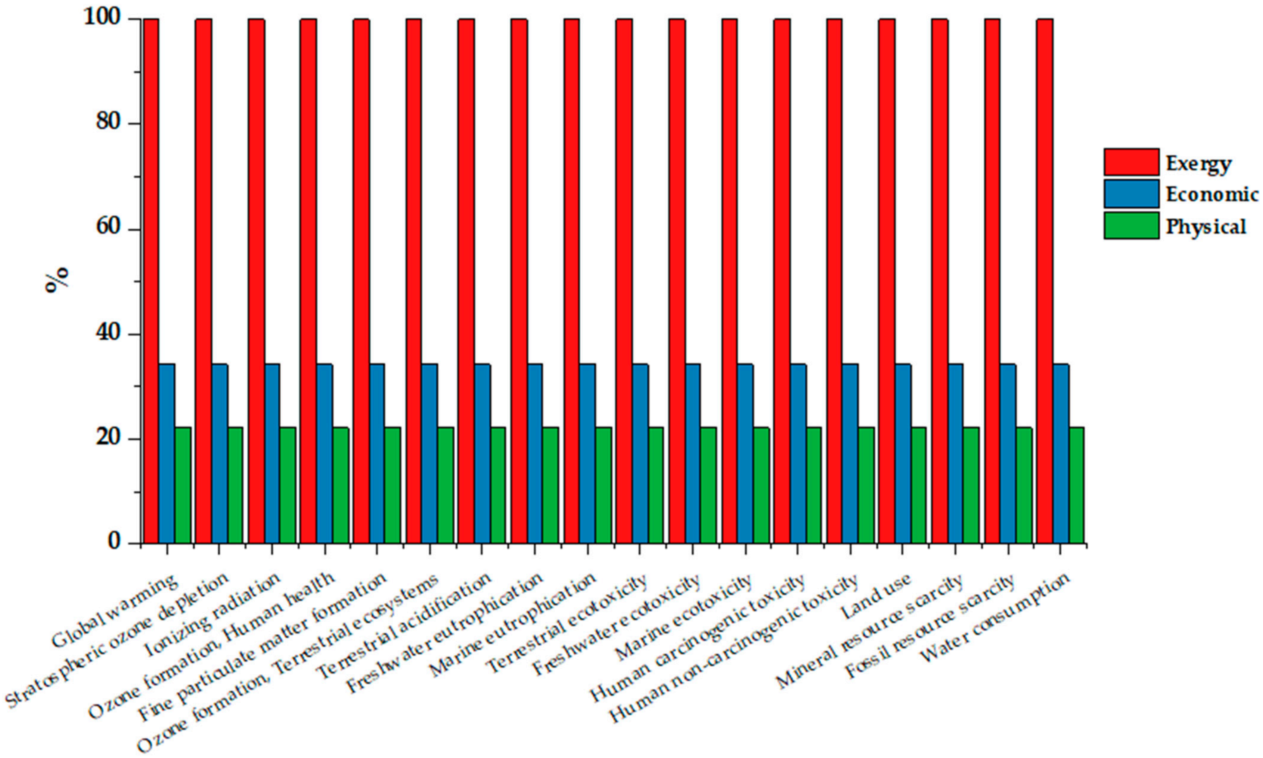

Figure 4. LCA results for different allocation schemes for Case 1, ReCiPe 2016, midpoint (H), and characterization.

3.2. Case 2—Power Generation Only with Indirect sCO_2 Cycle with ORC

The second Polish case included only power generation through an indirect sCO_2 cycle with the Organic Rankine Cycle with CO_2 mass flow of 100 kg/s. This case also indicates that the construction phase has the highest impact (Figure 5). Construction activities for assessed sCO_2-EGS involve energy-intensive processes such as drilling, transportation of equipment, and materials, as well as site preparation. These processes contribute to greenhouse gas emissions and other environmental impacts, particularly due to fossil fuels being used for transportation and for powering the machinery. The operation and maintenance stage, similarly to Case 1, is dominant in the global warming category and in water consumption, which stems from the additional water required for the cooling tower of the EGS unit.

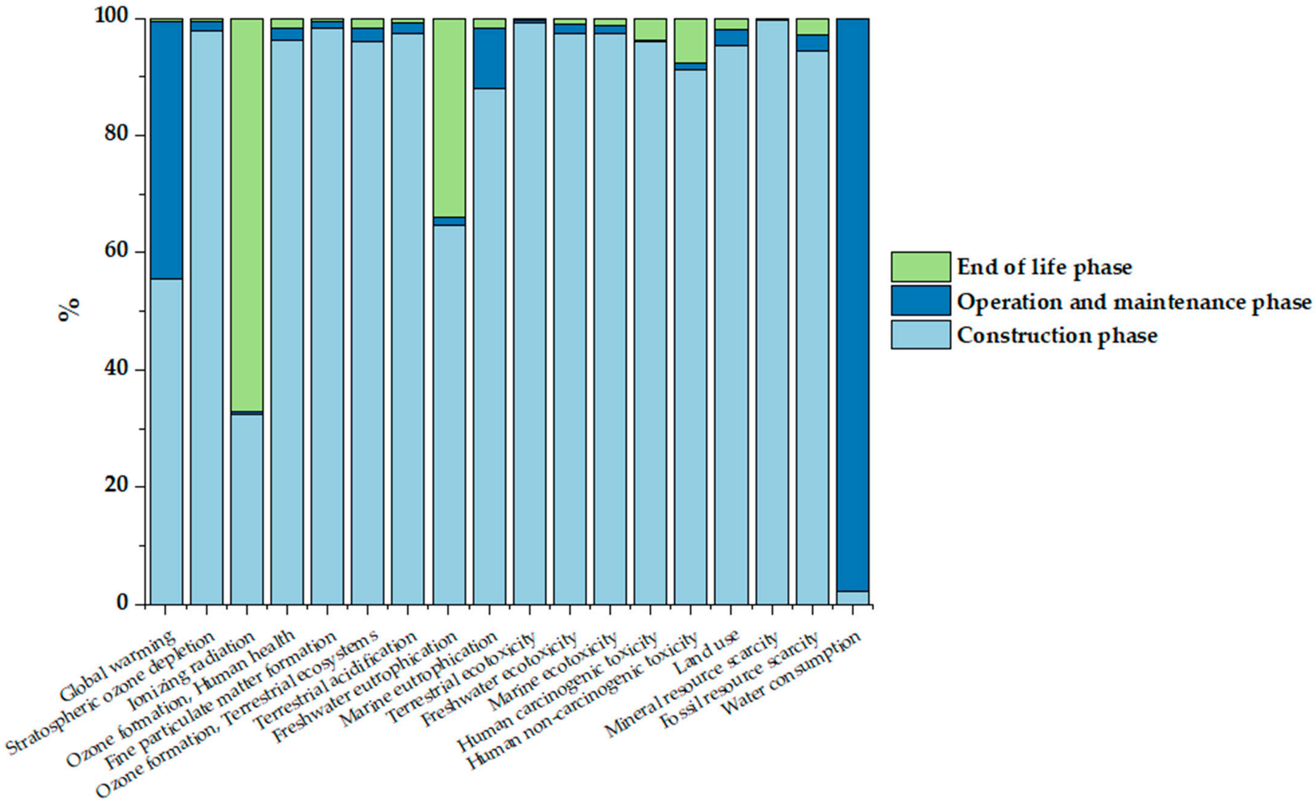

Figure 5. LCA results for Case 2, ReCiPe 2016, midpoint (H), and characterization.

To examine which process within the construction phase has the highest impact, this stage was evaluated separately (Figure 6). This assessment indicated that well drilling, which includes energy and materials for well preparation, was dominant.

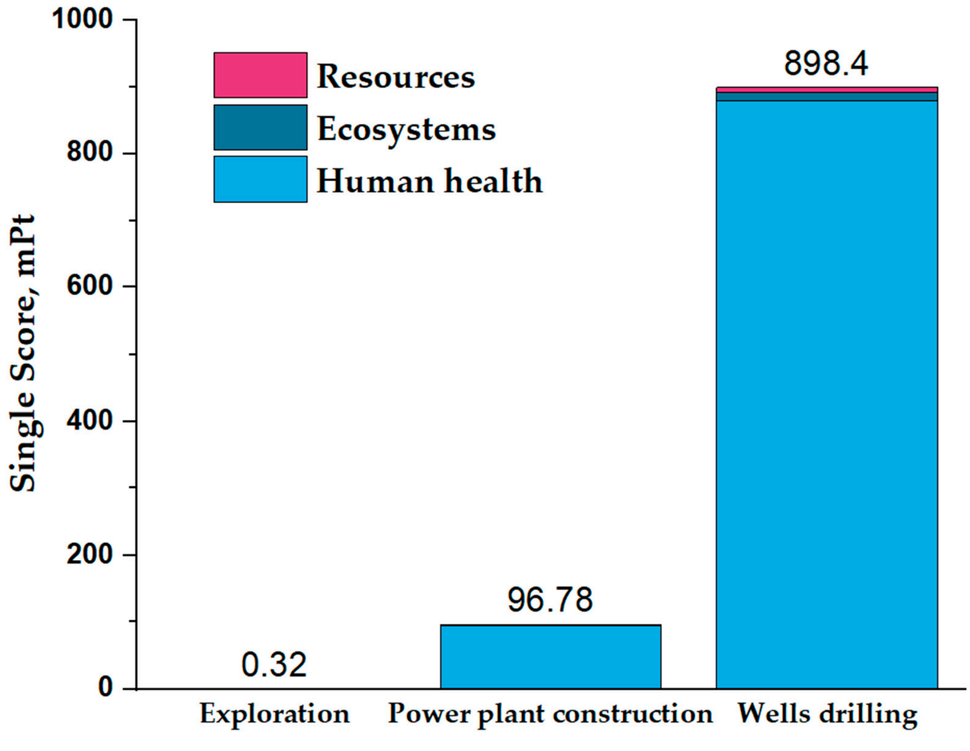

Figure 6. LCA results for Case 2 construction phase, ReCiPe 2016, endpoint (H), and single score.

3.3. Case 3—Power Generation Only with Indirect sCO$_2$ Cycle with ORC

The third case was conducted for the Norwegian site located on the sea floor, which generates only electricity—similar to the second case in Poland. In this configuration, nominal CO_2 mass flow totaled 200 kg/s, so electricity production was the highest among all cases, which has a significant impact on the results. The values obtained point to a similar trend to Cases 1 and 2, with the highest impact being within the construction phase (Figure 7). As a result of sea water cooling in this case, the operation and maintenance stage has an insubstantial impact on the category of water consumption. Moreover, higher working fluid mass flow also influences higher CO_2 pipeline losses through leakage, thus, the operation and maintenance phase accounts for around 56% of the global warming category.

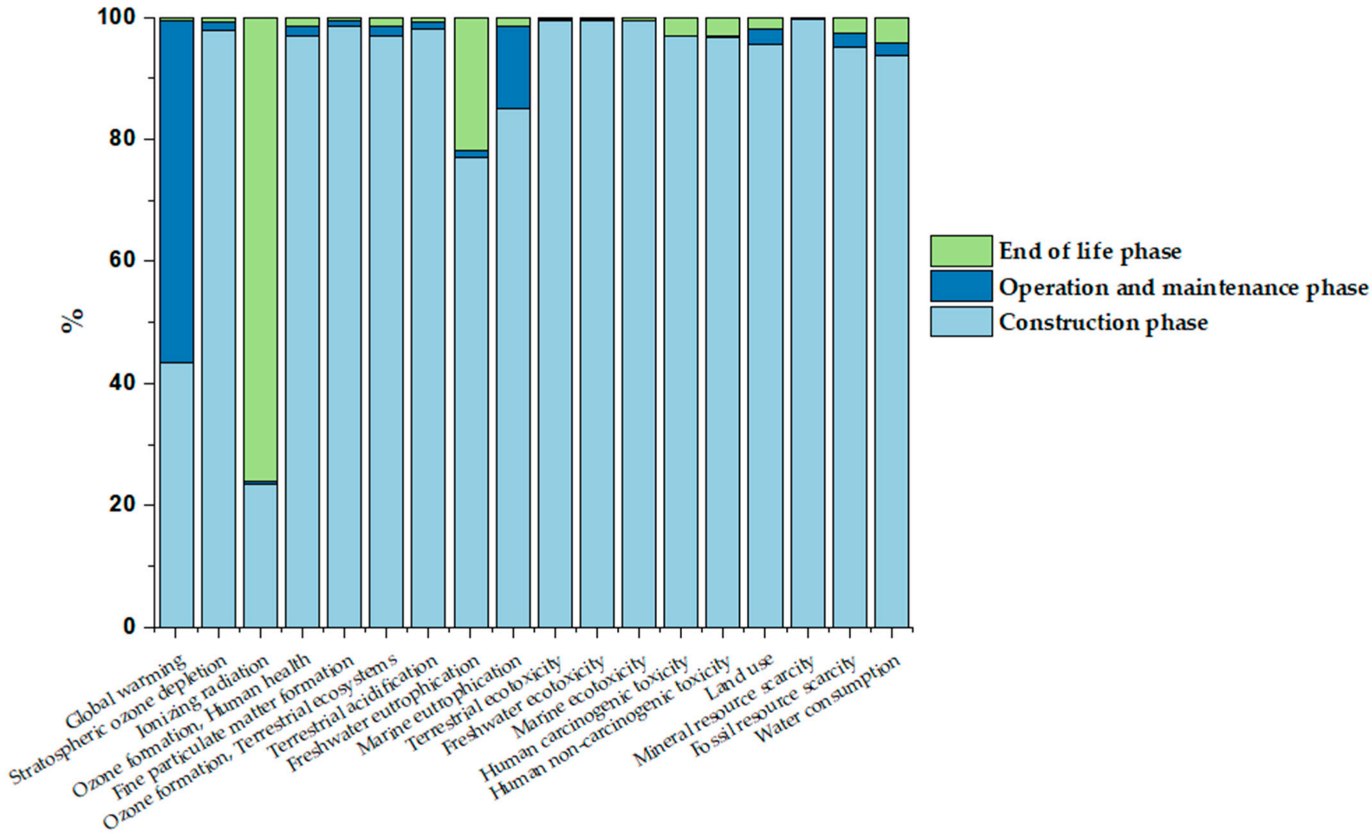

Figure 7. LCA results for case 3, ReCiPe 2016, midpoint (H), characterization.

In addition, for the Norwegian case assessment, two variants were taken into consideration. Variant A included local (on platform nearby) electricity consumption and variant B included electricity transmission to land. What can be noticed in Figure 8 is that Variant B has a significantly higher impact than for electricity utilized locally due to the additional cables and other appliances needed. Therefore, from the environmental point of view, it would be beneficial to destine produced electricity for oil platform needs or connect the EGS unit with the offshore wind farm grid. The data related to the cable were estimated based on export cables connecting offshore and onshore substations for power transmission from the wind farm [27].

The obtained results show that additional cable installations influence the overall LCA, with values almost 30 times higher than in the base case. Moreover, freshwater ecotoxicity, marine ecotoxicity, and human carcinogenic toxicity were dominant impact categories influencing the human health damage category, which has the highest share among other categories. The weighted single score results are presented in Table 5.

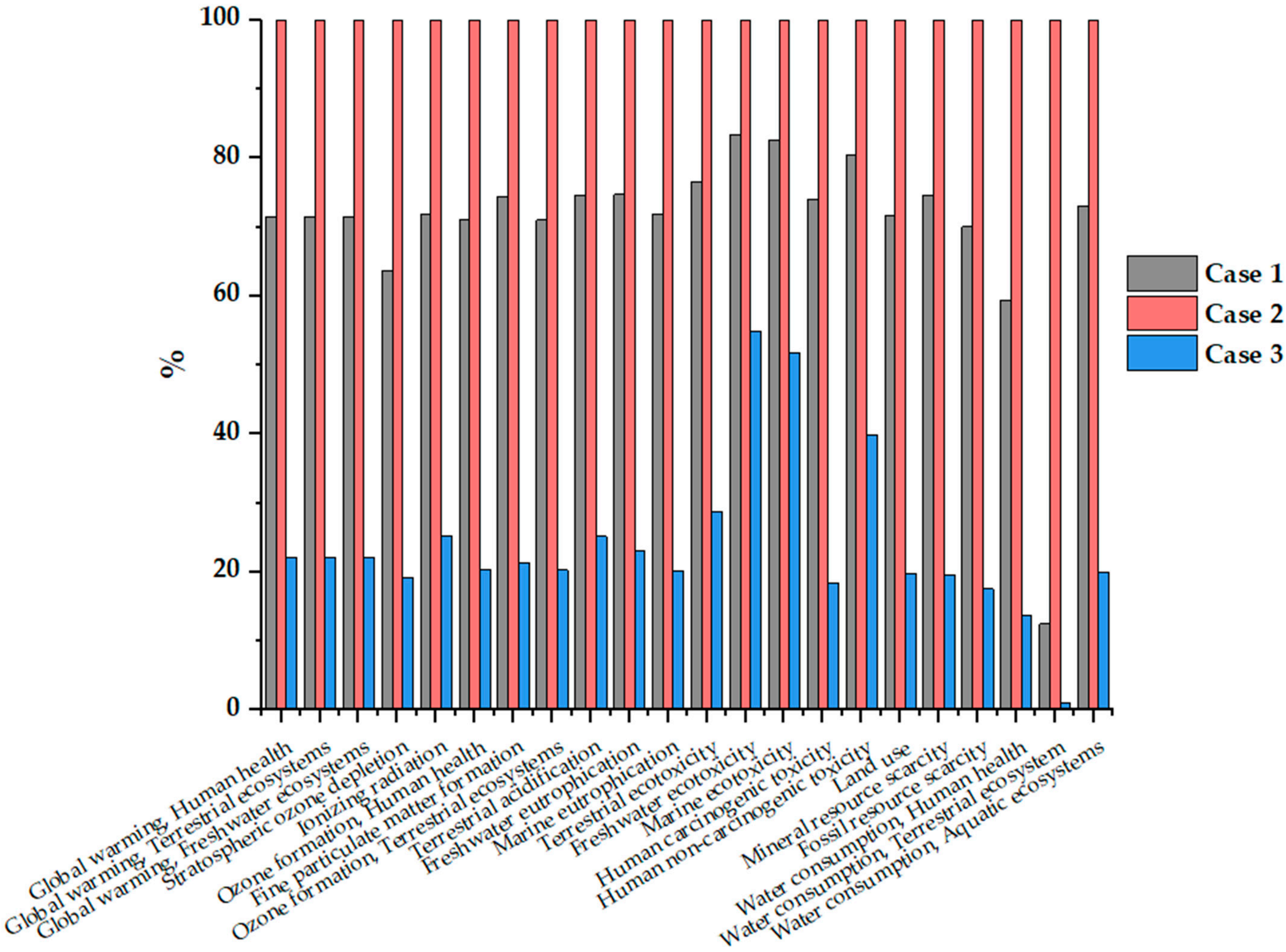

Figure 8. LCA results for comparison between cases, ReCiPe 2016, endpoint (H), and characterization.

Table 5. Results obtained for comparison between variants A and B of Case 3.

Damage Category	Variant A (Local Electricity Consumption)	Variant B (Electricity Transmission to Land)
Total, Pt	0.678	19.876
Human health, Pt	0.660	19.511
Ecosystems, Pt	0.013	0.320
Resources, Pt	0.004	0.045

3.4. Comparison between Polish and Norwegian Cases

Table 6 presents the results for the three cases analyzed—two Polish and one Norwegian. Case 3 has the lowest environmental impact among all midpoint categories in the ReCiPe method. This is mainly due to a much higher net electricity output, which compensates additional impacts related to sea transportation. For the Polish cases, despite higher power output in Case 2, the direct sCO_2 cycle has a lower impact because of additional heat production.

The graph in Figure 8 presents the comparison between analyzed cases in terms of ReCiPe endpoint categories.

Table 6. Results obtained for comparison between Cases 1, 2, and 3.

Impact Category	Unit	Case 1	Case 2	Case 3
		Poland, Direct sCO_2 Cycle	Poland, Indirect sCO_2 Cycle	Norway, Indirect sCO_2 Cycle
Global warming	kg CO_2 eq	38.682	54.148	11.929
Stratospheric ozone depletion	kg CFC11 eq	0.000	0.000	0.000
Ionizing radiation	kBq Co-60 eq	2.871	3.996	1.009
Ozone formation, Human health	kg NO_x eq	0.051	0.072	0.015
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.052	0.069	0.015
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.054	0.076	0.015
Terrestrial acidification	kg SO_2 eq	0.084	0.112	0.028
Freshwater eutrophication	kg P eq	0.012	0.016	0.004
Marine eutrophication	kg N eq	0.001	0.001	0.000
Terrestrial ecotoxicity	kg 1,4-DCB	415.091	542.357	156.104
Freshwater ecotoxicity	kg 1,4-DCB	2.314	2.773	1.523
Marine ecotoxicity	kg 1,4-DCB	3.137	3.794	1.968
Human carcinogenic toxicity	kg 1,4-DCB	17.772	24.013	4.419
Human non-carcinogenic toxicity	kg 1,4-DCB	39.411	48.943	19.529
Land use	m^2a crop eq	0.843	1.177	0.234
Mineral resource scarcity	kg Cu eq	1.028	1.377	0.270
Fossil resource scarcity	kg oil eq	6.173	8.681	1.573
Water consumption	m^3	1.702	17.114	0.070

4. Discussion

sCO_2-Enhanced Geothermal Systems offer a promising solution for sustainable energy production and carbon reduction. To widen their application and maximize their potential in mitigating carbon emissions, the research and development of the technology should be broadened in order to increase the technology readiness level (TRL), which currently may be stated as 4–5 [13], corresponding to an early stage. Moreover, an increase in deployment may also contribute to a fall in investment costs. This could also be achieved by introducing advancements in drilling techniques, reservoir characterization, and stimulation methods, as well as heat extraction technologies. In addition, comprehensive geoscientific studies may be conducted to identify suitable regions for EGS deployment. This involves assessing subsurface geology, temperature gradients, and hydraulic properties of regions with high geothermal potential.

While the main assumption and methodology used within the assessment may be used for further expanding the study to different countries, the results will be not applicable for other regions. The reason for that is the fact that processes from the Ecoinvent database used for this study represent average production conditions in a given geographic location, not for a particular company or for site-specific conditions. The work was developed using a location-based method, which means that the values used are based on greenhouse gas emissions resulting from energy production in the area where it is consumed—based on the average greenhouse gas emissions per 1 kWh in a given country (Poland or Norway).

Comparing the results obtained with other renewable sources and near-zero carbon solutions shows that, based on data from the National Renewable Energy Laboratory [28], total life cycle impacts of EGS are similar or even lower than those corresponding to photovoltaics (43 $kgCO_2eq/MWh_{el}$) or power generation from biomass (52 $kgCO_2eq/MWh_{el}$). Solar power was reported to have a higher environmental influence of 20–28 $kgCO_2eq/MWh_{el}$, primarily in the one-time upstream category, which relates to material acquisition and plant construction. For the remaining RES, hydropower and wind have the lowest GHG emissions. The life cycle impact of nuclear energy, considering a light-water reactor, was reported to be 13 $kgCO_2eq/MWh_{el}$, while other, nonrenewable sources such as natural gas, oil, or coal have GHG emissions between 486 and 1001 $kgCO_2eq/MWh_{el}$, which additionally highlights the importance of RES deployment in order to achieve climate goals.

5. Conclusions

The main goal of the work was to examine the Life Cycle Assessment of Enhanced Geothermal Systems which deploy supercritical carbon dioxide as a working fluid. So far, most studies in the field of EGSs have focused on their energetic and techno-economic performance. Therefore, based on LCA methodology, the authors proposed the sCO_2-EGS analysis for two localizations (Poland, Gorzów Block and Norway, Åre formation) to evaluate their environmental impacts based on regional conditions. The Åre case is found to have a much lower environmental footprint than the Gorzów case for power generation only (indirect sCO_2 cycle with ORC). It comes from higher energy utilization through higher values of power outputs.

The results obtained for the assessments conducted demonstrate similar values to those found in the literature regarding EGS units. Lacirignola et al. [18] obtained 36.7 $kgCO_2eq/MWh_{el}$ for a water-based CO_2 binary installation in Soultz, France. Frick et al. [17] analyzed different hypothetical water-based EGS units located in Germany and the results obtained in the study are in the range of 42–62 $kgCO_2eq/MWh_{el}$ and 4.5–6.48 $kgCO_2eq/MWh_{th}$ for electricity and heat production, respectively. In [29], the authors calculated the climate-change impacts of EGS in the Upper Rhine Valley and obtained results between 24.7 and 45.9 $kgCO_2eq/MWh_{el}$ in terms of electricity production and between 3.39 and 8 $kgCO_2eq/MWh_{th}$ for heat generation. In terms of GWP, the results from the calculation conducted for Cases 1 and 2 fit within the range of referenced values. In Case 3, they indicated lower global warming potential due to much higher electricity production, nonetheless, any of the mentioned studies have evaluated a sCO_2-based system.

The work also involved a comparison of the results evaluated for Case 1 for different allocation schemes. This highlighted the relevance of a proper allocation approach for the combined heat and power unit. In this study, exergy allocation was used as a recommended method. Exergy analysis considers not only the quantity of energy, but also its quality or usefulness for performing work. By accounting for the exergy content of different energy streams, exergy allocation captures losses and inefficiencies more accurately throughout the entire energy conversion process. The approach of process substitution could also be applied, although only Case 1 includes the configuration for both power and heat generation. Furthermore, partial CO_2 sequestration that occurs in such EGS installations should also be considered as a product to replace conventional CO_2 storage in saline formations. Thus, this constitutes an aspect to be developed in future work.

In all cases, the construction phase is dominant where the environmental impact is concerned. This is especially the case for the well drilling, which corresponds to more than 70% of environmental impacts in all cases. The construction stage of the EGS involves significant material extraction and processing activities, including drilling and well construction. These activities often require large amounts of materials, such as steel, cement, and drilling fluids, which have associated environmental impacts, including resource depletion, energy consumption, and emissions. The end-of-life stage has the lowest impact across the unit lifetime, although for future work, the impact of long-term monitoring should also be considered.

Based on the LCA study performed, the authors underlined the comprehensiveness of LCA, which is a tool for extensive environmental analysis, and pointed out the potential environmental impacts of sCO_2-EGS units, which is essential not only for reducing GHG emissions but also for addressing other, various environmental aspects.

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Nomenclature

CCUS	carbon capture, utilization and storage
CO_2	carbon dioxide
DHS	district heating system
EGS	Enhanced Geothermal System
GWP	global warming potential
HDR	hot, dry rock
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
ORC	Organic Rankine Cycle
RES	renewable energy sources
sCO_2	supercritical carbon dioxide
TRL	technology readiness level

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