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The Environmental Footprint Results of Geothermal Power for Adopting Superhot Geo-resources in Icelandic and Italian Perspectives

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ABSTRACT

Current well construction technologies have significant potential for improvement in very high-temperature geothermal conditions. The COMPASS initiative has the ambition to address the current challenges in geothermal well design for utilising superhot geo-resources, ensuring sustainable exploitation of geothermal energy, and unlocking the huge potential from near-magmatic resources, thereby contributing to reducing the costs and lowering the environmental footprint of geothermal projects. In this study, the environmental impacts of the proposed COMPASS geothermal power plants from Icelandic and Italian perspectives have been evaluated, alongside the environmental impacts of the Icelandic and Italian representative geothermal power plants, using a cradle-to-grave approach. The life cycle assessment (LCA) analysis was conducted with the SimaPro 9.5.0.0 LCA tool, following ISO standards 14040 and 14044. The functional unit of this LCA study is 1 MWh of electrical energy production from these plants. It has been reported that carbon footprint savings of about 31.9 % and 80.6 % could be achieved by the proposed COMPASS-enabled plants in Icelandic and Italian perspectives, as compared with the Icelandic and Italian representative plants, respectively. The results of these studies demonstrate the potential of COMPASS-enabled plants for improving environmental performance and thereby enhancing geothermal power growth in Europe and beyond.

1 INTRODUCTION

Geothermal energy has emerged as a proven, reliable, and environmentally friendly energy source that contributes significantly to a sustainable energy future. Its key advantage lies in its low carbon footprint compared to conventional fossil fuel-based power generation. However, despite being a renewable source, the environmental performance of geothermal power systems is not uniform. Life cycle environmental impacts vary significantly, with reported carbon intensities ranging from as low as 5 kg CO_2-eq / MWh to as high as 800 kg CO_2-eq / MWh (Paulillo et al., 2019). These differences are largely influenced by the specific power generation technologies employed (e.g., flash or binary systems), site-specific geological conditions (such as reservoir depth, geofluid composition), operational practices (e.g., reinjection strategies and venting of non-condensable gases), and the methodological approaches adopted during environmental assessments.

Technological innovation remains essential for overcoming existing challenges and enhancing the efficiency, reliability, and environmental performance of geothermal energy systems—particularly those targeting very hot or superhot geothermal resources. Such high-enthalpy resources, located at greater depths and subject to extreme pressure and temperature conditions, offer significant potential for increasing geothermal energy output. However, they also pose technical and environmental challenges, especially related to the integrity and durability of well components under aggressive geofluid conditions. In this context, the COMPASS project, funded by the European Union's Horizon Europe research and innovation programme, aims to improve the environmental sustainability of deep geothermal systems by developing and implementing advanced well infrastructure. This includes corrosion-resistant casing materials coated with anti-scaling and anticorrosion layers applied with extreme high-speed laser application, as well as the use of innovative foam cement solutions to enhance long-term well integrity. One of the objectives of the COMPASS project is to evaluate the environmental impacts of these innovative geothermal systems that can demonstrate meaningful environmental advantages when applied to superhot geothermal energy extraction.

This study presents a cradle-to-grave LCA of COMPASS-enabled geothermal power plants in Icelandic and Italian perspectives, comparing their environmental impacts to those of the representative geothermal power plants in Iceland and in Italy. The assessment considers all life cycle phases—construction, operation and maintenance (O&M), and end-of-life (EoL)—using plant-specific inventory data. These LCA evaluations have been conducted using the COMPASS Environmental Impact Estimator for surface plants (Compass | Home),

which interfaces with the LCA software tool SimaPro 9.5.0.0 through an Application Programming Interface (API). Environmental impact categories such as climate change, human health, ecosystem quality, and resources are quantified using the IMPACT 2002+ v2.15 Life Cycle Impact Assessment (LCIA) methodology. The functional unit of the cradle-to-grave LCA studies is 1 MWh of electrical energy production from the plant. The outcomes of this study demonstrated broader environmental benefits for the geothermal energy sector in both Icelandic and Italian contexts, highlighting the potential benefits of COMPASS-enabled solutions. Hence, the implementation of COMPASS-enabled geothermal power plants utilising superhot geo-resources represents a significant advancement in making geothermal energy toward a low-carbon, resource-efficient energy future.

2 METHODS

The cradle-to-grave life cycle assessment (LCA) modelling of a geothermal power plant using very hot and superhot geo-resources comprises three phases:

- Construction phase
- Operation & Maintenance (O&M) phase
- End of Life (EoL) phase

Basic data, relevant parameters, and components of the plants are collated from the representative flash-type Icelandic (Karlsdóttir et al., 2015) and Italian (Tosti et al., 2020) plants, along with the proposed COMPASS-enabled plant, utilising very hot and superhot geo-resources (Table 2.1).

Table 2.1 Basic data, relevant parameters and components involved in the representative Icelandic, Italian and the proposed COMPASS plants

Description	Unit	Icelandic Representative Plant	Italian Representative Plant	COMPASS-enabled Plant
Resource type	-		Hydrothermal	
Power technology	-		Flash	
Installed capacity	MW	303.3	60	350
Capacity factor	%	87	90	90
Plant downtime	%		10	
Predicted lifetime of the plant	y	30	40	40
Average geofluid flow rate	kg s^{-1} per well	53.4	40.1	100
Geofluid enthalpy	kJ kg^{-1}	1597	1800	2800
Average temperature at reservoir	^{0}C	268	325	375
Number of production wells	-	47	8	10
Number of reinjection wells	-	17	6	8
Average depth of the well	m	2150	2270	2800
Total estimated drilled length	m	137,600	31,780	50,400
Total collection pipeline length	M	36,000	10,400	9,000
Average injection well depth	m	1500	1500	2000
Total electrical energy production during the lifetime of the plant	MWh	6.24E+07	1.70E+07	9.93E+07

The reference flow data of various materials, energy and processes involved in construction, O&M and EoL phases of the plants have also been gathered from these representative plants. The resource consumption data in these three phases of the COMPASS-enabled plants in Icelandic and Italian perspectives have been calculated and estimated using the reference flow data of various processes and materials from the representative Icelandic and Italian plants, with the basic data of the COMPASS-enabled geothermal plant. The functional unit of the cradle-to-grave LCA studies is 1 MWh of electrical energy production from these plants. For obtaining functional flows of all the resource consumption data, the total mass and energy flows in the construction, O&M and EoL phases of the plants are divided by the total electrical energy production of the respective plant during the lifetime of the plant. Using these functional flow data in three phases, LCA tool

SimaPro 9.5.0.0 calculates the environmental footprints of the COMPASS-enabled plants in Icelandic and Italian perspectives, along with Icelandic and Italian representative geothermal power plants, in terms of a functional unit of 1 MWh of electrical energy production, considering the life cycle impact assessment methodology IMPACT 2002+ version 2.15.

3 RESULTS AND DISCUSSIONS

The environmental impact results of the COMPASS-enabled plants in Icelandic and Italian perspectives (COMPASS_IS and COMPASS_IT plants) have been compared with the representative Icelandic and Italian plants (IS_REP and IT_REP plants). The environmental benefits on geothermal power for adopting the COMPASS-enabled plants in Icelandic and Italian perspectives have also been discussed.

3.1 Environmental Impacts of Icelandic Plants

The LCIA results of the COMPASS_IS and the IS_REP plants have been evaluated in terms of 1 MWh of electrical energy production. The quantification of environmental footprints across 4 endpoint damage categories for 1 MWh electrical energy production from the COMPASS_IS and IS_REP plants is listed in Table 2.1 for comparison.

Table 3.1 Quantification of 4 endpoint damage categories for 1 MWh electrical energy production from the COMPASS_IS and the IS_REP plants.

Endpoint Damage Categories	Unit	COMPASS_IS plant	IS_REP plant	Net savings for adopting the COMPASS_IS plant
Human health	DALY / MWh	2.97E-06	6.11E-06	3.14E-06
Ecosystem quality	PDF*m^2*yr / MWh	1.75E-01	4.72E-01	2.97E-01
Climate change (carbon footprint)	kg CO_2-eq / MWh	8.85E+00	1.30E+01	4.15E+00
Resources	MJ primary / MWh	1.58E+01	4.65E+01	3.07E+01

It is seen from Table 3.1 that the net savings of carbon footprint, human health, ecosystem quality and resources for adopting the COMPASS_IS plant are about 4.15 kg CO_2-eq, 3.14 x 10^{-6} DALY, 2.97 x 10^{-1} PDF*m^2*yr and 30.7 MJ primary per MWh of electrical energy production, respectively. Figure 3.1 shows the relative contributions of the 4 endpoint damage categories of two Icelandic plants (COMPASS_IS and the IS_REP plants).

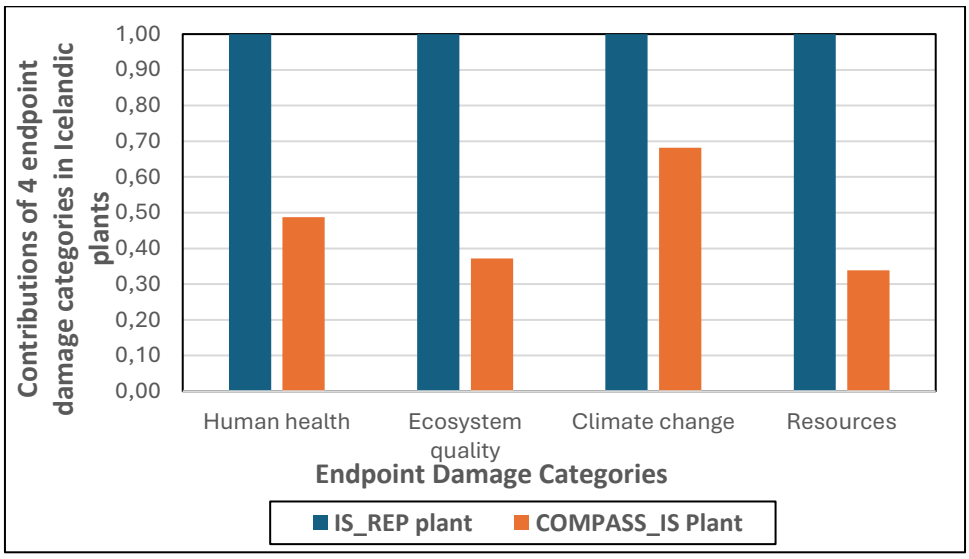


Figure 3.1 - Relative contributions of 4 endpoint damage categories in Icelandic representative and COMPASS-enbled plants.

The quantified values of four endpoint damage categories for 1 MWh of electrical energy production from the COMPASS_IS and the IS_REP plants (as listed in Table 3.1) have been converted to a single score value in units of points (Pt) and are presented in Table 3.2.

Table 3.2 – Single score values of four environmental footprints and the overall environmental footprint for 1 MWh electrical energy production from the COMPASS_IS and the IS_REP plants.

Environmental footprints	Unit	IS_REP plant	COMPASS_IS plant	Environmental footprint savings (%)
Total	mPt / MWh	2.51	1.43	43.1
Human health	mPt / MWh	0.86	0.42	51.3
Ecosystem quality	mPt / MWh	0.03	0.01	62.9
Climate change	mPt/ MWh	1.31	0.89	31.8
Resources	mPt / MWh	0.31	0.10	66.1

It is indicated that the percentage savings of the overall environmental footprint for adopting the COMPASS_IS plant is about 43.1% as compared with the IS_REP plant.

3.2 Environmental Impacts of Italian Plants

The LCIA results of the COMPASS_IT plant and the IT_REP plant have been evaluated in terms of 1 MWh of electrical energy production. Table 3.3 presents the quantification of environmental footprints over 4 endpoint damage categories for 1 MWh of electrical energy production from the COMPASS_IT and IT_REP plants for comparison.

Table 3.3 - Quantification of 4 endpoint damage categories for 1 MWh electrical energy production from the COMPASS_IT and IT_REP plants.

Endpoint Damage categories	Unit	COMPASS_IT plant	IT_REP plant	Net savings for adopting the COMPASS_IT plant
Human health	DALY / MWh	7.77E-06	1.60E-05	8.23E-06
Ecosystem quality	PDF*m^2*yr / MWh	1.30E+00	2.76E+00	1.46E+00
Climate change	kg CO_2 -eq / MWh	9.87E+00	5.08E+01	4.09E+01
Resources	MJ primary / MWh	2.73E+01	5.43E+01	2.70E+01

For adopting the COMPASS_IT plant, the net savings of carbon footprint (climate change), human health, ecosystem quality and resources are about 40.9 kg CO_2-eq, 8.23 x 10^{-6} DALY, 1.46 PDF*m^2*yr and 27.0 MJ primary per MWh of electrical energy production, respectively. Figure 3.2 shows the relative contributions of 4 endpoint damage categories of the COMPASS_IT and IT_REP plants.

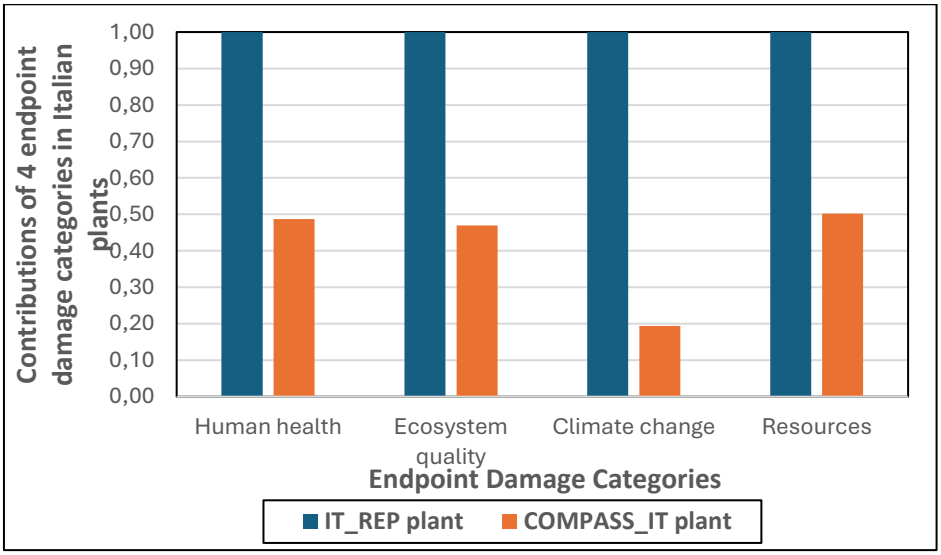


Figure 3.2 – Relative contributions of 4 endpoint damage categories in Italian representative and COMPASS-enabled plants.

The quantified values of four endpoint damage categories for 1 MWh electrical energy production from the COMPASS_IT and IT_REP plants (in Table 3.3) have been converted to a single score value in units of points (Pt) and listed in Table 3.4.

Table 3.4 – Single score values of four environmental footprints and overall environmental footprint for 1 MWh electrical energy production from the COMPASS_IT and IT_REP plants.

Environmental footprints	Unit	IT_REP plant	COMPASS_IT plant	Environmental footprints savings (%)
Total	mPt / MWh	7.94	2.37	70.2
Human health	mPt / MWh	2.25	1.10	51.1
Ecosystem quality	mPt / MWh	0.20	0.09	55.0
Climate change	mPt/ MWh	5.13	1.00	80.5
Resources	mPt / MWh	0.36	0.18	50.0

It is demonstrated that the percentage savings of the overall environmental footprint for adopting the COMPASS_IT plant is about 70.2 % as compared with the IT_REP plant.

4 CONCLUSIONS

The implementation of COMPASS-enabled geothermal systems in both Icelandic and Italian regions utilising superhot geo-resources, leads to substantial environmental benefits. Specifically:

Carbon footprint reductions of approximately 31.8% (Iceland) and 80.5% (Italy)

Overall environmental footprint reductions of 43.1% (Iceland) and 70.2% (Italy)

On a regional scale, these reductions translate into significant avoided emissions:

In the Tuscany region, Italy, with an installed geothermal plant capacity of 916 MW generating about 6 million MWh annually, adopting the COMPASS_IT plant could prevent approximately 245,000 tonnes of CO_2-eq emissions annually.

In the Hengill region, Iceland, with an installed geothermal plant capacity of 423 MW generating about 3.5 million MWh annually, adopting the COMPASS_IS plant could avoid 14,500 tonnes of CO_2-eq emissions annually.

These results confirm the environmental benefits of the COMPASS-enabled geothermal systems, particularly in high-enthalpy regions such as Tuscany in Italy, where emission reductions are most pronounced. The COMPASS-enabled geothermal power plants have demonstrated considerable potential to reduce both overall carbon and environmental footprints, thereby enhancing the sustainability of geothermal energy production. The adoption of these COMPASS-enabled geothermal systems marks a promising advancement toward more climate-resilient, resource-efficient, and environmentally responsible renewable energy infrastructure.

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