SOFTWARE TOOL ARTICLE

REVISED Geothermal Energy Impact Estimator: A software application for estimating the life-cycle environmental impacts of geothermal energy [version 3; peer review: 3 approved]

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Abstract
Geothermal energy is a renewable source of base-load power that is expected to play an important role in the transition to a low-carbon economy. In this article, we introduce a novel software application – named Geothermal Energy Impact Estimator – which computes the environmental impacts, including carbon emissions, of existing or future geothermal plants, using the Life Cycle Assessment (LCA) methodology. The software application is user-friendly and was designed to be used by geothermal companies and policy makers. We provide two specific use cases of the software application that represent existing plants in Iceland and in the UK.

Keywords
Renewable energy, geothermal wells, Enhanced Geothermal Systems, carbon footprint, simplified models, allocation strategy, policy-making, decision-making.

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REVISED **Amendments from Version 2**

In this revised version we have slightly amended four sentences, following comments from the Reviewer

- Two sentences are in the Introduction section, and concern i) the advantages of EGS and ii) the description of a geothermal power project in the UK.

- In the Methods - Operation sub-Section, we have clarified that the user can modify the success rate when the relevant toggle box is enabled.

- In the Use Cases Section, we have corrected that the UDDGP plant is expected to be operational in 2023.

Any further responses from the reviewers can be found at the end of the article

Introduction

Geothermal is a renewable source of energy: it embodies the natural heat content of the Earth that dates back to its formation and that it is continuously renewed via radioactive decay. Unlike other renewable energy sources such as solar and wind, geothermal energy is independent of seasonal and climatic conditions, and therefore it can generate base-load power. This and other features, including a substantial theoretical potential for electricity generation[1,2], make geothermal a promising energy source to expedite the decarbonisation of the power generation sector, and the transition to the low-carbon economy required to mitigate and when possible prevent long-term consequences of global warming[3]. However, the contribution of geothermal energy to global electricity production remains limited: in 2020, the industry generated only 0.3% of global electricity generation from all sources and 1.2% from renewable sources[4]. The International Energy Agency (IEA) projects the sector's output to grow at an annual rate of 5% to 2024; but, according to the Agency, this is only about half of what is required to meet worldwide carbon neutrality by 2050[5].

Nowadays, most of the geothermal installed capacity is represented by traditional geothermal power plants that use well-known technologies to convert thermal energy into electricity like dry steam, and single-/double-flash plants. The Geysers Complex in California (US) is the largest conventional geothermal field in the world, with a total electric capacity of ~1.5GW[6,7]. A more recent geothermal technology - known as Enhanced Geothermal Systems (EGS) – has attracted considerable interests. Whilst traditional geothermal plants take advantage of high-enthalpy hydrothermal reservoirs that are typically confined near geological plate boundaries, EGS harness geothermal energy in locations that lack reservoirs but that have higher-than-average thermal gradients; this is enabled via the development of "engineered" reservoir using stimulation techniques[8]. The ability of EGS to extract heat in areas that lack water or sufficient permeability significantly extends the applicability of geothermal energy to vast areas of the planet. In Europe, efforts to develop EGS have focused in the Upper Rhine Valley (a region that extends across France, Germany and Switzerland): the first worldwide commercial-scale power plant was commissioned at Soultz-sous-Forêts in France[9,10]. In the United Kingdom, the United Downs Deep Geothermal Power (UDDGP) project is aiming to develop the country's first commercial geothermal power plant, which relies on heat produced by the Cornish granites and exploits the natural permeability of a significant structural fracture zone[11,12].

Life Cycle Assessment (LCA) is a standardised and widely adopted methodology to quantify the environmental impacts associated with a product throughout its life-cycle[13,14]. The life-cycle perspective and the consideration of a number of environmental issues enable identification of trade-offs and hot spots, thus providing a robust framework for decision support. The LCA methodology has been widely applied to compare the environmental performance, including carbon emissions, of disparate energy technologies (e.g. see 15,16). Despite the standardised framework, the results of LCA studies on geothermal power generation show high variability; for example, the carbon footprint of geothermal-derived electricity stretches over two order of magnitudes, from ~5 and up to ~800 gCO_2-eq./kWh[17]. This variability is in part due to methodological choices like the definition of the system boundary, and in part to the fact that the environmental impacts strongly depend on site-specific conditions such as the composition of the geothermal fluid or the depth of the geothermal reservoir[18,19], which in turn determine, for example, the magnitude and type of gaseous emissions or the structural requirements of geothermal wells. Notably, the latter aspect emphasizes the importance of collecting high-quality field data to reliably estimate the environmental footprint - arguably the most time-consuming phase of LCA.

In this article, we present a software application - named Geothermal Energy Impact Estimator (GEIE) – that predicts the life-cycle environmental impacts of geothermal plants for generation of electricity generation or for co-generation of electricity and heat. An earlier, non-peer reviewed version of this article is available as a Horizon 2020 deliverable report[20]. The presented application has a twofold goal. First, it attempts to tackle the variability of LCA results due to methodological choices; notably, the variability of site-specific conditions and the importance of individual parameters has been investigated by Paulillo *et al.*[21], whose work represents the basis for the development of the software application presented in this article. Second, the application aims to provide a user-friendly tool designed for people not familiar with the LCA methodology; for instance, the application could be used by policy makers to support the development of energy policies, and by geothermal companies designing and operating geothermal power plants.

Methods

Implementation

Geothermal Energy Impact Estimator (GEIE) is a Microsoft Windows based application written using C# (see *Software availability*[22]). The objective of the software application is the quantification of the retrospective or prospective life-cycle environmental impacts of geothermal energy: retrospectively, to assess the environmental performance of an existing plant, and prospectively, to predict that of a future plant.

The computational core of GEIE relies on two parametric models, named "full" and "simplified"; both are described in detail in 20. The "full" model is a comprehensive parametric model featuring 32 input parameters that quantifies the environmental impacts of electricity and, when applicable, thermal energy generation. The input parameters are colour-coded according to whether default values are provided and how uncertain they are. The "full" model is a modified version of the model presented in Paulillo *et al.*[21]. The modified "full" model extends the application to cover the generation of thermal energy, including the case of co-generation (which is dealt with via allocation factors, as explained in the "Operation" sub-Section. The "simplified" model relies on a subset of influential input parameters (four for conventional and three for EGS plants), defined as those parameters that contribute the most to the variance of the "full" model. These parameters were identified by means of Global Sensitivity Analysis in 21; the resulting "simplified" model was presented in 23.

The "full" model is more accurate than the "simplified" model (provided that the input parameter values are accurate) but it requires more data to be collected. Both parametric models use detailed and validated life-cycle inventories obtained from the literature (see 20,21) and from Ecoinvent[24], a commercial LCA database. GEIE computes impacts using in the environmental categories included in the Environmental Footprint 2.0[25], which are reported in Table 1[1].

To develop a user-friendly application, we i) included input parameters expected to be available to geothermal companies, and ii) optimised the Graphical user interface (GUI) design to facilitate usage by those not familiar with LCA. We note that some parameters may not be available by for prospective studies; for examples, the amount of diesel consumed for drilling of wells would only be known after drilling is completed. For these parameters, users should input appropriate estimates based on e.g. data from similar sites or predicting models (e.g. 26 for diesel consumption). We envisage that the software can support policy makers in the development of energy policies and geothermal companies in designing and operating geothermal power plants.

Operation

The only requirement of the GEIE software application is .Net Framework 4.7.1 or later versions. Figure 1 shows the overall

[1] Note that some environmental categories (e.g. human toxicity for metals) may have higher uncertainty than others, which need to be accounted for when interpreting the results (see 25).

Table 1. Environmental impact categories of the Environmental Footprint 2.0 (EF2.0) method, as implemented in Geothermal Energy Impact Estimator (GEIE).

Impact categories	Units	Acronym
Acidification, terrestrial and freshwater	Mole of H+ eq.	A
Climate change	kg CO2 eq.	CC
Eutrophication, freshwater	kg P eq.	Ef
Eutrophication, marine	kg N eq.	Em
Eutrophication, terrestrial	Mole of N eq.	Et
Ecotoxicity, freshwater	CTUe	ETf
Human toxicity, cancer effects	CTUh	HT-c
Human toxicity, non-cancer effects	CTUh	HT-nc
Ionising radiations	Bq U235 air-eq.	IR
Land use	Points	LU
Ozone depletion	kg CFC-11 eq.	OD
Respiratory inorganics	kg PM2.5 eq.	RI
Photochemical ozone formation	kg NMVOC eq.	POF
Resource use, fossils	MJ	RUe
Resource use, mineral and metals	kg Sb eq.	RUm
Resource use, water	m^3 eq.	RUw

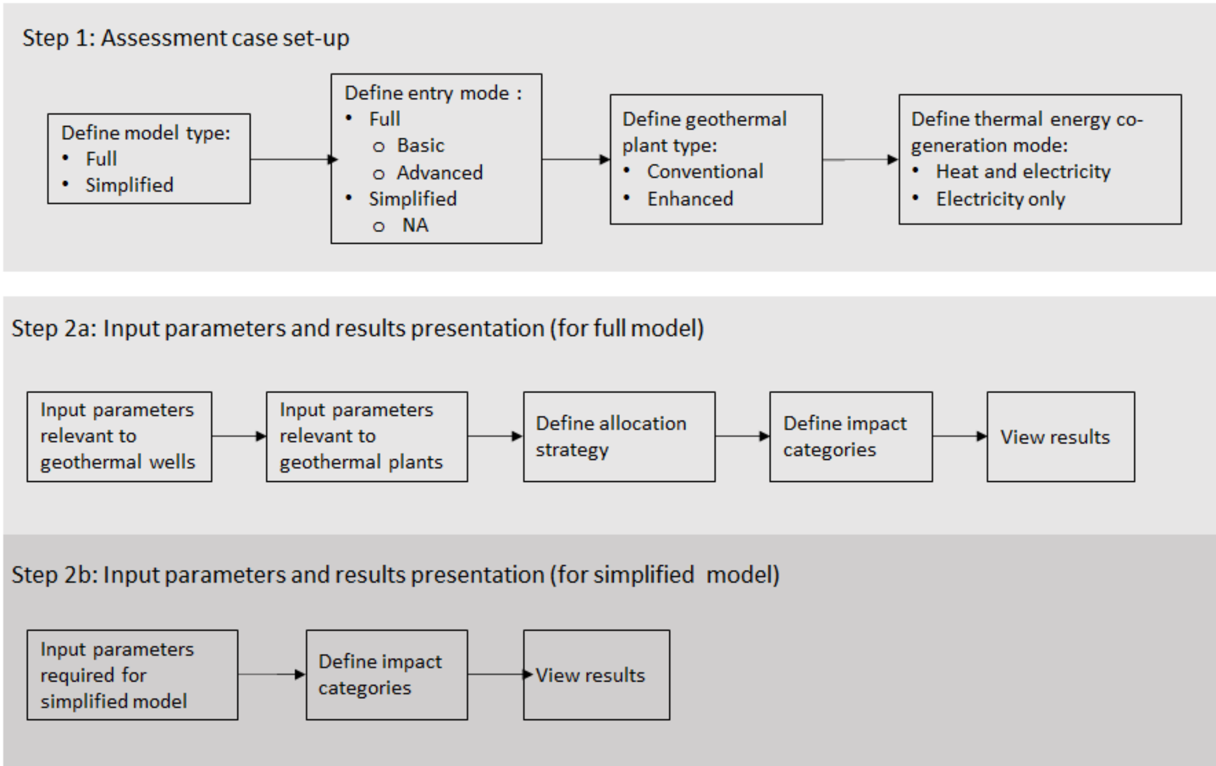

Figure 1. Overview of the GEIE (Geothermal Energy Impact Estimator) software application workflow.

workflow of the software application, whilst Figure 2–Figure 4 and Figure 5 provide an outlook of the GUI of GEIE.

The first step is the assessment case set-up. At the top of the interface shown in Figure 2, the User can choose between the “full” and the “simplified” model type. If the “full” model is selected, the User also needs to select the Entry Mode, i.e., “basic” or “advanced”, depending on the User’s preference on the level of control over all parameters. The “basic” Entry Mode only enables inserting values for the input parameters that are colour-coded in Green and in Yellow. The former identifies mandatory input parameters, whilst the latter those parameters that we recommend being provided by the User because the default values that we included are highly uncertain. The “advanced” Entry Mode allows to override input parameters for which default values are provided; these parameters are labelled in orange. Below the Entry Mode, the software application presents an additional drop-down menu that allows selection of the type of geothermal plant, i.e., conventional[2] and enhanced. Finally, the “thermal energy production” toggle box enables/disables the co-generation of heat and power; when the toggle box is deselected, the software assumes generation of electricity only.

[2] Following the classification in 21, with the term “conventional” we refer to plants that are based on dry-steam or single/multi-stage flash technologies.

The second step entails inserting values of the input parameters and viewing and/or exporting the results. If the “full” model is selected, the software features five tabs. The “Wells” (Figure 2) and “Plant” tabs enable entering values for the input parameters that are relevant to the geothermal wells and plant respectively. The “Wells” tab also includes a toggle box that applies to enhanced geothermal plants only and that enables/disables hydraulic stimulation of geothermal wells. The “Allocation” tab (Figure 3) is only relevant for the case of co-generation of heat and power: it allows selecting the strategy for allocating the environmental impacts between electricity and thermal energy, and, if the entry mode “advanced” is selected, also changing the values of the relevant parameters. When allocation is enabled, the activities that are partitioned include construction of wells and pipelines, and stimulation (if applicable). The remaining activities are allocated to the individual functions of electricity or thermal energy generation; more details are provided in 20. From the “Impact categories” tab the User can select the environmental categories for which the software will calculate the impact scores. Finally, the environmental impacts are reported in the “Results” tab (Figure 4) as numerical values and graphically, as contribution analysis. The environmental impacts are reported per unit of electricity (in kWh), and per unit of heat (in MJ) when the relevant option is enabled. The “Results” tab also provides the option to export the numerical values of the environmental impacts, for example into an Excel spreadsheet.

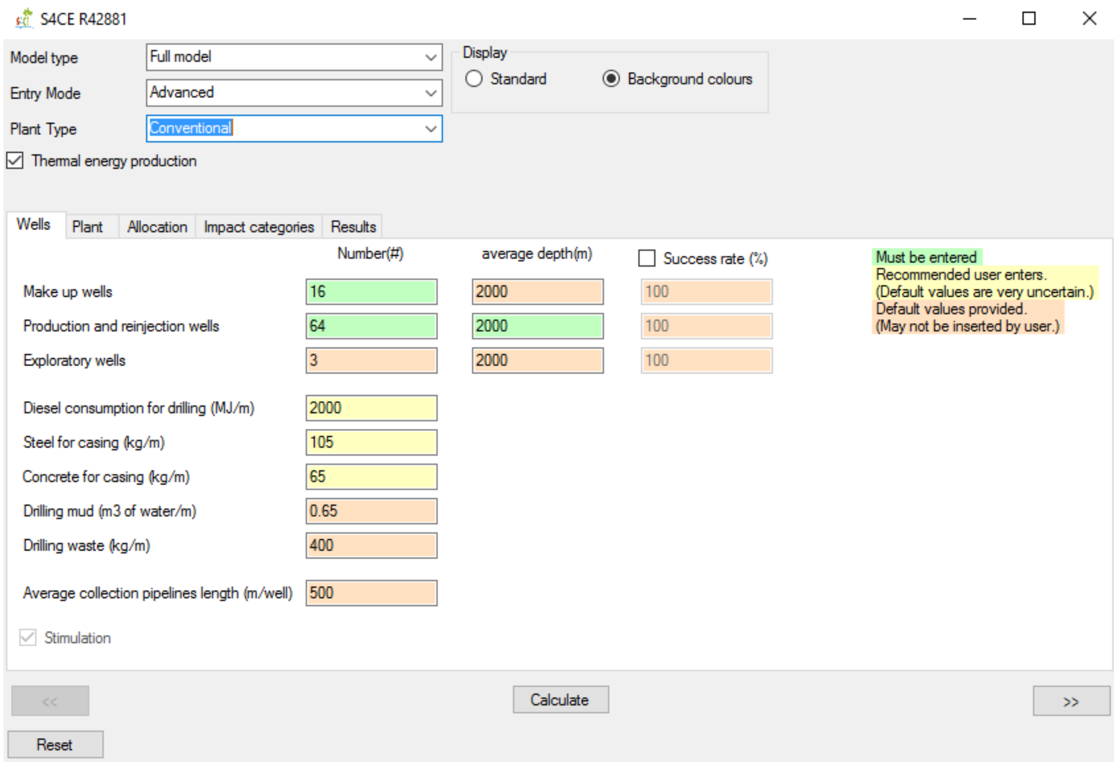

Figure 2. **Case set-up and Wells tab of the GEIE (Geothermal Energy Impact Estimator).**

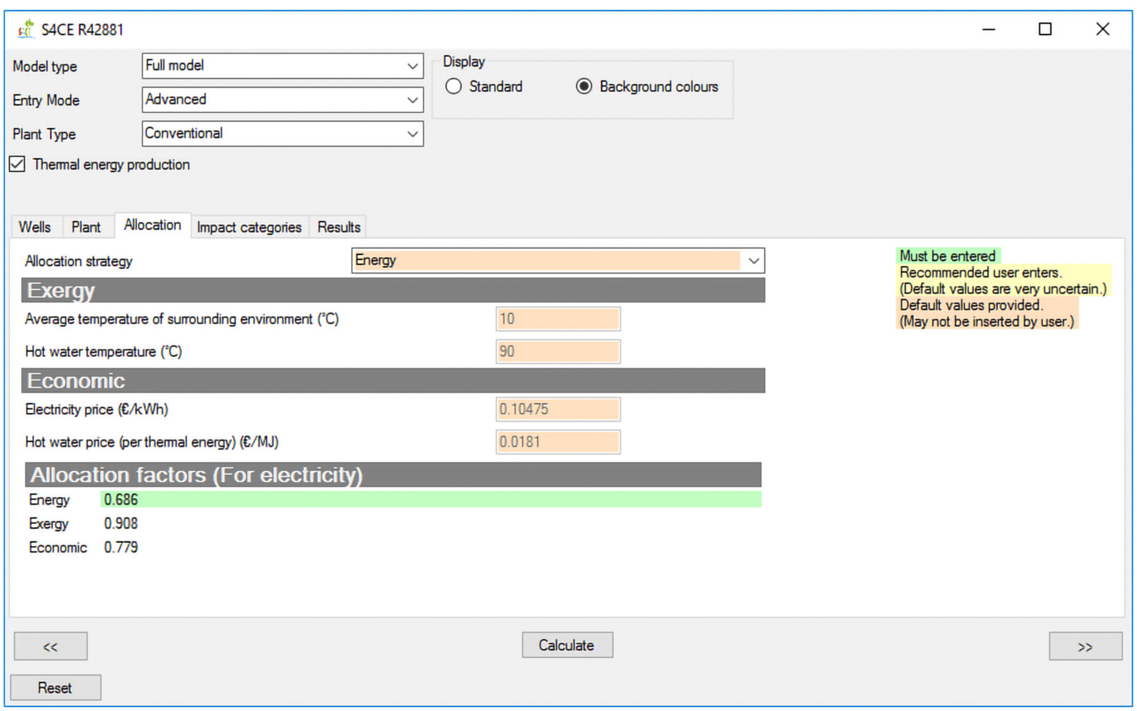

Figure 3. **Allocation tab of the GEIE (Geothermal Energy Impact Estimator).**

The application's operation for the model type "simplified" features three tabs. The main tab (Figure 5) allows the User to insert the relevant parameters, which differs between conventional and enhanced geothermal plants. The main tab also includes a toggle box related to the parameter "success rate", which is defined as the percentage of successfully drilled wells. When

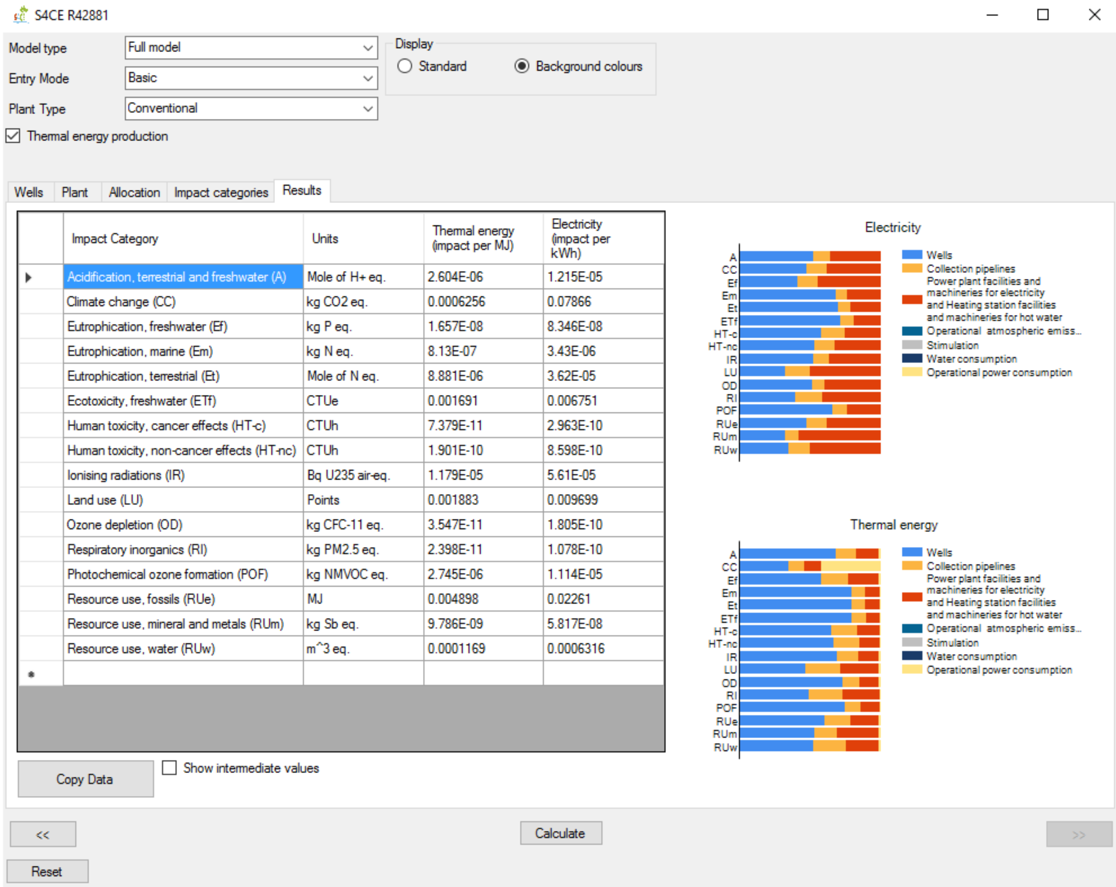

Figure 4. **Results tab of the GEIE (Geothermal Energy Impact Estimator).**

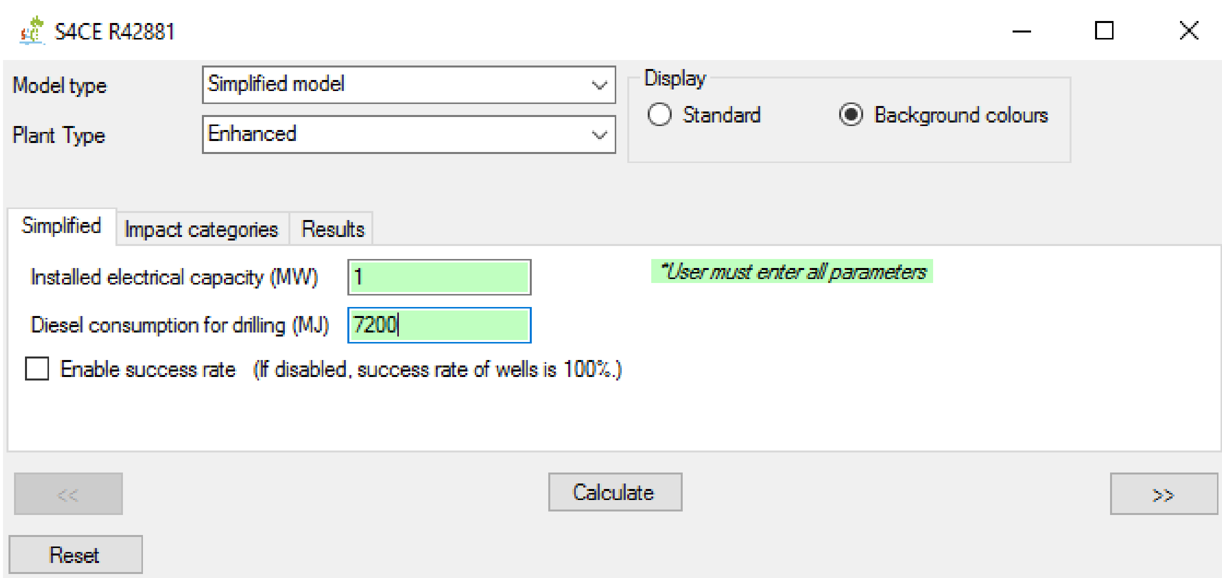

Figure 5. **"Simplified" main tab of the GEIE (Geothermal Energy Impact Estimator).**

the toggle box is disabled, the model assumes a 100% success rate for all wells' types; when it is enabled, the user can modify the success rate (the provided default value for primary wells is 72%[23]). The option to enable/disable the "success rate" parameter is important because this parameters can in some cases considerably affect the LCA results, although it is not as significant as the other parameters of the "simplified" model[21,23]. The remaining two tabs for the "simplified" model – "Impact categories" and "Results" – are similar to those for the "full" model.

Use cases

We developed two specific use cases of the GEIE software application representing two geothermal plants: the Hellisheidi heat-and-power cogeneration plant located near Reykjavik, Iceland and the United Downs Deep Geothermal Power Project (UDDGP) in Cornwall, United Kingdom. For each use case, we report both input parameters and GEIE's outputs (see also *Underlying data*[27]). We note that the validity of the "full" and the "simplified" models have been analysed in detail in 21,23; it is therefore outside the scope of the present article to discuss the results, including the differences between the outputs of the two models.

Hellisheidi geothermal plant

Hellisheidi, the most recent geothermal project in Iceland, is the largest geothermal plant in the country and the sixth largest in the world by electric capacity[7]. The environmental performance of Hellisheidi's operation has been assessed in detail by Karlsdottir *et al.*[28,29] and by Paulillo *et al.*[17,30]. In Table 2, we report the input parameters for the "full" model ("advanced" entry mode) for the Hellisheidi geothermal plant. The values are based on site-specific data collated by Karlsdottir *et al.* and reported in 28 and 17. In Table 3, we report the outputs of the GEIE software application. These are obtained using the "full" model with "advanced" entry mode, selecting "conventional" as plant type, enabling the co-production of thermal energy, adopting energy as allocation strategy, and selecting all environmental categories. Note that the table reports impacts for electricity and heat because the Hellisheidi plants co-generates both products and the relevant option in GEIE was enabled.

Table 2. Input parameters developed for the Hellisheidi geothermal power plant. These parameters are obtained from an open-access publication[17].

Parameter	Unit	Value
Wells		
Number		
Make up wells	#	16
Production and reinjection wells	#	64
Exploratory wells	#	0
Average depth		
Make up wells	m	2220
Production and reinjection wells	m	2220
Exploratory wells	m	0
Diesel (for drilling)	MJ/m	2262
Steel (for casing)	kg/m	100
Cement (for casing)	kg/m	40
Drilling mud	m3 of water	1.00
Drilling waste	kg/m	450
Success rate		
Production and Reinjection wells	-	1
Make-up wells	-	1
Exploratory wells	-	1
Plant		
Installed power, electricity	MW	303.3
Lifetime	years	30
Capacity factor	-	0.87
Auxiliary power	-	0.04
Installed power, thermal	MW	133
Heating station power consumption	kWh/s	0.40
Average collection pipelines length	m/well	500
Organic working fluid	kg/MWel	0
Cooling towers	#/MWel	0.023
Direct CO_2 emissions	kg CO_2/kWh	2.09E-02
Direct CH_4 emissions	kg CH_4/kWh	3.50E-05
Stimulation		
Number of wells to be stimulated	#	-
Water	m3 of water	-
Electricity	kWh/m3 of water	-
Allocation		
Average temperature of surrounding environment	°C	10
Hot water temperature	°C	90
Electricity price	kr/kWh	5.87
Hot water price (per thermal energy)	kr/MJ	0.708

Table 3. **Outputs of GEIE (Geothermal Energy Impact Estimator) as applied to data for the Hellisheidi geothermal plant.**

Category	Unit	Wells	Collection pipelines	Power plant/ Heating station facilities and machineries	Operational atmospheric emissions	Stimulation	Water consumption	Operational power consumption	Total
Electricity (1 kWh)									
Acidification, terrestrial and freshwater (A)	Mole of H+ eq./kWh	7.73E-06	1.43E-06	4.55E-06	0	0	0	0	1.37E-05
Climate change (CC)	kg CO2 eq./kWh	9.00E-04	2.55E-04	6.51E-04	3.33E-13	0	0	0	2.40E-02
Eutrophication, freshwater (Ef)	kg P eq./kWh	4.02E-08	1.18E-08	3.85E-08	0	0	0	0	9.05E-08
Eutrophication, marine (Em)	kg N eq./kWh	2.88E-06	2.85E-07	8.57E-07	0	0	0	0	4.02E-06
Eutrophication, terrestrial (Et)	Mole of N eq./kWh	3.12E-05	3.23E-06	8.14E-06	0	0	0	0	4.25E-05
Ecotoxicity, freshwater (ETf)	CTUe/kWh	5.87E-03	6.55E-04	1.36E-03	0	0	0	0	7.88E-03
Human toxicity, cancer effects (HT-c)	CTUh/kWh	1.97E-10	5.15E-11	7.75E-11	0	0	0	0	3.26E-10
Human toxicity, non-cancer effects (HT-nc)	CTUh/kWh	5.33E-10	1.24E-10	2.92E-10	0	0	0	0	9.48E-10
Ionising radiations (IR)	Bq U235 air-eq./kWh	3.50E-05	6.49E-06	2.12E-05	0	0	0	0	6.27E-05
Land use (LU)	Pt/kWh	3.45E-03	1.72E-03	5.04E-03	0	0	0	0	1.02E-02
Ozone depletion (OD)	kg CFC-11 eq./kWh	1.15E-10	1.60E-11	7.34E-11	0	0	0	0	2.04E-10
Respiratory inorganics (RI)	kg PM2.5 eq./kW	4.76E-11	2.09E-11	4.64E-11	0	0	0	0	1.15E-10
Photochemical ozone formation (POF)	kg NMVOC eq./kWh	9.00E-06	1.16E-06	2.79E-06	5.31E-18	0	0	0	1.33E-05
Resource use, fossils (RUe)	MJ/kWh	1.30E-02	3.31E-03	9.01E-03	0	0	0	0	2.53E-02
Resource use, mineral and metals (RUm)	kg Sb eq./kWh	1.71E-08	5.69E-09	3.50E-08	0	0	0	0	5.77E-08
Resource use, water (RUw)	m^3 eq./kWh	2.59E-04	9.79E-05	3.24E-04	0	0	0	0	6.81E-04
Heat (1 MJ)									
Acidification, terrestrial and freshwater (A)	Mole of H+ eq./kWh	2.15E-06	3.96E-07	4.27E-07	0	0	0	4.74E-08	3.02E-06

Category	Unit	Wells	Collection pipelines	Power plant/ Heating station facilities and machineries	Operational atmospheric emissions	Stimulation	Water consumption	Operational power consumption	Total
Climate change (CC)	kg CO2 eq./kWh	2.50E-04	7.09E-05	7.85E-05	0	0	0	8.29E-05	4.82E-04
Eutrophication, freshwater (Ef)	kg P eq./kWh	1.12E-08	3.29E-09	3.67E-09	0	0	0	3.13E-10	1.84E-08
Eutrophication, marine (Em)	kg N eq./kWh	8.00E-07	7.91E-08	8.36E-08	0	0	0	1.39E-08	9.76E-07
Eutrophication, terrestrial (Et)	Mole of N eq./kWh	8.66E-06	8.98E-07	9.30E-07	0	0	0	1.47E-07	1.06E-05
Ecotoxicity, freshwater (ETf)	CTUe/kWh	1.63E-03	1.82E-04	1.64E-04	0	0	0	2.73E-05	2.00E-03
Human toxicity, cancer effects (HT-c)	CTUh/kWh	5.47E-11	1.43E-11	1.17E-11	0	0	0	1.13E-12	8.19E-11
Human toxicity, non-cancer effects (HT-nc)	CTUh/kWh	1.48E-10	3.44E-11	2.80E-11	0	0	0	3.28E-12	2.14E-10
Ionising radiations (IR)	Bq U235 air-eq./ kWh	9.73E-06	1.80E-06	1.83E-06	0	0	0	2.17E-07	1.36E-05
Land use (LU)	Pt/kWh	9.59E-04	4.77E-04	5.34E-04	0	0	0	3.53E-05	2.01E-03
Ozone depletion (OD)	kg CFC-11 eq./kWh	3.18E-11	4.46E-12	4.96E-12	0	0	0	7.05E-13	4.20E-11
Respiratory inorganics (RI)	kg PM2.5 eq./kW	1.32E-11	5.81E-12	6.39E-12	0	0	0	3.97E-13	2.58E-11
Photochemical ozone formation (POF)	kg NMVOC eq./kWh	2.50E-06	3.23E-07	3.77E-07	0	0	0	4.60E-08	3.24E-06
Resource use, fossils (RUe)	MJ/kWh	3.60E-03	9.18E-04	1.01E-03	0	0	0	8.74E-05	5.61E-03
Resource use, mineral and metals (RUm)	kg Sb eq./kWh	4.74E-09	1.58E-09	2.94E-09	0	0	0	2.00E-10	9.46E-09
Resource use, water (RUw)	m^3 eq./kWh	7.20E-05	2.72E-05	2.82E-05	0	0	0	2.35E-06	1.30E-04

United Downs Deep Geothermal Power (UDDGP) project

The United Downs Deep Geothermal Power (UDDGP) represents the first deep geothermal power project in the UK. The project aims at harnessing the natural permeability of a significant structural fracture zone known as the Porthtowan Fault Zone[11]. The geothermal wells were completed in 2019, and the power plant is expected to be operational in 2023. The environmental impacts of the UDDGP project were investigated by Paulillo *et al*. using a combination of primary data gathered on site and secondary data obtained from the literature[12]; the full inventory data is publicly available[31]. From these data, we report the input parameters for the "simplified" model in Table 4 and GEIE's outputs in Table 5. Note that the outputs i) only refer to electricity (the "simplified" model does not include the case of co-generation) and ii) include both cases when the success rate is enabled (termed in the table "with success rate") and disabled ("without success rate").

Conclusions

In this article we presented a Microsoft Windows based software application - named Geothermal Energy Impact Estimator (GEIE) - which can be used to quantify the environmental impacts of existing or future geothermal plants, including both conventional and enhanced technologies. The computational core of the application relies on two parametric models, termed "full" and "simplified". The models, which have been developed and validated elsewhere, rely on life-cycle inventories obtained from the literature and from commercial LCA databases. Because the software application is user-friendly, it should be easily implemented by policy makers, consultants, and energy companies. The workflow of GEIE is straightforward,

Table 4. Input parameters developed for UGGDP (United Downs Deep Geothermal Power). These parameters are obtained from an open-access publication[31].

Parameter	Unit	Value
Installed electrical capacity	MW	1
Diesel consumption for drilling	MJ	7200

Table 5. GEIE (Geothermal Energy Impact Estimator) outputs as applied to data from UDDGP (United Downs Deep Geothermal Power).

Category	Unit	With Success rate	Without Success rate
Acidification, terrestrial and freshwater (A)	Mole of H+ eq./kWh	1.67E-03	1.29E-03
Climate change (CC)	kg CO_2 eq./kWh	1.42E-01	1.09E-01
Eutrophication, freshwater (Ef)	kg P eq./kWh	2.70E-06	1.98E-06
Eutrophication, marine (Em)	kg N eq./kWh	6.27E-04	4.91E-04
Eutrophication, terrestrial (Et)	Mole of N eq./kWh	6.86E-03	5.37E-03
Ecotoxicity, freshwater (ETf)	CTUe/kWh	3.71E-01	2.66E-01
Human toxicity, cancer effects (HT-c)	CTUh/kWh	1.27E-08	9.13E-09
Human toxicity, non-cancer effects (HT-nc)	CTUh/kWh	3.56E-08	2.58E-08
Ionising radiations (IR)	Bq U235 air-eq./kWh	7.15E-03	5.53E-03
Land use (LU)	Pt/kWh	2.78E-01	2.08E-01
Ozone depletion (OD)	kg CFC-11 eq./kWh	2.66E-08	2.08E-08
Respiratory inorganics (RI)	kg PM2.5 eq./kW	4.62E-09	3.48E-09
Photochemical ozone formation (POF)	kg NMVOC eq./kWh	2.07E-03	1.60E-03
Resource use, fossils (RUe)	MJ/kWh	1.91E+00	1.46E+00
Resource use, mineral and metals (RUm)	kg Sb eq./kWh	1.33E-06	1.03E-06
Resource use, water (RUw)	m^3 eq./kWh	1.77E-02	1.32E-02

consisting in a two-step process; the first being the definition of the assessment case set-up, and the second the insertion of the input parameter values and the viewing and/or exporting of the results. We have provided two specific use cases of GEIE as applied to two existing geothermal plants: Hellisheidi, a conventional co-generation plant in Iceland, and the United Downs Deep Geothermal Power (UDDGP) project in the UK. The details concerning the environmental impacts of these plants are available in the open literature, and have been referenced throughout the article.

Ethics and consent

No ethical approval or consent were required.

Data availability

Underlying data

Zenodo: GEIE use cases. https://doi.org/10.5281/zenodo.7333572[27].

This project contains the following underlying data:

- HSD_IN.xlsx (input parameters developed for the Hellisheidi geothermal power plant. These parameters are obtained from an open-access publication[17]).
- HSD_OUT.xlsx (outputs of GEIE as applied to data for the Hellisheidi geothermal plant).
- UGGDP_IN.xlsx (input parameters developed for UGGDP. These parameters are obtained from an open-access publication[31]).
- UGGDP_OUT.xlsx (GEIE outputs as applied to data from UDDGP).

Software availability

Source code available from: https://github.com/paul-brown-twi/GeothermalEnergyImpactEstimator/tree/v1.1

Note: the .exe file to install the software can be downloaded from the GitHub repository, under Releases.

Archived source code at time of publication: https://doi.org/10.5281/zenodo.7267704[22]

Licence: MIT

Acknowledgements

An earlier, non-peer reviewed version of this article is part of a deliverable report for the S4CE project titled "Demonstration of LCA software against field data" (see 20).

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Open Peer Review

Current Peer Review Status: ✔ ✔ ✔

Version 2

Reviewer Report 14 June 2023

https://doi.org/10.21956/openreseurope.17259.r31841

✔ **Neil Burnside**
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Paper does a good job of describing the software and providing guidance on its use. It looks like the authors have addressed previous reviewer comments. I believe it is is fit for purpose when considering the journal scope but recommend the authors address the, mostly minor, comments below.

The sentence, "*The ability to extract heat in the absence of water or sufficient permeability significantly extends the applicability of geothermal energy to vast areas of the planet",* is out of place here without further qualification. It's wedged between sentences regarding EGS, which primarily aims to create sufficient permeability and circulate water. Suggest make more relevant (e.g., by discussing single well / closed loop systems) or removing completely.

"In the United Kingdom, the United Downs Deep Geothermal Power (UDDGP) project is developing the first commercial geothermal power plant, which relies on heat produced by the Cornish granites and exploits the natural permeability of a significant structural fracture zone". Some information is presented as factual here when I don't believe this is the case. May depending on use of 'commercial', but the Eden Project is at a similar stage so in practice may prove to be the first commercial plant in the UK (also note 'UK' should be added here- sentence as written suggests that UDDGP would be the first commercial plant in the world). Until circulation between wells has been achieved the claim that this system 'exploits the natural permeability of a significant structural fracture zone' is unproven. Suggest re-writing sentence as follows: "In the United Kingdom, the United Downs Deep Geothermal Power (UDDGP) project is **aiming to develop** the **UK's** first commercial geothermal power plant, which relies on heat produced by the Cornish granites and **will aim to exploit** the natural permeability of a significant structural fracture zone". *Note* I see similar sentence is worded more appropriately in a later section.

"The geothermal wells were completed in 2019, and the power plant is expected to be operational in 2022". This article was first published in Jan 2023 and last updated in May 2023. This sentence

should also be updated as the expected year of operation is prior to publication of the paper. Suggest authors check if plant is currently operational or not and provide an updated year for expected operation if it's the latter.

"When the toggle box is disabled, the model assumes a 100% success rate for all wells' types; when it is enabled, the model assumes an average success rate lower than 100% (e.g. 72% for primary wells)". Does the 'e.g.' imply this ratio can be altered by the user? Or are there a set of defined valued baked into the tool? User alteration capability here would seem to have more use. Other studies suggest success rates of closer to 50%.

"The details concerning the environmental impacts of these plants are available in the open literature, and have been referenced". The details may be in other referenced publications but would be useful for readers of this guide to see a summary, even if a paragraph or two, of what the results mean for the examples provided. This would help emphasize the utility of the tool and benefit intended users who may be time-pressured and not have the capacity to review several different articles. Addition of a summary of what is 'good' and 'bad' impact results (e.g. in comparison with other energy generation options) would help place geothermal in context for policy makers, consultants, and energy companies (the intended users of the tool).

Is the rationale for developing the new software tool clearly explained?

Yes

Is the description of the software tool technically sound?

Yes

Are sufficient details of the code, methods and analysis (if applicable) provided to allow replication of the software development and its use by others?

Yes

Is sufficient information provided to allow interpretation of the expected output datasets and any results generated using the tool?

Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Geothermal, hydrogeology, low carbon energy

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 20 Jun 2023

Andrea Paulillo

Many thanks for reviewing our article. Below are short responses to the comments provided:

- To our understanding, EGS does extend the applicability of geothermal energy

because it enables extracting heat in areas that lack water or sufficient permeability. We have clarified the above sentence as follows:
"The ability of EGS to extract heat in areas that lack water or sufficient permeability significantly extends the applicability of geothermal energy to vast areas of the planet."

- We have modified the sentence accordingly.
- We have corrected the year the plant is expected to be operational to 2023.
- We believe that describing the LCA results falls outside the scope of this paper, which aims at describing a tool rather than the environmental performance of geothermal energy.

Competing Interests: No competing interests were disclosed.

Reviewer Report 14 June 2023

https://doi.org/10.21956/openreseurope.17259.r31249

Astu Sam Pratiwi
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The modification made in Version 2 of this article has addressed the major concerns associated to Version 1.

Point 5 in the initial feedback has not been addressed, however this is understandable as it would require a significant additional work. It is however recommended to have uncertainty range (or confident interval) included in future GEIE update.

The reviewer deemed, to the best of her knowledge, that this article is good to index. Reiterating previous impression, this work contributes to the advancement of scientific research in the geothermal industry by promoting LCA thinking and providing quantitative assessment.

Is the rationale for developing the new software tool clearly explained?
Partly

Is the description of the software tool technically sound?
Partly

Are sufficient details of the code, methods and analysis (if applicable) provided to allow replication of the software development and its use by others?
Partly

Is sufficient information provided to allow interpretation of the expected output datasets and any results generated using the tool?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Life cycle assessment modelling of geothermal power plant and heat plant in non volcanic regions, maintenance and operation of EGS power plant. I did not review the codes as this is not my area of expertise.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 06 April 2023

https://doi.org/10.21956/openreseurope.16546.r30773

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This article's scientific significance is underscored by its addressing of the need for prospective Life Cycle Assessment (LCA) in conventional and enhanced geothermal systems. By promoting LCA thinking in the development of energy systems, it contributes to the advancement of scientific understanding in this field. Furthermore, this research offers an accessible approach for comprehensively evaluating the environmental impacts of geothermal systems, providing a forward-looking perspective. However, to further enhance the article's contribution, it is suggested that the authors address the following points.

1. Elaborate what activities are being allocated in the co-generation scenario. I suppose the heat exchangers for heating production is accounted as the burden of only thermal energy.

2. Diesel consumption in GJ per m has been reported as an influential parameter. However, I am not convinced that it is the most appropriate input parameter for prospective LCA as the knowledge of diesel consumption per meter is normally known after drilling is accomplished. It is derived from other parameters such as hole size, geological formation/condition, and depth. You are invited to refer to Table A1 in the Supplementary data of https://doi.org/10.1016/j.geothermics.2020.101988 to see the possibility of predicting the diesel consumption from other input parameters.

3. Similarly, the capacity of geothermal plant depends on the temperature, flowrate (which itself depends on injectivity and productivity index) and the phase of geothermal fluid. However, the relationships can be very complex and defining the capacity as input parameter is acceptable.

4. The environmental impact of operational power consumption should also vary depending of installation country unless it is assumed that it will use part of the electricity generated from geothermal energy

5. Would be great if the level of accuracy of simple and full modes can be represented with visualization of uncertainty range. E.g, the values of impacts in simple mode will show higher uncertainty range than if full mode is selected.

6. I could not find a step by step installation for the user who wants to use the calculator here. Has it been provided in different location? It needs clarification.

   Further, the following bold words need correction:

7. Whilst traditional geothermal plants take advantage of high-enthalpy hydrothermal reservoirs that are typically confined near geological plate boundaries, EGS harness geothermal energy in locations that lack reservoirs but that have higher-than-average thermal gradients; **this is enable(d)** via the development of "engineered" reservoir using stimulation techniques.

8. Life Cycle Assessment (LCA) is a standardised and widely adopted methodology to quantify the environmental impacts associated with a product throughout its life-cycle. The life-cycle perspective and the consideration of a number of environmental issues **enables (no s)** identification of trade-offs and hot spots, thus providing a robust framework for decision support.

Is the rationale for developing the new software tool clearly explained?

Yes

Is the description of the software tool technically sound?

Yes

Are sufficient details of the code, methods and analysis (if applicable) provided to allow replication of the software development and its use by others?
Partly

Is sufficient information provided to allow interpretation of the expected output datasets and any results generated using the tool?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Life cycle assessment modelling of geothermal power plant and heat plant in non volcanic regions, maintenance and operation of EGS power plant. I did not review the codes as this is not my area of expertise.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 19 Apr 2023
Andrea Paulillo

Many thanks for reviewing our article. We are glad this was appreciated. Please find below point-by-point responses to the comments raised:

1. Thanks for raising this point, which is critical. We have added the following text to clarify how allocation has been implemented:
   "When allocation is enabled, the activities that are partitioned include construction of wells and pipelines, and stimulation (if applicable). The remaining activities are allocated to the individual functions of electricity or thermal energy generation; more details are provided in 20."

2. This is an important point. One could argue that other parameters like the hole size and/or conditions of the reservoir may not (or only partially) be known in advance for prospective LCAs. We chose diesel consumption as an input parameters because the underlying models in this study (refs 20, 21 and 23) are based on a detailed review of LCA studies available in the scientific literature, where diesel consumption is nearly always reported.
   We agree that some parameters may not be known in advance for prospective studies, but this should not limit the use of our software because users may estimate these parameters from e.g. the literature of predicting models like those that you mention. To clarify this point, we have added the following sentence:
   "We note that some parameters may not be available by for prospective studies; for examples, the amount of diesel consumed for drilling of wells would only be known after drilling is completed. For these parameters, users should input appropriate estimates based on e.g. data from similar sites or predicting models (e.g. 32 for diesel consumption)."

3. We agree

4. Yes: our model assumes that the operational power consumption will be met using part of the electricity generated by the plant.

5. This is a very interesting point. It is not applicable in the current software but we will consider it as a future improvement.

6. We have added a note to clarify how to use the software:
"the .exe file to install the software can be downloaded from the GitHub repository, under Releases."

Competing Interests: No competing interests were disclosed.

Reviewer Report 16 February 2023

https://doi.org/10.21956/openreseurope.16546.r30689

Giampaolo Manfrida
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The article proposed by Paulillo et al. is about a tool ("Geothermal Energy Impact Estimator") for estimating the environmental impacts through Life Cycle Assessment of geothermal plants. The article is well written, and correctly covers all the necessary aspects.

The overall assessment of the article is that its indexing should be approved.

Some comments are given below to improve both communication and the tool output potential:

- The advice to make the concept of variability clearer for non-experts is to point out that site-specific conditions and the technology used for the plant can determine the presence or absence of gas emissions to air and considerable differences in the number of wells. Both are elements that have a considerable environmental impact

- The text states that "*the full model is a modified version of the model presented in Paulillo et al.21 …".* For a better understanding, it would be important to specify briefly what modifications have been made.

- The text often mentions 'conventional plants', I would recommend to make it clear whether 'conventional' means exclusively flash plants or flash and ORC and Hybrid plants.

- Due to the use of the Environmental footprint 2.0 methodology, I would recommend to add a short comment on the uncertainty of the results for the categories of Toxicity (ecotoxicity and human toxicity), which can determine uncertainty in the final interpretation of the results.
- In the case of Co-generation, considering that there is high variability in the results obtained with different allocation factors, I believe that the authors could also indicate the most correct solution from a product point of view, i.e. to choose an exergy-based allocation principle.
- the quality of Figure 3 (screenshot capture) should be improved, particularly the grey characters on a light grey background (good for a screen, not for publication).
- In the case of cogeneration, it is stated in the text that environmental impacts refer to 1 kWh electricity and 1 MJ of heat. Was the possibility of reporting the results in terms of exergy considered? I think it could be an added value to the consistency of the results obtained.
- In the text, there is a parameter called 'success rate', which defines in generic terms the success rate of the well drilling. The concept should be extended: the reader should be aware of what is the meaning.
- For a scientific approach - as well as for decision-making, it is important to be able to compare different plants (obviously considering that the geological/resource context is very different). Moreover it would be good for decision-making to be able to compare the environmental footprint of a geothermal energy project with possible alternatives for Renewable Energy at regional scale (e.g. solar - PV or thermal conversion - and wind energy at least). It is quite common that such alternatives exist and this would be very useful for local policy-makers as well as for Energy Communities.

Is the rationale for developing the new software tool clearly explained?
The article clearly explains in the introduction the reason for the development of the software and in fact wants to solve the variability of LCA results for geothermal plants, which are very dependent on the case study and the methodology used, and also wants to make the application of these analyses easy even for non-experts in the field.

Is the description of the software tool technically sound?
The description of the tool is appropriate to the article, and uses technical terms related to both LCA analysis and the geothermal plants in an understandable manner.

Are sufficient details of the code, methods and analysis (if applicable) provided to allow replication of the software development and its use by others?
The methodology used is clear and easy to understand in all its aspects. The reader clearly follows the steps in the different cases of analysis (simplified, full). There is not enough detail of the code or analysis in this article. But in the text you will find all the specific references indicating where to find the information needed to correctly interpret the analysis as it has already been made public.

In addition, the reference to access the code via github is also given.

Is sufficient information provided to allow interpretation of the expected output datasets and any results generated using the tool?
In order to support non-expert readers, the results obtained from two case studies, a combined heat and power plant and an EGS plant, are given. In addition, references are given for the two case studies of previously published papers that cover the analysis in detail. This gives a complete insight into the interpretation of the outputs obtained.

Is the rationale for developing the new software tool clearly explained?

Yes

Is the description of the software tool technically sound?

Yes

Are sufficient details of the code, methods and analysis (if applicable) provided to allow replication of the software development and its use by others?

Partly

Is sufficient information provided to allow interpretation of the expected output datasets and any results generated using the tool?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Renewable Energy, Geothermal Power Plants, LCA, Exergy, Exergo-Economic and Exergo-Environmental Analyses, Advanced Energy Systems, Sustainability of Energy COnverion and Utilization

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.