SUPPORTING INFORMATION

Geothermal energy in the UK: the life-cycle environmental impacts of electricity production from the United Downs Deep Geothermal Power project

1 Impact categories

A brief explanation of the impact categories used in the study is provided below. This is largely based on the work of Rosembaum and colleagues (Rosenbaum et al., 2017) and Baumann and Tillman (Baumann and Tillman, 2004).

Acidification

The Acidification category quantifies the impact of pollutants with the potential of causing acidifications of soil or aquatic ecosystems. Acidifying pollutants are mainly released by combustion processes occurring in thermal power plants, combustion engines, waste incinerators, e.g. sulphur and nitrogen oxides and hydrochloric acid, and agriculture, which is the main contributor to emissions of ammonia. Following the release, acidifying compounds are trapped by water in the form of rain, fog and snow, and then deposited onto different receptors. Because of their high water solubility, the atmospheric residence time of acidifying pollutants is limited to a few days, and therefore acidification represents a regional effect.

Climate Change

The Climate Change category expresses the impact of greenhouse gas (GHG) emissions based on the extent to which they increase the radiative forcing in the atmosphere. The portion of the sunlight that is not reflected back into space heats up the planetary surface and is released back into the atmosphere as infrared radiation with a longer wave-length than the absorbed radiation. This infrared radiation is partially absorbed by GHGs and kept in the atmosphere instead of being expelled into space, explaining why the temperature of the atmosphere increases with its content of GHGs. The major anthropogenic contributions to the greenhouse effect are represented by emissions of carbon dioxide, methane and nitrogen oxides mainly from burning fossil fuels and deforestation.

Freshwater Ecotoxicity and Human Toxicity

Any substance emitted may lead to toxic impacts depending on a number of factors including emitted mobility, persistence, exposure patterns and bioavailability, and toxicity. The toxicity impact categories account for these four factors and focus on the impact on freshwater ecosystems and human beings.

Eutrophication, freshwater, marine and terrestrial

The three Eutrophication categories describe the impact of macro nutrients, the most important of which are nitrogen (N), and phosphorus (P), on aquatic and terrestrial ecosystems respectively. Excessive levels of nutrients in the aquatic ecosystem trigger a cause-effect chain that causes growth and blooming of algae and other aquatic plants, and reduction of oxygen availability, leading to degradation of water quality, altered species composition and loss of biodiversity. For terrestrial systems, eutrophication primarily causes changes in the function and species composition of nitrogen-poor ecosystems and also damages to crops and forests leading to reduced yields. Because of these environmental mechanisms, eutrophication is a regional impact category, highly dependent on local conditions.

Ionising radiations

The Ionising Radiations category covers impacts on human beings of radionuclides from direct emissions or that arise from nuclear waste disposed in a final repository. Exposure of humans to radioactive materials can lead to both stochastic and deterministic effects in terms of fatal and non-fatal cancers and hereditary effects.

Ozone Depletion

The Ozone Depletion category quantifies the effect of bromated and chlorinated substances on the depletion of the ozone layer. Ozone (O_3) is a harmful pollutant in the lower atmospheric layers, i.e. tropospheric and ground-level (See Photochemical Ozone Formation category), but it is an essential substance in the upper atmosphere (stratosphere) as it screens out more than 99% of the energy-rich ultraviolet (UV) radiation from the sun, preventing it from reaching the Earth's surface. The impact of UV on living organisms depends on its wavelength: short-wavelength UV (type C) is the most dangerous wavelength but it is almost completely filtered by the ozone layer; UV-B (medium wavelength) is of the greatest concern due to the ozone layer depletion; UV-A (long wavelength) is not absorbed by ozone. Impacts are also dependent on duration and intensity of the exposure, and include skin cancer, cataracts, immune system disease to humans, epidermal damage to animals, and radiation damage to the photosynthetic organs of plants.

Particulate Matter/Respiratory Inorganics

The category of Particulate Matter/Respiratory Inorganics quantifies toxicity-related effects on human health caused by Particulate Matter (PM). Exposure to PM leads to numerous detrimental effects including chronic and acute respiratory diseases, cardiovascular diseases, chronic and acute mortality and lung cancer. In 2013 outdoor and household PM pollution contributed alone to 71% of premature deaths attributable to environmental factors and 19% to all factors. PM can be distinguished according to formation type (primary and secondary) and aerodynamic diameter (respirable, coarse, fine and ultrafine). Primary PM includes particles that are directly emitted (e.g. from road transport or power plants), whilst secondary PM refers to particles formed by reactions with precursor substances such as nitrogen oxides, sulphur oxides, ammonia and Volatile Organic Compounds (VOCs).

Photochemical Ozone formation

The Photochemical Ozone formation category addresses the impacts caused by ozone and other reactive oxygen compounds; these are formed as secondary contaminants in the troposphere by the oxidation of the primary contaminants, mainly volatile organic compounds (VOC) and carbon monoxide, in the presence of nitrogen oxides and under the influence of light. The most important source of emissions of VOC derives from road traffic and use of organic solvents; whilst carbon monoxide is mainly emitted from combustion processes with insufficient supply of oxygen, including road traffic and other forms of incomplete combustion of fossil fuels and biomass. The negative impacts are associated with their reactive nature that enables them to oxidise organic molecules: when inhaled they can cause damages to the respiratory tract tissue and trigger respiratory diseases in humans; or they can attack surfaces of plants or even enter plant leaves damaging the photosynthetic organs.

Resource depletion, mineral, fossil and renewable

Natural resources can be classified according to their origin into biotic and abiotic, that is whether resources are or are not living at the moment of extraction, or according to their availability into stock (resources with a finite and fixed reserve), fund (resources that are regenerated but can be depleted if the extraction rate exceeds regeneration) and flows (resources that are provided as flows, e.g. solar radiation and wind). The most widely accepted method for quantifying impacts of resource use focuses on depletion of abiotic resources (stocks), using either the total estimated reserves of the resource (ultimate reserves approach) or only that part that has reasonable potential to become economically and technically feasible to exploit (reserve base approach).

Resource depletion, water

With respect to the distinction of natural resources made above, water is a resource provided as flow that cannot be depleted. There is sufficient water on our planet to meet current needs of ecosystems and humans: of the total water deposited every year on land only about 3% is used by humans and human activities. However, despite the small fraction, there are still important issues associated with water use; for instance, many rivers are running dry from overuse, leading to significant damages to local ecosystems. The issue is not about having too little water; rather it is about mismanagement of a resource that is required by both humans and ecosystems. Excessive consumption of water may lead to poor availability for humans, which may lead to deployment of backup technologies such as desalinisation of water if socio-economic resources are available, or otherwise cause deprivation and therefore water-associated diseases if socio-economics means are not sufficient. Excessive consumption of water also leads to damages to ecosystems such as loss of biodiversity due to reduction of available habitat.

2 Additional LCA results

TABLE S1 - ADDITIONAL IMPACT CATEGORIES.

IMPACT CATEGORY	METRIC
Acidification	Mole of H+ eq.
Eutrophication freshwater	kg P eq.
Eutrophication marine	kg N eq.
Eutrophication terrestrial	Mole of N eq.
Ionizing radiations	Bq U235 air eq.
Ozone depletion	kg CFC-11 eq.
Resource depletion, mineral, fossils and renewables	kg Sb eq.
Resource depletion, water	m^3 eq.

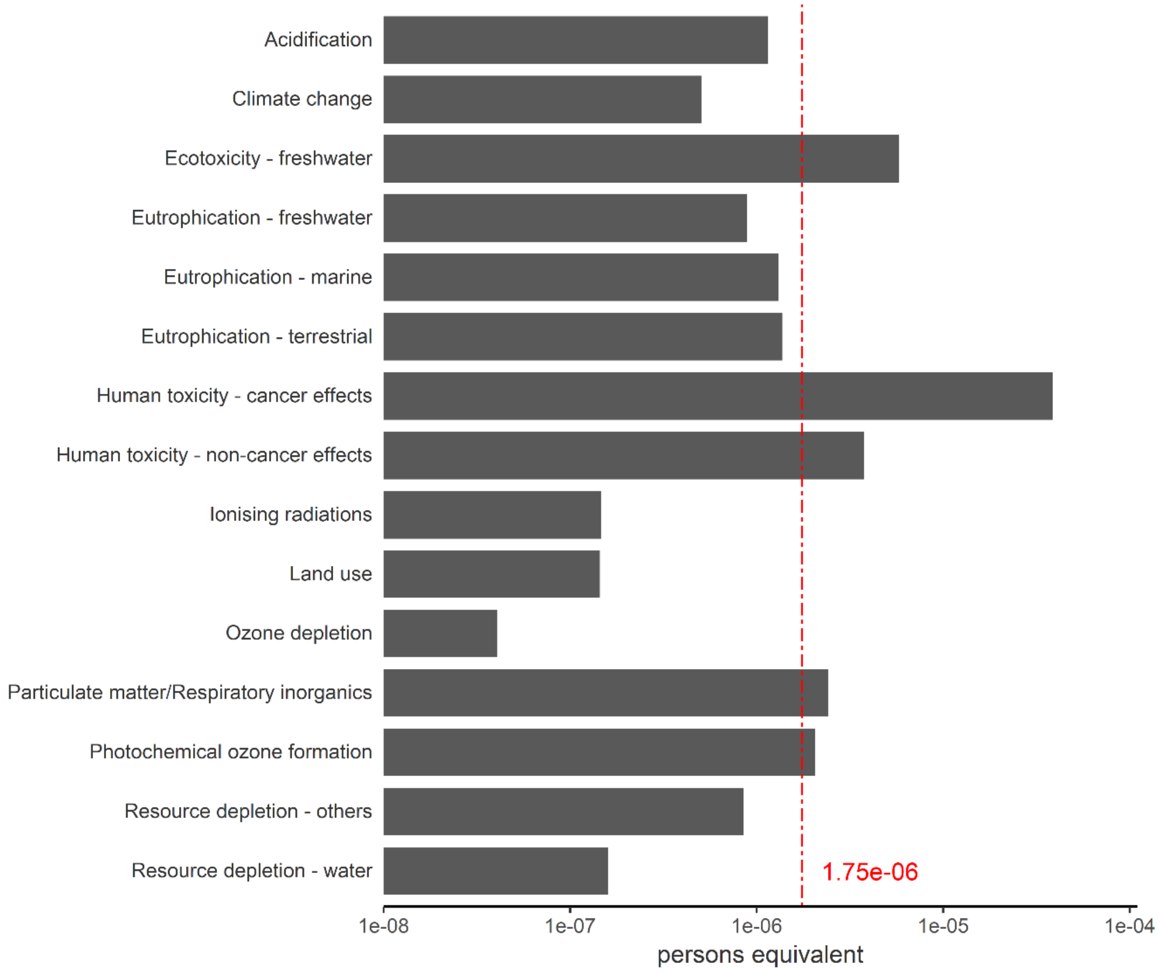

Figure S1 – Normalised LCA impacts. Normalisation factors refer to the impact per person of Europe in year 2010 (Benini et al., 2014). The value of 1.75e-06 has been used as threshold to identify the categories that have been included in the main article.

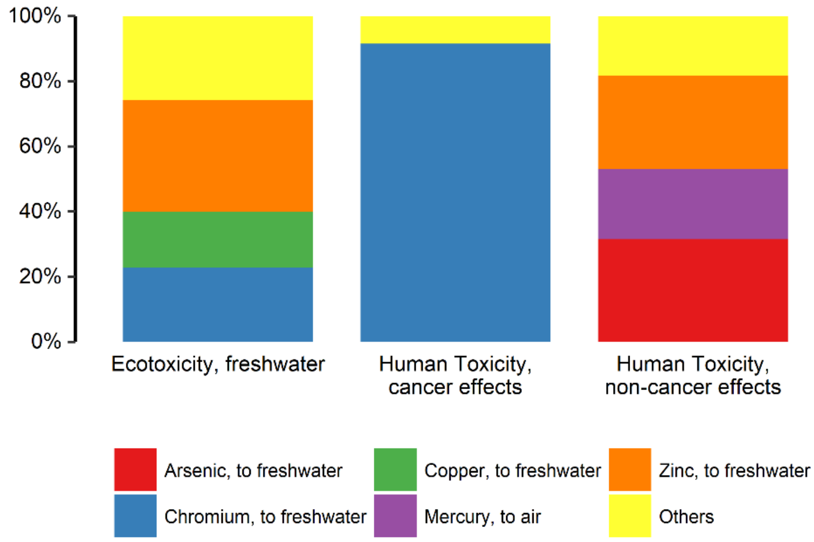

Figure S2 - Hot-spot analysis for the toxicity categories

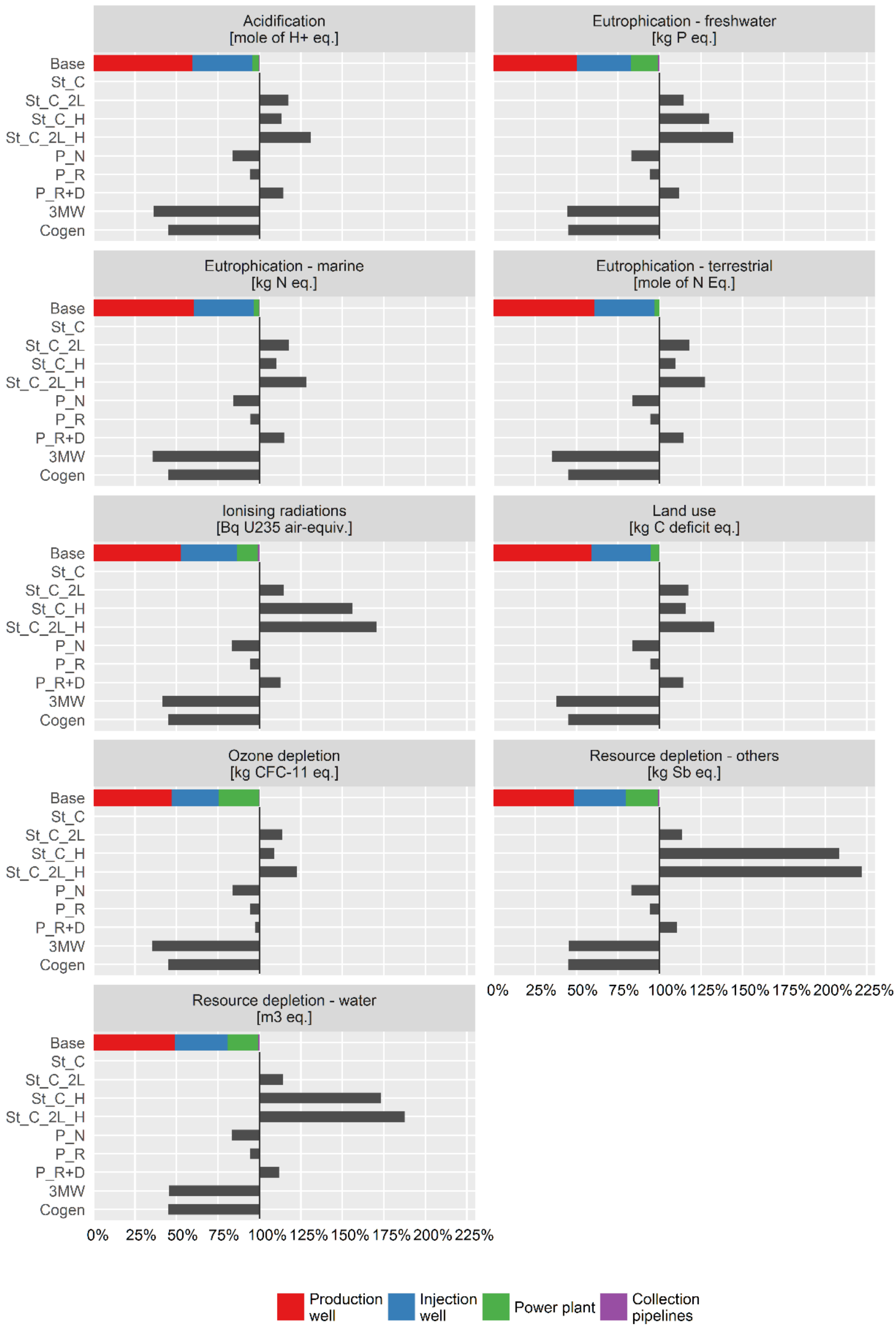

Figure S3 - Hot spot analysis for the base case, and percentage variations for the nine alternative scenarios, for the impact categories not included in the main paper. St_C= Chemical stimulation. St_C_L = Chemical stimulation + two-legged production well; St_C_H= Chemical + Hydraulic stimulation; St_C_L_H= Chemical and Hydraulic stimulation + two-legged production well; P_N = No pumps; P_R = Reinjection pump only; P_R+D = Reinjection + Downhole pump; 3MW= Power plant installed capacity of 3MW; Cogen = Heat and power cogeneration.

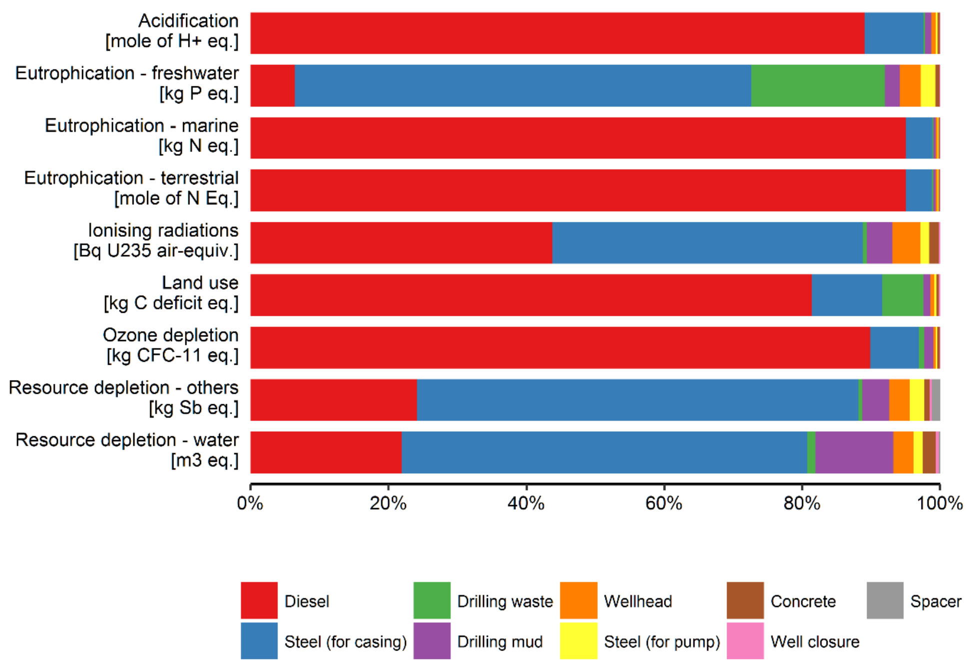

Figure S4 - Detailed hot-spot analysis on the construction and the end of life of the production well for the impact categories not included in the main paper.

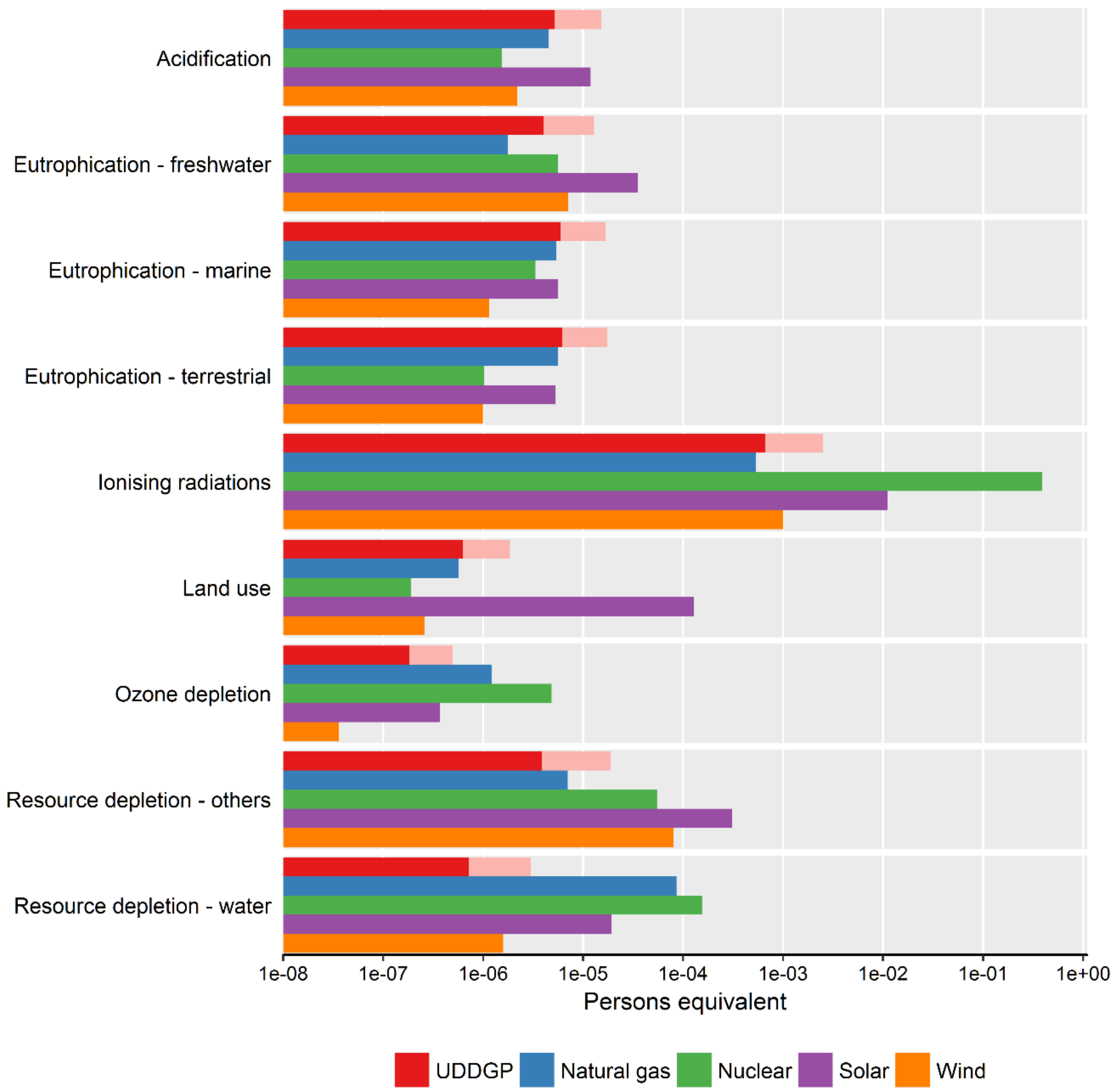

Figure S5 - Comparison of the normalised environmental impacts of 1 kWh of electricity produced from UDDGP with natural gas in combined cycle gas turbines, nuclear pressurised water reactors, utility-scale solar photovoltaic and offshore win farms.

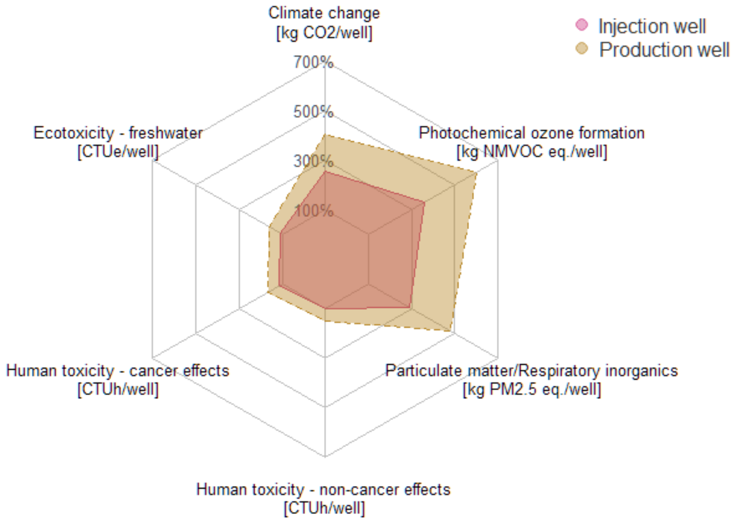

Figure S6 - Radar chart comparing the environmental impact scores in six environmental impact categories due to wells construction and decommissioning in the UDDGP project (injection and production wells) and the Hellisheidi geothermal plant in Iceland.

3 References

Baumann, H., Tillman, A.-M., 2004. The Hitch Hiker's Guide to LCA. An orientation in life cycle assessment methodology and application. Lund, Sweden, Studentlitteratur.

Benini, L., Mancini, L., Sala, S., Schau, E., Manfredi, S., Pant, R., 2014. Normalisation method and data for Environmental Footprints. doi:10.2788/16415

Rosenbaum, R.K., Hauschild, M.Z., Boulay, A.-M., Fantke, P., Laurent, A., Nuñez, M., Vieira, M., 2017. Life Cycle Impact Assessment, in: Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I. (Eds.), Life Cycle Assessment. Theory and Practice. Springer International Publishing. doi:10.1007/978-3-319-56475-3