Assessment of enhanced geothermal projects and their optimal long-term usage plans by using the DMS-TOUGE decision-making support tool

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ABSTRACT

This paper presents the main features of a Decision-Making Support Tool for Optimal Usage of Geothermal Energy (DMS-TOUGE) that is being developed for enhanced geothermal systems projects which will be able to economically and environmentally assess such investments and value cost of their integration into the energy systems by comparing different technology alternatives. The optimal long-term operating plans of enhanced geothermal systems will be investigated and presented for a particular site. The tool examines the enhanced geothermal systems projects in a holistic way considering: technology details, geothermal site characteristics, energy prices, and spatial data, social impact, and environmental impact. The decisions of the tool will be the results of a multiple-criteria decision-making analysis where the performance of a technology is assessed on credible criteria.

1. INTRODUCTION

Rising energy costs and the environmental impacts of supplying mankind's energy needs enlarges the exigency to find economical and environmentally energy alternatives. However, amidst the push to expand renewable energies, one option that is still not enough discussed is geothermal energy. Geothermal energy is an attractive renewable resource because it can provide a constant source of renewable baseload electricity compared to intermittent and fluctuating production from wind and sun. Geothermal energy has a low environmental risk and impact. Moreover, when exploited with a closed-loop binary power plant, those geothermal systems emit zero greenhouse gas emissions and have a near-zero environmental risk or impact. Despite all these advantages, geothermal energy is currently a small contributor to primary energy consumption. The main reasons are associated with the risks and uncertainties of sustained fluid production from the subsurface reservoirs and large upfront costs associated with exploration, well drilling and stimulation (Beckers, et al., 2014).

In Europe, enormous untapped geothermal potential consists of low permeable bedrock, only exploitable by Enhanced Geothermal Systems (EGS) technology. EGS, also known as Engineered Geothermal Systems or Hot Dry Rock (HDR) systems, differ from traditional hydrothermal systems in that the target reservoir typically consists of low permeability and low porosity rock with low fluid content and limited hydraulic connectivity between production and injection wells. Hydraulic stimulation is required to enhance the permeability of the reservoir to create enough connectivity for water or perhaps CO_2 as heat transfer fluid. By recirculating fluid through the reservoir, the thermal energy stored in the hot rock mass gets extracted.

Additional energy could be recovered from many onshore mature oil fields. Mature field means that the wells have been on production for a long time. The typical production pattern of most oil producing wells displays an increase of water with time, from 0% initially to a point, typically above 95%, when there is no longer economic to produce the remaining oil. In mature European oil fields, it is expected that wells are in the present producing much more water than oil, with average water-to-fluid ratio higher than 90% with temperature up to 90°C. This heat is currently wasted as water is simply re-injected into the reservoir for pressure maintenance or sweep purpose. There are several studies dealing with energy recovery from mature or abandoned oil fields. In (Alimonti, et al., 2014) a preliminary assessment of the potential for geothermal exploitation of the co-produced water from wells in the Villafortuna-Trecate oil field in Italy was made by comparing three different implementation scenarios for the possible use of the co-produced hot water: direct use district heating, electric power generation through Organic Rankin Cycle (ORC) plant, and co-generation of heat and power. Interesting research is given in (Zhang, et al., 2008) where energy from abandoned gas and oil reservoirs is obtained by oxidizing the residual oil with the injected air. In (Davis, et al., 2009) geothermal power production potential from abandoned oil wells is determined by injecting and retrieving a secondary fluid. Technical feasibility study of geothermal energy potential from abandoned oil and gas wells is given in (Bu, et al., 2012). In (Barbacki , 2000) abandoned oil and gas wells in Poland are used for recovering geothermal heat. Cost and investment cost analysis of EGS electricity is conducted in (Sanyal, et al., 2007) and (Stefánsson, 2002). The Huabei oil field were studied in (Xin, et al., 2012) where some important aspects of power generation from the co-produced hot oil and low-temperature liquid are analysed. In (Cheng, et al., 2013) some interesting insights are given regarding how to increase obtained heat from the abandoned oil wells with isobutane as working fluid.

Although, the EGS makes geothermal energy exploitable at a wide temperature range and large geographic scale, a clear integration strategy into existing power and heating grids is still lacking. According to (Lu, 2017), where a global review of the enhanced geothermal system was given for 18 significant EGS sites and technologies situated in the European Union, Japan, South Korea, Australia, and the USA, the site characteristics are a key factor of successful EGS development. Moreover, clear identification of the best-suited exploitation technology for a given site is also of major importance. Consequently, this research focuses mainly on the usage of existing infrastructure thereby avoiding a necessary drilling phase, which according to the literature and experts represents more than 40% of the capital expenditure (CAPEX).

Previous research is focused either on economic assessment, as summarized in (Olasolo, et al., 2016) or environmental assessment based on the life cycle environmental impact of geothermal power generation as studied in (Clark, et al., 2012) and (Bayer, et al., 2013). Considering a specific EGS site, the amount of recovered energy and consequently realized revenue from produced electricity or heat, depends not only on the local geological conditions like stress field, geothermal gradient, rock composition, the range of existing permeability, reservoir properties but also on the economic, environmental, social constraints and regulatory framework. The legislative and socio-economic overview on geothermal energy issues is available in (De Jesus, 1995), (Cataldi, 1997). While public and political acceptance issues is to be found in (Popovski, 2003). The environmental and sustainability issues of geothermal energy are discussed and analysed in (Rybach, 2003), (Ármannsson, 2003). This requires a holistic approach which should consider many influencing factors, from choosing the right extraction technology to the analysis of energy prices and market signals. A decision must be made timely, based on the issue which generates financial flows over a long period of time. The forecasted data is a necessity in order to account for future states of knowledge. Therefore, the DMS-TOUGE will be developed. Chapter 2. describes the study approach applied in this research, in Chapter 3 the methodology is explained with the basic overview of the tool's architecture, and in Chapter 4 the main conclusions are given.

2. STUDY APPROACH

The DMS-TOUGE will be capable of site-specific environmental and economic analysis with the focus on low-enthalpy energy from co-produced hot water and it will consider: existing infrastructure or future facilities, extension or upgrade, co-use/re-use of existing boreholes, different geological features such as sedimentary rocks, granitic rocks, volcanic and potential geothermal wells. Furthermore, the developed DMS-TOUGE will be useful for the decision makers involved in projects associated with: applications of EGS techniques to nearly unexploited reservoir types (Variscan orogenic belt) by means of doublets, increasing the productivity of existing power plants by reinjection of geothermal fluids with a colder temperature combined with the generation from the small-scale ORC units, and usage of hot fluids from mature and abandoned oil fields for electricity or heat production.

The DMS-TOUGE will be capable of using both internal and external data entered by a decision maker (DM), such as: water temperature, geothermal capacity, electricity and heat prices, injection water flow rate values, technology details on turbine, generator type, heat exchangers, working fluid or type of extraction technology (injector-producer doublets, wellbore heat exchanger) risk analysis (thermal effect, possible appearance of scaling, radioactive deposits, mechanical evolution of casing) or environmental data (CO_2 emission schemes, security of energy supply issues).

3. METHODOLOGY

The main core of DMS-TOUGE is a convex mathematical program which provides a global optimum (the integrity of the results is of high importance) (Rockafellar, 1974). The possible financial losses due to worst-case scenarios will be mitigated by conditional value-at-risk (CVaR) (Rockafellar & Uryasev, 2002). The choice, which technology to use at the particular geothermal site is a result of optimization techniques to value and quantify them, it will quantify environmental and social impacts and also calculate sLCOE (system levelized cost of electricity) of technology in order to find the best-suited option for a given site. As a subprocesses of the main core, market (price) risks and technical issues are accounted for, such as thermal effects, scaling effect, radioactive deposits and mechanical effect of the casing through the CVaR risk measure. The verification and validation of DMS-TOUGE is of high importance and will be conducted on the comparison between tool output and real-life expert analyses on existing operating EGS sites. Output data will be in two forms, as raw data, or in a form of decisions suitable for decision makers and investors. For that needs the raw data will be processed by a special subprocess, a separate multiple-criteria decision-making (MCDM) process, into a decision. The schematic depiction of the main features of the

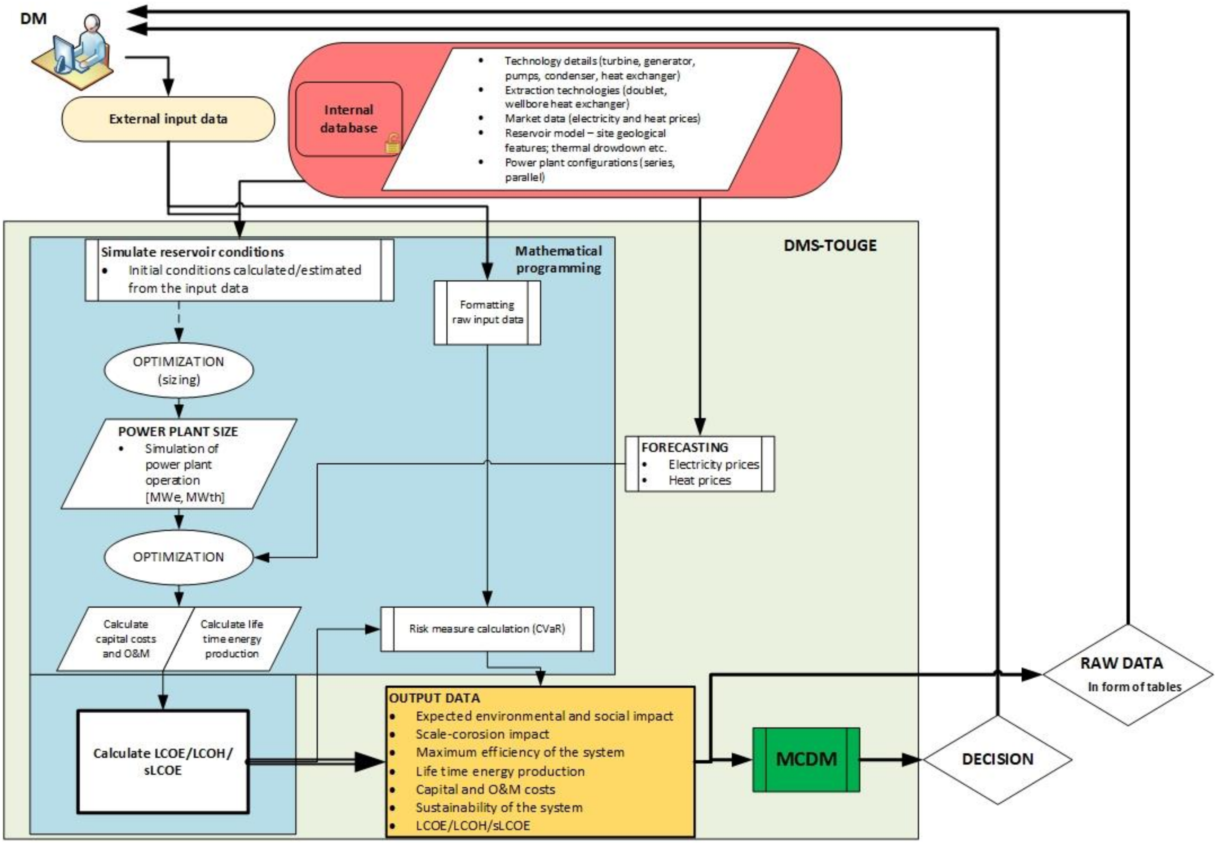

Figure 1: Schematic description of main processes in DMS-TOUGE

DMS-TOUGE is shown in Figure 1. The MCDM part will be described in sub-chapter 3.2.

3.1. Optimization model

After all the input data are submited, both external and internal, the optimisation takes place. Meaning the initial conditions, entered by the user or default values from the internal database, are used to estimate the input parameters for the first part of the optimization. Optimization consists of sizing of the possible power plant on the specific geothermal site. The design of the geothermal power plant needs to take into account the particular thermodynamic cycle, the pumps and the turbine, the heat exchanger and the cooling-system characteristics. The temperature, pressure of the geothermal fluid, the rejection temperature, the ambient temperature and the maximum rate of energy extraction that can be sustained without a significant decrease of the water temperature in the reservoir, can be considered as fundamental variables of the problem. Once the power plant size is determined, meaning that the installed power is calculated, the optimization of the operational life cycle of the sized power plant takes place. At this point, the optimal usage cycle of the installed power plant is calculated, and so are all the belonging capital, and operation and maintenance costs (O&M). The result of the optimization is the sLCOE, levelized cost of heat or levelized cost of energy, depending on the end-user option. (**Error! Reference source not found.**)

3.2. Multiple-criteria decision-making (MCDM)

For MCDM analysis in the DMS-TOUGE, the weighted decision matrix (WDM) will be used. In this subchapter, a set of criterions for valuing different EGS alternatives are defined. Each criterion has associated weight in order to value its relative importance in decision making. Performance, x_{ij}, of alternative i on criterion j is defined with a numerical value from 1 to 5, whose higher value means better performance, $x_{ij} \in \{1,2,4,5\}$. Finally, total performance, X_i, of i^{th} EGS alternative on all criteria, $\forall j$, is assessed by summing all performance values, x_{ij}, multiplied by its weight [1].

$$X_i = \sum_{j}^{J} w_j \cdot x_{ij} \quad [1]$$

where X_i is the total performance of i^{th} EGS alternative, $i \in I$, where I is a total number of EGS alternatives. The w_j is weight (here not quantified) i.e. relative importance in decision making of criterion j, $j \in J$, where J is a total number of criteria. The x_{ij} is the performance of alternative i on criterion j.

To use WDM successfully in assessing EGS alternatives for the particular geothermal site, a set of well-defined criteria is needed. The criteria on which EGS alternatives will be evaluated are:

1st criterion: installed power, $x_{i,1}$

Installed power is the first and most important parameter when considering energy investments (Soldo & Alimonti, 2015). It later determines both costs (CAPEX, OPEX-O&M) and revenues (power output). According to (Soldo & Alimonti, 2015), performance $x_{i,1}$ of alternative on 1st criterion should be determined by the P/P_r ratio in p.u. (ratio of installed power, P, of ORC technology in the *i*th alternative to the reference installed power, P_r, e.g. according to (Soldo & Alimonti, 2015) for ORC technology reference installed power is from 1 MW to 5 MW depending on site features) (Table I).

Table I: Performance values $x_{i,1}$ for 1st criterion

Ratio (*p.u.*)	$0 \leq P/P_r < 0.3$	$0.3 \leq P/P_r < 0.6$	$0.6 \leq P/P_r < 0.9$	$0.9 \leq P/P_r < 1.2$	$1.2 \leq P/P_r < \infty$
$x_{i,1}$	1	2	3	4	5

2nd criterion: fluid heat flow, $x_{i,2}$

Expected heat flow Q (W), for the two main extraction technologies, a traditional doublet with fluid extraction and reinjection, and wellbore heat exchanger, a closed loop system, is defined with

$$Q = q \cdot \rho \cdot c_p \cdot (T_H - T_C), \qquad [2]$$

where q is the fluid flow rate (m^3/s), ρ is fluid density (kg/m^3), c_p is heat capacity of fluid at constant pressure (J/kg·K). T_H is the fluid temperature at the wellhead (K), T_C is fluid temperature at exit of steam turbine (K). Heat flow criterion is the contribution of paper (Soldo & Alimonti, 2015) and is used here without modifications. The idea is to emphasize the importance of flow rate and temperature of the produced fluid and the impact of technology on flow rate and temperature. The (Soldo & Alimonti, 2015) proposes criterion, here referred as $x_{i,2}$, whose value is based on the ratio between the fluid flow rate, q, and flowing temperature at wellhead, T_H. According to (Soldo & Alimonti, 2015) best suited ranges for valuing performance $x_{i,2}$ in heat flow criterion are defined by flow rates between 0 m^3/h and 100 m^3/h and when temperatures are between 60 °C and 160 °C, since those ranges correspond to operative conditions for an ORC plant (Table II).

Table II: Performance values $x_{i,2}$ for 2nd criterion

Ratio	$1.67 \leq q/T_H < \infty$	$0.679 \leq q/T_H < 1.67$	$0.357 \leq q/T_H < 0.679$	$0.056 \leq q/T_H < 0.357$	$0 \leq q/T_H < 0.056$
$x_{i,2}$	1	2	3	4	5

3rd criterion: theoretical maximum efficiency, $x_{i,3}$

For electricity generation, the ORC power plants are prosed in this study. It is primarily due to the low-to-medium temperature range of the produced fluids. The thermal efficiency assessed at the heat exchanger of the conversion plant in such fields is usually less than 10%, and it could be calculated from temperature of the produced fluid T_H, for binary power plants as according to (Moon & Zarrouk, 2012):

$$\eta_{max} = 6.9681 \cdot \ln(T_H) - 29.713 \qquad [3]$$

However, in case that the other type of conversion plants is used the thermal exchanged cycle between the two fluids can be evaluated using Carnot's ideal efficiency. Therefore, in those cases, the expected theoretical maximum efficiency of conversion, η_{max}, is defined with the:

$$\eta_{max} = (1 - T_C/T_H) \cdot 100\%, \qquad [4]$$

and depends on the geological site features (the T_H part) and technology and environment features (the T_C part). The performance is valued as shown in Table III.

Table III: Performance values $x_{i,3}$ for 3rd criterion

Efficiency of conversion - ORC (%)	$\eta_{max} < 4$	$4 \leq \eta_{max} < 6$	$6 \leq \eta_{max} < 10$	$10 \leq \eta_{max} < 12$	$\eta_{max} \geq 12$
Theoretical max. efficiency (%)	$\eta_{max} < 30$	$30 \leq \eta_{max} < 40$	$40 \leq \eta_{max} < 50$	$50 \leq \eta_{max} < 60$	$\eta_{max} \geq 60$
$x_{i,3}$	1	2	3	4	5

4th criterion: geothermal gradient, $x_{i,4}$

When setting the starting point of the feasibility analysis the geological factors should be considered. The efficiency of the heat transfer through the wellbore is highly dependent on the reservoir's initial temperature, which is a function of well depth. Also, high thermal conductivity is required, so that the heat stored in the rocks could be transferred to the wellbore fluid. According to (AL-Mahrouqi & Falcone, 2016) these two influencing factors could be collectively combined and represented with geothermal gradient, G_T (°C/100m). The paper also suggested a range of geothermal gradient based on measured gradients for several analyzed oil fields across the world, which was taken for evaluating the performance $x_{i,4}$ in the geothermal gradient criterion (Table IV).

Table IV: Performance values $x_{i,4}$ for 4th criterion

Geo.grad. (°C/100m)	$G_T < 0.5$	$0.5 \leq G_T < 2$	$2 \leq G_T < 4$	$4 \leq G_T < 6$	$G_T \geq 6$
$x_{i,4}$	1	2	3	4	5

5th criterion: the fluid temperature at wellhead, $x_{i,5}$

According to (Soldo & Alimonti, 2015), this temperature is one of the main features of the geological site; it later determines installed power, technology, efficiency, revenues and costs. Performance $x_{i,5}$ of alternative on 5th criterion increases linearly depending on fluid temperature, T_H, (Table V). This research focuses on the utilization of temperatures from 60 °C to 160 °C (although upper bound for analyzed geo sites is expected at 90 °C) for cases of smart Organic Rankine Cycle (ORC) units.

Table V: Performance values $x_{i,5}$ for 5th criterion

Temp. (°C)	$T_H \leq 60$	$60 < T_H \leq 90$	$90 < T_H \leq 120$	$120 < T_H \leq 150$	$150 < T_H \leq \infty$
$x_{i,5}$	1	2	3	4	5

6th criterion: global efficiency, $x_{i,6}$

Aside from the geological setting and wellbore conditions, the supply of heat or/and power generation is directly connected to the performance of the conversion plant. Therefore, a global efficiency criterion should be established to evaluate the multi-stage heat loss within the conversion cycle and the impact of the ambient temperature on stored heat. According to (AL-Mahrouqi & Falcone, 2016) the total heat loss is addressed by means of coefficients of the different stages of the conversion cycle giving a conversion plant an overall performance evaluation.

$$\eta_{NCG} = 1 - 0.0059 \cdot C, \qquad [5]$$

$$\eta_{TPL} = 1 - P_{TLP}/P_{gross} \qquad [6]$$

$$\eta_{pipe} = 1 - 0.003 \cdot L_p \qquad [7]$$

Equations [3]-[7] represent those coefficients, where [5] represents the heat loss due to Non-Condensable Gases (NCG), where C is the estimates of NCG weight, because the presence of NCG can negatively impact the operation of the plant turbine. The [6] represents the parasitic load heat loss, including well pumps, cooling tower, condenser, where P_{TPL} is total parasitic load and P_{gross} gross thermal power. Moreover, [7] is used to cover the parasitic loss during the working fluid transport where the L_p is the pipe length. Global efficiency is then calculated according to the equations [8]-[10], where [8] represents evaluation of electricity generation, [9] is used to evaluate combined heat-electricity production (CHP) projects, where the second heat exchanger is required to exploit the remaining thermal power of geothermal water into another district heating fluid, and [10] represents evaluation of direct usage, district heating (DH) projects. Moreover, to measure the operational performance of the turbine and the generator, η_t and η_g, were included.

$$\eta_{G(E)} = \eta_{max} \cdot \eta_{NCG} \cdot \eta_t \cdot \eta_g \cdot \eta_{TPL} \cdot \eta_{pipe} \qquad [8]$$

$$\eta_{G(CHP)} = \eta_{max1} \cdot \eta_{NCG} \cdot \eta_t \cdot \eta_g \cdot \eta_{TPL} \cdot \eta_{pipe} \cdot \eta_{max2} \qquad [9]$$

$$\eta_{G(DH)} = \eta_{max} \cdot \eta_{pipe} \cdot \eta_{TPL} \qquad [10]$$

Table VI: Performance values $x_{i,6}$ for 6th criterion

Global efficiency	$\eta_G < 0.2$	$0.2 \leq \eta_G < 0.3$	$0.3 \leq \eta_G < 0.4$	$0.4 \leq \eta_G < 0.5$	$\eta_G \geq 0.5$
$x_{i,6}$	1	2	3	4	5

7th criterion: corrosion and scaling hazard, $x_{i,7}$

The corrosive or scaling tendency of the geothermal site is evaluated with the Langelier Saturation Index (LSI) (Table VII). The LSI later determines O&M costs. The less the LSI, the better the performance of the alternative will be (see (Soldo & Alimonti, 2015)).

Table VII: Performance values $x_{i,7}$ for 7th criterion

LSI	$1.5 < LSI \leq 2$	$1 < LSI \leq 1.5$	$0.5 < LSI \leq 1$	$0 < LSI \leq 0.5$	$LSI = 0$
$x_{i,7}$	1	2	3	4	5

8th criterion: distance from the power/heat grid, $x_{i,8}$

Construction of power lines and substations presents significant costs and should be addressed accordingly. Therefore, the distance between the geothermal power plant production site and the nearest power and/or district heating system connection point must be addressed. Depending on that distance d (km), the investment costs and also sLCOE vary. Apart from the distance, considering that the grid connection costs are site-specific, there are many other factors that have an impact on the investment costs. Due to the complexity if all the factors were included, the main influencing factor, namely the distance, was taken for the evaluation of the performance $x_{i,8}$. The range is shown in the next table (Table VIII), finishing with the most favored onsite use, respectively a very small distance between the power plant facility and the grid connection point.

Table VIII: Performance values $x_{i,8}$ for 8th criterion

Distance (km)	$d > 4$	$3 \leq d < 4$	$2 \leq d < 3$	$1 \leq d < 2$	$d < 1$
$x_{i,8}$	1	2	3	4	5

9th criterion: district heating, $x_{i,9}$

Combined heat production and the power generation increases the net efficiency of the power plant, which in turn improves power plant economics. This is even more important in the case of geothermal plants, where thermodynamic efficiencies are typically much lower compared to conventional power plants, due to the lower working fluid temperatures. Considering direct-use systems, heat is only supplied to the process, the greenhouse, the building, etc., when it is needed. As a result, according to the research-driven in (Rafferty, 2003), the load factor, f_L, can vary from 15% to 75% depending on the application. The (Rafferty, 2003) examined the costs of the delivered heat as a function of a load factor for U.S. climates, which are comparable with the European climates. Knowing that industrial applications can have a load factor of 0.30 to 0.75, the space heating only application 0.15 to 0.20, aquaculture 0.50 to 0.80 and greenhouses 0.18 to 0.24, the results showed that the high load factor correlates with lower cost of delivered heat and consequently affects the project's economic feasibility and sLCOE. Based, on forenamed results, the range for performance $x_{i,9}$ of alternative is determined and shown in the Table IX.

Table IX: Performance values $x_{i,9}$ for 9th criterion

Load factor	$f_L \leq 0.2$	$0.2 < f_L \leq 0.4$	$0.4 < f_L \leq 0.6$	$0.6 \leq f_L \leq 0.8$	$0.8 < f_L \leq 1$
$x_{i,9}$	1	2	3	4	5

10th criterion: sLCOE, $x_{i,10}$

The average cost of the project over the lifetime will be addressed by the sLCOE (system LCOE) which also accounts for the costs of integration. Performance $x_{i,10}$ of alternative on sLCOE criterion is determined by the sLCOE$/\overline{\pi}$ ratio in p.u. (ratio of sLCOE of ORC technology in the *i*th alternative to the average market price, $\overline{\pi}$, in different forecasts and for different horizons (Table X).

Table X: Performance values $x_{i,10}$ for 10th criterion

Ratio	$1 \leq sLCOE/\overline{\pi} < \infty$	$0.8 \leq sLCOE/\overline{\pi} < 1$	$0.6 \leq sLCOE/\overline{\pi} < 0.8$	$0.4 \leq sLCOE/\overline{\pi} < 0.6$	$0 \leq sLCOE/\overline{\pi} < 0.4$
$x_{i,10}$	1	2	3	4	5

11th criterion: social impact, $x_{i,11}$

According to (De Jesus, 1995) the social acceptability is conditioned by the deviation from the regular condition in the area and utility of the affected parties from the project. As geothermal technologies are site-specific (the geology is different all over Europe and knowledge of the local conditions is essential) and capital-intensive, the needs regarding exploration, resource development, construction, and O&M are covered by the local workforce. According to (Cataldi, 1997) the costs of social acceptance could be presented as the external costs of a geothermal project. Depending on the site, type and size of the project the amount of those external costs range, on the average, between 17-220×10³ € and 265-7040×10³ €, for direct use and multi-purpose projects, respectively. Moreover, employment potential could be divided into direct, indirect and induced employment effect and quantified in terms of full-time jobs/MW and person*years of construction and manufacturing employment (Table XI). Total direct, indirect and induced employment ratio is a ratio of the installed capacity (MW) and full-time jobs calculated previously from the function [11] (shown in **Figure 2**).

Equation [12] represents construction and manufacturing employment, where those jobs are expressed as full-time positions for one year ($person * year$). However, those C&M jobs are spread over several years depending upon the development time frame for the new projects.

$$FT\ jobs = log_{1.068}(P_{inst.}) \qquad [11]$$

$$C\&M\ jobs = 22.4 \cdot P_{inst.} \qquad [12]$$

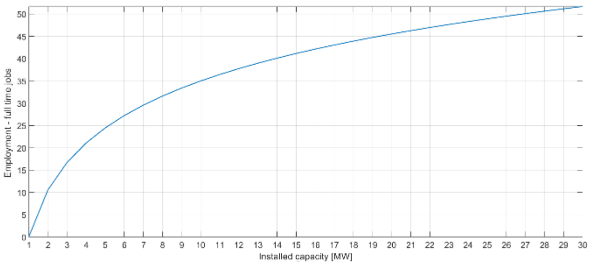

Figure 2: Total employment- full-time jobs function

Table XI: Performance values $x_{i,11}$ for 11th criterion

Social acceptance costs direct use $(€ \cdot 10^3)$	$sac_{d.u} > 295$	$145 < sac_{d.u} \leq 295$	$30 < sac_{d.u} \leq 145$	$4.5 < sac_{d.u} \leq 30$	$sac_{d.u} \leq 4.5$
$x_{i,11,1}$	1	2	3	4	5
Social acceptance costs Combined heat – electricity $(€ \cdot 10^3)$	$sac_{CHP} > 6155$	$2640 < sac_{CHP} \leq 6155$	$880 < sac_{CHP} \leq 2640$	$350 < sac_{CHP} \leq 880$	$sac_{CHP} \leq 350$
$x_{i,11,2}$	1	2	3	4	5
Employ-ment FT ratio $\left(\frac{dFT}{dP_{inst.}}\right)$	$erFT < 1$	$1 \leq erFT < 1.5$	$1.5 \leq erFT < 2$	$2 \leq erFT < 4$	$erFT \geq 4$
$x_{i,11,3}$	1	2	3	4	5
Employ-ment C&M	$e_{C\&M} \leq 50$	$50 < e_{C\&M} \leq 150$	$150 < e_{C\&M} \leq 250$	$250 < e_{C\&M} \leq 350$	$e_{C\&M} > 350$
$x_{i,11,4}$	1	2	3	4	5
Total social impact	$AV \leq 1$	$1 < AV \leq 2$	$2 < AV \leq 3$	$3 < AV \leq 4$	$4 < AV \leq 5$
$x_{i,11}$	1	2	3	4	5

12th criterion: environmental impact, $x_{i,12}$

According to (Soldo & Alimonti, 2015) the environmental impact should account for the impact on sustainability, landscape, subsidence, potentially induced micro-seismicity and also account for the amount of noise, atmospheric emissions, potential water contamination, and radioactivity. The fluid extraction could cause subsidence because of reservoir pressure decline. This is measured in mm/year of soil decay. Moreover, the pore pressure reduction in production and increase in reinjection operations have been associated with increased induced seismicity, often microseisms of low energy (< 2-3 M Richter scale) (Soldo & Alimonti, 2015). According to (Zang, et al., 2014), the ranges for this sub-criterion were assigned. The impact on the landscape is measured as land use intensity (LUI) for installed power in m^2/kW, and the range was estimated according to the (Johansson, et al., 2012). The noise impact during routine operation is mainly caused by cooling towers and electrical transformers, but it is acceptable, typically 71-83 dB at 900 meters according to (DiPippo, 1991). When considering atmospheric emissions, closed cycles, such as binary plants, have no gaseous emissions or they are close to zero and so do not contribute to air pollution. Considering that the objects of this research are closed-loop binary plants, the impact on surface waters can be excluded. Groundwater contamination may occur if the casings in reinjection wells should fail, allowing fluid to leak. According to WHO, the range of total dissolved solids (TDS) and pH values was determined for the quantification of this sub-criterion. Radioactivity is mainly caused by interaction between the geothermal fluid and certain formations containing radioactive elements. As emphasized in (Johnson, 1991), generally, the content of radionuclides in acidic magmatic rocks is higher compared to sedimentary rocks. Furthermore, uranium (U) and thorium (Th) are the most common radioactive elements found in granites. The environmental impact criterion will be obtained by the average of performances of the following sub-criterions: $x_{i,12,1}$ subsidence sub-criterion, $x_{i,12,2}$ potential seismicity sub-criterion, $x_{i,12,3}$ land use sub-criterion, $x_{i,12,4}$ noise sub-criterion, $x_{i,12,5}$ potential water contamination sub-criterion and $x_{i,12,6}$ radioactivity sub-criterion. Each sub-criterion will be evaluated with a weight in a range from 1 to 5. (Table XII)

Table XII: Performance values $x_{i,12,j}$ for 12th criterion according to (Soldo & Alimonti, 2015), (Zang, et al., 2014), (Johansson, et al., 2012), (DiPippo, 1991) and (Johnson, 1991)

Subsidence v_h $(mm/year)$	$v_h \geq 100$	$100 > v_h \geq 60$	$60 > v_h \geq 40$	$40 > v_h \geq 20$	$v_h < 20$
$x_{i,12,1}$	1	2	3	4	5
Potential seismicity $PGV\ (cm/s)$ $PGA\ (cm/s^2)$	$0.5 \leq PGV \leq 1.6$ $9 \leq PGA \leq 43$	$0.2 \leq PGV \leq 0.6$ $4 \leq PGA \leq 18$	$0.07 \leq PGV \leq 0.23$ $1.5 \leq PGA \leq 7.3$	$0.03 \leq PGV \leq 0.09$ $0.6 \leq PGA \leq 3$	$0.01 \leq PGV \leq 0.02$ $0.2 \leq PGA \leq 1.2$
$x_{i,12,2}$	1	2	3	4	5
Land use (m^2/kW)	$LUI > 40$	$40 \geq LUI > 30$	$30 \geq LUI > 20$	$20 \geq LUI > 10$	$LUI \leq 10$
$x_{i,12,3}$	1	2	3	4	5
Noise (dB)	$dB \geq 100$	$100 > dB \geq 90$	$90 > dB \geq 80$	$80 > dB \geq 70$	$dB < 70$
$x_{i,12,4}$	1	2	3	4	5
Potential water contamination $TDS\ (mg/l)$ (pH)	$TDS \geq 1200$; $pH \leq 3$ or $pH > 8.5$	$900 \leq TDS < 1200$; $3 < pH < 4$	$600 \leq TDS < 900$; $4 \leq pH < 5$	$300 \leq TDS < 600$; $5 \leq pH < 6.5$ or $7.5 < pH \leq 8.5$	$TDS < 300$; $6.5 \leq pH \leq 7.5$
$x_{i,12,5}$	1	2	3	4	5
Radioactivity (ppm)	$2 \leq K^{40} < 6$; $1 \leq Th \leq 25$; $1 \leq U \leq 7$	$1.6 \leq K^{40} < 4.2$; $8 \leq Th \leq 18$; $1.5 \leq U \leq 5.5$	$0.2 \leq K^{40} < 2$; $0.5 \leq Th \leq 10$; $0.2 \leq U \leq 0.4$	$0.7 \leq K^{40} < 3.8$; $0.7 \leq Th \leq 3.8$; $0.2 \leq U \leq 0.6$	$0 \leq K^{40} < 2$; $0.1 \leq Th \leq 7$; $0.1 \leq U \leq 9$
$x_{i,12,6}$	1	2	3	4	5
Total environmental impact	$AV \leq 1$	$1 < AV \leq 2$	$2 < AV \leq 3$	$3 < AV \leq 4$	$4 < AV \leq 5$
$x_{i,12}$	1	2	3	4	5

4. CONCLUSIONS

In this paper the main characteristics of the decision-making support tool for enhanced geothermal systems integration into energy systems are briefly presented. The decision-making support tool evaluates the technical and economic feasibility of the particular project. The tool will, among others, provide sLCOE of the selected technology, environmental and social impact. The obtained results will later be used for mapping of several layers (of the main promising European sites where EGS can or should be implemented in a near future) in different resolutions: EU wide layer, layer considering different geologic features and pilot site layer. The developed tool will be useful for the decision makers involved in enhanced geothermal systems projects associated with applications to nearly unexploited reservoir types (Variscan orogenic belt). Next steps in tool development are incorporation of most of relevant decision-making parameters, testing its capabilities and subsequent verification and validation of the tool. Its proper function is of key importance for few work packages and several deliverables of H2020 project in which framework this tool is being developed.

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