The environmental impact of renewable energy technologies shown in case of ORC-Based Geothermal Power Plant

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Abstract. Considering energy as one of the basic needs essential for proper functioning of countries, new technologies are developed and evaluated. Providing various energy services – such as electricity, heating and cooling – forces the use of the available energy sources, both fossil and renewable. While the environmental impact of technologies based on fossil energy sources is widely known, those based on renewable sources already less. Considering the life cycle assessment (LCA), it is possible to assess the real impact of renewable energy technologies on the environment and human health. This paper presents an optimization model of Organic Rankine Cycle (ORC) geothermal power plant. The optimal design and configuration of geothermal conversion systems have been conducted by taking under evaluation process integration techniques combined with life cycle assessments (LCA) methods. This approach allowed for the optimization of this ORC technology system used for conversion of geothermal source and to estimate its impact on the environment using a various of LCA's methods. The research was conducted for different working fluids.

1. Introduction
Environmental impacts are an integral part of producing and providing different energy services, such as electricity, district heating and cooling. Various studies had shown that energy production from fossil-fuels sources has greater negative effect on the natural environment and human health than renewable energy sources. What is probably the most important argument for changing energy conversion technologies based on fossil fuels to those based on renewable sources. At the same time, it seems to be important not to forget that even renewable energy technologies can have an negative impact on the environment [1]. The method and approach used in evaluation environmental impact of given technology have significant influence on obtained results.

Life cycle assessment (LCA) is common use to estimate the overall energy usage and environmental impact of given technologies. The evaluation of the environmental impact by LCA method is based on ‘from cradle to grave’ approach, which means that all stages (raw materials extraction, refinement, construction, use, and disposal) of give technology lifetime are taken under consideration during evaluation. Despite this approach, there is no established standard for carrying out such analysis which may cause some difficulties in comparing the environmental impact of different technologies. LCA studies provided estimation about life cycle emission of GHG in CO₂e and shown that solar PV technologies have one of the highest through renewable energy technologies
(from 21 to 71 g CO$_2$e/kWh) [2-4]. The CO$_2$e emission from biomass is affected by various factor such as feedstock, conversion technology used but also yield, fertilizer, fuel used and mostly its estimate from 15 to 52 g CO$_2$e/kWh [4,5]. Some authors claim that biomass can act as GHG sink and have "negative" CO2e emissions [6]. In case of geothermal conversion technologies most papers focus on SO$_2$ emissions [7] but there can be find studies presented process integration with LCA integration for such systems [8] or traditional LCA analysis, which shows small CO$_2$e/kWh emissions (15 g CO$_2$e/kWh for double-flash geothermal conversion technology) [2]. Also, the use of conventional hydropower and wind technologies are estimated as low emitters during its life time [2,4,9].

Different approach to environmental impact of renewable energy technologies proposes a system of systems (SoS) framework, which estimate the relative aggregate footprint (RAF) based on previously determined performances values. The integration various footprint indicators (carbon footprint, water footprint, land footprint and cost) in the RAF index, aims to provide a deeper understanding of the overall negative impacts of given technology [1].

![Figure 1. Relative aggregate footprint (RAF) of different energy sources (0–100) [1].](image)

The estimation of RAF index for various renewable and non-renewable technologies was present in figure 1. The study suggest that the geothermal energy seems to be the most promising one in terms of SoS framework, while from miscanthus - the least. Moreover, evaluation shown that some of renewable energy technologies are less promising than non-renewable one from SoS approach - despite their lower carbon footprint. It is caused by consideration not only GHG emissions but also water and land use with costs [1, 10-12].

In this paper the development of systematic methodology for integration thermo-economic model with LCA is presented. The evaluation of the environmental impact has been done for optimal design of geothermal conversion system. Modeled here overall geothermal conversion system consist from three parts: the superstructure of the geothermal exploitable resources - in this case the enhanced geothermal resource (EGS) has been chosen, the superstructure of conversion technology – organic Rankine cycle (ORC) and the demand profile for energy services (table 1).
Table 1. The demand profiles parameters for city Nyon in Switzerland [13].

| Demand profile  | Load [kW] | Supply temperature [°C] | Return temperature [°C] | Operating time [h] |
|-----------------|-----------|-------------------------|-------------------------|-------------------|
| Summer          | 200       | 60                      | 25                      | 525               |
|                 | 300       | 25                      | 21                      |                   |
| Interseason     | 150       | 60                      | 32                      | 3942              |
|                 | 500       | 32                      | 26                      |                   |
|                 | 300       | 28                      | 26                      |                   |
| Winter          | 100       | 60                      | 50                      | 4205              |
|                 | 1200      | 50                      | 40                      |                   |
|                 | 100       | 40                      | 34                      |                   |
|                 | 700       | 34                      | 28                      |                   |
|                 | 100       | 28                      | 20                      |                   |
| Extreme winter  | 100       | 75                      | 65                      | 88                |
|                 | 1750      | 65                      | 50                      |                   |
|                 | 150       | 50                      | 40                      |                   |
|                 | 1000      | 40                      | 32                      |                   |
|                 | 100       | 32                      | 10                      |                   |

The demand profiles for district heating are provided for residential area of city Nyon in Switzerland. The demand profile for district heating has been divided into four periods (summer, interseason, winter, extreme winter) to better present annual changes of the heat demand in the city. The generation of electricity is not limited by any demand and is treat as additional good in discussed system. During system optimization, the specific LCA data has been used [14], also the LCA methodology is based on different studies [15,16].

2. Methodology

The diversity of the works, in which evaluated the environmental impact of energy technologies using LCA has been presented above - however, to a large extend, these are works describing the use of LCA in context of product design [17]. It is much harder to find works which describe the methodology to conduct LCA into an optimization analysis. The works describing multi-objective optimization with trade-offs between environmental and economic performance indicators are limited. The problem, which seems to appeared very often in these works, is not to include multi period approach in energy system design [18-20]. Multi-objective optimization in the field of energy systems can be find in Papendreoun and Shang [21], while Li et al. [22] and Bernier et al. [23] considered the LCA use in a multi-objective optimization with energy integration techniques. In case of geothermal conversion systems, the methodology to identified optimal exploitation scheme has been presented [24]. However, the LCA methodology was not taken under account and there is no possibility to estimate environmental impact in those cases.

In this paper the geothermal conversion system design has been presented as multi-period problem, which means that it should be considered with seasonal variations of the energy demand. In practice, the calculation sequence is applied separately for each seasonal variation of the demand and then propose for them different seasonal variations. The general concept of computational framework is shown at figure 2.
Figure 2. Computational framework [25].

Separately modeled subsystems (the superstructure of exploitable resource, the superstructure of usable technology and demand profile) are integrate together by using the process integration techniques. However, the superstructure of geothermal conversion system is built with developing not only thermo-economic model but also life cycle assessment. Based on that performance indicators for single period are calculated. The procedure of calculation is repeated for each period and then combined performances for system are evaluated. Finally, the evolutionary-algorithm is launched for running multi-objective optimization.

2.1 LCA model

LCA model evaluating potential environmental impact of given system has been prepared based on standard methodology [26,27]. It was assumed that during LCA analysis, system will be evaluated in frame of the whole lifetime. Those ‘cradle-to-grave’ approach means that all phases (construction, operation and decommissioning) are taken under consideration in modeling.

LCA model consists from main stages, which are listed at figure 3 and briefly described below.

Figure 3. Representation of the major step to be conducted in LCA.
In first step, the goal and scope of this study should be defined – from point of this project the most important is to find the most environmental friendly process configuration, where the negative impact will be minimized. For this purpose as the functional unit (FU) of the system – 1 kWh available from the exploitable geothermal resource has been chosen. The system boundaries are determined by the life of geothermal plant and it means that three main phases (construction, operation and dismantling) are taken under consideration.

In second stage (Life Cycle Inventory) every flow of extraction and emission, which influence process, has been identified and quantified (figure 4). The different material and energy flows of the LCI are identified based on the examined systems. Ecovinvent® life cycle inventories database is used to determine the equivalence for each flow. The identified LCA flows are quantified and each flow is represented as function of design and scale parameters. This approach causes that scaled emissions and impact are returned as an output.

![Figure 4. Flows of environmental concern in block diagram for EGS ORC-Based Organic Rankine Cycle.](image-url)

During the Life Cycle Impact Assessment stage – the emission and extraction identified and quantified previously are cumulated to create global indicators. At the end, the obtain results are interpreted.

2.2 Multi-period strategy

This study focus on multi-period strategy, which is used in optimization. This mean that the calculation sequence is run for each period separately and the overall system evaluation is launched for each period. This approach causes that for each period different performance indicators are obtained and after that they are aggregate together to obtain global performances.

The use of multi-period strategy in modeling gives opportunity to observe the changes, which occurred in each period and stage of life cycle. This approach also help during designing process – reasonable design of the core system and the auxiliary system when demand increase (in extreme winter).

Global performances of total impact are calculated according ‘as in equation 1’.

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\[ I_{\text{tot}} = \sum_{p=1}^{n_p} \sum_{i=1}^{n_{eo}} I_{o,i,p} + \sum_{i=1}^{n_{ec}} \max(I_{c,i})_p + \sum_{i=1}^{n_{ee}} \max(I_{e,i})_p \] (1)

Where: \(I_{\text{tot}}\) – the total impact of the system, \(n_p\) – number of the periods considered in the problem, \(n_{ec}\) – the number of LCI elements belonging to the construction phase, \(n_{eo}\) – the number of LCI elements belonging to the operation phase, \(n_{ee}\) – the number of LCI elements belonging to the end-of-life phase, \(I_c\) - the impact of the construction phase, \(I_o\) - the impact of the operation phase, \(I_e\) - the impact of the end-of-life phase.

2.3 Objective function

During multi-objective optimization there have been considered three types of performance indicators: the thermodynamic, economic and environmental (calculated based on life cycle assessment). Research presented in this paper focuses only on thermodynamic and environmental criteria and so as performance indicator the exergy efficiency and the environmental impact have been chosen.

Selecting the exergy efficiency as the thermodynamic performance indicator is dictated by that this indicator takes under account environment. The exergy efficiency is described as the ration between the output exergy to the input exergy, and is presented below ‘as in equation 2’:

\[
\eta = \frac{\sum_{p=1}^{n_p} \dot{E}_p^+ t_p + \sum_{p=1}^{n_p} \dot{E}^x t_p}{\sum_{p=1}^{n_p} \dot{E}^x t_p} 
\] (2)

Where: \(\dot{E}^-\) - the electricity produced by overall system during period \(p\), \(t_p\) – the duration of the period \(p\), \(\dot{E}^x^+\) - the exergy transfer to the district heating during period \(p\).

To evaluate the environmental performance indicator, the total impact of overall geothermal conversion systems is selected. The equation for calculating the specific impact generated per kWh of district heating is presented ‘as in equation 3’:

\[
I_O = \frac{\sum_{p=1}^{n_p} \dot{E}_p^+ t_p + \sum_{p=1}^{n_p} \dot{E}^x t_p}{\sum_{p=1}^{n_p} \dot{E}^x t_p} 
\] (3)

Where: \(I_O\) - the impact due to the operation phase for period \(p\) of the LCI element \(i\), \(n_{eo}\) – the total number of LCI elements from the operation phases, \(I_c\) – the impact due to construction phase of the element \(I\) for period \(p\), \(n_{ec}\) – the total number of LCI elements from the construction phases, \(I_e\) – the impact due to end-of-life phase of the element \(I\) for period \(p\), \(n_{ee}\) – the total number of LCI elements from the end-of-life phases, \(t_{life}\) – the overall lifetime of the geothermal system (in this study it was assumed 40 years).

2.4 Case study application

The presented methodology of integration LCA into thermo-economic model can identify optimal model of conversion system and evaluate the environmental impact of it. This study shows described methodology in case of extraction heat from enhanced geothermal system (EGS) with the use of ORC-based power plant. To modeled the geothermal resource, the linear geothermal gradient has been selected – it helped to evaluate the geothermal temperature profile, which is representative for Swiss Plateau. The demand profile has been based on the real one for city Nyon and has been shown in table 1.
It has been chosen that multi-objective optimization will be performed to show the trade-offs between the exergy efficiency and the environmental impact. From process point of view, the aim is to maximize the exergy efficiency and minimize the negative environmental impact. To process optimization some decision variables has been selected and thus: the evaporation temperature (in range 80 - 120°C), the superheating temperature (in range 120-230°C), the depth (in range 3000-6000 m) and the reinjection temperature (in range 70-110°C).

Seven different working fluids for ORC-based geothermal power plant had been selected and multi-objective optimization was launched for all of them. To calculated the environmental impact of described system three LCA methods has been used: Ecological Footprint, Impact 2002+ and Cumulative Energy Demand.

3. Results and discussion

To determine the environmental impact and the optimal configuration of presented system a three LCA methods has been used, these are: Ecological Footprint, Impact 2002+ and Cumulative Energy Demand. In each case, the calculation has been launched for seven different working fluids: benzene (BZ), cyclo-butane (CYC4), iso-butane (IC4), iso-pentane (IC5), n-butane (NC4), n-pentane (NC5), toluene.

The ecological footprint method is used to evaluate the impact and in short is defined as the aggregate water and land, which are required to regenerated used by human resources. In our case, using iso-butane as working fluid results in saving about 0,244 m²/a per each kWh generated (figure 5) and in this context iso-butane is recommended as working fluid. Moreover, The evaluation shows that all working fluid can be used with beneficial impact on environment.

Using the Impact 2002+ methodology in optimization also shows that all used working fluids have good influence on environment. This method has a lot common with the most popular LCA method – Ecoindicator99-(h,a) – both methods take under consideration the same impact categories, such as: human health, exocystem quality and resources. However, in Impact 2002+ is added a one new one – the climate change. The other difference between methods is that the Ecoindicator99-(h,a) method is using the damage oriented approach, while in the Impact 2002+ is used the combination of damage approach and a problems (midpoints). The various in approaches, which occurred in methods, cause different results – even when the same impact categories are evaluated.

![Pareto curve for Ecological Footprint.](image)
It can be seen the increment of the exergy efficiency with the decrease of the reinjection temperature (figure 6) – this dependence is associated with treating the reinjection temperature as hot source low temperature. In this case, the lower reinjection temperature is, the higher – exergy efficiency. This method also has been showing that the most suitable working fluids is iso-butane.

![Figure 6. Pareto curve for Impact 2002+](image)

The third used method is the Cumulative Energy Demand (called also Cumulative Energy Requirements Analysis - CERA), which investigate the use of energy through the life cycle of our ORC-based power plant (from construction, through operation to end-of-life). This method takes under account not only the direct use of energy but the use of green or indirect, e.g. during transport raw materials. The results of multi-objective optimization with using CERA as LCA method are presented in figure 7 below. As it was evaluated before, also in this case all working fluids can be used without adversely affecting the environment. Both from environmental and thermodynamic point of view iso-butane is the most suitable working fluid.
Figure 7. Pareto curve for Cumulative Energy Demand.

The analysis shows that in given case major impact contribution on results have not only used conversion system (ORC) but also the extraction of brine from EGS system. And thus, the major impact contributions from ORC site have: working fluid loss and electricity produced, working fluid loss at decommissioning, while from EGS system: steal high-alloyed and low-alloyed for casing, components, diesel used for reservoir enhancement, starch used for drilling mud, water used for reservoir enhancement, diesel used drilling mud and remaining processes.

4. Conclusion
This paper presents the methodology developed for LCA integration with thermo-economic model to obtain not only optimal design of geothermal conversion system but also to evaluate the environmental impact of this proposed, optimal design. Additionally, in the proposed methodology the multi-period approach has been used, which gives an insight into optimal structure during each season and its impact on environment.

The methodology has been applied for optimal working fluid selection for ORC cycle, which convert energy from EGS system. The described system has been proposed for city Nyon in Switzerland to satisfy its heat demand. The calculation has been launched for three different LCA methods: Ecological Footprint, Impact 2002+ and Cumulative Energy Demand and for all of them showed that all analyzed working fluid have beneficial influence on environment. However, iso-butane is recommended most in this case due to the highest exergy efficiency and beneficial influence on environment.

During the single run resolution it was clear that the impact of construction and end-of-life phases can be harmful on environment, while operation – beneficial. This can be a direction for the future, what should be thoroughly analyzed during designing.

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