Substitution Approach in Carbon Dioxide Emission Reduction Evaluation: Case Study on Geothermal Power Station Project Plan – Šúrakov (Košice Basin, Slovakia)

Branislav Fričovský, Stanislav Jacko Jr., Miroslava Popovičová, and Ladislav Tometz

Abstract—Application of substitution approach (fossil fuels heat and power production duty essential in high CO\textsubscript{2} emissions is replaced by low-emissions based geothermal source in the same process at the same intensity) in CO\textsubscript{2} emission reduction potential analysis for proposed cogeneration Šúrakov power station project is presented in the paper. Project can contribute relevant in project economical considerations. Potential analysis for proposed cogeneration same process at the same intensity) in CO\textsubscript{2} is replaced by low-emissions based geothermal source in the heat and power production duty essential in high CO\textsubscript{2}.

Index Terms—Carbon dioxide savings, Šúrakov power station project, geothermal energy, implementation approach.

I. INTRODUCTION

Recent concern in environmental aspects of increasing energy demand, responding to global scientific and public consensus on disturbances in natural CO\textsubscript{2} cycle, triggers actions and policies regarding renewable energy sources introduction into primary energy mix worldwide.

Pioneer studies in 1965 – 1969 defined the Šúrakov area as the most appropriate for geothermal power production in Slovakia [1]. However, there is no project that operates nowadays. Besides high T.D.S. content in brine, conflicts of interests or technical limitations, any existence of geothermal power station reflects typical feature of complex projects – high investment costs and initial economical uncertainties [2]. CO\textsubscript{2} savings derived environmental subsidies become relevant in project economical considerations.

Submission evaluates CO\textsubscript{2} mitigation potential applying substitution approach for a cogeneration based – ORC geothermal power plant project in the Šúrakov area. Presented results can contribute on forthcoming enviro-economical studies once the project applies for global CO\textsubscript{2} credits market. Authors try to explain methodology and provide essential basement and implications for preliminary environmental and cost-effectiveness analysis in akin projects worldwide.

II. KOŠICE BASIN – CLIMATE AND PRIMARY ENERGY MIX

A. Climate

Located in the SE part of the East Slovakian Basin, the Košice Basin is dominant in climate conditions of warm regions, split into moderately humid (south) and moderately dry subregions (north), all surrounded from the east and west with moderately warm, humid, highland-type subregion [3] (Fig. 1), defining 220 heating days and 9.5 °C mean annual temperature [4].

B. Primary Energy Mix – Electricity and Heat Supply

Slovak Republic, high-advanced economy is still fossil fuels oriented, regarding a heat and electricity supply for industry or municipalities, where renewables cover 19.8 % of power and less than 7 % of heat production only (Table I) [5]. In the Košice Basin, considering district urban heat and power supply, fossil fuels control the whole market (Table II) [6].

| TABLE I: PRIMARY ENERGY MIX – HEAT AND POWER SUPPLY (SLOVAKIA) |
|-------------------------|-----------|--------|--------|---------|
| Primary energy          | Black coal | N. Gas | Oil    | Renewables |
| Heat                    | 23 %       | 53 %   | 12 %   | 7 %       |
| Power                   | 15 %       | 6 %    | 1 %    | 19.8 %    |

| TABLE II: PRIMARY ENERGY MIX – HEAT AND POWER SUPPLY (KOŠICE B.) |
|------------------------|-----------|--------|----------|
| Primary energy         | Black coal | N. Gas | Oil      |
| Heat                   | 85 %      | 15 %   | -        |
| Power                  | 60 %      | 28 %   | 12 %     |

III. ŠÚRakov GEOTHERMAL POWER STATION PROJECT

Geothermal sources in the Šúrakov area associate with Mesozoic carbonates at depths of 1250 – 2600 m [7], where temperature varies 100 – 150 °C (trend increases SE-wards). By now, three wells (GTD-1, GTD-2, GTD 3) are in a trial operation [8] identifying high saline fluids with total dissolved solids at 20 – 35 g.l\textsuperscript{-1} and 0.07 g.l\textsuperscript{-1} of free CO\textsubscript{2} [9].
Recent power station project plans to operate geothermal power plant with 2 exploitation (GTD-2, GTD-3) and 1 reinjection (GTD-1) wells at total 115 kg.s⁻¹ extraction rate and wellhead pressure of 1.4 MPa [10]. Call for energy efficiency improvements predefined the project to operate as cogenerating – a power production waste heat is then used in optimized district heating grid. High geothermal salinity limits the station to operate as binary (Organic Rankine Cycle based). While in a regard to national directives the power production counts the whole year, the district heating is optimized for 220 days – a number that corresponds to required mean temperature interval of -13°C to +13 °C.

Output parameters are outdoor temperature and comfortable indoor temperature in the district heating controlled thus vary in time as extracted brine mass diverts heat potential duty reaches 15 844 kW th and power turbine output counts 1 654 kW e, at minimum temperature (Tout = -13 °C) the heat output decreases to 6 628 kW th and power produced in the turbine turns to 3100 kW e (tab. III) However, turbine of installed power output over 3 394 kW e is required according to maximum output calculated for Tout of 2 – 4 °C [11].

Based on efficiency analysis of turbine inlet pressures and power output, a most proper working fluid for power turbine is n-Pentane, even of considerably higher costs in comparison to other fluids (e.g. Isobutane). N-Pentane allows ratio of real cumulative over gross cumulative savings lifetime LTgp turns to cumulative gross savings (CO2g_c). A ratio of real cumulative over gross cumulative savings expresses in reduction effectiveness ηR (5) [16]:

\[
\eta_R = \left( \frac{CO_{2_r,c}}{CO_{2g,c}} \right) \times 100
\] (5)

where: ηR – reduction effectiveness (%), CO2r,c – cumulative real savings, CO2g,c – cumulative gross savings.

### IV. METHODOLOGY

Several methods for CO2 emission reduction evaluation are introduced into praxis nowadays – e.g. [13], [14], mostly derived from peak-load analysis and substitution. The Đurkov project, however, operates as base-load. Consequently, here is the reduction understood as a mitigation process [4], resulting from emissive fossil fuels substitution either in a heat and power production by low emissive renewable – geothermal, in the same process at the same intensity [15].

Let us state the gross savings (CO2g) in combined heat and power production are bound to covered energy duty (Qed), local primary energy mix (Ppem) defining substitution rate for each fossil fuel, and fossil fuels emission factor (EFff) – (1)

\[
CO_{2g} = \sum \left( Q_{ed} \cdot P_{pem} \cdot EF_{ff} \right)
\] (1)

where: CO2g – yearly gross savings (tCO2 yr⁻¹), Qhp – heat and power duty (TJ yr⁻¹ or MWe yr⁻¹), Ppem – primary energy mix proportion (-), EFff – carbon dioxide emission factor of fossil fuels (tCO2 TJ⁻¹ or tCO2 MWe⁻¹).

Operation of geothermal power plant defines emissions produced – CO2p (2) during its run, controlled by duty of both processes (Qed) and emission factor of geothermal fluid (EFgeo) calculated from hydrogeochemical sampling:

\[
CO_{2p,c} = \sum \left( Q_{ed} \cdot EF_{geo} \right)
\] (2)

where: CO2p – yearly CO2 produced at the station (tCO2 yr⁻¹), Qhp – heat and power duty (TJ yr⁻¹ or MWe yr⁻¹), EFgeo – emission factor of geothermal source (tCO2 TJ⁻¹ or tCO2 MWe⁻¹)

Subtraction of CO2p produced from gross savings itinerary results in yearly real carbon dioxide savings – CO2r (3):

\[
CO_{2r} = CO_{2g} - CO_{2p}
\] (3)

where: CO2r – yearly real carbon dioxide savings (tCO2 yr⁻¹), CO2g – yearly gross CO2 savings (tCO2 yr⁻¹), CO2p – yearly CO2 savings produced at the site (tCO2 yr⁻¹).

If the average lifetime (LTgp) of cogeneration projects at 40 years is accepted [6], real savings expected at the end of operation period are projected as cumulative – CO2r,c (4):

\[
CO_{2r,c} = CO_{2r} \cdot LT_{gp}
\] (4)

where: CO2r,c – cumulative real savings (tCO2), CO2g,c – cumulative gross CO2 savings (tCO2 yr⁻¹), LTgp – lifetime (yr)

Substitution of yearly gross savings into (4) with preserved lifetime LTgp turns to gross cumulative savings (CO2g,c). A ratio of real cumulative over gross cumulative savings expresses in reduction effectiveness ηR (5) [16]:

\[
\eta_R = \left( \frac{CO_{2r,c}}{CO_{2g,c}} \right) \times 100
\] (5)

A. Carbon Dioxide Savings

Substitution approach expects the power station project to supply energies constantly 24 hours a day, as in a case of conventional combined heat – and - power plants of a base-load service.

In both processes, the substituted bulk of energy duty equals 100 % with proportion related to primary energy mix for heat and power (Table II). In a heat production savings, the accepted duty (Qhp) of 83 GWth equals 298, 4 TJ yearly the project is able to cover. Substitution of PEM and emission factors typical for Slovak Republic [17] - [18] (Table IV) into (1) defines yearly gross CO2 savings from a heating section of 26 811 tCO2 yr⁻¹, as a result of partial coal (24 349 tCO2 yr⁻¹) and natural gas (2 461 tCO2 yr⁻¹) removal (Fig. 2)
TABLE IV: EMISSION FACTORS AND GROSS CARBON DIOXIDE SAVINGS

<table>
<thead>
<tr>
<th>Fossil fuels</th>
<th>Emission factor [t.TJ⁻¹]</th>
<th>Emission factor [t.MW⁻¹]</th>
<th>CO₂g (heat) [tCO₂.yr⁻¹]</th>
<th>CO₂g (power) [tCO₂.yr⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total coal</td>
<td>96</td>
<td>1,04</td>
<td>24 349</td>
<td>16 255</td>
</tr>
<tr>
<td>Natural gas</td>
<td>55</td>
<td>0,55</td>
<td>2 461</td>
<td>4 011</td>
</tr>
<tr>
<td>Oil products</td>
<td>-</td>
<td>0,9</td>
<td>-</td>
<td>2 813</td>
</tr>
<tr>
<td>Geothermal</td>
<td>0,27</td>
<td>0,002</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Analogously according to (1) in a power production section, substitution of related emission factors (Table IV) and proportion factors (Table II) for partial yearly gross CO₂ reduction turns to total 23 080 tCO₂.yr⁻¹ removal potential as a sum of partial emissions avoided from substitution of different fossil fuels (Table IV). A sum of bulk reduction from heat and power production defines then total yearly gross savings – CO₂g of 49 891 tCO₂.yr⁻¹ (Fig. 2).

Fig. 2. Graphic display of partial gross CO₂ savings in power and heat production

Observed contrasts in partial CO₂ savings clearly reflect proportion of fossil fuels on heat and power production as well as correspond to various emission factors.

Each installation and operation of geothermal power plant defines a need for CO₂ related to utilizing of geothermal fluids definition. The carbon dioxide produced (2) then reflects geochemistry of thermal fluids, essentially free CO₂ compound and functions energy duty the fluid covers in a heat (Qed = 298,4 T J) and power (Qed = 26 050 MWth) production with calculated [19] emission factor of thermal fluid for both processes (table IV). Solution of (2) gives then 132 tCO₂.yr⁻¹ of carbon dioxide produced at the station (CO₂p) as a sum of partial emissions on a heat production (80tCO₂.yr⁻¹) and power production (52 tCO₂.yr⁻¹) side.

With total yearly gross savings (CO₂g = 49 891 tCO₂.yr⁻¹) and in-situ emissions produced during utilization (CO₂p = 132 tCO₂.yr⁻¹) predicted, solution of (3) defines then real carbon dioxide emissions mitigated (CO₂g) inventory at a level of 49 578 tCO₂.yr⁻¹. As emissions potentially produced at the station represent 0,2 % from a bulk saved, the gap is almost negligible and the fluid is considered emissions- inactive [15].

Recent design of combined heat and power geothermal plants expects projects to operate at least for 40 years [20], a period that is set as lifespans (LTgp) to enter calculations of cumulative gross (CO₂gₕ) and real (CO₂gₚ) CO₂ savings(4). Relation understands cumulative savings as itinerary of emissions the project mitigated at the end of operation, and calculates with both, gross (CO₂g) and real (CO₂p) bulks. As a result, 1,995 MtCO₂ of gross cumulative or 1,990 MtCO₂ of real cumulative savings are expected for the project (Fig. 3, table V) in case the system operates constantly as expected for a base-load supply.

![Fig. 3. Screen of cumulative real CO₂ savings](image)

TABLE V: SUMMARIZING TABLE ON CARBON DIOXIDE SAVINGS

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly</td>
<td>0,0498</td>
<td>0,04975</td>
<td>26,1</td>
<td>298,4</td>
</tr>
<tr>
<td>Cumulative</td>
<td>1,995</td>
<td>1,990</td>
<td>1 044</td>
<td>11 936</td>
</tr>
</tbody>
</table>

B. Environmental Economics Considerations

Every geothermal project consideration meets unique limits regarding economical investment aspects. Investment costs in power-plant projects compose of a) exploration and resource confirmation, b) borehole drilling campaign, c) surface facilities and infrastructure emplacement and d) power plant design [21]. If we assume overall installation costs for a project for both, power and heat production at – 6 400 €.kW⁻¹, and add to an investment analysis expected operation and maintenance costs at 190 €.kw⁻¹.yr⁻¹ [22], with optimized installed plant for 40 years projected lifespans at installed capacity of 3 500 kWt and heat production installed capacity of 16 MWth, investment costs may roughly reach 64,6 mil. €. This is an amount potential developer (private or national-owned) should consider in preliminary economic feasibility studies. By a contrast, a mean selling price of 0,03 €.kWh⁻¹ for electricity and 15 €.GJ⁻¹ can be expected in local conditions [23]. Additionally, with yearly real carbon dioxide savings known (49 578 tCO₂), project can apply for environmental government subsidies regarding a CO₂ carbon credit market at a level of 6 €.t⁻¹ [5]. Yearly environmental subsidies then can contribute with 0,3 mil. € on benefits side. A simple payback period calculated is then 2,32 years. However, such an analysis is clearly preliminary and detailed study is needed, where yearly incomes will depend on initial energy production and then break-away energy prices.

C. National Reflections – Towards the EU Road Map

National targets for EU member countries regarding
introduction of renewables into primary energy mix in heat and power production defined proportion the Slovak Republic is supposed to achieve in 2020 for 14 % on heat and 31 % on power production [24]. Set-up targets are mandatory to meet under optional legal and financial penalties.

By now, renewables share 7 % on heat and 19,8 % on power (large hydro included) or 2,3 % (without large hydro plants) [5].

In case the project will operate, yearly power supply for a grid will reach 26,1 GW_{he}. In primary energy mix we subtract the electricity produced from recent proportion of fossil fuels according to their share in electricity sector. As the total electricity generated yearly counts 26 155 GW_{elec}, geothermal project power supply will take 0,1 %. Then, proportion of renewables will increase for 19,9 % (large hydro included) or 2,4 % (without large hydro).

Actual geothermal yearly heat production in Slovakia reaches 144 TJ defining its 0,3 % proportion on total national heat supply (42 210 TJ). Constant co-generated geothermal heat delivery from a project into a mix calculated for 298,4 TJ yearly, balanced with energy mix related subtraction of coal and gas in a heat delivery, will lead to increase of geothermal proportion up to 1,05 % and increase of renewables share on heat production from 7,04 % to 7,8 % (Fig. 4).

![Reflection of geothermal project on primary energy mix](image)

**Fig. 4. Impact of geothermal system implementation for a power and heat supply renewable contribution towards the EU road map.**

Observed increase of renewables proportion on heat and power national market imply the geothermal sector may not be able to cover the gap between recent situation and targets in the EU road map individually. However, while the Košice Basin is among three perspective localities for a geothermal power supply [25], thus possibilities of growth in geothermal power are rather unlikely, 26 areas perspective for geothermal heat production are identified [26] with a total thermal potential of 6 653 MW_{th} [27], providing a background high enough for rapid improvements. Then, every national progress towards the EU road map targets is a question of government financial and technical support – supposed-to-be motivated by moral, legal and environmental merits.

**D. Limitations and Adds**

Authors accent the study is a background for potential ongoing detailed research. Additional approach is definitely needed considering operation characteristics of geothermal, combined heat and power binary plant projected, as well as detailed economic and environmental-economic analysis of a market is necessary. Data used in calculations of carbon dioxide savings are kept constant in time, however, they may seasonally vary.

**VI. CONCLUSIONS**

The substitution approach for carbon dioxide savings evaluation is presented in the paper on a case study on actual considered geothermal power plant project in the Štúrovo area, Košice Basin, eastern Slovakia. Later on, results are nominally analyzed and reflected regarding project environmental economics and impact for a national primary energy mix scheme towards the EU road map set-up targets. Essential philosophy of the approach understands reduction as a mitigation-substitution process, within that CO₂ intensively emitte fossil fuels are replaced with a renewable source of low CO₂ emissions intensity in the same process and nominal duty. Analyzed model of a power plant operates as binary and base-load at combined, heat-and-power principle.

Introduction of the power plant into the heat and power grid may contribute with overall yearly gross 49 891 tCO₂ mitigated, out of that 28 811 tCO₂ refer to fossil fuels substitution in a heat and 23 080 tCO₂ to power production sector (corresponding to actual fossil fuels regional energy mix proportion). Use of geothermal fluids leads to yearly potential in-situ emissions of carbon dioxide evaluated for 132 tCO₂ yr⁻¹ characterizing fluid as carbon-inactive. After subtraction of emissions produced from a gross itinerary, yearly real CO₂ savings calculated drop negligibly down to 49 578 tCO₂. If the 40 years lifespan of a geothermal project is accepted, cumulative savings at the end of a period increase up to 1,995 tCO₂ of gross or 1,990 tCO₂ of real bulk reduced. Carbon dioxide emission reduction potential then reflects in potential environmental subsidies at yearly rate of 0,3 mil. €, contributing on a project’s payback period shortening.

Even of proven environmental impact and relatively low (preliminary) calculated payback period (2,32 years), introduction of projected plan producing 26,1 GW_{he} of power and 298,4 TJ of heat yearly will not dramatically effect national primary energy mix. Observed 0,1 % upturn in renewables proportion on power and 0,8 % on a heat production will not solve a nations’ rough path to meet EU set-up targets regarding renewables proportion on energy mix.

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**REFERENCES**


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Technology in study program of Energy, with a focus on design and criteria optimization of ORC—binary based geothermal systems.

Her primary research activities relate to definition, optimization and modeling of design criteria for binary and cogeneration-operated geothermal power plants, with a most of the scope set at the Košice Basin. Affine to her research topics, she published or submitted several papers about the topic.

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