GEOTHERMAL POWER PLANT WITH INTEGRATED H_2/O_2 SOLID OXIDE FUEL CELL and / or GAS TURBINE

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ABSTRACT
The GeoHybrid-SOFC (H_2/O_2) concept of re-powering existing geothermal power plant with a solid oxide fuel cell (SOFC) is proposed in the paper. It is based on thermal integration of the H_2/O_2 SOFC into the steam-based Rankine cycle of existing geothermal power plant. Because of further need of extensive research and development of the SOFC and cost-effective hydrogen production, this concept is being considered as a long-term technology. As a near-term re-powering system the GeoHybrid-GT system is proposed, based on thermal integration of the current gas turbine (GT) technology into existing geothermal power plant. Thermodynamic simulation of the two concepts, discussion of results together with approximate economic feasibility analysis are introduced in the paper.

INTRODUICTION
Increasing demand for energy and growing awareness of global environmental problems need to produce more power while reducing pollution. Solution of the problem will depend on changing the present energy mix to include a greater portion of clean and safe energy technologies. Geothermal energy, as being a renewable energy resource, will thus have growing importance in meeting this effort.

The viability of geothermal power production is strongly influenced by the efficiency of converting geothermal heat to electricity and by the cost of equipment and construction.

Geothermal power generation typically involves high levels of capital investment for exploration, drilling wells and installation of plant, but low operating costs because of the low marginal cost of fuel. Low temperature level of geothermal heat addition into the power plant cycle (120 – 250) °C results in low thermal efficiency.

Additional generating capacity and improved efficiency may be obtained by re-powering existing geothermal power plants without drilling additional high cost-demanding geothermal wells. Re-powering without any additional well field cost, improving efficiency and generating capacity, can thus be a favourable option, since it conserves energy while reducing waste heat (Kaplan and Schochet, 2000).

A possible re-powering can be accomplished with GeoHybrid system which is based on the idea of superheating the steam cycle (Kohl et al., 2000, 2004). In this concept the working fluid is preheated and evaporated (producing saturated steam) by geothermal energy, while the second heating source is employed for steam superheating in the steam-based Rankine cycle. Depending on the second heating source it could have potential for a smooth transition from conventional (fossil fuels) to renewable system when the energy source for the superheating is a renewable-based fuel.

High-temperature steam electrolysis (HTE) in the hydrogen production process, assisted with geothermal resources or high temperature reactors (HTR), is currently the object of many research and development in the world (Jónsson et al., 1992), (Sigurvinsson et al., 2006), (Mansilla et al., 2007), (Madisha, 2006). Similar situation concerns the research activities in development of efficient, reliable and cost-effective systems of the solid oxide fuel cells (SOFC) (Singhal and Kendal, 2004). These technologies (HTE, SOFC) in coupling with geothermal resources are expected to be a serious candidates as regards future mass production of hydrogen and electric and heat power, potentially free from greenhouse-gas emissions.

In the paper a combined geothermal power plant concept is proposed i.e. GeoHybrid-SOFC, which is based on thermal integration of a H_2/O_2 SOFC into the steam cycle with condensing reheat steam turbine. Heat needed for driving the steam-based Rankine cycle is provided by heat transfer from geothermal steam source (preheating, steam generation) and by heat transfer from external cooling (EXCO) of the SOFC (superheating). In addition, the outlet steam from the high-pressure (HP) turbine is combined with the hot steam from the SOFC (thermochemical reaction: $H_2 + 1/2O_2 = H_2O$, 650-900 °C) and thus reheated before it enters low-pressure (LP) turbine.

For comparison, the another combined system i.e. GeoHybrid-GT is also proposed in the paper. It consists of a fossil fuelled gas turbine (GT) thermally integrated into the geothermal power plant. In this case the steam is superheated by heat transfer from gas turbine exhaust gases. The concept could be considered as a link between today's fossil-based and tomorrow's renewable-based technology.

The paper contains thermodynamic conceptual analysis of proposed concepts (GeoHybrid-SOFC and GeoHybrid-GT), discussion of results together with preliminary economic feasibility analysis.

FUEL CELL MODEL
Hydrogen is proposed as a possible future energy carrier (like electricity or as a transport fuel), because of possibility to be transported and stored at high densities and, to be produced in a pollution-free way with renewable/or nuclear energy. Conversion of hydrogen to electricity can be attained with the best fuel utilisation

in a fuel cell. The fuel cell (FC) combines hydrogen and oxygen electrochemically to produce steam, electricity and heat. High-temperature (800-1000) °C solid oxide fuel cell (SOFC) is a leading technology that is well suited to applications in industry and in public power supply (Singhal and Kendal, 2004).

In this conceptual analysis a simplified approach was used in modelling of a SOFC, based on fundamental SOFC thermodynamics and existing typical test data (Petr, 2007). A multi-stage H_2/O_2 SOFC is considered, because of possibility to attain higher fuel utilization and performance improvement.

The layout of used 5-stage SOFC system is seen in Fig. 1. The outlet gases of each stage (j = 1-5) are directly ducted to the inlet of the next one. Each stage is designed to accommodate the next higher temperature regime. Fuel (H_2) and oxidant (O_2) at ambient conditions (25 °C, 1 bar) are compressed to

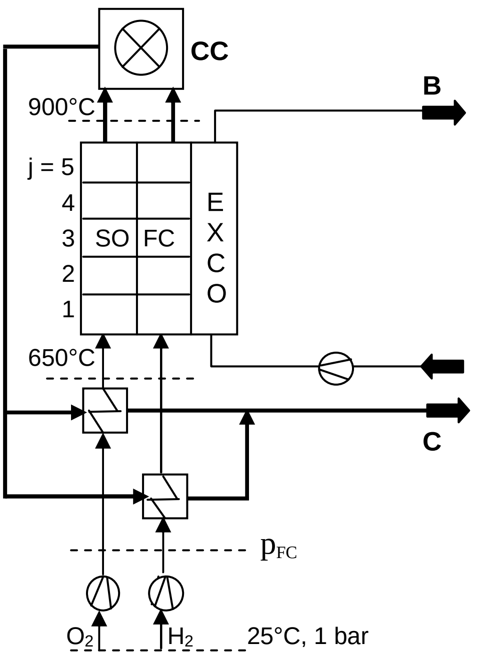


Fig.1. SOFC system with external cooling.

given fuel cell operating pressure p_{FC} and subsequently heated with outlet steam to 650 °C. The temperature difference per stage is assumed to be 50 °C what gives the outlet temperature 900 °C. Unreacted hydrogen and oxygen leaving the last stage (j = 5) are combusted in the combustion chamber CC. Assuming stoichiometric processes in the FC and CC (H_2 + ½ O_2 = H_2O), then pure steam leaves the SOFC system (Fig.1.- C).

The total heat produced during the irreversible electrochemical process, occurring within each stage, is used for internal heating of H_2, O_2 and steam to match prescribed temperature difference 50 °C. Remainder of the heat Q_{ext} has to be extracted (Fig.1.-B) by means of external cooling EXCO (Winkler and Lorenz, 2002). Engineering design of the external cooling concept will need extensive research and development effort.

The external cooling and produced steam give possibility to integrate proposed SOFC system into the steam cycle of geothermal power plant to build GeoHybrid-SOFC concept.

Basic equations for the FC efficiency, electric power and produced heat power were used for each FC-stage (j=1-5, Fig.1.) as follows (Singhal and Kendall, 2004), (Petr, 2007).

Electrochemical FC efficiency is product of reversible efficiency η_{rev}, voltage efficiency η_v and fuel utilization U_f i.e.

$$\eta_{FC} = \eta_{rev} \cdot \eta_v \cdot U_f \tag{1}$$

The reversible efficiency is the maximum FC efficiency and relates the maximum available work (-ΔG) to the maximum amonnt of heat energy available (-ΔH) i.e.

$$\eta_{rev} = \frac{(-\Delta G)}{(-\Delta H)} \tag{2}$$

The voltage efficiency relates the actual voltage E produced to the reversible voltage E_{rev}

$$\eta_v = \frac{E}{E_{rev}} \tag{3}$$

where

$$E_{rev} = \frac{-\Delta G}{n \cdot F} \cdot M_{H2} \tag{4}$$

(n=2 for H_2+ ½ O_2 = H_2O FC reaction, Faraday's constant F= 9.649·10^4 C/mol, M_{H2} = 2.016 kg/kmol).

The fuel utilization in each FC stage relates converted fuel (H_2) Δm_f [kg/s] to inlet fuel mass flow rate m_f i.e.

$$U_f = \frac{\Delta m_f}{m_f} \tag{5}$$

With use of η_{FC} the corresponding electric power P_{FC} and produced heat power Q_{FC} in each stage can be evaluated as

$$P_{FC} = \eta_{FC} \cdot (-\Delta H) \cdot m_f \tag{6}$$

$$Q_{FC} = (-\Delta H) \cdot m_f \cdot U_f - P_{FC} \tag{7}$$

If internal heat power Q_{int} consumed for heating the fuel (H_2), oxidant (O_2) and steam is predicted from the stage heat balance equation, then external heat power to be extracted by external cooling (EXCO-Fig.1.) will be

$$Q_{ext} = Q_{FC} - Q_{int} \tag{8}$$

Introduced equations Eq. (1) – (8) represent basic thermodynamic relations that apply generally for each considered FC stage, assuming the actual fuel cell potential E (Eq.(3)) was known. Due to irreversible losses (activation, ohmic and concentration polarization) the FC voltage E is less than its ideal potential E_{rev} (Eq.(4)). Accounting for fundamental effects i.e. FC operating temperature, pressure and fuel utilization, together with use of typical SOFC test data (Singhal and Kendall, 2004) the following correlation equation was obtained and used in the present analysis

$$E = \bar{a} \cdot E_{NERNST} - \bar{b} \cdot exp\left(\frac{\bar{c}}{T}\right) \cdot I \tag{9}$$

where

$$E_{NERNST} = E^o(T) + \frac{RT}{2F} \cdot ln\left(\frac{1-U_f}{U_f}\right) + \frac{RT}{4F} \cdot ln\left(\frac{p}{p_o}\right) \tag{10}$$

$$E^o(T) = \frac{-\Delta G(T)}{2F} \cdot M_{H2} \tag{11}$$

R = 8.314 J/mol . K

F = 9.649 . 10^4 C/mol

The constants $\bar{a}, \bar{b}, \bar{c}$ together with relation I = f(U_f) between the FC current density and fuel utilization (generally defined by Faraday's law), were predicted by matching Eq.(9) to the test data i.e.

$\bar{a} = 0.9588$	[-]
$\bar{b} = 3.673 \cdot 10^{-4}$	[$\Omega \cdot cm^2$]
$\bar{c} = 7.316 \cdot 10^{-4}$	[K]
I = 1.37 . U_f	[A/cm^2]

The approximate correlation model represented by the system of Eqs.(1)–(11) was employed in the GeoHybrid-SOFC power plant cycle simulation as follows.

Numerical simulation of the multi-stage pressurized SOFC module (Fig.1.) resulted in the following model equations for the FC electric power (P_{FC}), external (cooling) heat power (Q_{ext}), compression power (P_C) and for specific enthalpy of produced steam (h_C)-Fig.1.

$$P_{FC}[kW] = [97 \cdot 395 \cdot ln(p_{FC}) + 3474.1] \cdot \left(\frac{m_f}{0.05}\right) \tag{12}$$

$$Q_{ext}[kW] = 1127.2 \cdot (p_{FC})^{-0.0981} \cdot \left(\frac{m_f}{0.05}\right) \tag{13}$$

$$P_c[kW] = (0.2876 \cdot p_{FC}^3 - 7.479 \cdot p_{FC}^2 + 88.836 \cdot p_{FC} - 69.69) \cdot \left(\frac{m_f}{0.05}\right) \tag{14}$$

$$h_C[kJ/kg] = 0.6419 \cdot p_{FC}^3 - 16.662 \cdot p_{FC}^2 + 195.77 \cdot p_{FC} + 3355 \tag{15}$$

where p_{FC} [bar] is inlet operating pressure of the SOFC and m_f [kg/s] is the inlet fuel (H_2) mass flow rate. These model equations match results of numerical simulation of the SOFC module (Fig.1.) with uncertainty of about 0.2 % for p_{FC} = (1 - 10) bar.

Because of considered stoichiometric reactions ($H_2 + 1/2O_2 = H_2O$) in the FC and CC (Fig.1.), the mass flow rate of produced steam will be (at position C in Fig.1)

$$m_C = 9 \cdot m_f \tag{16}$$

Equations (12)-(16) were introduced by means of Macros into the professional SW Gate-Cycle that was used in realized numerical simulations of the combined GeoHybrid-SOFC power plant cycle.

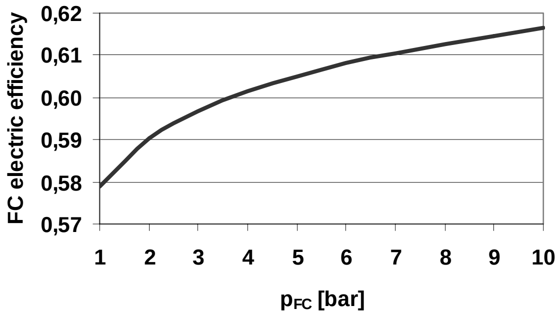


Fig. 2. Fuel cell electric efficiency.

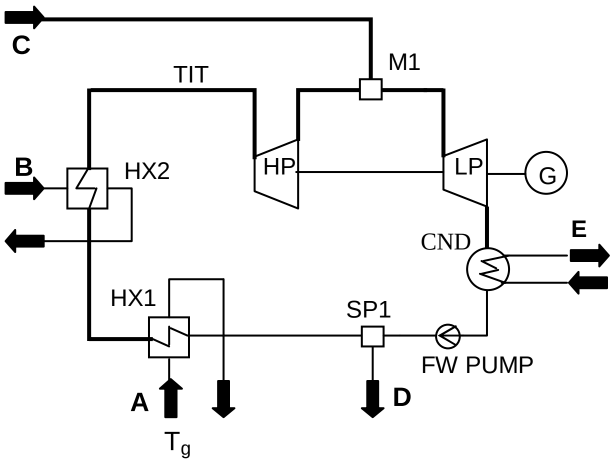
Variation of the SOFC electric efficiency

$$\eta_{FC} = \frac{P_{FC}}{m_f \cdot \Delta H^o}, \quad \Delta H^o = 1.2 \cdot 10^5 \, kJ/kgH_2 \tag{17}$$

can be seen in Fig. 2. It suggests high fuel utilization in the considered SOFC concept (Fig.1.) together with important effect of operating FC pressure p_{FC}.

GeoHybrid-SOFC POWER PLANT CYCLE

The GeoHybrid-SOFC concept considered in this analysis is based on thermal integration of the SOFC into the geothermal steam-based Rankine cycle. It principally corresponds to re-powering of existing geothermal power



A – Geothermal heat
B – Heat from EXCO (SOFC)
C – Steam from SOFC
D – Bleed water (that equals C)
E – Waste heat

Fig.3. GeoHybrid-SOFC power plant cycle.

plant. Principal scheme of the system is introduced in Fig.3.

Feed water pump (FW PUMP) provides high-pressure water that is preheated and evaporated in the heat exchanger HX1 by heat transfer from the geothermal heat source (A) of temperature T_g. Produced saturated steam then enters the heat exchanger HX2 to be superheated to the HP turbine inlet temperature TIT with cooling heat Q_{ext} (Eq.(2)) from the SOFC (B). The steam then expands through the HP turbine producing an exhaust low pressure steam which is combined with the hot steam from the SOFC (C). It is thus reheated in the mixer M1 before being expanded through the LP turbine to condenser (CND) pressure. A bleed stream of water that equals m_C (Eq.(16)) is taken from the cycle (D) in the splitter SP1.

Thermodynamic analysis

Numerical simulations of the cycle (Fig.3) were carried out by means of professional SW Gate-Cycle, while the model of the SOFC was considered through Eqs.(12)-(16) included into the SW by means of Macros.

Temperature of a geothermal heat source T_g, steam turbine inlet temperature TIT and operating pressure of the fuel cell p_{FC} were considered as basic parameters affecting efficiency and power output of the GeoHybrid-SOFC power plant cycle (Fig.3). As it was mentioned the feed water is preheated and evaporated in the heat exchanger HX1. The evaporation temperature, assumed to be $T_s = (T_g - 25)$ °C, predicts FW pump exit pressure and thus the steam turbine inlet pressure. The SOFC operating pressure p_{FC} defines the reheat pressure (when accounting for the SOFC pressure losses) and by means of Eq.(15) and steam properties it provides the reheat temperature. The pressure p_{FC} can be optimized with regard to efficiency and constraint conditions (e.g. LP turbine steam exit quality > 0.9). Finally, the SOFC fuel (H_2) mass flow rate m_f is predicted from the heat balance equation of the heat exchanger HX2, together with Eq.(13), provided TIT was prescribed.

The power output and thermal efficiency of the cycle are defined as follows

$$P_{tot} = P_{FC} - P_c + P_g \tag{18}$$

$$\eta_t = \frac{P_{tot}}{\left(m_f \cdot \Delta H^o + Q_g\right)}, \tag{19}$$

$$\Delta H^o = 1.2 \cdot 10^5\, kJ / kgH_2$$

The geothermal heat power output Q_g is predicted from the heat balance equation of the heat Exchange HX1.

The following basic assumptions have been used in the computational simulation of the considered GeoHybrid-SOFC power plant cycle (Fig.3)

- Temperature of a geothermal heat source (175-250)°C
- Steam turbine inlet temperature (150-550)°C
- SOFC operating pressure (2 - 8)bar
- Adiabatic efficiency of steam turbine 0.9
- Polytropic efficiency of compressors (H_2, O_2) 0.87
- Mechanical(shaft) efficiency 0.985
- Generator efficiency 0.985
- SOFC converter (DC/AC) efficiency 0.95
- SOFC pressure loss 12%
- Pressure loss of heat exchangers 2%
- Condenser pressure 5kPa

The re-powering concept considered in this conceptual thermodynamic analysis means that numerical simulation of the GeoHybrid-SOFC power plant has been carried out for geothermal heat power output $Q_g = Q_{go}$ = const., where Q_{go} corresponds to existing geothermal power plant.

Variation of the thermal efficiency (Eq.(19)) with the turbine inlet temperature is seen in Fig. 4.

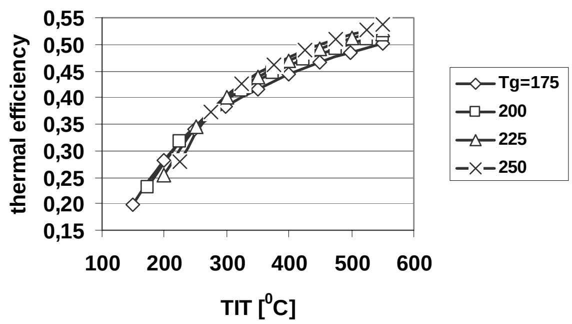


Fig.4. Thermal efficiency of GeoHybrid-SOFC power plant.

It is seen that thermal efficiency exceeding 50% can be attained for steam turbine inlet temperature 550 °C. It is mainly result of increased mean temperature of heat addition and the SOFC contribution with high efficiency (Fig.2.).

The corresponding enhancement of the total power output (Eq.(18)) is introduced in Fig.5. It is result of increased fuel mass flow rate (higher superheating) and thus increased SOFC output power (Eq.(12)).

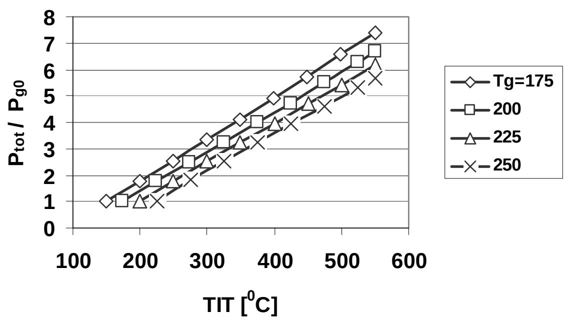


Fig.5. Power enhancement in GeoHybrid-SOFC power plant.

Depending on T_g = (175-250) °C, (5 – 7) - times higher total power output can be observed for steam turbine inlet temperature 550 °C in comparison with existing (reference) geothermal power plant (P_{go}). It suggests a considerable possibility of re-powering existing geothermal power plants.

Additional positive effect of re-powering can be seen in Fig.6, suggesting nearly (2.5 - 4) - times relative reduction (depending on T_g) of the waste heat taken from the GeoHybrid-SOFC power plant by cooling water in the condenser CND (Fig.3).

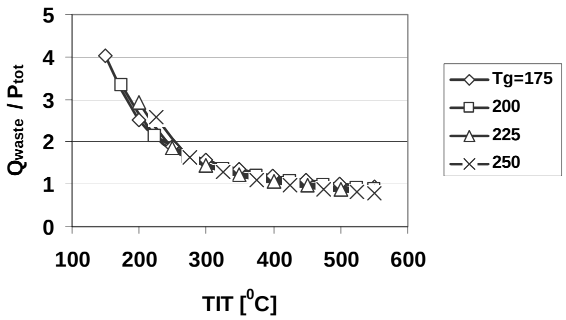


Fig.6. Reduction of waste heat in GeoHybrid-SOFC power plant.

The positive effects of proposed re-powering introduced in Figs.4 - 6 were possible due to increased high-cost fuel (H_2) mass flow rate. This unfavourable affect is seen in Fig.7.

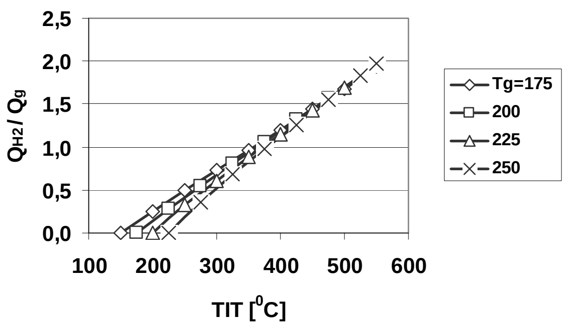


Fig.7. The ratio of hydrogen heat in GeoHybrid-SOFC power plant.

It can be observed that almost 2-times more heat (for TIT = 550 °C) has to be supplied in form of hydrogen heat in comparison with geothermal heat needed in the reference geothermal power plant. Economic analysis, therefore, has to be accomplished to decide whether /or under which conditions the proposed re-powering concept could be economically feasible option.

Estimation of power cost

A simplified economic feasibility analysis, based on assessing the unite price of electricity, was used in predicting the relative merits of the reference geothermal and GeoHybrid-SOFC power plants. In the following relations the subscript “1” relates to the reference while the “2” means the hybrid power plant.

The annual cost of produced electricity for the power plant 1 will be (Horlock, 1992)

$$C_{e1} = a_g \cdot \left(C_{inv}\right)_g + \left(OM\right)_g = c_{e1} \cdot P_{go} \tau_1 \qquad (20)$$

where

$$a = \frac{i\left(1+i\right)^N}{\left(1+i\right)^N - 1} \qquad (21)$$

is the annuity present worth factor.

Assuming C_{e1} is approximately unchanged ($Q_g = Q_{go}$ = const in re-powering concept) and neglecting in the case 2 operation and maintenance cost against the fuel cost, then, the annual cost of produced electricity in the power plant 2 may be considered as

$$C_{e2} = C_{e1} + a_{FC} \cdot \left(C_{inv}\right)_{FC} + Q_f \cdot \tau_2 \cdot c_f \qquad (22)$$

The unit cost of produced electricity will then be

$$c_{e2} = \frac{P_{go}}{P_{tot}} \cdot c_{e1} + a_{FC} \cdot \frac{P_{FC}}{P_{tot}} \cdot \frac{c_{FC}}{\tau_2} + c_f \cdot \frac{Q_f}{P_{tot}} \qquad (23)$$

Assuming further the power plant utilization remains unchanged i.e. $\tau_1 = \tau_2 = \tau$, then final relation between c_{e2} and c_{e1} will be

$$\frac{c_{e2}}{c_{e1}} = \frac{P_{FC}}{P_{tot}} \left(a_{FC} \cdot \frac{c_{FC}}{\tau} + c_f \cdot \frac{Q_f}{P_{FC}} \right) \cdot \frac{1}{c_{e1}} + \frac{P_{go}}{P_{tot}} \qquad (24)$$

An increased economic performance of the GeoHybrid-SOFC power plant will be obtained for

$$\frac{c_{e2}}{c_{e1}} < 1 \qquad (25)$$

It is seen from Eq.(24) there are several parameters that could affect the ratio c_{e2} / c_{e1} . By means of parametric simulation of the GeoHybrid-SOFC power plant cycle (Fig.3.) the values of parameters, meeting Eq.(25), were predicted assuming:

- SOFC life time N_{FC} = 15 year
- interest rate i = 0.085
- power plant utilization τ = 8000 hours/year

The effect of the steam turbine inlet temperature can be seen in Fig 8.

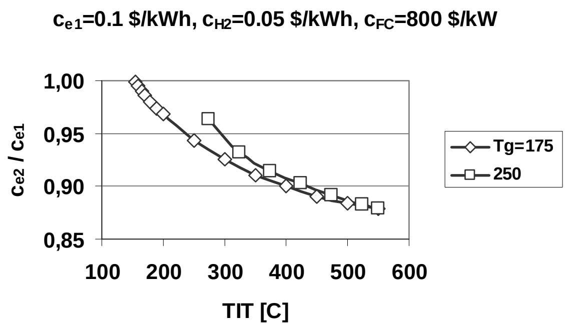


Fig.8. The effect of the steam turbine inlet temperature.

It suggests that the best economic performance can be attained with the highest considered TIT = 550 °C. It is in accordance with Fig.5 (P_{tot} attains maximal value). This TIT was therefore used in the next analysis.

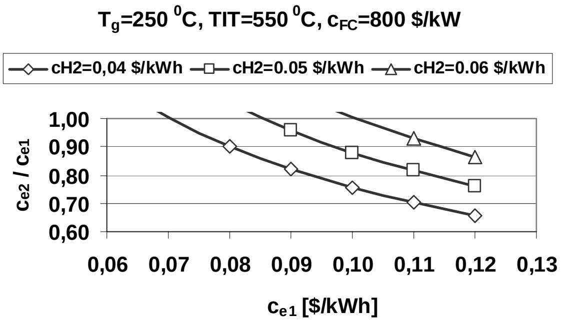


Fig.9. The effect of reference electricity cost and cost of hydrogen.

The electricity cost c_{e1} of the reference geothermal power plant and the cost of hydrogen $c_f = c_{H2}$ supplied to GeoHybrid-SOFC power plant, were found to be the most important parameters affecting the ratio c_{e2}/c_{e1} (Eq.(24)). The effect can be observed in Fig.9. Better economic performance (of power plant 2) can be attained for more expensive electricity c_{e1} and lower cost of hydrogen c_{H2}.

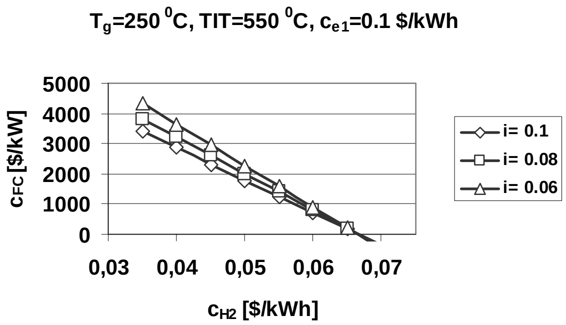


Fig.10. Limiting investment cost of the SOFC (c_{e2}/c_{e1} = 1).

Investment cost c_{FC} of the SOFC system (Fig.1) is of a considerable importance too, as it can be seen in Fig10. The limiting values of c_{FC} (providing c_{e2}/c_{e1} = 1) are introduced here for different hydrogen costs c_{H2} , together with interest rate i as a parameter. To meet Eq.(25) the c_{FC} must be lower than corresponding value in Fig.10 for given (c_{H2}, i).

Introduced results should be supported with existing data mainly concerning the costs c_{e1} and c_{H2}. the cost of electricity c_{e1} produced in the current geothermal power plants varies within broad range of (0.02 - 0.16) $/kWh, depending on type, size, location, geological conditions etc. (Kitson et al., 2004), (Kohl and Speck, 2004), (Sanyal, 2007). The cost of hydrogen c_{H2} strongly depends on used technology. Assuming HTE technology, reported costs vary within the range of (0.055 - 0.1) $/kWh, depending on electricity and heat costs (Jónsson et al., 1992) (Herring et al., 2003), (Medisha, 2006).

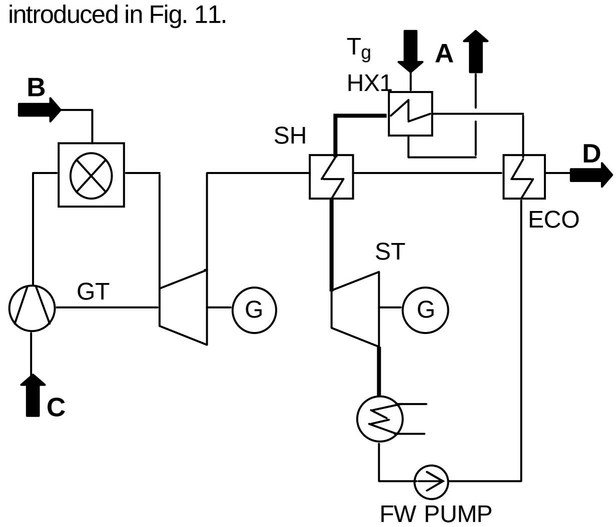
Comparing these values of c_{e1} and c_{H2} with Fig.9 it can be concluded that economic feasibility of proposed re-powering existing geothermal power plant cannot be stated generally. Possible increased economic improvement (Eq.(25)) has to be confirmed separately for different conditions of considered geothermal power plants.

Future development of the SOFC and HTE technologies can further reduce investment cost and cost of hydrogen. The GeoHybrid-SOFC system (Fig.3) may thus become more economically feasible in the future, supposing the hydrogen economy would exist.

GeoHybrid-GT POWER PLANT CYCLE

Proposed GeoHybrid-SOFC system (Fig.3) will need further extensive research and development effort mainly in technology improvement of the SOFC and cost-effective hydrogen production. For near-term applications the another hybrid re-powering system (GeoHybrid-GT) can be proposed. It is based on thermal integration of a fossil-fuelled gas turbine into the geothermal steam-based Rankine cycle. The concept is completely based on existing technology and can represent a link between current fossil-and future renewable-based electricity production.

The layout of the GeoHybrid-GT power plant cycle is introduced in Fig. 11.



A – Geothermal heat
B – Fossil fuel
C – Inlet air
D – Exhaust gases

Fig.11. GeoHybrid – GT power plant cycle.

Thermal integration consists in heat utilization of GT exit gases for superheating (SH) of the steam turbine inlet steam (SH) and preheating of the feed water (ECO). The geothermal heat source is used to produce saturated steam in the heat exchanger HX1. Avoiding the evaporation by heat transfer from GT exit gases (like in a CCGT) results in a more favourable power ration between GT and steam cycle, which may be nearly the same.

Thermodynamic simulation of the GeoHybrid-GT power plant concept (Fig.11) was carried out for the following input data:

- GT inlet temperature 1250° C
- GT compression ratio 18

- compressor adiabatic efficiency 0,88
- ST inlet temperature 550° C
- ST adiabatic efficiency 0.9
- condenser pressure 5 kPa
- fuel (NG) LHV 47 451 kJ/kg

Basic results of simulation are introduced in Tab. 1.

Table 1. GeoHybrid-GT simulation results

T_g [°C]	175	250
η_t [-]	0.4147	0.4583
Q_f/Q_{go} [-]	1.28	1.263
P_{GT}/P_{tot} [-]	0,5193	0.4721
P_{tot}/P_{go} [-]	4.1	3.45

The results introduced in Table 1 made possible to accomplish the economic feasibility analysis according to Eq.(24) – (GT instead of FC) with results that may be observed in Fig.12. and Fig.13.

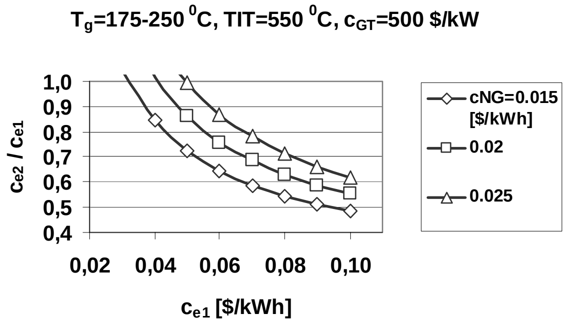


Fig.12. The effect of reference electricity cost and cost of fuel (NG).

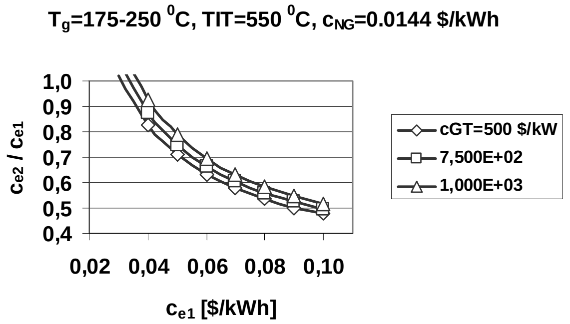


Fig.13. The effect of reference electricity cost and GT unit cost.

Comparing Fig.12 and Fig.9 it can be seen that in the GeoHybrid-GT power plant concept the increased economic performance ($c_{e2}/c_{e1} < 1$) has moved to the lower values of electricity cost c_{e1} (due to lower cost of fuel). This favourable effect suggests that for current cost of natural gas (NG) of about $c_{NG} \sim 0.015$ $/kWh, the GeoHybrid/GT concept could be economically feasible for electricity cost c_{e1} > (0.035 - 0.04) $/kWh. This condition seems to be realistic for most of existing geothermal power plants. The hybrid concept thus represents not only a favourable re-powering option but, also more efficient way of combusting the fossil fuel (NG) than in the GT alone.

The GT unit cost that is seen in Fig. 13 implies acceptable effect of the power plant size as regards the mentioned feasibility conclusions.

CONCLUSIONS

- Thermodynamic analysis of the GeoHybrid-SOFC (H_2/O_2) power plant cycle (Fig.3.) suggests that thermal efficiency exceeding 50% and (5 - 6) - times enhanced power output can be attained in comparison with the reference geothermal power plant. It thus implies favourable potential for re-powering.
- Improved economic performance of re-powering concept mainly depends on the cost c_{e1} of electricity produced in the reference geothermal power plant and on the hydrogen cost c_{H2}. The improvement (c_{e2} / c_{e1} < 1) can be attained approximately for c_{e1} > (0.07 – 0.09) $ / kWh, while c_{H2} < (0.04 – 0.06) $/kWh – Fig.9.
- The GeoHybrid-SOFC (H_2/O_2) concept will need further extensive research and development effort regarding the SOFC and cost-effective hydrogen production. It may thus be considered as a future long-term technology, supposing the hydrogen economy would exist.
- The GeoHybrid-GT concept (Fig.11) proposed as a near term re-powering system is based on current technology. With natural gas (NG) used as a GT fuel it could be economically feasible for the geothermal electricity cost c_{e1} > (0.035 – 0.04) $/kWh - (Fig. 12.). This condition seems to be realistic for most of current geothermal power plants. The concept could thus be a favourable re-powering option combusting, in addition, the fossil fuel (NG) more efficiently than GT alone.

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NOMENCLATURE

a annuity present worth factor, [-]
c unit cost, USD/kWh, USD/kW
C annual cost, USD/year
E FC voltage, V
F Faraday's constant (=9.649.10^4 C/mol)
ΔG change in Gibbs free energy, kJ/kg H_2
h specific enthalpy, kJ/kg
ΔH reaction enthalpy, kJ/kg H_2
i interest rate, [-]
I FC current density, A/cm^2
m mass flow rate, kg/s
M molecular mass, kg/kmol
N life time, years
OM operation and maintenance cost, USD/year
p pressure, kPa, bar
P output power, kW
Q heat power, kW

R gas constant (= 8.314 J/mol °K)
T temperature, °K
T_g temperature of geothermal heat source, °C
TIT turbine inlet temperature, °C
U_f fuel utilization, [-]
η efficiency, [-]
τ power plant utilization, h/year

Subscripts
c compression
e electricity
ext external (FC cooling)
f fuel
FC fuel cell
g geothermal
int internal (in a FC)
inv investment
rev reversible (FC efficiency)
t thermal
tot total
v voltage (FC efficiency)
0 reference value
1 relates the reference geothermal power plant
2 relates GeoHybrid power plant

Acronyms
CC combustion chamber
ECO economizer
EXCO external cooling
FC fuel cell
GeoHybrid geothermal power plant with external steam superheating
GT gas turbine
HP high-pressure steam turbine
HX heat exchanger
LP low-pressure steam turbine
SOFC solid oxide fuel cell
SH super-heater

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