Techno-economic analysis of a solid biomass retrofit of an air-cooled ORC geothermal power plant

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ABSTRACT

In this work, the techno-economic feasibility of a solid biomass retrofit of an existing binary geothermal power plant is investigated. According to the use of the program Aspen V8.8, a model of the geothermal power plant related to the boundary conditions in Oberhaching (Germany) is developed. The geothermal unit, which provides 4355 kW_{el}, is retrofitted according to three case studies, with different amount of additional biomass thermal power (2 MW_{th}, 4 MW_{th} and 6 MW_{th}). The 6 MW_{th} case study provides the maximum power increase, equal to +872 kW_{el}. Real ambient temperature data are implemented and each model is yearly simulated. Economic parameters are calculated, such as the simple pay-back and the LCOE. The 6 MW_{th} case study provides the lowest LCOE, equal to 10.33 €ct/kWh, according to a cost of biomass equal to 10 €/MWh and 2180 €/kW_{el} as cost of hybridization by the retrofit. Next to power-only case studies, also CHP configurations are developed according to a real heat demand curve. Several sensitivity analyses are proposed in this work, varying the assumed cost of biomass, the biomass capacity factor and the cost of the retrofit upgrade.

1. INTRODUCTION

Nowadays, the effects of climate change are increasingly encouraging the interest and developments of renewable sources. Germany defined an ambitious social and economic plan in order to cut 80 % of CO_2 emissions by 2050 (Patt et al. 2011). In this context, geothermal energy can play a key-role, since the high capacity factor and the possible CHP configuration (DiPippo 2016). Several power plants and district heating systems are running in Germany on geothermal sources (Agemar et al. 2014). Coupling an existing geothermal power plant with another renewable source represents a valuable opportunity to increase power production and improve technical properties (DiPippo 2016). According to Southern Germany boundary conditions, the adoption of solid biomass as secondary source is a valuable opportunity to hybridize an existing geothermal power plant. A few examples regarding biomass based hybridization processes have already been studied. Thain et al. (2015) investigated the technical feasibility of a biomass-geothermal hybrid power plant. The system runs on a flash-binary combined geothermal layout, with 29 MW_{el} original power output. The combustion of solid biomass superheats the dry geothermal steam providing almost +20 MW_{th}, generating a +32 % yearly increase in power generation. Srinivas et al. (2014) investigated the potential of integrating a biomass combustor into an existing geothermal power plant, identifying the most cost-effective approach. Dal Porto et al. (2016) presented several results coming from the biomass retrofit of the Cornia 2 geothermal power plant. The additional biomass thermal power increases the steam temperature from 155 °C to 370 °C with an additional gross power equal to 6 MW_{el}. A few examples regard also the exploitation of waste heat from a biogas engine. Heberle et al. (2014) presented a thermo-economic analysis of a CHP hybrid binary geothermal solution. The secondary source is waste thermal power provided by a biogas engine. The hybrid solution provides better economic results than the simple geothermal ones, especially relying on the reduction of costs of maintenance. Toselli et al. (2018) investigated a hybrid geothermal and biogas WHR system in power-only configuration. Particular attention is dedicated to flexible power generation and ambient temperature fluctuations during the year.

In this work, the solid biomass retrofit of an existing binary geothermal power plant in Germany is investigated. The intent is to increase the yearly power production of ORC unit through the exploitation of additional thermal power provided by the combustion of solid biomass. The additional thermal power is varied according to three different case studies and exploited in order to increase the geothermal well-head temperature. Moreover, both power-only and parallel CHP solutions are performed.

2. METHODOLOGY

2.1 ORC model

The geothermal reservoir in Oberhaching is considered as the typical medium-low enthalpy geothermal source available in Molasse Basin, Germany (Agemar et al. 2014). The assumed power plant layout is showed in Figure 1.

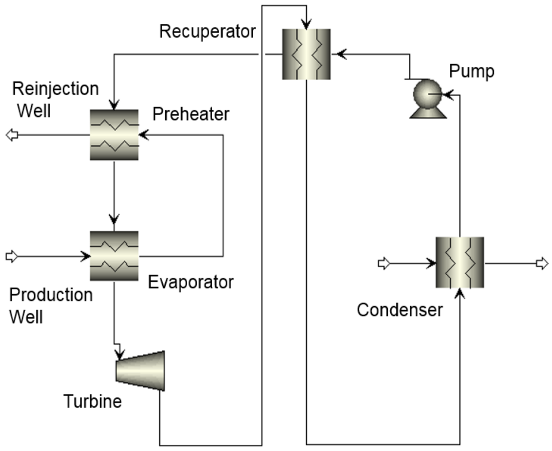

Figure 1: Geothermal power plant scheme in Oberhaching.

In Table 1, the main geothermal reservoir properties in Oberhaching are listed.

Parameter	Value
Geothermal water temperature	130 °C
Geothermal water mass flow	150 kg/s
Geothermal phase state	Liquid only

Table 1: Oberhaching geothermal reservoir data.

In accordance to the real application in Oberhaching, isobutane is chosen as the most suitable working fluid for this application. An on-design model of the ORC power plant operating in Oberhaching is developed starting from reliable assumptions regarding the power unit (Astolfi et al. 2014). The main assumed boundary conditions are resumed in Table 2.

Parameter	Value
ΔT_{pp} evaporator	4 K
ΔT_{pp} condenser	4 K
ΔT_{pp} recuperator	5 K
$\eta_{is,turbine}$	84 %
$\eta_{is,pump}$	70 %
$\eta_{generator}$	95 %
Evaporating pressure	optimized
Pressure losses	neglected
Capacity factor	90 %

Table 2: Technical assumptions regarding the power unit.

The on-design ambient temperature is 10 °C, equal to the average yearly ambient temperature in Southern Germany. All the models presented in this work are simulated according to the use of Aspen V8.8.

2.2 Off-design configuration

The off-design configuration is developed implementing different part load models for the heat exchangers, the turbine and the pump. The heat exchangers' off-design trend is described according to Toffolo et al. (2012), where the UA is defined as a function of the ORC mass flow. The turbine off-design behaviour is modelled according to the equation proposed by Ghasemi et al. (2013): the isentropic turbine efficiency is a function of the variable enthalpy difference and of the outlet volume flow rate. The pump off-design trend is described according to the curve of a real pump, applied in a similar geothermal application and provided by the manufacturer.

2.3 Retrofit model

In this work, the solid biomass retrofit of a geothermal power plant is investigated. In this case, the retrofit consists on combustion of solid biomass. The additional thermal power is released to the geothermal water before entering the ORC unit. The biomass combustion gases provide heat at a temperature range of 180 and 950 °C. In this study, the nature of the used biomass is not investigated. Several retrofit models are evaluated with different amounts of additional thermal power: 2 MW$_{th}$, 4 MW$_{th}$ and 6 MW$_{th}$. The capacity factor of the biomass source is initially assumed equal to 90 %. First, a power-only configuration is assumed and investigated. The retrofit and simple geothermal case studies are compared according to both technical and economic parameters. Later, the same procedure is applied in a parallel CHP case study. In this model, a real heat demand curve is implemented (Eller et al. 2019), assuming 5 MW$_{th}$ as maximum heat demand value. In the CHP retrofit case study, the biomass thermal power is firstly provided to the heating network: the unexploited amount is sent to the ORC unit. Here, only the 6 MW$_{th}$ retrofit case study is investigated and compared to the simple geothermal one.

2.4 Technical analysis

The technical performance of the retrofit is evaluated according to the following parameters. The biomass to electricity efficiency is defined as

$$\eta_{BTE} = \frac{\dot{W}_{hybrid} - \dot{W}_{geo}}{\dot{Q}_{biomass}}. \qquad [1]$$

In this work, this parameter is firstly presented as on-design value and later as yearly evaluation. During the year, the biomass to electricity efficiency is also allocated to only summer and winter evaluation as

$$\eta_{BTE\_summer} = \left(\frac{\dot{W}_{hybrid} - \dot{W}_{geo}}{\dot{Q}_{bio}}\right)\Bigg|_{summer}, \qquad [2]$$

$$\eta_{BTE\_winter} = \left(\frac{\dot{W}_{hybrid} - \dot{W}_{geo}}{\dot{Q}_{bio}}\right)\Bigg|_{winter}. \qquad [3]$$

In particular, “summer” is the assumed denomination when the ambient temperature is higher than 10 °C (equal to the yearly average temperature in Germany), “winter” if lower. The thermal efficiency of the power unit is calculated as

$$\eta_{th} = \frac{\dot{W}_{turbine} - \dot{W}_{auxiliary}}{\dot{Q}_{inlet}}. \qquad [4]$$

The auxiliary power $\dot{W}_{auxiliary}$ is defined as the sum of the ORC pump and of the air-cooled condenser consumption. The relative power increase by the retrofit is calculated both in winter and summer as

$$\Delta P = \dot{W}_{hybrid} - \dot{W}_{geo} \qquad [5]$$

or also expressed as percentage variation for yearly evaluations.

2.5 Economic analysis

The economic model presented in this work aims to proof the feasibility of the investigated retrofit: consequently, the only biomass source is evaluated according to a differential approach. In each retrofit configuration, the difference in power output between retrofit and simple geothermal is hourly calculated. Later, the biomass differential revenue is calculated according to the proper feed-in tariff available in Germany, assumed equal to 11 €ct/kWh (RES 2017). The biomass feed-in tariff in Germany ranges between 5 €ct/kWh and 14 €ct/kWh, according to the power plant size (RES 2017). The cost of biomass (C_{biom}) is initially assumed equal to 10 €/MWh (Macchi et al. 2017). The entire cost of hybridization depends on the cost of the necessary up-grade steps and components (Macchi et al. 2017). The retrofit cost results in 2180 €/kW$_{el}$ in the 6 MW$_{th}$ case study. Here, also the cost of the turbine and generator upgrade is considered (Astolfi et al. 2011). According to Turton (2012), the six-to-tenth rule is applied in order to calculate the cost of hybridization also for the other investigated examples. Each yearly net revenue is calculated as:

$$\text{Net Revenue} = \text{Revenue} - C_{biom} - C_{ofm}. \qquad [6]$$

The cost of maintenance (C_{ofm}) is calculated as 4 % of the total investment in the geothermal simple case study, while 3 % in the retrofit solution, both for geothermal and biomass source. The Simple Payback period (SPB) is defined as

$$\text{SPB} = \frac{C_{tot}}{\text{Net Revenue}}. \qquad [7]$$

The levelized cost of electricity (LCOE) is calculated as

$$\text{LCOE} = \frac{C_{tot} + \sum_{n=1}^{t} \frac{C_{ofm} + C_{biomass}}{(1+i)^n}}{\sum_{n=1}^{t} \frac{\dot{W}_{hybrid} - \dot{W}_{geo}}{(1+i)^n}}, \qquad [8]$$

where i is the interest rate, equal to 7 %, and t is the time duration, here 30 years. Moreover, the LCOE represents the effectiveness of biomass in power production and not in heat provision. Since the maximum investment reached in a retrofit example is lower than 2 M€, the SPB is preferred to the Break Even Point. Nevertheless, the SPB does not represent a discounted parameter. In the CHP configuration, the cost of the district heating network is neglected, since it does not represent a differential value according to hybridization.

2.5 Modelling of the complete system

The present work is developed according to the following steps:

- First, the model of the simple geothermal power plant in Oberhaching is created. This model is hourly simulated during all the year in power-only configuration.
- Second, the solid biomass retrofit in power-only configuration is applied according to three different examples, where the available amount of additional thermal power is varied. Technical and thermodynamic aspects are investigated. These models are also analysed from an economic perspective, investigating the profitability and economic feasibility of different case studies. Sensitivity analysis are performed varying the biomass cost, the biomass capacity factor and the cost of hybridization.
- Third, a CHP configuration is evaluated for both simple geothermal and the 6 MW$_{th}$ retrofit example: techno-economic results are investigated and compared.

3. RESULTS AND DISCUSSION

3.1 Oberhaching geothermal case study

The Oberhaching geothermal power plant model is performed according to the boundary conditions assumed in Table 1 and Table 2. The main geothermal power plant results are resumed in Table 3:

Parameter	Value
Turbine Power	4355 kW$_{el}$
Evaporating Pressure	14.26 bar
Thermal Efficiency	10.18 %
Reinjection Temperature	66.81 °C
Pressure ratio	3.72

Table 3: Simple geothermal on-design results.

In order to develop further analysis, the simple geothermal model is also yearly simulated: results are shown in Table 4.

Parameter	Value
Yearly average turbine isentropic efficiency	80.03 %
Yearly average thermal efficiency	9.66 %
Yearly total energy production	32.766 GWh

Table 4: Yearly simple geothermal case study results.

The averaged performance underlines the not negligible effect of ambient temperature fluctuations. For instance, the turbine isentropic efficiency drops from 84 % on-design value to 80.03 % as yearly average. A similar trend regards also the thermal efficiency.

3.2 Retrofit power-only: technical analysis

The heat provided by solid biomass is realised to the geothermal water before entering the ORC unit, according to the layout shown in Appendix. The evaporating pressure is optimized in the retrofit example, since the increase in available thermal power. In Table 5, the main results for the considered retrofit examples are resumed, at 10 °C ambient temperature and after evaporating pressure optimization.

Parameter	2 MW$_{th}$	4 MW$_{th}$	6 MW$_{th}$
Turbine Power	4643 kW$_{el}$	4933 kW$_{el}$	5227 kW$_{el}$
Evaporating pressure	15.05 bar	15.85 bar	16.80 bar
Thermal efficiency	10.00 %	9.83 %	9.69 %
Power increase	+288 kW$_{el}$	+578 kW$_{el}$	+872 kW$_{el}$
Reinjection temperature	66.20 °C	67.22 °C	68.43 °C
η_{BTE}	14.36 %	14.45 %	14.52 %
Biomass thermal power	4.87 %	9.42 %	13.74 %
Pressure Ratio	3.91	4.10	4.33

Table 5: Retrofit on-design results according to three different case studies.

The highest turbine power is reached in the retrofit 6 MW$_{th}$ case study, according to +872 kW$_{el}$ increase on the simple geothermal power production. Consequently, a technical upgrade of both the turbine and generator is necessary. The optimized evaporating pressure increases while incrementing the available biomass thermal power, up to +17.8 % of the on-design pressure value. On the contrary, the retrofit affects the thermal efficiency, with a maximum drop of 0.49 % in the 6 MW$_{th}$ case study. In the same example, the reinjection temperature reaches 68.43 °C, a +2.4 % increase due to the retrofit. The biomass to electricity efficiency slightly increases while switching to higher turbine power outputs. Due to the increasing evaporating pressure and almost constant condensing one, the pressure ratio is also improved. Since the proposed solution is an air-cooled ORC, ambient temperature variations are investigated according to the off-design models.

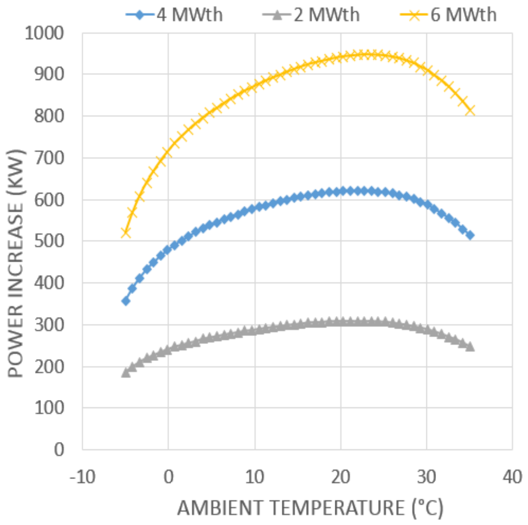

Figure 2: Power increase as a function of the ambient temperature in the three retrofit cases.

In Figure 2, the power increase obtained from the retrofit is shown for each case study as a function of the ambient temperature. This diagram underlines how the maximum point on each curve is shifted from the on-design ambient temperature (10 °C) to higher values (between 20 and 25 °C, according to the examined retrofit example). Taking into account only the 6 MW$_{th}$ case study, other trends are discussed. Figure 3 shows how the retrofit improves the thermal efficiency only at temperatures higher than about 18 °C. On the other hand, the simple geothermal example provides up to +1.36 % as thermal efficiency at -5 °C. In Figure 4, the turbine isentropic efficiency is improved only at temperatures higher than 10 °C, with a maximum increase of +11 % at 35 °C. In particular, this is due to the increase in evaporating pressure. Moreover, in

Figure 5, the retrofit shows a continuous improvement with regard to the turbine electric power as a function of the ambient temperature.

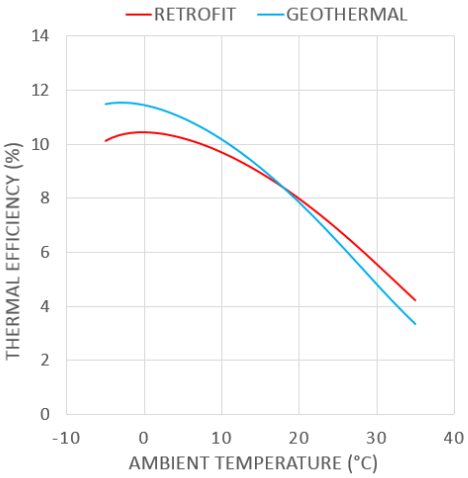

Figure 3: Thermal efficiency as a function of the ambient temperature, comparing the geothermal and the retrofit 6 MWth case study.

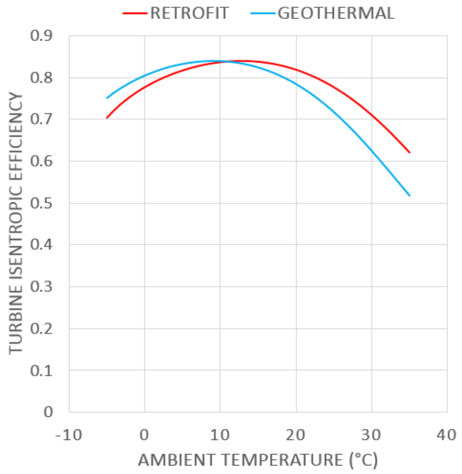

Figure 4: Turbine isentropic efficiency as a function of the ambient temperature, comparing the geothermal and the retrofit 6 MWth case study.

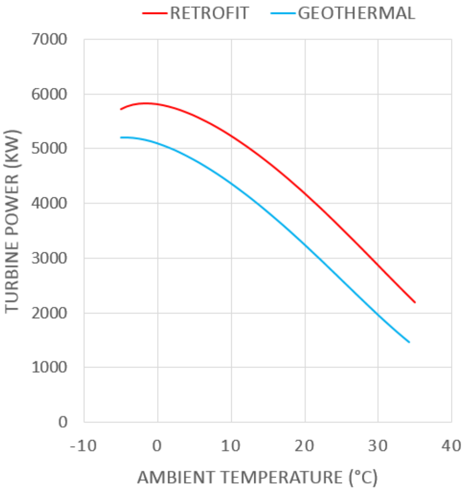

Figure 5: Turbine power as a function of the ambient temperature, comparing the geothermal and the retrofit 6 MWth case study.

The retrofit models are now simulated implementing real yearly ambient temperature data. The main results are resumed for each case study in Table 6. All the evaluated case studies show a very similar biomass to electricity efficiency, with a slight improvement through the increase of the available thermal power. In particular, the biomass to electricity efficiency is revealed to be higher in summer than in winter, with a controversial trend while varying the biomass thermal power. The seasonal difference in biomass to electricity efficiency tends to increase while increasing the available thermal power. This effect is a consequence of the turbine isentropic efficiency trend, as shown in Figure 4. Consequently, also the power production is improved more in summer than in winter, according to the same dependence. Even though the yearly turbine isentropic efficiency tends to be stable, the 4 MWth case study provides a slightly higher value than the 6 MWth one. On the other hand, the highest yearly thermal efficiency is provided by the 2 MWth case study. According to the yearly total power production, the 6 MWth example provides an increase of +20.16 % on the simple geothermal case study.

Parameter	2 MWth	4 MWth	6 MWth
η_{BTE}	13.84 %	13.88 %	13.97 %
η_{BTE_SUMMER}	14.92 %	15.01 %	15.22 %
η_{BTE_WINTER}	12.81 %	12.77 %	12.76 %
Summer power increase	8.70 %	17.52 %	26.63 %
Winter power increase	5.26 %	10.49 %	15.72 %
Yearly turbine isentropic efficiency	80.28 %	80.37 %	80.32 %
Yearly thermal efficiency	9.51 %	9.35 %	9.24 %
Yearly total energy production	34.949 GWh	37.141 GWh	39.373 GWh

Table 6: Technical yearly results in power-only retrofit case studies.

3.3 Retrofit power-only: economic analysis

The economic investigation is performed in order to estimate the feasibility of the retrofit solution, evaluating the previously assumed case studies. The main results are shown in Table 7. The SPB decreases while increasing the additional thermal power, as direct consequence of the economy of scale. In fact, the increase in available thermal power is related to a decrease of the fixed cost of hybridization per installed kW_{el} (Turton 2012). A similar trend results also in revenues and in LCOE estimation. According to the initially assumed biomass feed-in tariff (11 €ct/kWh), the 2 MW_{th} case study provides a LCOE higher than the considered feed-in tariff, while the 4 MW_{th} represents a borderline example. A similar trend is also shown according to the SPB: the 2 MW_{th} case provides a SPB higher than 18 years, while only the 6 MW_{th} one is lower than 10 years. Besides, the 6 MW_{th} case study provides a feasible LCOE, even if just 0.67 €ct/kWh lower than the assumed feed-in tariff.

Parameter	2 MW_{th}	4 MW_{th}	6 MW_{th}
SPB	18.48 years	12.30 years	9.64 years
Revenues	492,794 €	616,378 €	736,899 €
LCOE	12.19 €ct/kWh	10.97 €ct/kWh	10.33 €ct/kWh

Table 7: Economic results in power-only case studies.

The convenience and feasibility of the investigated retrofit case studies can be improved according to higher feed-in tariffs or to other boundary conditions' variations. Thus, further sensitivity analyses are performed.

Different values of cost of biomass may be available in the nowadays market, from 10 to 25 €/MWh (Macchi et al. 2017). Since the variation of this parameter may lead to different economic results, several sensitivities are proposed in this work. A cost of biomass equal to 5 €/MWh is firstly considered and results are shown in Table 8. LCOE and BEP highlight the feasibility of all the examples. The LCOE in the 2 MW_{th} case study is still lower than 9 €ct/kWh, guaranteeing SPB lower than 8 years. As underlined before, the economy of scale effect always enables the 6 MW_{th} case study as the most performing one.

Parameter	2 MW_{th}	4 MW_{th}	6 MW_{th}
SPB	7.43 years	5.35 years	4.38 years
Net revenues	571,634 €	774,058 €	973,409 €
LCOE	8.58 €ct/kWh	7.37 €ct/kWh	6.75 €ct/kWh

Table 8: Economic results in retrofit power-only examples according to cost of biomass equal to 5 €/MWh.

Additional cost of biomass values are investigated: In the 6 MW_{th} case study a cost of biomass of 10.95 €/MWh provides a LCOE equal to the initially assumed feed-in tariff (11 €ct/kWh), defining thus the feasibility borderline of this example. The economic feasibility of the retrofit solution strictly depends on the cost of biomass. In particular, the presented sensitivity analysis underlines how the retrofit feasibility is deeply encouraged by a sensible decrease in the cost of biomass. Consequently, the retrofit represents an interesting solution in order to valorise a low price biomass source, generally under 10 €/MWh.

The availability of biomass may strongly vary according to the evaluated real case study, determining different possible capacity factor values (Macchi et al. 2017). Consequently, a second sensitivity is applied on the biomass capacity factor. At on-design, biomass availability is equal to 90 %, as for the geothermal source. The power-only 6 MW_{th} retrofit case study is investigated and the main results are resumed in Table 9. While increasing the biomass capacity factor, the economic parameters are reasonably improved. The 6 MW_{th} retrofit example, according to the LCOE results, is no more feasible for capacity factor values lower than 60 %. Even though a lower capacity factor means a lower yearly cost of biomass, economic results demonstrate how increasing the biomass capacity factor improves the retrofit feasibility. This trend demonstrates how the decrease of fuel consumption is not an effective solution in order to improve the economic feasibility of the retrofit.

Parameter	50%	60%	70%	80%	90%
SPB (years)	13.3	12.14	11.17	10.35	9.64
Cost of biomass (k€/year)	263	316	368	421	473
LCOE (€ct/kWh)	11.3	10.93	10.69	10.49	10.33

Table 9: Results in capacity factor sensitivity for the 6 MWth power-only retrofit.

The cost of the retrofit is initially assumed equal to 2180 €/kW_{el} in the 6 MW_{th} case study, according to Macchi et al. (2017) and calculated for the other retrofit examples through the use of the six-to-tenth rule (Turton et al. 2012). According to best practice, the estimated costs may reasonably vary from the values assumed in this work. Consequently, a third sensitivity is evaluated. In the 6 MW_{th} retrofit case study, the cost of the retrofit is varied between 1500 and 2500 €/kWel. In the meantime, also the cost of biomass is varied between 5 €/MWh and 15 €/MWh. Results are plotted in Appendix. This diagram clearly shows the trend of the calculated LCOE as a function of both the cost of hybridization and the cost of biomass. The diagram underlines how a lower cost of hybridization may allow a higher cost of the biomass fuel, or vice versa, and still complying with a feasible LCOE. According to this picture, the feasibility of a certain retrofit case study depends on the available feed-in tariff. In this work, the biomass feed-in tariff is always assumed equal to 11 €ct/kWh: Higher values or additional bonus may encourage the retrofit application.

In Figure 6, different economic case studies for ORC systems from different heat sources are plotted in the diagram, showing the cost of installation per kW$_{el}$ as a function of the electric nominal power (Quoilin et al. 2011). The 6 MW$_{th}$ on-design example is placed in the diagram for a valuable comparison. The proposed case study provides a cost of installation comparable to an entire WHR unit but still lower than a CHP case study.

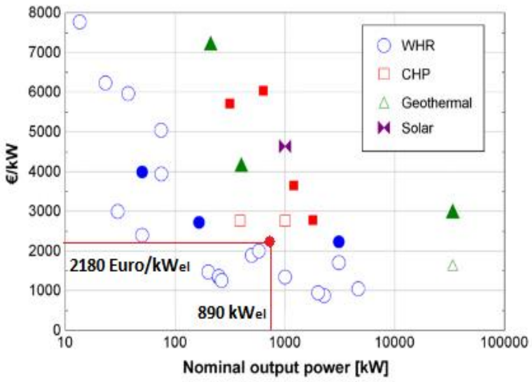

Figure 6: Cost of installation for ORC applications as a function of the nominal output power (Quoilin et al. 2011).

3.4 Retrofit in CHP scenario

In this work, also a CHP configuration is investigated, comparing the retrofit 6 MW$_{th}$ with the simple geothermal example. Both models are simulated according to the same real ambient temperature and heat demand data, with a maximum peak equal to 5 MW$_{th}$. Since heat production does not represent a differential factor, technical and economic results regard only electric power production. The CHP retrofit is investigated according to the previous assumed costs of hybridization and to allocated costs of biomass as fuel. In the CHP retrofit configuration, the yearly heat demand (17,715 MWh$_{th}$) is satisfied by biomass, while the remaining biomass heat (52,542 MWh$_{th}$) is exploited by the ORC unit. The difference between the retrofit and simple geothermal example in yearly total produced power is 5304 MWh, equal to a percentage increase of +16.83 %. Besides, the yearly average turbine efficiency results 80.60 % in the retrofit case study while 80.17 % in the simple geothermal one. The LCOE of the CHP retrofit results 9.86 €ct/kWh, while the SPB results 8.89 years. Since the feasibility of the retrofit in CHP configuration is proved, results can be compared with the power-only ones in Table 7. The LCOE in the retrofit CHP is 0.47 €ct/kWh lower than in power-only and the SPB in the retrofit CHP results 0.75 years lower. In fact, since the allocation of biomass to power production depends on the heat demand, more biomass thermal power is exploited at relatively high ambient temperatures, taking advantage of the better improvement in turbine efficiency. This is demonstrated also by the higher yearly turbine isentropic efficiency in CHP than in power-only (80.60 % > 80.32 %).

4. CONCLUSIONS

This work provides an extended techno-economic analysis regarding the possibility to increase the power output of an existing geothermal binary unit through additional biomass thermal power. For a single geothermal model, three different retrofit examples are analysed varying the amount of additional thermal power. The 6 MW$_{th}$ case study allows an increase of 872 kW$_{el}$, with a turbine power output equal to 5227 kW$_{el}$. As a consequence, the reinjection temperature inevitably increases, as demonstrated also in other studies (Heberle et al. 2017). Real ambient temperature data allows to simulate each model for each hour of the year. The 6 MW$_{th}$ retrofit case study results as the best case study, with a LCOE equal to 10.33 €ct/kWh and a SPB of 9.64 years. The on-design case is calculated according to a cost of biomass equal to 10 €/MWh, biomass capacity factor of 90 % and 2180 €/kW$_{el}$ as cost of hybridization. Due to the reasonable volatility of these parameters, several sensitivities are investigated. The cost of biomass is demonstrated to greatly affect the retrofit feasibility: only low biomass prices (<10.95 €/MWh) are feasible according to the initially assumed feed-in tariff. The capacity factor of solid biomass is ranged between 50 % and 90 %, revealing that the decrease in yearly fuel costs is not enough to counterbalance the missed power production benefit. A combined sensitivity, cost of biomass vs cost of hybridization, reveals the LCOE trend. Of course, if the cost of the retrofit per kW$_{el}$ is lowered, higher costs of biomass are still acceptable. In addition, a CHP configuration is also performed according to real heat demand data. The retrofit CHP configuration results slightly better than the power-only one, with a decrease of 0.47 €ct/kWh as LCOE and 0.75 years as SPB. Further investigations may regard a more detailed determination of the cost of hybridization: only best practice can provide reliable costs, according to the selected size. In this work, the biomass feed-in tariff is assumed to be 11 €ct/kWh. Nevertheless, policy variations or additional benefits may guarantee higher values, improving the economic feasibility of the retrofit.

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APPENDIX

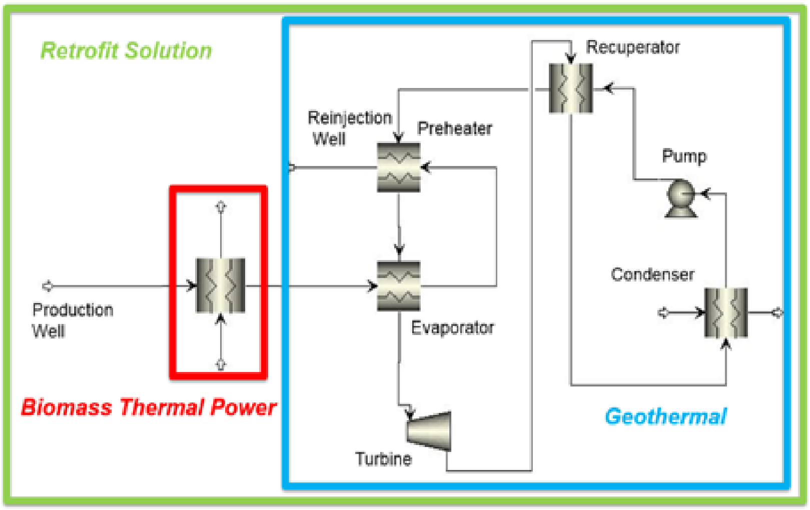

Figure 7: Retrofitted power plant layout.

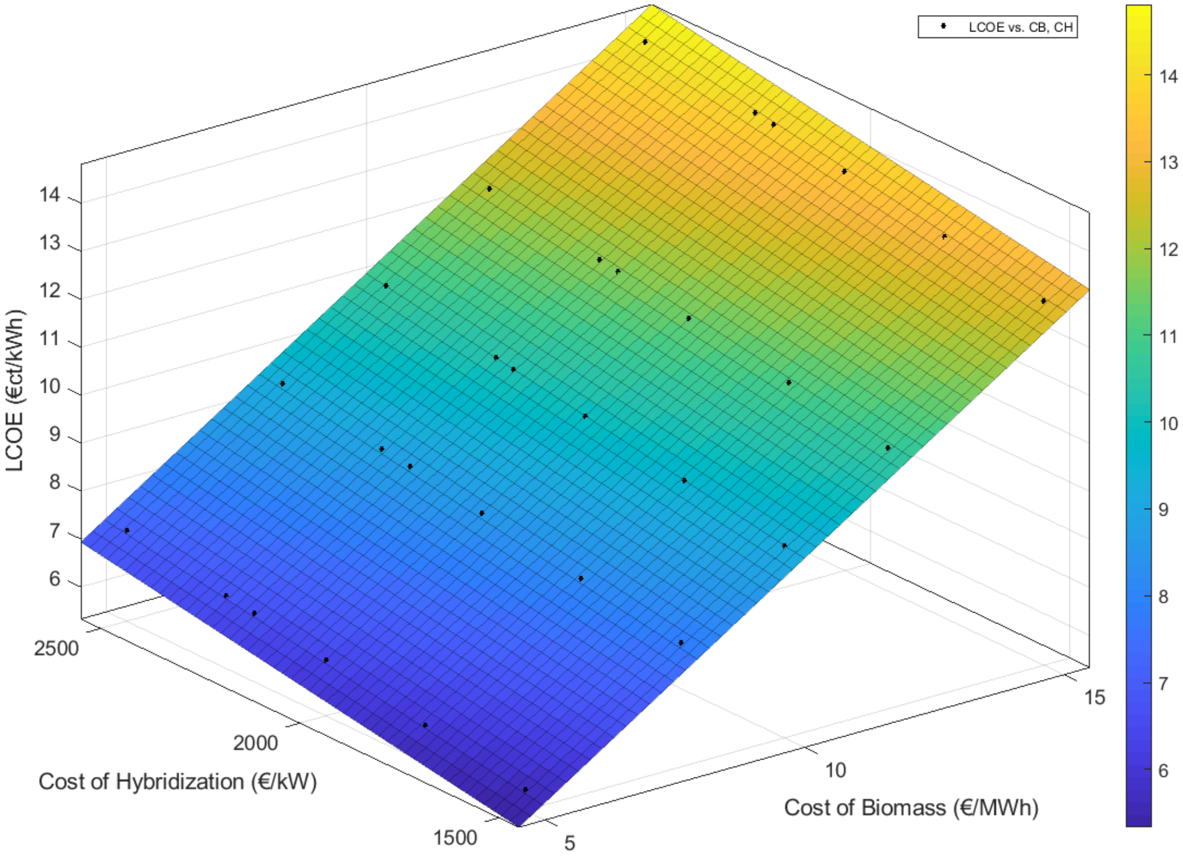

Figure 8: LCOE trend as a function of the cost of hybridization and of the cost of biomass.