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Techno-Economic Analysis of Hybrid Binary Cycles with Geothermal Energy and Biogas Waste Heat Recovery †

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Abstract: In Germany, enhancing renewable power generation represents a leading step to comply with the requirements of the Energiewende agenda. The geothermal reservoir in Oberhaching is assumed as a case study, with a gross electric power equal to 4.3 MW_{el}. The intent of this work is to design a hybrid binary geothermal power plant and to integrate it into the German energy market. Biogas waste thermal power equal to 1350 kW_{th} is assumed as a secondary source. Two different layouts are defined for the hybrid solution: increasing the geothermal fluid temperature before entering the organic Rankine cycle (ORC) unit and superheating the working fluid after the evaporator. Stationary and quasi-stationary simulations have been performed with Aspen Plus V8.8. Results demonstrate how hybridization allows a maximum electric power increase of about 240 kW_{el}. Off-design conditions are investigated regarding both the switch-off of exhaust gases and the annual ambient temperature fluctuations. In spite of the additional secondary source, the selected case studies cannot comply with the Minute reserve requirements (MRL). Moreover, economic results for both power-only and combined heat and power (CHP) configuration are provided. In the power-only configuration, the new-build hybrid system provides 15.42 €ct/kWh as levelized cost of electricity (LCOE), slightly lower than 16.4 €ct/kWh, as calculated in the geothermal-only solution. A CHP hybrid configuration shows a +19.22% increase in net cash flow at the end of the investment on the CHP geothermal solution.

Keywords: organic Rankine cycle; geothermal energy; flexible power generation; techno-economic analysis

1. Introduction

Since the beginning of the industrial revolution, the world's economic growth and human prosperity has always been dependent on energy supply. Nowadays, global population growth and climate changes are encouraging new interests and investments in renewable sources in order to provide access to reliable and sustainable energy [1].

Geothermal sources are worldwide available, especially in the USA, in the Philippines, Indonesia, Italy and New Zealand [2]. Technologies like organic Rankine cycle (ORC) and Kalina cycles allow the exploitation of low and medium enthalpy sources [3]. Therefore, geothermal energy can also be exploited in countries with a lack of high-enthalpy reservoirs, such as Germany. Geothermal power plants provide sustainable and reliable energy with very high capacity factors, both in power-only and combined heat and power (CHP) configuration [2]. Nevertheless, ORC geothermal solutions generally have a low thermal efficiency with a worldwide average value equal to 12% [4]. In fact, auxiliary power consumptions (ORC pumps, reinjection pumps, air-cooled condenser) are not negligible. Even though an air-cooled condenser is a positive solution to the lack of water for the wet condensation process, the ORC unit inevitably becomes ambient temperature dependent, reducing the annual net energy production. In particular, electric power production decreases in summer when the electricity demand increases, creating inconvenient working load conditions [5]. Consequently, part load working conditions and turbine isentropic efficiency deviations during the year have to be considered [6].

Technical and economic parameters of geothermal applications can be improved through hybridization, coupling the geothermal source with other renewable sources. Most of the investigated hybrid geothermal case studies are thermal solar based. The Stillwater triple hybrid power plant, built by Enel Green Power, is a geothermal hybrid power plant with additional power provided by a CSP and PV field [7]. Heberle et al. [8] investigated the solar thermal retrofit of a binary geothermal application in Turkey. Here, hybridization regards superheating the working fluid before entering the turbine, improving annual power production. Ghasemi et al. [6] also investigated a hybrid geothermal thermal solar solution, where solar power preheats geothermal water before entering the ORC unit.

Hybridization with biomass also represents a possible solution. Enel Green Power [9] hybridized the existing geothermal power plant Cornia 2 with a biomass combustor, providing an overall power increase of 5 MW_{el}, superheating the dry steam before entering the turbine. Thain et al. [10] investigated three different layouts at the power plant Rotokawa I, New Zealand. The most promising concept concerns a biomass system where the geothermal water preheats the combustion air, enhancing the overall thermal efficiency. Srinivas et al. [11] investigated several hybrid biomass concepts with an extended focus on economic results.

In Germany, there are nowadays 9 running geothermal power plants with a total installed capacity of 37.13 MW_{el}, while the installed heat capacity is equal to 374 MW_{th} [12]. In fact, the development of the ORC technology makes geothermal for electric power production feasible also in Germany, in spite of the lack of high enthalpy resources in shallow depth [12].

In 2016, Bioenergy [13] counted 8500 biogas installations in Germany with 4.5 GW as a total installed capacity. In the same year, the biogas electricity production in Germany was equal to 32,370 GWh, while heat production resulted in 17,437 GWh [13]. Biogas is versatile, sustainable and can partially replace fossil fuels both in heat and power production, also being integrated in the existing natural gas grid and used as renewable vehicle fuel [13]. In biogas installations, the generated thermal power is partially used for heating the digester but it can also be used for other agricultural applications such as drying or directly for heat production [13]. Nevertheless, heating applications may encounter several obstacles, like high costs and a lack of a closely located heat demand. Therefore, producing additional electricity from waste heat is a valuable alternative.

Benato et al. [14] investigated the use of an ORC unit for a 1 MW_{el} biogas engine waste heat recovery. According to thermodynamic results, toluene appeared as the most performing working fluid. Nevertheless, due to the very high inlet turbine temperature and to the very low condensing pressure, authors suggested benzene as the most suitable working fluid. Part load conditions, dynamic behavior and complete economic analysis are addressed in future works. David et al. [15] investigated an ORC biogas waste heat recovery example producing 160 kW_{el} with a 20% thermal efficiency, using toluene as working fluid. The economic analysis highlights a payback period lower than five years, thanks to a special feed-in tariff available in France for this application.

Heberle et al. [16] performed a techno-economic analysis of a hybrid binary geothermal power plant coupled with a biogas WHR, comparing hybrid and simple solutions in different CHP configuration (parallel and serial). Results demonstrated how hybrid solutions are promising concepts: The most performing case study is a hybrid CHP parallel circuit. Currently, there are no investigations providing results on flexible power generation, hybrid retrofit configurations and hybrid CHP layouts with an integrated real heat demand.

This paper is focused on the case study of a new-build hybrid binary geothermal power plant and biogas WHR is investigated according to boundary conditions available in Bavaria, Southern Germany. Two different hybrid power plant layouts are performed and the working fluid is selected in order to maximize the electric power generation.

The main objectives of this work are:

- Techno-economic analysis of the new-build hybrid system in comparison to the geothermal-only one.
- Investigation of flexible power generation (MRL).
- Next to the new-build system, analysis of a hybrid retrofit one.
- Analysis of a CHP configuration, according to the implementation of a real heat demand.

Hybridization is investigated in order to improve technical and economic parameters, comparing results of hybrid models to geothermal-only solutions. The considered models are evaluated also according to the switch-off of the second resource and to ambient temperature fluctuations during the year. Hybrid concept feasibility is analyzed also from the perspective of flexible power generation, considering the current requirements of the Minute reserve (MRL). Hybridization is investigated both as new-build configuration (first approach) and as retrofit solutions. In the end, also a CHP configuration is proposed.

2. Methodology

2.1. New-Build Model

The ORC new-build model simultaneously exploits geothermal water and biogas waste heat in hybrid configuration. The geothermal reservoir in Oberhaching is assumed as the typical low-temperature geothermal case study available in the Molasse Basin, Southern Germany. The additional waste heat is provided by the JMS 620 GS-B.L Jenbacher biogas engine. The technical performance and electric power contribution of the biogas engine are not integral part of this work. The main assumed boundary conditions are resumed in Table 1.

Table 1. Main boundary conditions regarding the geothermal and biogas waste heat recovery source.

Oberhaching Geothermal Reservoir		Jenbacher Biogas Engine	
Parameter	**Value**	**Parameter**	**Value**
Geothermal water temperature	130 °C	Exhaust gases maximum temperature	467 °C
Geothermal water mass flow	150 kg/s	Exhaust gases minimum temperature	180 °C
Geothermal phase state	Liquid only	Thermal Power	1350 kW_{th}

Two different hybrid layouts are proposed and investigated. The former, defined as concept A, is represented in Figure 1a: biogas waste heat preheats the geothermal water before entering the ORC unit. The latter, concept B, is shown in Figure 1b: Biogas waste heat superheats the working fluid before entering the turbine. In both examples, the working fluid pressure is raised by the pump before entering the recuperator. The adoption of an internal recuperator increases the thermal efficiency of the system. Heat is released from the geothermal water to the working fluid through the preheater and the evaporator. In concept B, the adoption of an additional superheater definitely increases the superheating degree of the working fluid before being expanded in the turbine. The air-cooled condenser finally condenses the working fluid before entering the pump again.

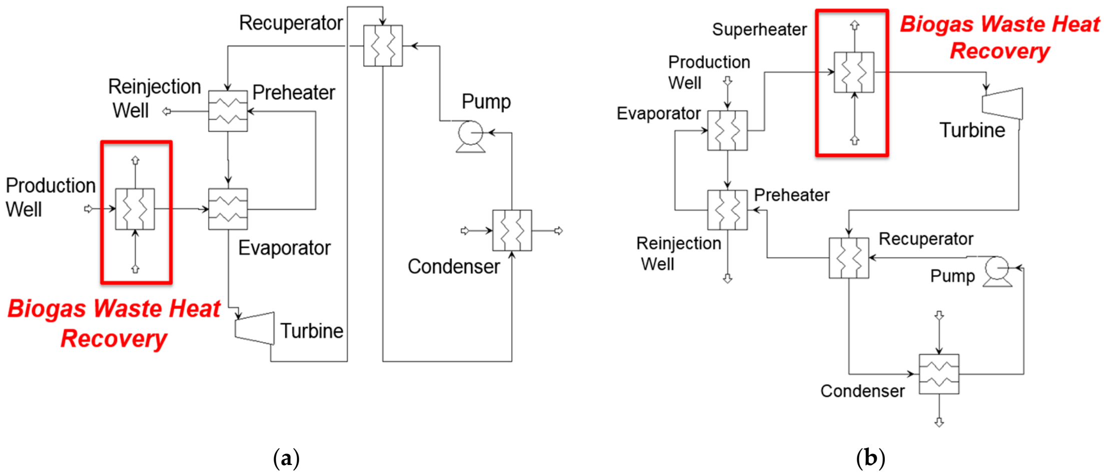


Figure 1. Concept A (**a**): Biogas waste heat is recovered preheating the geothermal water before entering the organic Rankine cycle (ORC) unit. Concept B (**b**): Biogas waste heat is exploited in order to superheat the working fluid before entering the turbine.

The assumptions regarding the on-design model in both concepts are resumed in Table 2.

Table 2. Assumptions regarding the on-design layout.

Parameter	Value	Parameter	Value
ΔT_{pp} evaporator	5 K	$\eta_{is,turbine}$	84%
ΔT_{pp} condenser	5 K	$\eta_{is,pump}$	70%
ΔT_{pp} recuperator	5 K	$\eta_{mec\text{-}el,turbine}$	95%
ΔT_{sh} evaporator	1 K	$\eta_{mec\text{-}el,pump}$	95%
ΔT_{sub} evaporator	0.5 K	Evaporating pressure	optimized
ΔT_{sub} condenser	0.5 K	Pressure losses	neglected

ΔT_{pp} and ΔT_{sub} represent respectively the pinch point temperature and the subcooling degree in heat exchangers. ΔT_{sh} is the superheating degree of the working fluid before entering the turbine. Moreover, η_{is} is the isentropic efficiency while $\eta_{mec\text{-}el}$ the mechanical one. The on-design ambient temperature is 10 °C, which corresponds to the annual average ambient temperature in Germany. All the models are performed according to the use of Aspen V8.8 [17]. Organic fluid properties are calculated according to the Peng-Robinson-method, whereas the Steamnbs-model for water [17].

2.2. Off-Design Model

The off-design model regards the implementation of part load equations for each component of the system. The heat exchangers off-design is defined according to the equation proposed by Toffolo et al. [18], where the UA, the heat transfer capacity, is calculated at part load as a function of the variable mass flow. The turbine off-design behavior is described according to the equation proposed by Ghasemi et al. [6]. Here, the isentropic efficiency of the turbine is calculated at off-design conditions as a function of the outlet volume flow rate and of the enthalpy drop variations. The pump isentropic efficiency is assumed to be constant. In this work, off-design models are required while investigating:

- The biogas waste heat recovery switch-off in hybrid configuration.
- The annual ambient temperature fluctuations.
- The CHP configurations.

2.3. Technical Analysis

Parameters for the further discussion of the on-design results are described in the following. The turbine power output $\dot{W}_{turb}$ is maximized by evaporating pressure optimization. The power plant thermal efficiency η_{th} is calculated as

$$\eta_{th} = \frac{\dot{W}_{turb} - \dot{W}_{pump} - \dot{W}_{acc}}{\dot{Q}_{geo} + \dot{Q}_{biogas}}, \tag{1}$$

where $\dot{W}_{pump}$ is the ORC pump power consumption and the power consumption of the air-cooled condenser $\dot{W}_{acc}$ is estimated according to [18]. $\dot{Q}_{geo}$ and $\dot{Q}_{biogas}$ respectively represent the geothermal and biogas waste thermal power. The power increase ΔP underlines the difference in power between the hybrid and the geothermal-only case study:

$$\Delta P = \frac{\dot{W}_{hybrid} - \dot{W}_{geo}}{\dot{W}_{geo}} \%, \tag{2}$$

where $\dot{W}_{hybrid}$ and $\dot{W}_{geo}$ are the turbine power outputs respectively in hybrid and geothermal-only configurations. The back work ratio BWR is calculated as

$$BWR = \frac{\dot{W}_{pump} + \dot{W}_{acc}}{\dot{W}_{turbine}} \tag{3}$$

while the specific net power output is defined according to

$$\beta_{ORC} = \frac{\dot{W}_{turb} - \dot{W}_{pump} - \dot{W}_{acc}}{\dot{m}_{ORC}}, \tag{4}$$

where $\dot{m}_{ORC}$ is the mass flow of the ORC working fluid. The pressure ratio is the ratio between the evaporating p_{EVA} and the condensing pressure p_{COND}

$$PR = \frac{p_{EVA}}{p_{COND}}. \tag{5}$$

Next to on-design parameters, also annual trends are investigated. Consequently, real ambient temperature data [19] are implemented in the model, simulating each example for each hour of the year. Hybridization efficiency η_{hyb} is defined as

$$\eta_{hyb} = \frac{\dot{W}_{hyb} - \dot{W}_{geo}}{\dot{Q}_{biogas}} \tag{6}$$

and it is calculated both as on-design and average value. The thermal efficiency is also hourly calculated during the year, according to (1). Flexible power generation FI is discussed as flexibility index:

$$FI = \frac{\dot{W}_{hybrid}}{\dot{W}_{geo}} \tag{7}$$

In this work, flexible power generation is investigated considering the requirements of the minute reserve (MRL). The minute reserve is a particular type of energy market available in Germany and designed for flexible power generation [20]. When grid instabilities cannot be solved according to the primary and secondary reserve, additional (or lower) electric power is provided according to the minute reserve. Currently, power plants complying with the minute reserve are required to meet two main requirements: they have to provide at least 5 MW_{el} as nominal power and 1 MW_{el} as power granularity for at least 4 h [21]. In this work, dynamic requirements are assumed to be satisfied [22].

2.4. Economic Analysis

The power plant availability during the year is assumed equal to 95%, both for geothermal and biogas WHR. The geothermal feed-in tariff is 25.0 €ct/kWh, while 11.0 €ct/kWh for biogas waste heat recovery [21]. Regarding heat generation in CHP applications, a heat price equal to 5.0 €ct/kWh is assumed [16]. In the hybrid case study, the annual power production is allocated between the two different feed-in tariffs according to the percentage of the two available sources (96.72% geothermal, 3.28% biogas WHR). The annual cost of operation and maintenance is assumed to be 3% of the total investment in the hybrid solution, while 4% in the geothermal-only concept. This assumption is reasonably motivated in the hybrid case study since the personal cost regarding operation and maintenance $C_{O\&M}$ of the biogas engine and of the ORC unit can be shared. In Table 3, the main assumptions for the economic model are resumed:

Table 3. Assumptions for the economic analysis, according to Heberle et al. [3].

Parameter	Value
Cost of hybridization (€/kW_{el})	2180
Cost of the ORC unit (€/kW_{el})	3567
Cost of drilling (M€)	20.38
Cost of insurance (M€)	2.038
Cost of auxiliary components consumption (€ct/kWh)	12.23

The cost of hybridization is estimated according to the following procedure. In Table 4, a list of necessary steps to apply hybridization is shown [23]. These costs are referred to a 6 MW_{th} biomass application [23].

Table 4. List of cost of hybridization for a 6 MW_{th} biomass case study [23].

Parameter	Value
Installation (k€)	100
Electric works (k€)	150
Engineering (k€)	100
ORC and turbine upgrade (k€)	500
Civil works (k€)	350
Total (k€)	1200

In addition, due to the different power plant size, the six-to-tenth rule [24] is applied. For a thermal power equal to 1350 kW_{th}, the specific cost of hybridization results in 2180 €/kW_{el} (see Table 3). For all the economic boundary conditions, the assumed reference year is 2017 [24]. The economic feasibility of the proposed case studies is estimated according to the levelized cost of electricity, defined as

$$LCOE = \frac{C_{tot} + \sum_{n=1}^{t} \frac{C_{O\&M} + C_{auxiliary}}{(1+i)^n}}{\sum_{n=1}^{t} \frac{\dot{W}_{turb}}{(1+i)^n}}, \tag{8}$$

where C_{tot} represents the total investment. The break-even point is calculated as

$$0 = -C_{tot} + \sum_{t=0}^{T} \left(R_{ev} - C_{O\&M} - C_{auxiliary}\right)(1+i)^{-t}, \tag{9}$$

where i, the interest rate, is equal to 7% and the investment duration t is 30 years. The first two years of the entire investment are assumed for the power plant construction. A combined heat and power (CHP) configuration is also investigated according to a parallel configuration. Here, the feasibility of the CHP case study is inevitably dependent on the cost of the district heating network. In this work, the district heating network is initially assumed to be 8 km long, with a cost of 510 k€/km. A real annual heat demand is implemented in the models [19]. The heating system is required to provide hot water between 60 and 90 °C to the network.

2.5. Simulation

Before proceeding with the results, the followed simulation strategy is explained (Figure 2). First, several hybrid layouts are investigated [25], but only two are proposed and simulated in this work. A working fluid comparison is developed in order to find the most suitable medium for the selected case studies. On-design working conditions are found at the maximum turbine power output while optimizing the evaporating pressure. Later, off-design models are implemented in order to completely simulate the models also at part load conditions. In the end, economic parameters are also investigated.

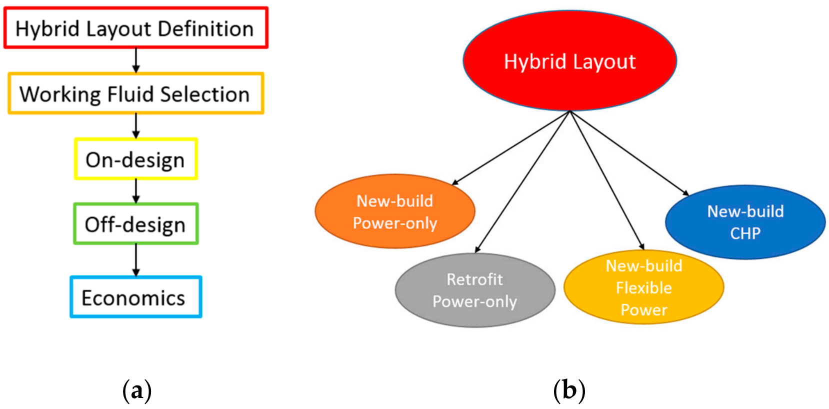


Figure 2. Followed strategy for the development of this work (**a**). Types of investigated power plant applications in this work (**b**).

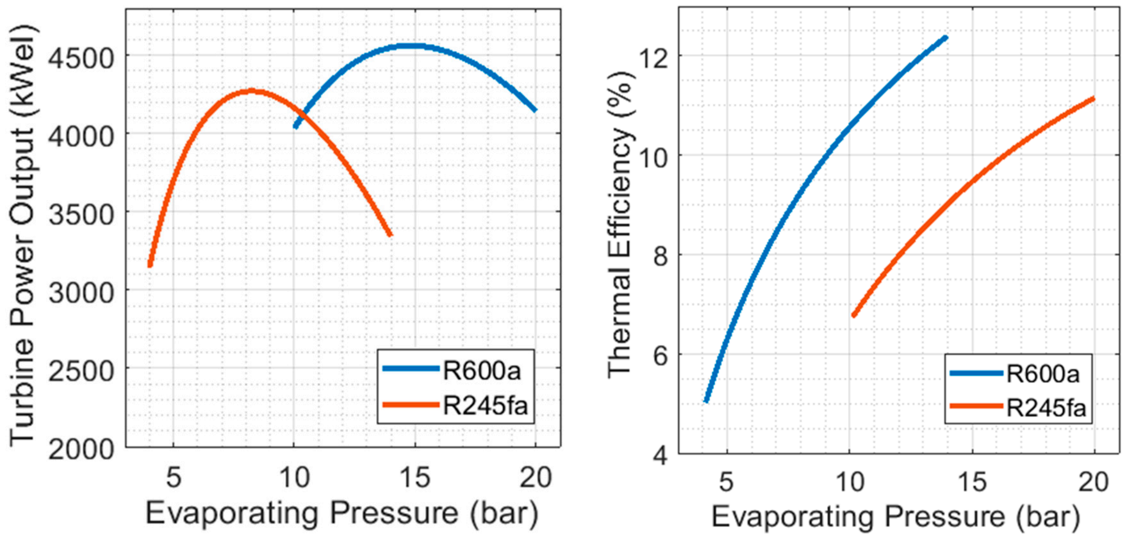
In Figure 2 the different power plant solutions investigated in this work are shown. Hybrid power-only regards a system where hybridization occurs at a new-build system. The retrofit represents the improvement of an existing geothermal power plant through a postponed hybridization. The investigation of flexible power generation aims to test the feasibility of the proposed solutions for the minute reserve market. A CHP configuration is also investigated, since it represents a typical case study in geothermal applications.

3. Results

3.1. New-Build System

The hybrid new-build case study is developed according to the simultaneous exploitation of the geothermal source and biogas WHR. On-design models are defined regarding concept A, B and compared to the geothermal-only example, according to the assumptions shown in Table 2. For each case study, the on-design point is obtained optimizing the evaporating pressure in order to maximize the turbine power output.

A performance evaluation is developed for R245fa and R600a since they are the most used working fluids in geothermal ORC power plants in the Molasse Basin [16,26,27]. Nevertheless, wet fluids [28] (such as R134a, without recuperator), isopentane and R227ea have also been tested, even though showing unfeasible results due to the very low reinjection temperature. This would lead to scaling in the heat exchangers and to an unfavourable management of the geothermal reservoir. Both hybrid concepts, A and B, are simulated according to the use of R245fa and R600a at on-design conditions. Selected results are here resumed only regarding concept A, since the resulting trends are similar in both investigated layouts. In Figure 3a, the turbine power is represented as a function of the evaporating pressure, comparing the trend of the two selected working fluids. For the considered single stage ORC, R600a provides 4595 kW_{el} at 14.85 bar as maximum point, while R245fa only reaches 4270 kW_{el} at 8.20 bar. In Figure 3b, the thermal efficiency is shown for both working fluids as a function of the evaporating pressure. At 14.85 bar, R600a thermal efficiency is 9.62%, while R245fa reaches 9.4% at 8.20 bar. However, for a certain evaporating pressure, R600a provides a higher turbine power output, while R245fa a better thermal efficiency. Since the intent is to maximize the turbine power output, the following models are performed with R600a: On-design results are resumed in Table 5.



(**a**) (**b**)

Figure 3. Turbine power is plotted as a function of the evaporating pressure, comparing R600a and R245fa as selected working fluid (**a**). Thermal efficiency is shown as a function of the evaporating pressure, comparing R600a and R245fa as selected working fluid (**b**).

Table 5. On-design results in hybrid case studies and in geothermal-only model.

Parameter	Concept A	Concept B	Geothermal-Only
Turbine Power (kW_{el})	4561	4467	4336
Evaporating Pressure (bar)	14.85	14.65	14.38
ORC mass flow (kg/s)	108.60	104.27	105.80
Reinjection Temperature (°C)	67.12	69.57	66.82
Turbine Inlet Temperature (°C)	85.91	90.94	84.32
Thermal Efficiency (%)	9.40	9.61	9.20
Back Work Ratio	0.152	0.147	0.153
β_{ORC} (kW/(kg/s))	35.60	36.52	34.73
Pressure ratio	3.75	3.70	3.63
Hybridization efficiency (%)	16.66	9.70	-

Hybrid case studies reasonably provide a higher turbine power than the geothermal-only example. Concept A provides the highest turbine power output, +94 kW_{el} more than B and +225 kW_{el} more than the geothermal-only example. Concept A also requires the highest evaporating pressure: +0.20 bar more than B and +0.47 bar more than geothermal-only. The increase in working fluid mass flow is proportionally related to the available thermal power for fixed ΔTpp in all the case studies. The geothermal example is characterized by the lowest reinjection temperature, due to the lowest evaporating pressure. Concept B, due to the increased superheating degree, provides the highest turbine inlet temperature: +5.03 K more than A and +6.62 K more than geothermal-only. The thermal efficiency results to be slightly improved in hybrid case studies, +0.20% in A and +0.41% in B. Concept B shows a barely higher thermal efficiency than A, even though A provides the highest turbine power output. Concept B provides the lowest BWR and also the highest specific net power; this is a consequence of the lower auxiliary power consumption. The highest pressure ratio is found in A, as a direct consequence of the high evaporating pressure. Hybridization efficiency in concept A results in 16.66%, lower but still comparable to the dedicated ORC biogas WHR system [15], where the overall efficiency is about 20%. Nevertheless, concept B provides a definitely lower efficiency: 9.70%.

3.2. Annual Ambient Temperature Fluctuations

Real ambient temperature data from 2015 [19] are implemented and the hybrid concepts are simulated: For one year, the main results are resumed in Table 6. Concept A provides +2.11% and +5.27% more than case B and geothermal-only respectively in annual energy production. Nevertheless, thermal efficiency in Concept B is 0.21% higher than in A and annual isentropic efficiency is slightly improved. The annual turbine isentropic efficiency is about 4% lower than the on-design value and thermal efficiency diminishes of about 0.52% in all the examples.

Table 6. Average analysis results based on one year.

Parameter	Concept A	Concept B	Geothermal-Only
Annual power production	36.255 GWh	35.505 GWh	34.437 GWh
Average thermal efficiency	8.88%	9.09%	8.67%
Average turbine isentropic efficiency	80.136%	80.137%	80.05%
Average hybridization efficiency	16.18%	9.51%	-

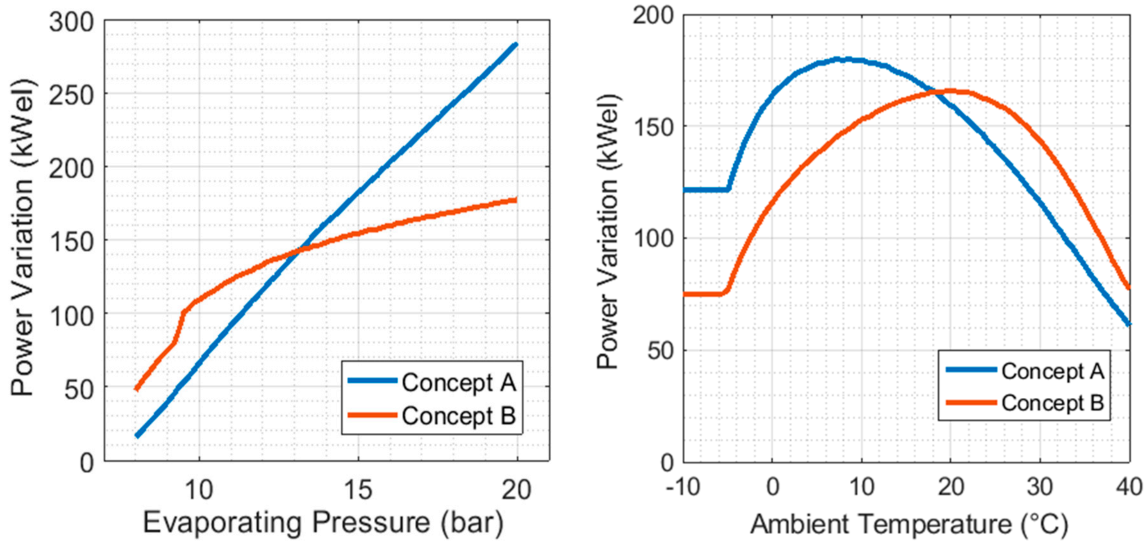
3.3. Decoupling Biogas WHR

In this section, the switch-off of biogas waste heat recovery is investigated, decoupling exhaust gases in the hybrid examples in order to obtain a flexible system. Therefore, the total available thermal power is reduced and part load occurs. Since the biogas source represents only 3.28% of the total available thermal power, part load results are expected to be slightly different after decoupling exhaust gases. A summary of the main results is shown in Table 7.

Table 7. Part load decoupling results in concept A and B.

Parameter	Concept A	Concept B
Turbine Efficiency (%)	83.85	83.86
Power Variation (kW_{el})	−179	−152
Thermal Efficiency (%)	9.42	9.37
Flexibility Index	1.040	1.035

The turbine isentropic efficiency decrease is only 0.25% in concept A and 0.24% in B. Case study A highlights a barely higher flexibility than B: this trend is underlined by both the power variation and the flexibility coefficient differences, as a consequence of the different power plant layout. Thermal efficiency in concept A remains almost unchanged, while in concept B a decrease of 0.24% occurs. Part load conditions after decoupling are investigated also varying evaporating pressure and ambient temperature. Flexibility might be improved by varying the evaporating pressure while decoupling exhaust gases. In Figure 4, sensitivity analyses are performed and results are plotted. Case study A shows an almost linear trend, where high power variations correspond to high evaporating pressures (+284 kW_{el} at 20 bars). In concept B, the increase in evaporating pressure also provides an increase in power variation, in spite of the trend unsteadiness (+177 kW_{el} at 20 bars). This results as a consequence of the different power plant layout and different off-design deviations (turbine isentropic efficiency, heat transfer capacity UA in heat exchangers).



(**a**) (**b**)

Figure 4. The difference between on- and off-design power is here represented for both concepts as a function of the evaporating pressure (**a**). Power variation is represented as a function of the ambient temperature (**b**).

Since the investigated solutions are ORC with air-cooled condenser, ambient temperature variations are performed. At ambient temperatures higher than 17 °C, the power variation in concept B becomes higher. Anyway, both examples show a parabolic trend with minimum values at low and high ambient temperatures. It is demonstrated how flexibility is a function of the power plant layout, of the evaporating pressure and of the ambient temperature.

3.4. The Minute Reserve Requirements

From Tables 5 and 7, it is demonstrated that the assumed case studies cannot comply with the MRL requirements. In particular, the installed capacity is lower than 5 MW_{el} and, while decoupling biogas WHR, the power variation is only about 150 kW_{el}: Definitely lower than the required 1 MW_{el}. Consequently, the compliance with these two requirements is separately discussed.

First, several solutions can be proposed in order to provide at least 5 MW_{el} nominal power:

1. The assumed geothermal reservoir can be changed in favor of a more productive one.
2. The electric power provided by the biogas engine can be summed to the hybrid system one and delivered to the energy market as a virtual power plant.
3. The biogas thermal power can be increased. In this work, it is calculated that an additional thermal power of 3935 kW_{th} is necessary to provide 5 MW_{el} nominal power, according to hybrid layout A at 10 °C ambient temperature. Since the very high amount of thermal power, adopting biogas waste heat appears unrealistic and unfeasible. In this work, a large biogas engine (2370 kW_{el} as nominal power) has already been adopted. Even though several (and even larger) engines are running in Southern Germany, most of the systems have an installed electric power capacity between 150 and 500 kW_{el} [29]. Solid biomass can be suggested as alternative source.

A power granularity equal to 1 MW_{el}, for at least 4 h, can be provided according to the implementation of a thermal storage. Instead of exploiting biogas heat during the whole day, the secondary source can be stored and exploited in shorter time to provide +1 MW_{el} as power granularity for at least 4 h. According to a basic and 100% efficiency calculation, about 83% of the daily available thermal energy is necessary to provide +1 MW_{el} turbine power for at least 4 h.

3.5. Retrofit Examples

In the previous sections, the hybrid solution is always evaluated as new-build case study. Now, the same hybrid layouts are investigated but according to a retrofit solution. In this section, an existing geothermal power plant is hybridized and, therefore, it results as a retrofit. Consequently, turbine power outputs in retrofit A and B are expected to be lower than new-build hybrid ones. The evaporating pressure is optimized again in order to maximize the turbine power output: results are summarized in Table 8.

Table 8. Comparison between geothermal-only and hybrid retrofit examples (concept A and B).

Parameter	Geothermal-Only	Retrofit A	Retrofit B
Turbine Power (kW_{el})	4336	4537	4428
Evaporating Pressure (bar)	14.38	15.60	16.55
ORC mass flow (kg/s)	105.80	104.24	95.20
Reinjection Temperature (°C)	66.82	69.39	73.61
Turbine Inlet Temperature (°C)	84.32	88.36	91.34
Thermal Efficiency (%)	9.33	9.78	10.70
Back Work Ratio	0.153	0.152	0.149
Turbine Isentropic Efficiency (%)	84	83.84	82.35

Retrofit A provides +201 kW_{el} while Retrofit B highlights only +92 kW_{el}. The evaporating pressure increases of 1.22 bar in example A while 2.17 bar in B. In comparison to the geothermal-only case study, the ORC mass flow tends to decrease while retrofitting as a direct consequence of the increased evaporating pressure, with a minimum decrease of 10.60 kg/s in case B. The reinjection temperature also augments, up to 10.16% in retrofit B: this is mainly due to the higher evaporating pressure. Consequently, thermal efficiency results to be improved, especially due to the lower amount of exploited thermal power. In retrofit A, the thermal efficiency increase is 0.45% while even 1.37% in B. The inlet turbine temperature rises depending on the optimized evaporating pressure and on the superheating degree in retrofit B (+4.04 K in A and +7.02 K in B). The turbine isentropic efficiency decrease is just 0.26% in A, while 1.65% in B. The BWR is slightly decreased as a consequence of the increased turbine power.

Again, also in the retrofit case study, concept B is more affected by turbine isentropic efficiency variations than concept A. In comparison to new-build hybrid examples (Table 5), retrofit case studies always provide a lower turbine power output (–24 kW_{el} in A, –39 kW_{el} in B), while the evaporating pressure is always higher (+0.75 bar in A, +1.9 bar in B).

3.6. Economic Analysis

3.6.1. Power-Only Scenario

An economic analysis is provided to prove the economic feasibility of hybridization. A comparison between the hybrid new-build case study A and the geothermal-only example is proposed. Example A is preferred to B due to the higher turbine power output. Real ambient temperature data from Southern Germany [19] are implemented in the models, simulating the two examples for each hour of the year. Economically based annual parameters are therefore calculated. The main economic results are shown in Table 9, comparing the hybrid case A and the geothermal-only example.

Table 9. Economic results comparison.

Parameter	Hybrid A	Geothermal
LCOE (€ct/kWh)	15.42	16.74
Break Even Point (years)	10.82	11.49
Net Cash Flow (k€)	35,068	30,155

Hybrid A leads to a decrease in LCOE of 1.32 €ct/kWh, also while the BEP is 0.67 years lower in comparison to the simple geothermal case study. In addition, a net cash flow increase of 16.29% occurs. Hybridization allows a smooth improvement of the economic parameters, considering that the slight variation is dependent on the low amount of additional thermal power provided by the secondary source.

In this context, two different sensitivities are applied. First, the cost of operation and maintenance is varied in the geothermal-only case study, assuming also 3% and 5% of the total fixed costs. Results are compared to the new-build hybrid case study, where the percentage of cost of operation and maintenance is equal to 3%. The main results are resumed in Table 10. In the 3% cost of operation and maintenance geothermal case study, LCOE results are still 0.22 €ct/kWh higher than the hybrid case study. Comparing these two examples, the BEP is nearly the same. The hybrid example provides +2.60% in net revenues. Therefore, when the cost of operation and maintenance is assumed equal in geothermal and hybrid examples, the positive contribution of hybridization is still justifiable but significantly reduced. A more effective contribution of hybridization may be guaranteed if the percentage of the cost of operation and maintenance is assumed equal to 5% in the geothermal example. Here, the LCOE is 2.43 €ct/kWh higher than the hybrid case, while the BEP difference is 1.42 years. Even though in Table 10 only a few sensitivity points are analyzed, results clearly underline the importance of lowering the cost of operation and maintenance in the hybrid case (3%) compared to the geothermal example (4%).

Table 10. Results according to the sensitivity on cost of operation and maintenance.

Parameter	Geothermal_3%_$C_{O\&M}$	Geothermal_5%_$C_{O\&M}$
LCOE (€ct/kWh)	15.64	17.85
Break Even Point (years)	10.76	12.24
Net Cash Flow (k€)	34,179	26,132

Comparing hybrid A and the geothermal_3%_*CO&M* example, it can be observed that the former provides a lower LCOE but a slightly higher BEP. In fact, even if hybrid A provides a higher annual energy production (36,270 MWh > 34,452 MWh) and a higher net annual revenue (7018 k€ > 6804 k€), the total investment is reasonably higher (39,331 k€ > 37,952 k€) anyway. In particular, it can be observed that a non-discounted difference on the first year between the total investment and the net revenue provides a slight advantage in the geothermal case study (−32,313 k€ < −31,148 k€).

A second sensitivity is performed varying the cost of hybridization. In spite of the assumed boundary conditions, the estimation of real costs may significantly vary. Thus, a sensitivity analysis is performed varying the cost of hybridization from 1000 €/kW_{el} to 4000 €/kW_{el}. The sensitivity trend, shown in Figure 5, underlines very smooth deviations in LCOE while varying the cost of hybridization. The LCOE results in 15.32 €ct/kWh at 1000 €/kW_{el}, while 15.57 €ct/kWh at 4000 €/kWel. The slight influence of the cost of hybridization on LCOE of the hybrid solution reasonably derives from the assumption that the additional thermal power provided by biogas WHR only accounts for the 3.28% of the total available power. Moreover, it is important to estimate that even large variations in the cost of hybridization does not sensibly affect the overall results.

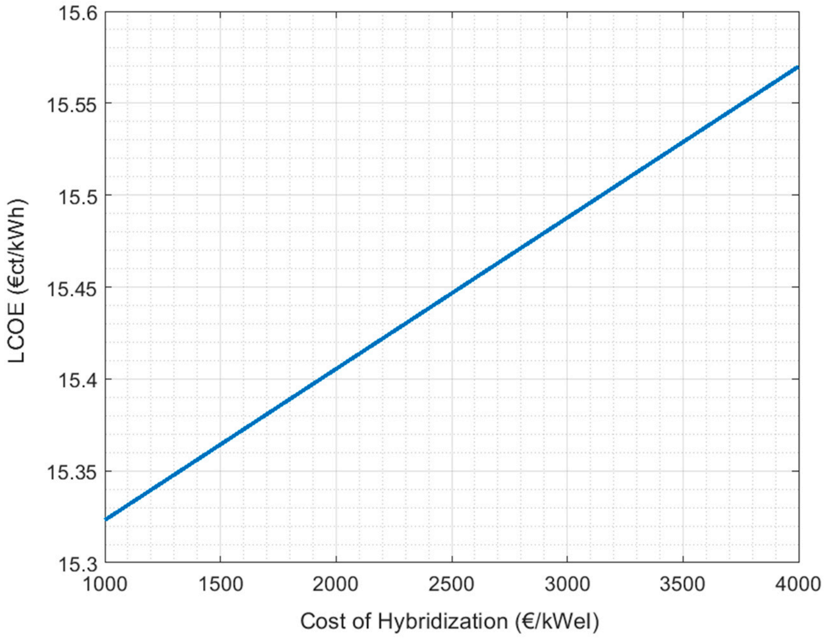


Figure 5. Levelized cost of electricity (LCOE) in the hybrid case study as a function of the cost of hybridization.

3.6.2. CHP Scenario

Since most of the geothermal binary applications in Southern Germany provide both heat and power [12], a hybrid CHP configuration is also investigated. Heat production may result in a valuable opportunity to improve economic feasibility. The following hybrid concept regards only the new-build layout A. Both CHP models are developed from the on-design power-only configurations, implementing a real heat demand curve from an existing geothermal heating system in Southern Germany [19]. The maximum peak is equal to 5 MW_{th}, while the annual produced heat is 841.5 MWh. In both examples, the system results in a heat-driven solution, where the geothermal water is split between the ORC unit and the district heating network, according to the variable heat demand. In the hybrid case study, biogas waste heat is released to the geothermal water before being split.

In Table 11 the main results of the two CHP configurations are resumed. In this context, the LCOE does not take into account heat production, as shown in Equation (8). Hybridization, as in the power-only case study, allows an improvement of the selected parameters: here the LCOE is 1.66 €ct/kWh lower, while the BEP difference is lower than 1 year. The comparison between these results with the ones in Table 9 allows to highlight the main differences between a power-only and a CHP configuration, both hybrid and not. The lowest LCOE is found in the hybrid power-only case study with 15.42 €ct/kWh, while the highest value is provided by the geothermal CHP model, which is equal to 19.13 €ct/kWh. Very smooth variations regard the BEP: again, the lowest value is found in hybrid power-only (10.82 years) while the highest (12.22 years) in the geothermal CHP. The net cash flow calculated at the end of the investment provides in the hybrid CHP +19.22% more than the geothermal CHP.

Table 11. Main economic results in combined heat and power (CHP) configurations.

Parameter	Hybrid CHP (Layout A)	Geothermal CHP
LCOE (€ct/kWh)	17.47	19.13
BEP (years)	11.38	12.22
Net cash flow (k€)	35,100	29,441

Further sensitivities are developed increasing the heat price up to 10 €ct/kWh. The main results (Tables 12 and 13) highlight how the increasing price for heat improves the feasibility of the investigated case studies. According to the same heat price, the hybrid case study reasonably provides better results than the geothermal-only one. In the hybrid case study, the BEP diminishes of 0.68 year and 1.29 year, while the net cash flow increases of 12.71% and 25.41% (Table 12). Comparable variations regard the geothermal-only case study, even though with lower absolute values. Nevertheless, the geothermal-only example at 10.0 €ct/kWh as heat price provides better results than the 5.0 €ct/kWh hybrid ones. Moreover, the geothermal-only example at 10.0 €ct/kWh provides comparable results to the 7.5 €ct/kWh ones in hybrid configuration. In particular, the geothermal-only has a lower BEP but lower net cash flow: this trend is related to the difference in total investment, cost of maintenance and gross revenues per year between the hybrid and the geothermal-only case study.

Table 12. Economic results in hybrid CHP case study with sensitivity in heat price.

Parameter	Hybrid Case Study	
	7.5 (€ct/kWh)	10.0 (€ct/kWh)
BEP (years)	10.70	10.09
Net cash flow (k€)	39,560	44,020

Table 13. Economic results in geothermal CHP case study with sensitivity in heat price.

Parameter	Geothermal Case Study	
	7.5 (€ct/kWh)	10.0 (€ct/kWh)
BEP (years)	11.40	10.69
Net cash flow (k€)	33,902	38,362

Consequently, it is demonstrated how the price of heat can play a significant role in the economic feasibility of hybridization.

4. Conclusions

In this work a new-build binary hybrid geothermal and biogas waste heat recovery application is investigated, according to boundary conditions related to Southern Germany. Considering on-design working load conditions, biogas WHR represents only 3.28% of the total available thermal power. Consequently, decoupling the second source does not profoundly influence off-design deviations. It is demonstrated that ambient temperature fluctuations deeply affect technical results during the year, as described by Toselli et al. [25]. Nevertheless, hybridization represents an interesting step to improve the technical and economic performance compared to the geothermal-only case. In this context, the following points for the new-build hybrid system should be pointed out:

- Concept A: preheating the geothermal water, is the most feasible concept with an increase in annual energy production of +5.28% (Table 6). Nowadays, this is the most conventional hybrid layout [6,9].
- Reinjection temperature in new-build A is 0.29 K higher than in the geothermal-only example. This configuration also guarantees a lower reinjection temperature than in superheating (case B), as underlined by Heberle et al. [8].
- In addition, the LCOE in the new-build case study is 1.32 €ct/kWh lower than in the geothermal-only one.

Furthermore, hybridization is analyzed from the perspective of flexible power generation:

- According to the assumed boundary conditions, the proposed examples are not able to comply with the requirements of the minute reserve.

- In order to meet the existing requirements, several solutions are suggested, such as adopting heat from the combustion of solid biomass as secondary source or implementing a thermal storage system. Additional flexible power generation can also be obtained by varying the ORC dynamic behavior.
- Toselli et al. [25] showed better power flexibility results considering the turbine off-design and fixed pinch points temperature in the heat exchangers.

The retrofit case study is mainly linked to the following points:

- Turbine power output in retrofit A is only 24 kW_{el} lower than in new-build A.
- LCOE in retrofit A is comparable to the new-build A (Appendix A).
- The main disadvantage of the retrofit regards the increase in reinjection temperature and consequently the less efficient exploitation of the geothermal source (Table 8).

Finally, regarding the CHP-mode:

- The economic analysis is developed without considering the economic impact of the biogas engine, as done by Heberle et al. [16]. This hypothesis is assumed in order to highlight the direct effect of hybridization.
- The LCOE in new-build power-only is 2.05 €ct/kWh lower than in new-build CHP-mode.
- The new-build hybrid CHP-mode provides a higher BEP (+0.56 years) than in power-only configuration and comparable total revenues at the end of the investment.
- According to a price of heat higher than 7 €ct/kWh, the BEP in geothermal-only example is comparable or even lower than in the new-build hybrid power-only. CHP configuration results reveal moderate improvements in the investment profitability.
- In the meantime, the sensitivity on the cost of hybridization highlights no particular variations on the hybrid LCOE.

Hybridization feasibility firstly relies on the availability of both sources in the same location. Regardless, the presence of numerous biogas engines is demonstrated in Southern Germany [29].

The economic feasibility of hybridization is strictly dependent on the assumed cost of maintenance, which can be reasonably lowered by exploiting possible synergies between the geothermal system and the biogas engine. In literature, there are currently no detailed economic data regarding this type of hybridization and related costs.

In this work, direct heat transfer from exhaust gases to geothermal water is assumed. In practice, the use of an internal loop with pressurized water or silicon oil may be suggested in order to reduce eventual thermal losses and optimize the area of heat exchangers. Dynamic calculations are addressed in future works; both biogas engines and ORC geothermal units are anyway able to provide fast ramps. In future works, the investigation of a real case study, both technically and economically, would represent an important step. Moreover, further calculations can be developed also according to different geothermal sources, such as dry steam reservoirs, increasing power plant thermal efficiency.

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Abbreviations

MRL	Minute reserve
CHP	Combined heat and power
LCOE	Levelized cost of electricity
ORC	Organic Rankine Cycle
CSP	Concentrated solar power
PV	Photovoltaic
WHR	Waste heat recovery
BWR	Back work ratio
PR	Pressure ratio
FI	Flexibility index
BEP	Break-even point

Nomenclature

ΔT_{pp}	Pinch point temperature	(K)
ΔT_{sub}	Subcooling degree	(K)
ΔT_{sh}	Superheating degree	(K)
η	Efficiency	(%)
UA	Heat capacity	(kW/K)
$\dot{W}$	Turbine power output	(Kw)
$\dot{Q}$	Thermal power	(kW)
p	Pressure	(bar)
β_{ORC}	Specific net power	(kW/(kg/s))
C	Cost	(€)
Rev	Revenues	(€)

Subscript

is	Isentropic
mec	Mechanical
th	Thermal
acc	Air-cooled condenser
geo	Geothermal
hyb	Hybrid
eva	Evaporation
cond	Condensation
O&M	Operation and maintenance

Appendix A

Table A1. Case study results overview.

Parameter	On-Design			Decoupled		Retrofit	
	A_on	**B_on**	**Geoth**	**A_off**	**B_off**	**A**	**B**
$\dot{W}_{turb}$(kW)	4561	4467	4336	4382	4314	4537	4427
$\eta_{is,turb}$ (%)	84.0	84.0	84.0	83.85	83.86	83.84	82.34
$peva$ (bar)	14.85	14.65	14.38	14.85	14.65	15.60	16.55
T_{reinj} (°C)	67.11	69.57	66.82	67.68	68.30	69.38	73.61
η_{th}	9.41	9.61	9.20	9.42	9.37	9.74	10.69
BWR	0.152	0.147	0.153	0.152	0.152	0.152	0.149
ΔT_{pp_eva} (K)	5	5	5	4.65	5.12	5.10	4.42
ΔT_{pp_cond} (K)	5	5	5	4.77	4.87	4.95	4.65
ΔT_{pp_reku} (K)	5	5	5	4.92	4.37	5.28	7.97
$\dot{m}_{ORC}$ (kg/s)	108.6	104.26	105.80	104.02	103.95	104.24	95.19
LCOE (€ct/kWh)	15.42	nc	16.74	nc	nc	15.46	nc
BEP (years)	10.82	nc	11.49	nc	nc	10.74	nc

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