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Theoretical analysis of the combination of CSP with a biomass CHP-plant using ORC-technology in Central Europe

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Abstract

In this paper the results of the preliminary performance assessment of an emerging hybrid CHP-technology using Organic-Rankine-Cycle technology comprising biomass combustion and concentrating solar thermal power in areas with low DNI is presented. The study was conducted in course of the research project BIOconSOLAR, which was funded by the climate fund of the Austrian government. The assessment is based on the technical design and economic conditions of an existing CHP-plant with nominal electric power output of 1.5 MW, which is located in the city Salzburg in Austria. The solar thermal energy provided by a parabolic trough collector field is primary used for electric power production in order to reduce biomass consumption and operation costs accordingly, but also to boost the thermal energy supply for the district heating of the city Salzburg. For electric power production the solar thermal energy is fed into the ORC-power cycle at a temperature level of at least 270°C. A transient simulation model of both the biomass CHP-plant and the parabolic trough plant was developed in IPSEpro. Based on the results of the process simulation the economic performance was assessed by conducting a dynamic investment calculation. Despite the technical and economic uncertainties of this preliminary assessment the retrofitting of biomass-solar CHP-plants with CSP in areas with low DNI is a promising option to improve the economic performance of about 100 CHP-plants in operation in Central Europe. A feed-in-tariff for solar thermal electricity in the same order of magnitude as for photovoltaic could trigger the retrofit of biomass CHP-plants.

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Nomenclature

DNI	Direct Normal Irradiance
IDR	Incident Direct Radiation
$A_{aperture}$	area of aperture of collector
Q_{col}	thermal energy produced by the collector
Q_{abs}	solar radiation absorbed by the receiver tube
$Q_{HCE,heatloss}$	heat losses of heat collection element (HCE)
IAM	Incidence Angle Modifier
θ	angle of incidence of direct irradiance
$\eta_{opt,mir}$	optical efficiency of mirror
$\eta_{opt,HCE}$	optical efficiency of heat collection element (HCE)
f_{shadow}	performance factor that accounts for mutual shading of parallel collector rows
$f_{endloss}$	performance factor that accounts for losses from ends of heat collection element (HCE)

1. Introduction

For economic applications of concentrated solar power (CSP) in areas with low direct normal irradiance (DNI), e.g. in Central Europe, new concepts need to be developed. In the range of an electric power output of 200 kW up to 10 MW, hybrid power plant concepts with combined usage of heat and power (CHP) and the application of processes with low operation temperature and pressure are beneficial [1]. Applying the Organic-Rankine-Cycle (ORC)-technology already a temperature level of about 300°C can be used for the production of electric power. Although, low operation temperatures yield low efficiency in comparison to conventional steam cycles, the application of the ORC in general and for CSP in particular has a number of advantages [2]. Fundamental research about the application of the ORC-technology in CSP-plants was conducted by the National Renewable Energy Laboratory (NREL) more than 10 years ago [3]. So far several publications dealt with the application of the ORC-technology in CSP-plants and 2005 the first plant started operation in Saguaro, Arizona, USA [4]. Several research projects emphasized on the hybridization of biomass CHP-plants and CSP using conventional Clausius-Rankine-Cycle, e.g. the Spanish project BIOMASOL, whereas few studies investigated the application of the ORC-technology [5,6,7,8]. In the alpine regions in Central Europe the ORC-technology is predominantly used in biomass CHP-plants. Currently more than 100 biomass CHP-plants are in operation in Austria, Germany, Switzerland and Italy [9]. The hybridization of biomass CHP-plants with CSP offers the possibility of economic application of CSP in Central Europe, hence opens up a new market for the solar thermal power industry.

2. Method

This section presents the developed process simulation model of the hybrid CHP-plant including a description of the existing biomass CHP-plant, the concept of integration of the solar field, the design of the concentrating solar field as well as a resource assessment of the available DNI for the city Salzburg.

2.1. Resource assessment of available DNI

Choosing representative meteorological data is the first hurdle to be taken in the planning and engineering phase. Two different hourly meteo data files for the city Salzburg in Austria were analyzed [10]. The first meteo data file with an annual DNI of 806 kWh/m^2 was obtained from the METEONORM software database [11]. The other meteo data file is based on ground measurements of direct irradiance on the horizontal plane at the airport of the city Salzburg over the years 1970 - 1985 by the *Zentralanstalt für Meteorologie und Geodynamik* (ZAMG) [10]. The files show similar irradiance distribution, but the annual DNI determined on the basis of the meteo data of the ZAMG is 7.8 % higher (869 kWh/m^2). METEONORM data are used for the process simulations of two other sites in Central Europe, Klagenfurt in southern Austria and Pisa in northern Italy.

2.2. Design of solar field

As the collector EuroTrough 150 is well characterized and documented in several studies, this collector type is considered for the theoretical investigation of the thermodynamic performance of the hybrid CHP-plant [12,13]. The receiver being considered in this preliminary assessment is the receiver of the manufacturer Schott PTR 70 [14,15].

For single-axis tracking of the parabolic trough collectors the maximum available direct irradiance of 837 kWh/(m^2a) can be obtained by north-south orientation and an installation angel of 43°. From an engineering point of view the installation of the EuroTrough 150 at an angel of 43° is unfeasible. Therefore the simulations have been conducted for horizontal positioning of the trough collectors. Besides the orientation of the collectors the spacing between the collector rows is important due to shadowing in particular the further north the solar field is located. For the design layout of the solar field a spacing of 30 m was assumed, although the solar energy yield could be increased with further spacing of collector rows, but the required land area will also increase accordingly.

Table 1. Direct irradiance at the city Salzburg for different orientation and tracking of the parabolic trough collector.

Annual direct irradiance for different orientation and tracking	METEONORM	ZAMG
Horizontal plane [kWh/(m^2a)]	418	466
Two-axis-tracking (DNI) [kWh/(m^2a)]	806	869
Single-axis tracking (east-west orientation, horizontal axis) [kWh/(m^2a)]	615	671
Single-axis tracking (north-south orientation, horizontal axis) [kWh/(m^2a)]	653	709
Single-axis tracking (north-south orientation, 43° inclination of axis) [kWh/(m^2a)]	775	837

The sizing of the solar field is based on the assumption that the total solar thermal energy can always be fed into the biomass CHP-plant throughout the entire year. The fluctuation of the solar thermal energy is balanced by part load operation of the biomass combustion unit. Therefore, a high annual solar energy yield can be achieved without the application of expensive thermal storages. In order to determine an appropriate design layout of the solar field, a design point was defined at which the solar field performance is nominal. The design point was fixed at the 21st of June at solar-noon (12:00 solar time). The nominal power output was determined by a steady-state calculation at design conditions. The planned concentrating solar field with a total collector area of about 10,000 m^2 provides thermal power of up to 6.2 MW; hence it provides maximally 60 % of total power input of the biomass CHP-plant.

Table 2. Design parameters of the concentrating solar field.

Parameter	
Number of loops	3
Total number of collectors	12
Type of collector	EuroTrough 150
Type of receiver	Schott PTR 70
Total area of aperture	9,810 m^2
Required land area	25,000 m^2

The collector loop configuration has been set according to current engineering layout for oil cooled parabolic trough collector fields [16]. Each loop consists of four collectors, arranged in two parallel rows of two collectors each. The total length of one collector loop is 600 m. The heat transfer fluid (HTF) Therminol VP-1 was selected, which can be used in for a temperature range of 12-400°C [17]. A less expensive alternative is Therminol 66, which is usable in a temperature range of 0-345°C [18]. Therminol 66 is also used in the biomass CHP-plant. Freeze protection will be activated below a HTF-temperature of 50°C. The required heat will be provided by the biomass boiler. The nominal mass flow through the collector loop is 5.6 kg/s in order to have a temperature increment of the fluid of 100°C at design conditions. An expansion vessel covering 10 % of the total quantity of the thermal oil in solar cycle of approximately 11,000 litres is incorporated.

2.3. Biomass CHP-plant

The biomass CHP-plant is located in the city Salzburg in Austria. The plant has a nominal electric power output of 1.68 MW and a thermal power output of 7.28 MW, which is supplied to the district heating network of the city Salzburg. Biomass combustion takes place in thermal oil boiler followed by a thermal oil economizer. The flue gases of the biomass-fired boiler pass through a heat recovery unit (thermal oil economizer, combustion air pre-heater and water economizer) in order to optimize the overall efficiency of the CHP-plant. The electric efficiency (= net electric power output/fuel power input into the biomass-fired thermal oil boiler) is approximately 16 %. The fuel utilization rate of the biomass CHP-plant is about 91 %. Due to the fact that sufficient heat consumption is ensured in the city Salzburg and the integration of a thermal storage tank with a capacity of 27,000 m^3 into the district heating network the biomass CHP-plant can be operated at nominal load almost throughout the entire year.

As discussed later, the integration of the solar thermal energy produced by the solar field is of particular importance. In the project several feed-in points have been taken into consideration and analyzed in detail. Feed-in point 1, which is located in the return of the thermal oil cycle, is best suited. At this point the temperature of the HTF of the biomass cycle is about 260°C. The main advantage of this feed-in location is that the exhaust path and the resulting exhaust gas temperature of the existing plant will not be influenced. If the temperature level of the produced solar heat is lower than 270°C, the solar thermal energy is going to be fed into the water cycle of the district heating at a temperature level of about 100°C (feed-in point 2) in order to boost the thermal heat production. The feed-in of the thermal energy into the thermal oil cycle of the existing biomass CHP-plant is carried out hydraulically separated by a heat exchanger. But for new installations also direct feed-in is possible, on condition that the same thermal oil is used in both hydraulic circuits, the biomass thermal oil cycle and the solar field cycle.

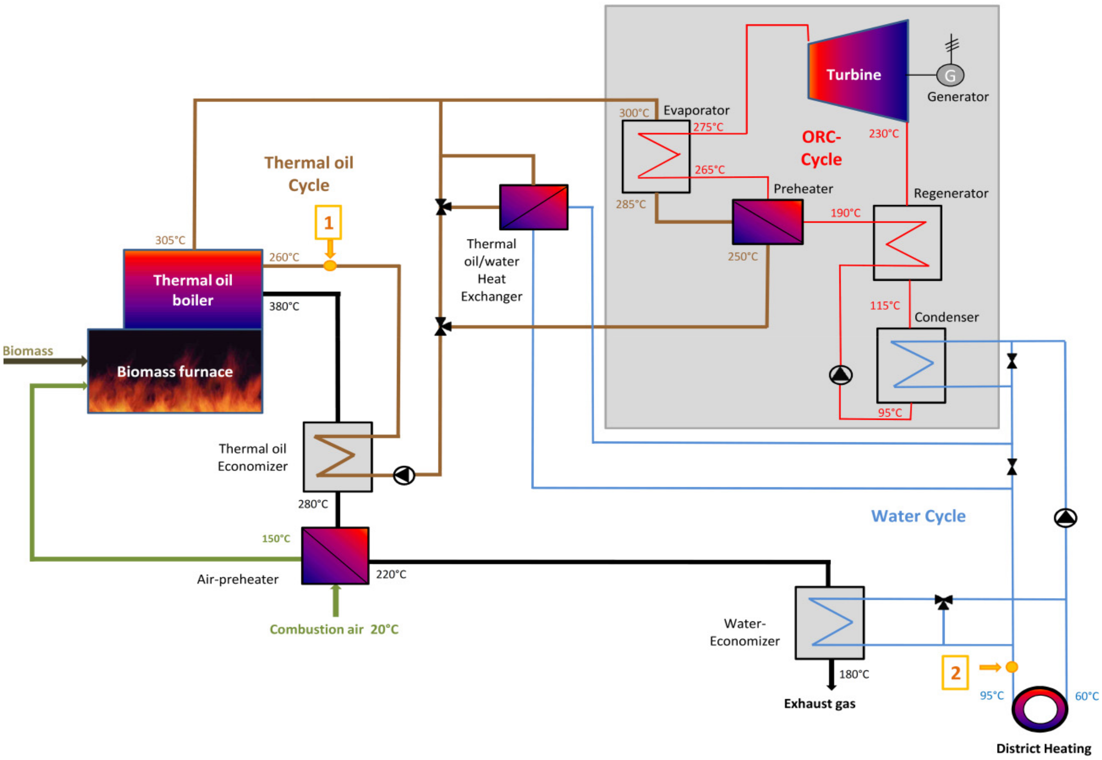

Fig. 1. Flow sheet of the biomass CHP-Plant with ORC-power unit and feed-in points for solar thermal energy.

2.4. Simulation tools

In a first step the solar field was modelled with TRNSYS 17 using the library „*High Temperature Solar”* provided by Thermal Energy Systems Specialist (TESS) in Wisconsin, USA [10,19]. The thermal energy produced by the parabolic trough collector was calculated as following [20]:

$$\dot{Q}_{col} = \dot{Q}_{abs} - \dot{Q}_{HCE,heatloss} \tag{1}$$

$$\dot{Q}_{abs} = DNI \cdot \cos\theta \cdot A_{aperture} \cdot IAM \cdot \eta_{opt,HCE} \cdot \eta_{opt,mir} \cdot f_{shadow} \cdot f_{endloss} \tag{2}$$

$$\dot{Q}_{abs} = IDR \cdot \cos\theta \cdot A_{aperture} \cdot \eta_{opt,HCE} \cdot \eta_{opt,mir} \tag{3}$$

The heat loss of the receiver tube and the piping was calculated with empirical equations used in TRNSYS developed by Burkhard [21]; the coefficients were taken from the System Adviser Model (SAM) [12]. In a next step both the hybrid CHP-plant and the solar field have been modelled using IPSEpro [22]. The model is shown in Figure 4. The collector model in IPSEpro is based on the model used in TRNSYS [19]. Due to intrinsically non-stationary nature of the solar thermal energy production, additionally a dynamic model of the parabolic trough collector was developed in IPSEpro by implementing a FORTRAN Dynamic Link Library (DLL), which numerically solves the differential equation of the transient heat transfer process of the receiver tube in the course of time and space.

$$\left(m_{HTF} \cdot c_{HTF} + m_{HCE} \cdot c_{HCE}\right) \cdot \frac{\partial \vartheta}{\partial t} = \dot{Q}_{abs} - \dot{Q}_{HCE,heatloss} - \dot{m}_{HTF} \cdot c_{HTF} \cdot \frac{\partial \vartheta}{\partial x} dx \tag{4}$$

The simulation models of the solar field and the biomass CHP-plant in IPSEpro are verified with TRNSYS simulations and performance data of the existing biomass CHP-plant, respectively.

3. Simulation results

Due to the low DNI in Salzburg, the resulting reduction of fuel is modest in comparison to the other sites chosen. The total annual biomass consumption of 14,000 tons of dry biomass can be reduced by approximately 3 %. The reduction of biomass rises with increasing DNI. Therefore the biomass reduction in Klagenfurt is 3.8 % and in Pisa 5.3 % of the total annual biomass consumption (Table 3).

Table 3. Results of annual process simulation of the hybrid CHP-plant for different sites in Central Europe.

Site	SALZBURG		KLAGENFURT	PISA (ITALY)
Source of meteo-data	METEONORM	ZAMG	METEONORM	METEONORM
DNI [kWh/(m²a)]	806	869	1,071	1,345
IDR (= $DNI*cos\theta*IAM*f_{shadow}*f_{end\ loss}$) [kWh/(m²a)]	596	649	813	1,086
Solar energy yield [MWh/a]	2,959	3,226	4,236	5,940
Specific solar energy yield [kWh/(m²a)]	324	352	457	635
Annual solar plant efficiency (= $Q_{col}/IDR*A_{aperture}$) [%]	50.6	50.6	53.1	55.8
Solar energy for power production (feed-in at 260°C) [MWh/a]	1,891	2,061	2,690	3,746
Solar energy for thermal heat production (feed-in at 100°C) [MWh/a]	1,068	1,165	1,546	2,194
Solar electricity production [MWh/a]	255	266	347	483
Reduction of biomass consumption [tons/a]	378	412	538	749

At constant-flow operation the annual process simulations showed that the temperature level of the solar thermal energy is at about 20 % (1,864 h) of the hourly values above the required feed-in temperature of 270°C. Solar thermal energy can be supplied to ORC-process throughout the entire year as it can be seen in Figure 2. Although the supplied solar thermal energy for electric power production strongly decreases in winter months because of the low solar energy yield (see Figure 3). The solar thermal energy, which cannot be provided to the ORC-process at a temperature of at least 270°C is supplied to the district heating at a temperature of about 100°C (feed-in point 2).

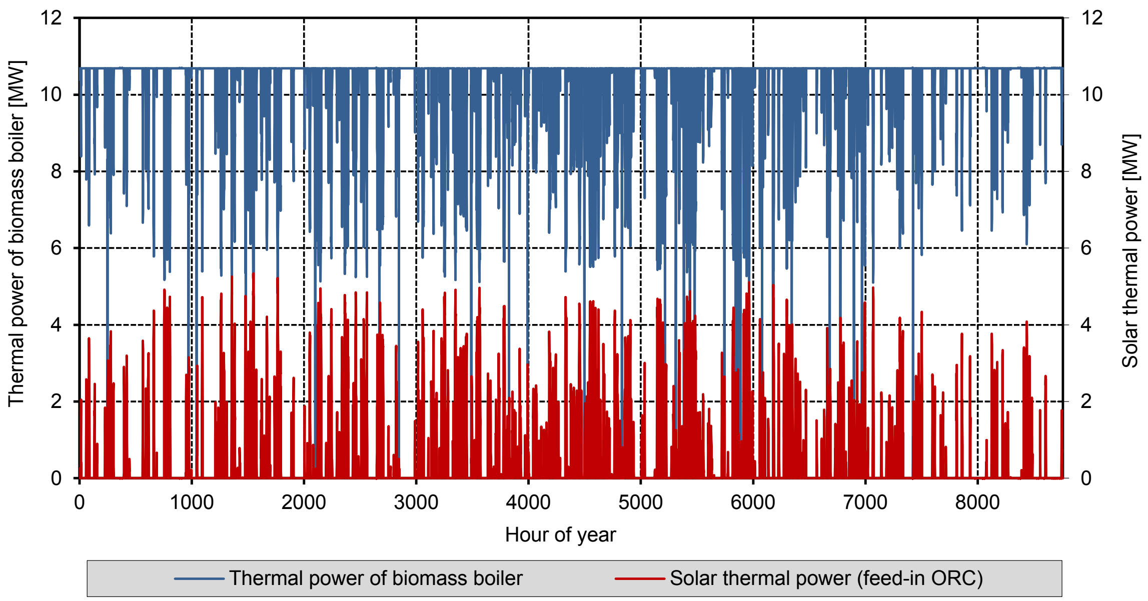

Fig. 2. Thermal power of biomass boiler and solar thermal power supply to ORC.

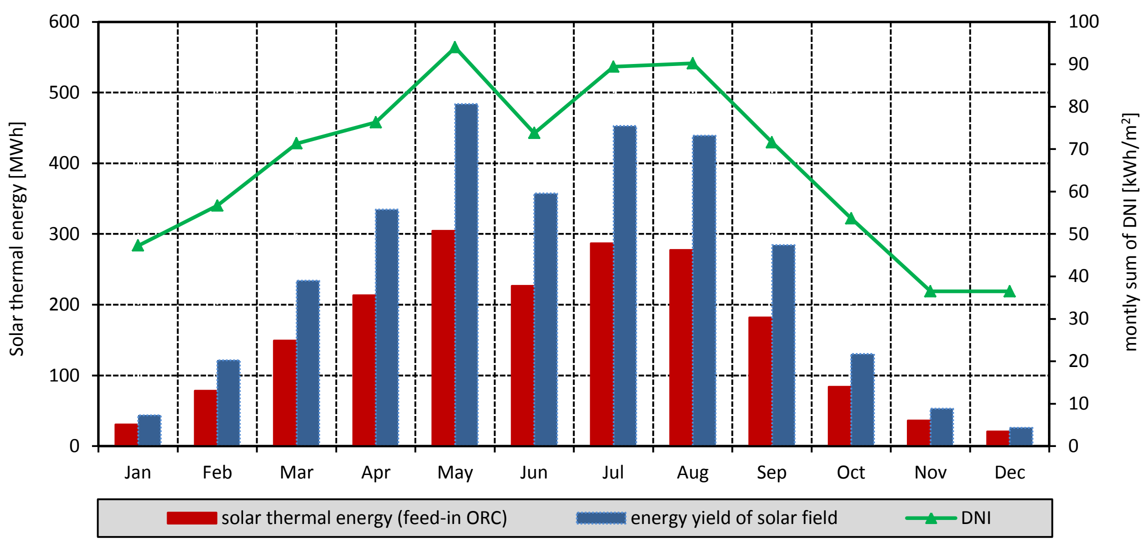

Fig. 3. Monthly sum of DNI, solar thermal energy yield and solar thermal energy supply to ORC.

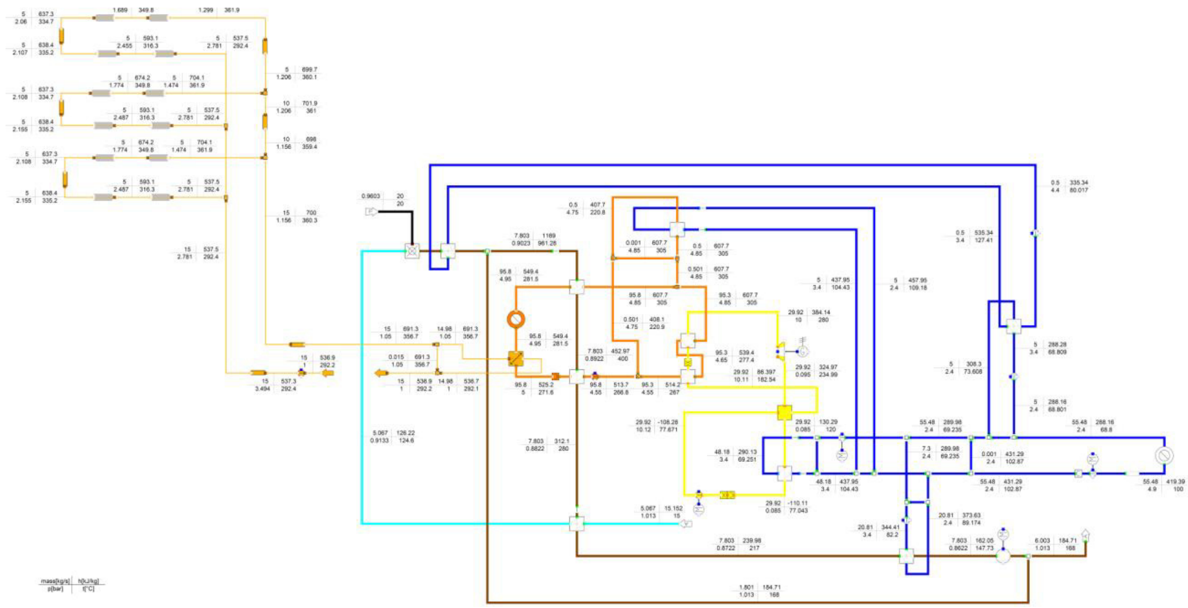

Fig. 4. Model of hybrid biomass-solar CHP-plant in IPSEpro including solar thermal cycle (light orange), biomass combustion (black), exhaust gas path (brown), thermal oil cycle (dark orange), Organic-Rankine-cycle (yellow) and water cycle – district heating (blue) at DNI = 600 W/m^2.

Although the attained efficiency of the concentrating solar plant of more than 50 % is acceptable, both the solar energy yield and the provided solar energy for electricity production are low. Therefore, emphasis of future work is to optimize the solar field and increase the amount of solar energy, which is fed into the ORC-power unit. This includes optimization measures such as the implementation of a matched-flow operation of the solar field in order to ensure constant solar field outlet temperature as well as cascading feed-in into the ORC-process at different temperature levels.

4. Economic analysis

A dynamic investment calculation, the annuity method was applied to calculate the net present value (NPV) of the investment [23]. The economic profitability is assessed by the payback period of the investment costs. The investment costs include the costs for the solar field and the integration e.g. heat exchanger. The generated revenues comprise the fuel cost reduction as well as revenues created due to the feed-in-tariff (FIT) for solar thermal electricity. It was assumed that the feed-in-tariff for solar thermal electricity is as high as the feed-in-tariff for photovoltaic electricity guaranteed by the Austrian regulation on eco-electricity for the duration of 13 years [24]. Additionally, revenues can be earned by boosting thermal heat production and supply to the district heating. The information about the cost of biomass and the prize for district heating were provided by the plant operator. The annual cost increase of biomass and district heating is based on the prize development in Austria in the years from 2002 - 2012 and on the development of the price index for district heating in Austria in the years from 1970 - 2008, respectively [25],[26]. The FIT for biomass electricity was also chosen according to the Austrian regulation on eco-electricity [24]. The financial conditions are shown in Table 4.

The total investment costs of the solar field are estimated to be approximately € 2.2 million [12]. The costs of the balance of plant (BOP) and the HTF-system are about € 300,000 and € 400,000, respectively [12]. Additionally, costs for civil engineering of about € 150,000 are considered [12]. Therefore, the total investment costs for the solar field are approximately € 3.1 million. The operational costs include the electricity costs for the operation of the thermo oil pump of the solar field (11,000 €/a).

The maintenance costs are estimated to make up 0.5 % of the total investment costs. In the first year the maintenance costs are € 15,000 and rise with increasing age of the solar field by 0.5 % per year. The life expectancy of the solar plant was set to 25 years [27].

Table 4. Financial conditions of dynamic investment calculation.

Revenue	
Cost of biomass [€/tons dry biomass]	120
Annual cost increase of biomass [%/p.a.]	5.0
FIT for biomass electricity [€/MWh]	138
FIT for solar thermal electricity [€/MWh]	190
Price for thermal energy – biomass/solar thermal [€/MWh]	35
Annual price increase for thermal energy - district heating [%/p.a.]	3.0

The results show that the NPV of the investment for the concentrating solar plant in city Salzburg is about € 450,000 after a service life of 25 years and the payback period is 22.9 years. However, if the financial conditions are slightly unfavourable (annual price increase of biomass and FIT for thermal energy is only 4 % and 2 %, respectively) the NPV gets negative (€ -85,302). Therefore, a hybridization of the existing biomass CHP-plant in Salzburg with CSP is hardly economically applicable. Different is the situation for the southern part of Austria, in Klagenfurt. Assuming that all technical and financial conditions remain unchanged except the available DIN, a profit of € 1.75 million could be achieved after 25 years of service and the payback period of the investment is 18.4 years. Even better is the economic performance of the hybrid CHP-plant in Pisa, where the payback period decreases further to about 13.6 years and the resulting profit after 25 years already exceeds the total investment costs (see Figure 5a).

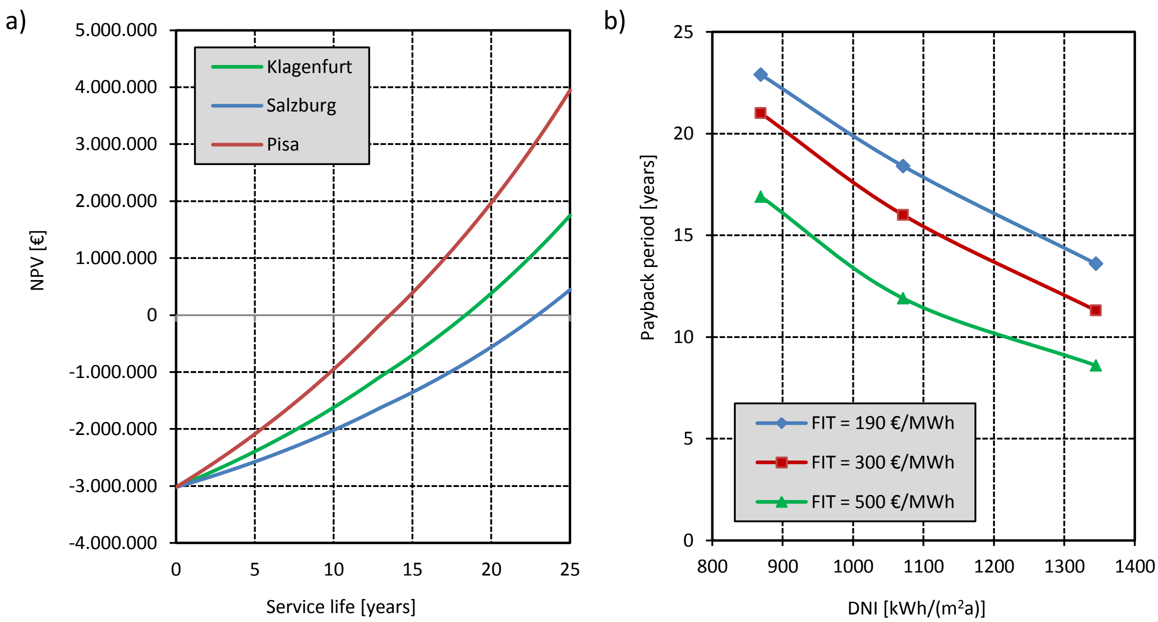

Fig. 5. (a) Net present value (NPV) as a function of service life of concentrating solar plant at the city Salzburg, Klagenfurt and Pisa; (b) payback period as function of DNI and FIT for solar thermal electricity.

For the economic assessment a FIT of 190 €/MWh was assumed, but which is currently not yet provided by the Austrian legislation on eco-electricity. However in future it seems reasonable that the law could be adopted according to Germany's Renewable Energy Act, where a FIT is guaranteed for solar electricity regardless of the applied technology [28]. The results of this study serve as basis for suggesting legislative adaptations in Austria. In Figure 5b the effect of the FIT for solar thermal electricity on the economic performance of the hybrid CHP-plant can be seen. By retrofitting biomass CHP-plants the payback period of the investment costs of the concentrating solar plant in areas with low annual DNI of about 1,100 kWh/(m^2a) is about 15 years, assuming a guaranteed FIT of 300 €/MWh for solar thermal electricity. Although the economic performance increases as expected with increasing FIT for solar thermal electricity, the improvement is nevertheless modest. Mainly due to the fact that besides the reduction of fuel costs only the difference to the FIT for biomass electricity, which is currently 138 €/MWh, generates an additional benefit of the solar thermal plant. Beside the FIT for solar thermal electricity the cost of the biomass and the price of district heating have the biggest influence on the economic performance.

5. Conclusion

The analysis shows that the retrofit of biomass CHP-plants with concentration solar plants is a promising option to improve the economic performance of CHP-plants in Central Europe. Despite the uncertainty of the preliminary performance analysis, in particular of the costs of the solar field and financial conditions, the operation in the city Salzburg is considered economically unfeasible. But an implementation in southern Austria e.g. Klagenfurt at higher DNI is realistic. A feed-in-tariff determined by law in the same order of magnitude as for photovoltaic could trigger the retrofit of the first biomass CHP-plants in Austria. However, some technical questions still remain unanswered. Hence, the focus in further research will be on technical and engineering questions such as the detailed planning of the solar field, the optimization of the solar energy yield through the positioning of the parabolic trough collectors as well as the development of an intelligent operation and control strategy for cascading feed-in of solar thermal energy into the ORC-process at different temperature levels. Additionally, the part load operation and dynamic behaviour of the biomass boiler will be analyzed, whether it is technically suitable to balance the short-term fluctuations of the solar thermal energy production.

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