Integration of torrefaction and CHP plant: Operational and economic analysis

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Abstract: Biomass torrefaction is a pre-treatment technology with high potential to convert biomass into a valuable commodity. The heat integration of torrefaction and combined heat and power (CHP) plant was investigated in previous work [1]. The aim of the present study is to assess possible economic benefits from integration. Three most promising integration concepts from the previous work were studied in terms of seasonal operational changes of district heating demand and varying ambient conditions. The performance of two integration concepts were evaluated together with stand-alone and co-located plants. The integration leads to a higher utilization of the CHP boiler capacity during part-load operation, possible increase of the operation time and growth of electricity generation as a result. The total efficiencies of the integrated cases (around 72% in higher heating value terms) are slightly higher than the stand-alone CHP plant (69%) or the co-located option (71%). The integration requires 40% more capital investments than the stand-alone CHP. On the other hand, the total capital investments of the integration cases are 20% lower than in co-located plants, and a profitability evaluation shows that lower investment costs may make integration schemes advantageous over the non-integrated plants. Feedstock price and investment costs are the main economic drivers affecting the profitability of the integrated options. An integration case which uses back pressure steam to account for the torrefaction heat demand showed the highest profitability due to a longer annual operating time, resulting in a growth of electricity and DH production over the stand-alone CHP plant.

Keywords: biomass torrefaction; combined heat and power plant; integration; economic analysis

Nomenclature

c	energy price [€/MWh]
E	energy (MJ)
HHV	higher heating value (MJ/kg)
i	interest rate (%)
LHV	lower heating value (MJ/kg)
MC	biomass moisture content (%)
n	plant economic lifetime (y)
Q	heat (MJ)
r	ratio of annual operation and maintenance cost to total capital investment (-)
t	time (h)

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Greek letters

α	scaling factor (-)
η	efficiency (%)
Σ	sum

Abbreviations

CBM	bare module cost
CEPCI	Chemical Engineering Plant Cost Index
CHP	combined heat and power
DH	district heat
EU	European Union
EY	energy yield
FCI	fixed capital investment
GHG	greenhouse gas
IRR	internal rate of return
MY	mass yield
NPV	net present value
PBP	payback period
PEC	purchased equipment cost
TCI	total capital investment
USD	United States dollar

Subscripts

b	boiler
bc	biocoal
chips	total fuel input
dry	dry basis
el	electricity
f	boiler fuel
feed	torrefaction feedstock
net	net
O&M	operation and maintenance
p	purchased
s	sold
wet	wet basis

1. Introduction

Modern society depends on materials and products that have been historically produced from fossil fuels. At the same time, the concept of sustainability in various industrial spheres is attracting increasing attention, especially considering the growing environmental concerns associated with fossil fuel combustion. Under these circumstances, the demand for efficient utilization of renewable sources is increasing. Biomass can be efficiently used for the production of various commodities, such as vehicle fuels (e.g. bioethanol and biodiesel), chemicals and plastics, fertilizers and pharmaceuticals as well as for energy generation [2, 3]. The complete recovery of different by-products and wastes from agriculture and industry along with the utilization of other biomass sources has a significant potential for substituting traditional fossil fuels.

Biomass-based combined heat and power (CHP) production or co-generation is a proven technology that can be effectively applied for local biomass feedstocks. Simultaneously, despite the positive environmental and potential economic benefits, the untreated woody biomass as a fuel is associated with certain problems: heterogeneous nature, poor grindability, relatively high moisture content and low bulk density [4, 5]. Torrefaction is a thermal pre-treatment process to convert raw biomass into more homogeneous and with subsequent pelletizing energy-dense product. In torrefaction, the feedstock is heated slowly (<50 °C/min) to the reaction temperature, typically 200 °C to 300 °C, under atmospheric pressure in the absence of oxygen [5-7].

The torrefied biomass (biocoal) with improved properties can be then co-fired with pulverized coal. Torrefaction thus makes it possible to increase the use of biomass in coal-fired boilers, reducing greenhouse gas (GHG) emissions and making the energy production more sustainable [8-10]. Even though there is still limited amount of available related data from industrial applications, the research in this area shows that co-firing of torrefied biomass with coal allows a significant reduction of CO_2 emissions without a major penalty in boiler efficiency [8, 11]. Torrefied pellets also have certain advantages in comparison with traditional wood pellets considering not only their physical properties and energy content but also the gas emissions from combustion. McNamee et al. [12] evaluated the life-cycle GHG emissions of several supply chains for torrefied pine and reported that torrefaction could allow to produce lower GHG emissions per output energy content, compared to conventional wood pellets. In another study [13], the gas emissions from the combustion of a range of fuels (torrefied spruce, peat, biomass/coal blend and two coals) were investigated. The results indicated the lowest levels of NO_x and CO emissions for the torrefied wood briquettes among all the studied fuel samples and a significant reduction (approx. 40%) of particulate emissions from combustion of torrefied wood compared to the source material.

The integration of biomass pre-treatment processes with industrial systems can lead to benefits through more efficient utilization of the available mass and energy streams. Various integration possibilities of biomass conversion processes with CHP plants or other industrial processes have been evaluated recently. Technical, economic and environmental benefits of integration of the biomass gasification into CHP based district heating (DH) system have been reported in [14] and [15]. The combination of cellulosic bioethanol production and a CHP plant may help to increase the operating hours, resulting in an increased power generation and improved overall system efficiency [16]. Opportunities for integrating pellet production and a CHP plant have been also intensively studied in [17-19] with the main outcomes of annual power production growth, significant reduction of CO_2 emissions and additional economic benefits from pellets trade obtained. The integration of torrefaction within a CHP plant can potentially cover the energy requirements of the torrefaction process and simultaneously increase the power generation and annual operating hours of plant as well as generate the valuable product for sale. Starfelt et al. [20] investigated the advantages of a combined system of torrefaction and CHP that covers the energy demand of the torrefaction reactor and keeps the heat and power generation at required levels. Possibilities of co-location of torrefaction facilities with coal-fired power plants and corn ethanol plants were evaluated in [21]. Kohl et al. [22] compared the energetic and environmental performance of the retrofit-integration schemes of a CHP plant and three biomass pre-treatment processes (fast pyrolysis, torrefied pellets and wood pellets production).

Typically, the annual operation of a CHP plant follows the pattern of seasonally varying district heat demand [22]. In addition to quantitative changes in the DH demand, the required DH supply temperature, temperature of combustion air, and the moisture and temperature of the boiler fuel vary during the year. Despite the aforementioned issues, the CHP plant operating parameters are often calculated only at design point to evaluate the possibilities of integration [15,18,21,23]. Some researchers investigated the effect of part-load operation on the performance of integration schemes [17,22,24,25]. At the same time, the comprehensive evaluation of the integration scheme is only possible when all the seasonal changes of operational conditions along with the characteristic features of the CHP plant at part load are taken into account.

In a previous study [1], six integration concepts of torrefaction and a CHP plant were assessed within the typical range of torrefaction temperatures. The effect of the plant configuration and available boiler capacity on the thermodynamic performance of the integrated plants were evaluated by simulating the integration of torrefaction with two different CHP plants. The performance of both plants was evaluated only in one specific operation mode. In order to expand the evaluation to cover the seasonal operational changes, a multiperiod model was implemented to approximate the DH demand duration curve and to consider the annual variations of the fuel quality and ambient conditions in the present paper.

In Northern Europe co-generation plants are often backpressure steam plants for producing mainly district heat. Consequently, the plant annual operation time and corresponding power generation are limited by the DH network demand. The integration of this type of plant with torrefaction process allows utilizing the available plant capacity for a longer period to lower DH loads, thus increasing the annual production and thereby investment profitability. At the same time, fulfilling the heat demand of torrefaction without compromising the required thermal output can become problematic during the cold period of the year. Therefore, the changes of the plant operational parameters have to be taken into account for a proper and detailed evaluation of different integration schemes. On the basis of the results from the previous work, the current study evaluates the operability of the three most promising integration schemes in terms of varying the DH loads and ambient conditions.

In addition to the operational analysis, the present work evaluates the overall economic performance of the chosen alternatives of torrefaction integration into CHP plant. Considering a relatively high uncertainty of future energy prices, emission trading schemes and government support and taxes, the accurate prediction of profitability for new energy technologies can be challenging. At the same time, even preliminary assessment of these factors brings valuable information for determining technology potential. In the work, the integration cases together with stand-alone options are compared in terms of payback period (PBP), net present value (NPV) and internal rate of return (IRR) using three scenarios for electricity market prices and investment costs for the plants. The annual net cash flow for the considered cases is calculated at varying interest rate values. A sensitivity analysis for the internal rate of return is performed to determine the main economic factors influencing the profitability of each scenario.

2. Studied cases

CHP plants in district heating systems are typically base load plants; in Finland, as an example of a northern EU country, they are typically sized to cover approximately 40-60% of the peak DH load. The CHP plant can usually operate down to 40-50% part load. [26] The annual heat consumption and heat load duration curve of a DH demand strongly depends on the climate and can vary significantly from region to region. In addition, the types of heat consumers determine the DH load curve. The district heating systems in Northern Europe must be able to cover both winter peak load (usually a relatively short period), and minimum load (ca. 10% or less of the peak load) during the non-heating season [26]. Generally, the heat production of base load CHP plants accounts for at least 4000…5000 annual full-load operating hours and covers approximately 80% of the total heat demand. Auxiliary hot water boilers are usually operated to provide the heat to the DH network outside the limits of the CHP plant operation, i.e. at peak load and when the demand is less than the minimum load of the CHP plant.

Table 1 summarizes the main characteristics of the wood-fired CHP plant considered for the integration options. The small-scale co-generation backpressure plant has maximum and minimum district heating loads of 20 MW and 8 MW correspondingly, and a power generation of 8 MW_{el} at full load. In the following, the evaluated models are described briefly; more detailed description of the part-load modeling can be found from reference [27].

Table 1. CHP plant main characteristics.

Parameter	Full load	Minimum load
Net power output	8.0 MW	2.0 MW
District heating output	20.0 MW	8.0 MW
Total (CHP) efficiency	85 %	83 %
Live steam parameters	90 bar / 500 °C	90 bar / 450 °C
Furnace temperature	900 °C	700 °C

The torrefaction unit operational parameters are set to a temperature of 250 °C and 30 min of residence time. The resulting mass and energy yields are MY = 82.7% and EY = 92.5%, and the biocoal heating values of LHV_{dry} = 21.8 MJ/kg and HHV_{dry} = 23.0 MJ/kg. Modeling assumptions and further details on torrefaction unit simulation can be found in a previous study [16]. The electricity consumption of the biocoal pelletizing process (the pellet press is not presented in the process diagrams) is assumed to be 180 kJ/kg [28].

Three different integration concepts from the previous work [1] are considered: Case 1, Case 5 and Case 6. All cases are designed for torrefied pellet production at a rate of 5 t/h (1.39 kg/s). The process flow diagrams are presented in Fig. 1. The integrated cases are compared to the separate CHP plant and torrefaction unit co-located at the same site (Case 0). In this case, the heat demand of torrefaction is covered with a stoker boiler having an efficiency of η_b = 82 %. Co-location of the considered processes will result in benefits for feedstock logistics, storage and handling even if the units themselves are not integrated.

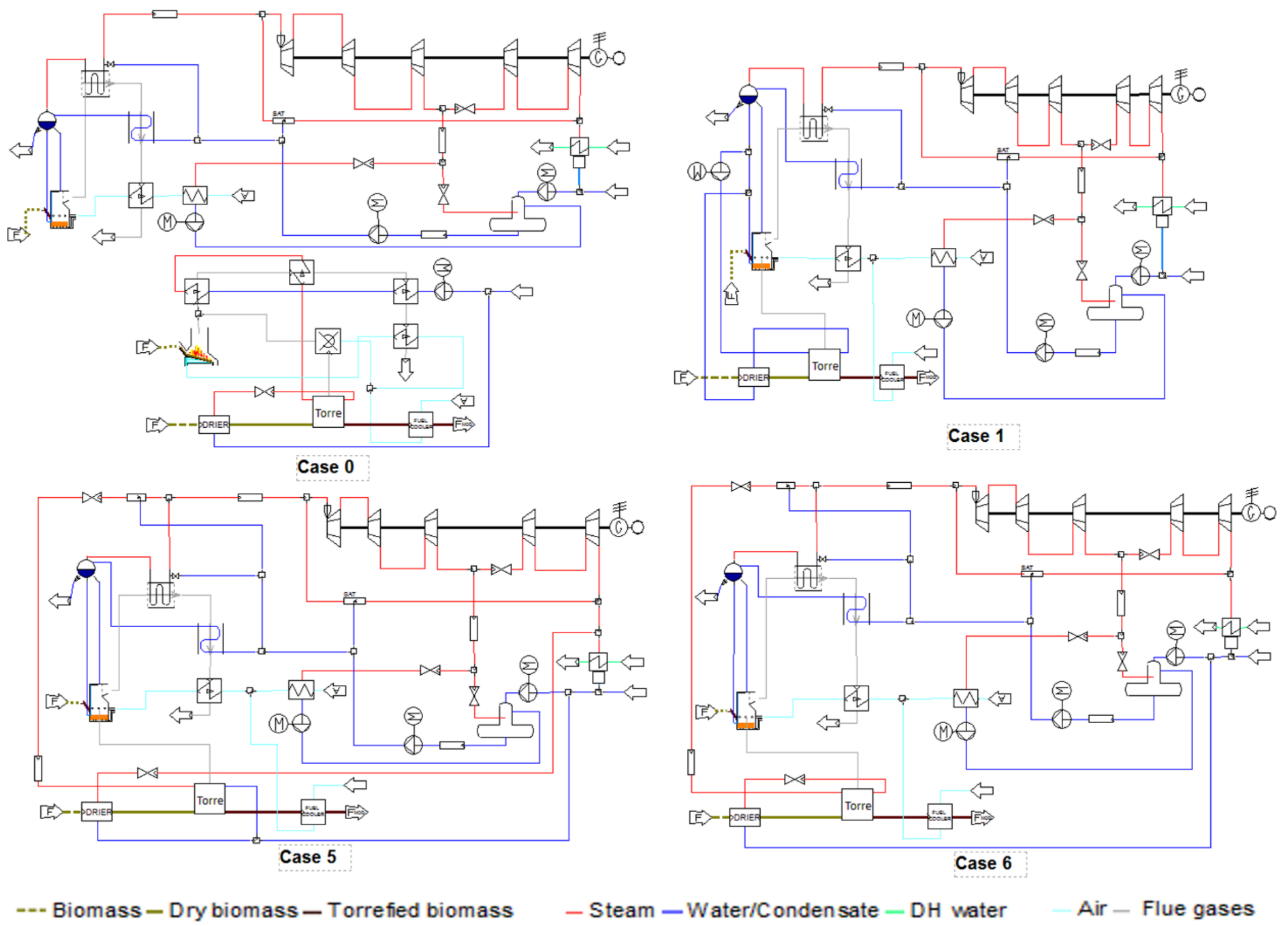

Fig. 1. Process flow diagrams of the co-located CHP and torrefaction units (Case 0) and three integrates (Case 1: saturated water from the drum for torrefier and drier; Case 5: live steam for torrefier and low pressure steam for drier; Case 6: live steam for torrefier and steam after torrefier to the drier).

For the integrated cases, the operating strategy is to fulfil completely the DH demand at any given load while maintaining also full-rate torrefaction, leaving electricity generation as a free variable. During part-load operation of the CHP plant certain operation parameters of the CHP cycle become limiting factors for the plant operation. The minimum boiler furnace temperature is set as 700 °C to maintain efficient combustion. Another boundary parameter is the stack temperature of flue gases, which is maintained higher or equal to 135 °C in order to avoid low temperature corrosion caused by flue gas condensation.

2.1. Multiperiod model

A multiperiod DH load model has been used in some earlier studies, such as Savola [29] and Kohl et al. [22,25]. In the current work, a typical Finnish DH demand curve of a small municipality is represented by 35 MW peak winter load with a linear approximation between a 20 MW heat load at 1800 hours and 2.6 MW minimum load during the non-heating season. The annual district heating production amounts to 4740 full-load hours. The considered CHP plant operates 1800 hours at full load with total annual operating time of 6000 hours.

In order to consider the annual variation in heat load in the DH network and ambient conditions, a multiperiod approach is developed. The CHP plant DH load is modeled with two full-load periods (P1 and P2) which differ only in their DH temperatures and ambient conditions. These periods are then followed by a steady reduction of load by 4 MW intervals (from P3 to P6) until the summer low-load period P7 and minimum-load period P8.

The ambient temperature data is based on 30-year monthly average temperatures gathered by the Finnish Meteorological Institute [30] for city Jyväskylä (central Finland). The temperature of the boiler fuel and torrefaction feedstock is set equal to the average ambient temperature of each period. The combustion air temperature, taken from the boiler room, is assumed to be 20 °C higher than ambient temperature. The district heating water output and return temperatures are based on the temperature levels from [26]. The seasonal changes of wood chips quality is affected by their moisture levels that typically increase towards the winter. The main characteristics for each load point level within the multiperiod model are summarized in Table 2. The annual variation of district heat demand as well as the heat and electricity production is illustrated in Fig. 2.

Table 2. Summary of the load points and their duration during the year in the multiperiod model.

Parameter	P0	P1	P2	P3	P4	P5	P6	P7	P8
Time									
period duration [h]	0	240	1560	1400	1400	1400	1400	490	870
cumulative at end [h]	0	240	1800	3200	4600	6000	7400	7890	8760
Load and production									
mean heat load [MW]	35	30	22.5	18	14	10	6	4	2.6
CHP heat output [MW]	20	20	20	18	14	10	8	0	0
Temperatures									
ambient [°C]	-20	-10	-5	0	5	10	12	15	15
makeup water [°C]	5	5	5	5	10	10	10	10	10
DH water supply [°C]	105	90	85	80	75	75	75	75	75
DH water return [°C]	60	50	50	50	45	45	45	45	45
Fuel									
MC_{wet} [%]	55	55	55	50	50	45	45	40	40
temperature [°C]	-20	-10	-5	0	5	10	12	15	15
LHV_{wet} [MJ/kg]	7.43	7.43	7.43	8.53	8.53	9.62	9.62	10.72	10.72

MC_{wet}: moisture content on wet basis; LHV_{wet}: lower heating value on wet basis

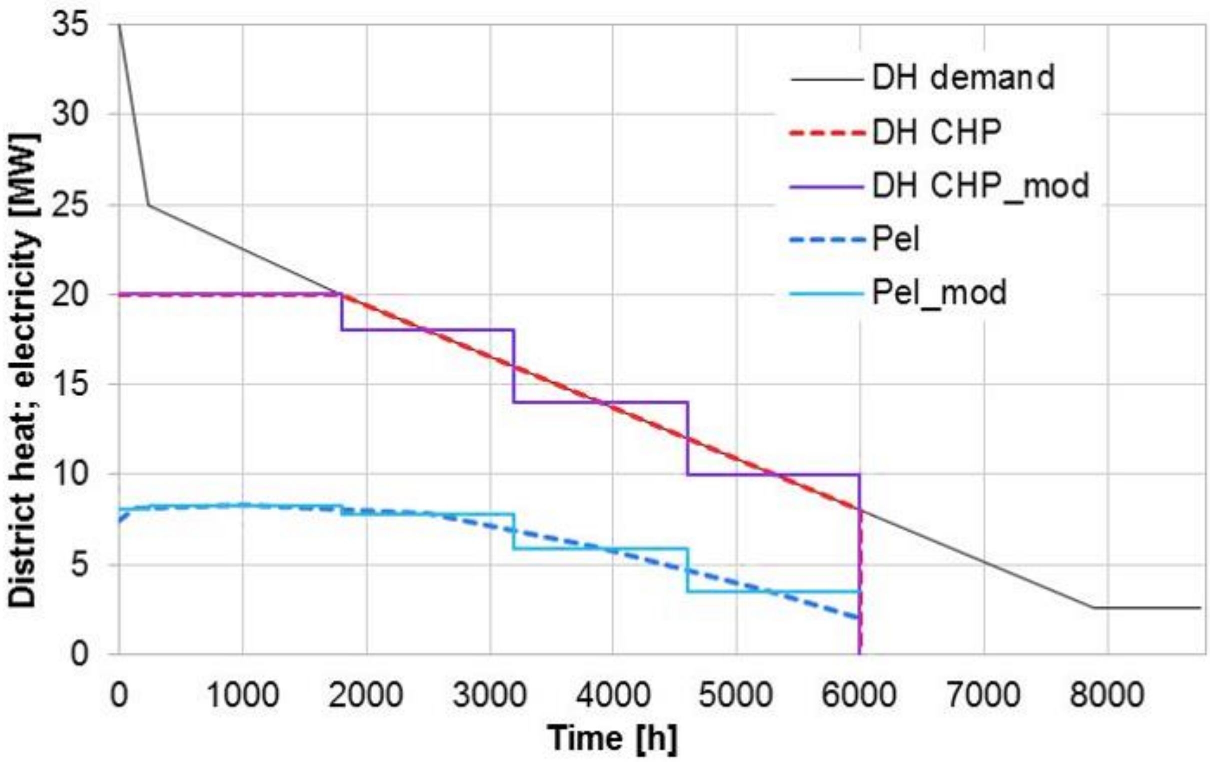

Fig. 2. DH load duration curve, DH production and electricity generation of the CHP plant with corresponding multiperiod approximations DH CHP_mod and Pel_mod.

3. Annual production and consumption

The integration schemes require heat and electricity from the CHP plant. At the same time, by increasing the operating hours it is possible to obtain revenues from higher power production by means of supplementary heat consumer – the torrefaction unit. The biocoal production capacity of the torrefaction unit is set at 30.3 MW_{LHV} throughout whole the operating period: 8000 hours in Case 0, and equal to the CHP operating hours in the integrated cases. The torrefaction feedstock rate increases from 27.8 to 30.0 MW_{LHV} as the feedstock moisture reduces from 55% (in winter) to 40% (in summer).

Under the assumptions considered in the present work, Case 1 cannot be operated during winter months with the required torrefaction output. In this integration scenario, the heat of drum water for the torrefaction needs is taken straight from the boiler cycle, hampering remarkably the boiler performance, especially during high district heating demand. Because of this, the following analysis is concentrated on two other integration cases.

Figure 3 presents the multiperiod model approximation of the obtained electricity and DH output levels produced within a year. The variation of boiler fuel input (including the stoker boiler in Case 0) together with the DH heat demand curve are also shown.

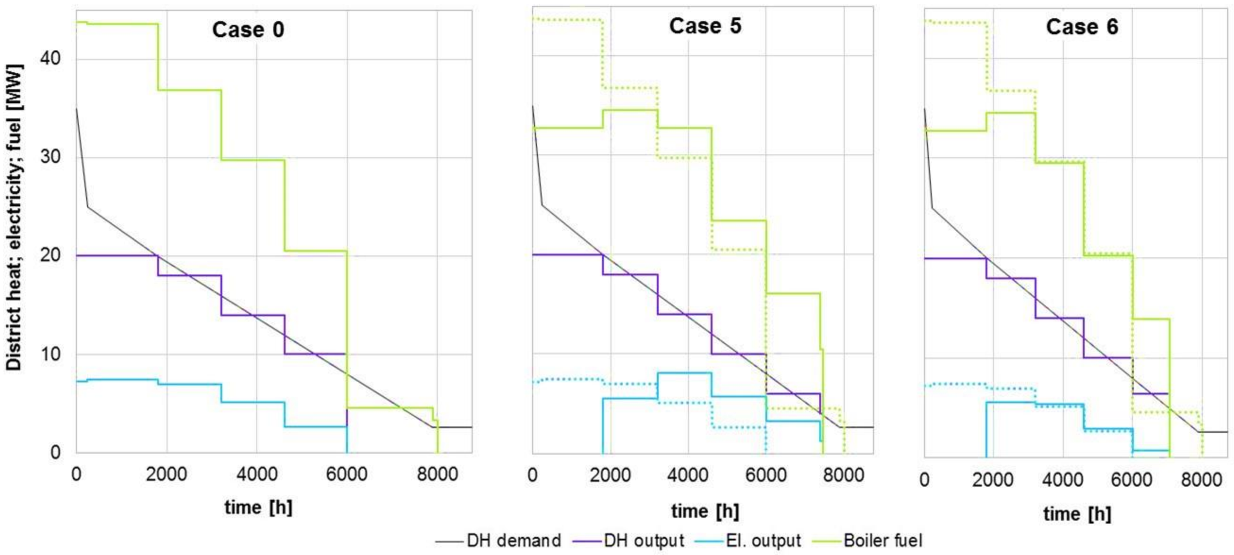

Fig. 3. DH load duration curve, annual district heat and power production of the CHP plant together with boiler fuel consumption (CHP and stoker boiler in Case 0) using the multiperiod model. Dashed lines in Cases 5 and 6 refer to Case 0 values.

For the integrated cases, the heat demand of the dryer (ranging from 9.6 MW in winter to 3.7 MW in summer) presents a significant share in the overall balance of the considered CHP plant. At low loads, the flue gas temperatures decrease and start to approach the lower limit. The minimum operating point of 6.4 MW district heat output for Case 6 corresponding to the furnace temperature limit (700 °C) is reached at 7085 h operational time. When the heat requirement of the dryer is covered with low pressure steam before the DH condenser (Case 5), the steam flow through the turbine and consequently the boiler output are increased. Due to this further increase of the boiler load, the operating time of Case 5 integrated plant is prolonged to 7470 h corresponding to 4 MW district heat output.

The boiler fuel input for Case 6 differs clearly from Case 0 during full load and reduced-load periods (after 6000 h). At the same time, during a significant part of the year, the difference is very small (compare to the dashed lines Fig.3). Case 5 shows a different pattern: covering the heat demand of the dryer with low pressure steam yields a clear increase of power generation from approximately 3000 hours onwards, and thus also requires more boiler fuel input. At the full-load periods, however, the integration with torrefaction reduces the net power output of both integrated scenarios to approximately zero (in fact, slightly negative). This is due to the need to bypass most of the boiler steam production through the reduction valve to the torrefaction plant dryer and the district heat condenser to maintain both torrefaction and necessary DH output. The very small remaining power output is exceeded by the combined power consumption of the torrefaction plant and the auxiliary systems of the CHP plant.

Table 3 summarizes the overall figures of annual net production and consumption of various energy streams. The sold and purchased electricity is separated for the purposes of further economic analysis, since these have different prices. The trigeneration efficiencies of the plants are evaluated with Eq.(1) and (2). The results are presented in Table 3. The values are calculated in both lower heating value (LHV) and higher heating value

(HHV) terms from the net annual energy production of electricity $E_{el,net}$, district heating Q_{DH} and biocoal Q_{bc}, and the wood chips input as boiler fuel Q_f and torrefaction feedstock Q_{feed}:

$$\eta_{LHV} = \frac{E_{el,net} + Q_{DH} + Q_{bc,LHV}}{Q_{feed,\,LHV} + Q_{f,\,LHV}} \tag{1}$$

$$\eta_{HHV} = \frac{E_{el,net} + Q_{DH} + Q_{bc,HHV}}{Q_{feed,\,HHV} + Q_{f,\,HHV}} \tag{2}$$

Table 3.
Annual energy inputs and outputs of separate CHP and torrefaction plants, co-located plants (Case 0), and two integration options.

Case	CHP	Torrefaction	Case 0	Case 5	Case 6
Fuel input					
CHP boiler fuel $Q_{f,BFB}$ [GWh_{LHV}]	157.27	-	157.27	209.01	191.85
Stoker boiler $Q_{f,S}$ [GWh_{LHV}]	-	51.39	51.39	-	-
Torre feedstock $Q_{feed,LHV}$ [GWh_{LHV}]	-	230.57	230.57	214.66	203.29
Total $Q_{chips,HHV}$ [GWh_{HHV}]	193.59	342.69	536.28	516.79	482.80
Total $Q_{chips,LHV}$ [GWh_{LHV}]	157.27	281.96	439.24	423.67	395.14
Energy products					
Net electricity $E_{el,net}$ [GWh]	38.96	-6.58	32.38	30.35	18.85
Sold electricity $E_{el,s}$ [GWh]	38.96	0	33.96	31.68	20.22
Purchased electricity $E_{el,p}$ [GWh]	0	6.58	1.59	1.33	1.37
District heat output Q_{DH} [GWh]	94.80	0	94.80	103.47	101.80
Biocoal output $Q_{bc,HHV}$[GWh_{HHV}]	0	255.79	255.79	238.71	226.53
Biocoal output $Q_{bc,LHV}$ [GWh_{LHV}]	0	242.35	242.35	226.30	214.63
Trigeneration efficiency					
η_{LHV} [%]	85.05	83.62	84.13	85.00	84.85
η_{HHV} [%]	69.09	72.72	71.41	72.09	71.91

As can be expected, the total fuel input for the integrated cases is much higher than in the case of CHP plant. At the same time, the generation of an additional revenue stream through biocoal and the possible growth in power and heat production can make the integration schemes beneficial. The biocoal output along with the electricity and DH generation are the largest in Case 5 due to the longest plant operating time among all the other integrated cases. The stand-alone co-generation plant has higher efficiency in LHV terms than the stand-alone torrefaction case and any of the considered integrates. Nevertheless, since the feedstock for torrefaction is not burned except for the gaseous product from the torrefaction reactor, the loss with latent heat of biomass moisture decreases and the differences in trigeneration efficiencies in HHV terms of the integrated cases are relatively small. Even though the co-location of CHP and torrefaction plants (Case 0) is more advantageous in LHV terms than the stand-alone operation of torrefaction, the integration scenarios show better efficiencies in both LHV and HHV terms.

Figure 4 illustrates the distribution of the relative fractions of the annual outgoing energy streams from the studied processes. The generated products are presented in blue-green tones, while the energy losses are coloured in orange-brown. The overall rating of the considered factors are quite similar for all the studied cases with the main differences in the products' share distribution between integrated and co-located cases. Biocoal takes the highest share among the outgoing streams, followed by district heating load and electricity production. DH production and power generation are gaining a slightly higher share in the case of integration. Among the losses, the heat demand of the dryer and the boiler losses are the largest. The heat consumption of torrefaction unit itself and electromechanical losses of the plant are relatively small within the balance. The main variations of the balance among the integrated options are connected to the plant operation time during the year, and the absolute amount of energy produced or lost will be determined by the annual performance. At the same time, the relative fractions of energy streams give an overall distribution between energy products and process losses for the integrated cases.

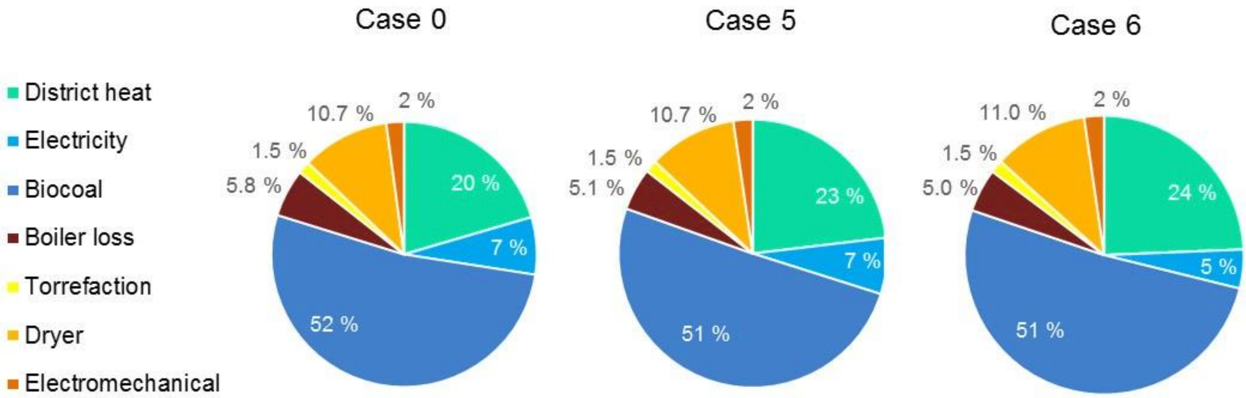

Fig. 4. Outgoing energy flows as fractions of plant annual operation.

The variation of the trigeneration efficiencies in LHV and HHV terms within the operating time is shown in Fig. 5a. As it can be seen, the efficiencies of the considered integrated schemes are virtually the same. Certain alterations between stand-alone CHP, co-located plants and integration cases can be explained by varying levels of energy inputs and outputs which were mentioned earlier. The part-load operation with the higher electricity generation and the longer operating time make the differences between the integrated cases and CHP plant more pronounced. Closer to the minimum DH loads, efficiency of the CHP plant starts to reduce, while integration cases are still able to use more of the available boiler capacity, and maintain better efficiency. The operation of the co-located plants (Case 0) at the minimum load periods is determined only by the performance of the torrefaction unit with the stoker boiler. As a result, the HHV efficiency increases stepwise at 6000 h. This change proceeds more smoothly in the case of the LHV efficiency, since the difference between its value for the CHP plant at low loads and the torrefaction unit is quite small.

Figure 5b represents the annual variations of boiler losses as one of the major loss components changing within a year. The lower efficiency of the stoker boiler results in slightly increased boiler loss in Case 0 compared to the integrated cases. The operating period between 6000 h and 8000 h for the co-located plants is associated solely with the loss from the stoker boiler as the CHP boiler is not used. The shutdown of the CHP boiler results in a step decrease of the boiler loss curve at 6000 h. Both graphs at the Fig.5 illustrate and underline the importance of considering the operational conditions throughout the year, since these result in significant seasonal variation of plant performance.

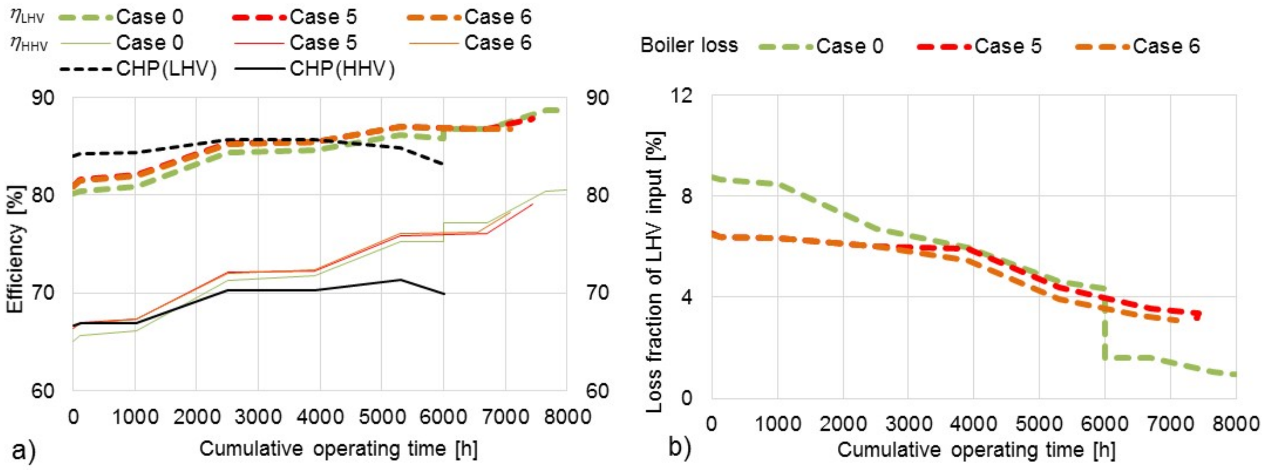

Fig. 5. Variation of efficiency and boiler losses as a function of cumulative operating time for the different cases.

4. Economic analysis

4.1. Total capital investment

The equipment of the integration plants was sized on the basis of the maximum capacity obtained from the simulation results and increased by overdesign factors. Typical values of overdesign factors (1.1–1.2) allow to mitigate design uncertainties and possible alterations of the operating performance. [31]

The cost of purchased equipment (PEC) was calculated by means of cost indexes and scaling factors. Cost indexes are used to predict the costs of materials and equipment based on historical cost data. The Chemical Engineering Plant Cost Index (CEPCI) was applied to make a general estimate of the processing equipment investment [31]. All prices were converted from year *y* to the base year 2014 Euro; the cost data given in US dollars (USD) was converted to Euro with the average annual exchange rate in the year of interest [32]:

$$Cost_{€,2014} = Cost_{USD,y} \frac{CEPCI_{2014}}{CEPCI_y} \frac{€_y}{USD_y} \tag{3}$$

If the cost for the particular operational capacity or size of the equipment is not available, it can be approximated on the basis of available cost data for the similar equipment of another capacity. The scaling factors allow to estimate the cost of an item *a* ($Cost_a$) of capacity X_a on the basis of the available data ($Cost_b$) for the equipment of the same type but different size or capacity (X_b) [28,33]:

$$Cost_a = Cost_b \left(\frac{X_a}{X_b} \right)^{\alpha} \tag{4}$$

where α is the equipment-specific scaling factor, and X is the capacity of the item.

Since torrefaction is a developing technology, the estimation of the equipment investment costs has some uncertainties due to the limited available information. In the present work, the equipment cost data for biomass processing (torrefaction reactor, pellet press, wood chips dryer and conveyor) was taken from a specific vendor information presented in [28]. The cost for standard equipment (e.g., heat exchangers) was taken from available literature [28,34]. The purchased cost of the CHP plant was evaluated from available data: [35] for the boiler; [36] for the turbine and generator; [31] and [33] for other equipment. The torrefaction stand-alone plant equipment assets along with the total module costs (CBM) are listed in Table 4.

Table 4. Total module cost for torrefaction unit equipment

Equipment	Specification	Capacity	CBM [M€]	Source
Torrefaction reactor	moving bed reactor	6.4 t/h	2.2	[7,28]
Biomass dryer	belt dryer	7075 kg_{H_2Oev}/h	2.7	[28]
Biomass feeding and storage	wood conveyor and storage	18.4 t/h	0.7	[28]
Stoker boiler	biomass fired boiler	10 MWth	5.2	[37]
Biocoal cooler	air-cooled heat exchanger	18 m^2	0.2	[28,31]
Pellet press and handling	pellet press including conditioning	4.9 t/h	1.1	[28]
Biocoal storage/handling	pellet storage	4.9 t/h	0.5	[28]

The total module cost of equipment consists of the sum of the PEC and other cost factors directly related to the erection of the purchased equipment (i.e. instrumentation and controls, equipment erection and construction expenses, piping and electrical equipment and materials). If no item specific data is available, the ratio CBM/PEC was assumed to be 2.88 for the CHP plant components and 2.46 for the torrefaction plant as suggested in [38].

In order to calculate the total capital investments (TCI) of the studied integrated and stand-alone cases, the fixed capital investment (FCI) costs and working capital should be evaluated. The offsite costs (45% of PEC) summarize the cost for land, ancillary buildings, site development and utilities. The total module cost together with offsite costs are the direct costs. Start-up expenses (10% of PEC) cover the cost of possible start-up changes in materials and equipment and the loss of income before reaching the maximum design capacity. The expenses on engineering and construction design together with purchasing, procurement and construction supervision are addressed as the the engineering and supervision cost component (12% of PEC). Start-up and engineering cost factors contribute to the indirect costs category. Contractor's fee is implemented as 5% of the indirect and direct costs. The contingencies (10% of indirect and direct costs) take into account the expenses on unpredictable circumstances (e.g. strikes, price changes, storms, floods, errors in estimations). The sum of the aforementioned cost factors represents the fixed capital investment category which covers all the capital required for the installed equipment together with all auxiliaries. The working capital for the industrial plant (15% of FCI) estimates the total amount of money needed above the fixed capital to start the plant up and to operate until the moment of receiving the first income. The final value of the total capital investments consists of the working and fixed capital. The aforementioned assumptions for the total capital investment component calculations were taken from the literature [31,33]. Table 5 summarizes the cost data for the considered plants.

Table 5. Total capital investment calculation for studied cases. All numbers in millions of euro.

			CHP	Torrefaction	Case 0	Case 5	Case 6
Purchased equipment cost		Torrefaction unit	-	3.0	3.0	2.7	2.7
		Stoker boiler	-	1.8	1.8	-	-
		CHP	5.8	-	5.8	5.8	5.8
Fixed-capital investment	Direct costs	Total module cost	16.6	12.5	29.1	23.2	23.2
		Offsite cost	2.6	2.1	4.7	3.8	3.8
		Σ	19.2	14.6	33.8	27.0	27.0
	Indirect costs	Engineering	0.7	0.6	1.3	1.0	1.0
		Start-up	0.6	0.5	1.1	0.8	0.8
		Σ	1.27	1.05	2.3	1.9	1.9
		Contractor's fee	1.0	0.8	1.8	1.4	1.4
		Contingencies	2.0	1.6	3.6	2.9	2.9
		Σ	23.5	18.0	41.5	33.2	33.2
		Working capital	3.5	2.7	6.2	5.0	5.0
		Total capital investment	**27.1**	**20.7**	**47.7**	**38.1**	**38.1**

The investment cost for torrefaction reactors published in the literature varies widely depending on the reactor type and other auxiliary equipment. Several selected facilities presented in [39] give a range of costs from 1.4 M€/(t/h) to 4.5 M€/(t/h) with annual capacities of 10-70 kt/a of torrefied biomass. The specific TCI cost for the reactor considered in the current work is at the level of 4 M€/(t/h) within the mentioned limits. The differences between the equipment of the integrated cases are assumed to be negligible and their investment costs are thus identical. The integration of torrefaction and CHP requires 20% less capital investment than co-located plants. The torrefaction unit represents 32% of the total purchased equipment cost of the integrated plant and results in approximately 40% higher capital investments of the integrates over the stand-alone CHP plant.

4.2. Profitability evaluation

The most commonly used methods for profitability evaluation - net present value (NPV), internal rate of return (IRR) and payback period (PBP) - are used for the economical assessment of the considered integration schemes at three different price assumption scenarios. Among the methods, NPV and IRR are usually applied for project evaluation.

Different electricity price scenarios (high, medium and low) were set for the market price of sold electricity on the basis of a report ordered by the Finnish Ministry of Employment and Economy [40]. Table 6 summarizes the values of the parameters when they were not treated as variables for economical evaluation applied in current study.

Table 6. Values of parameters (when not treated as variables in the economic analysis).

Parameter	Value	Energy product	Price
Maximum annual operating time t [h]	8000	Wood chips price c_f [€/MWh$_{LHV}$]	20
Interest rate i [%]	10	Sold electricity price (high) $c_{el,s}$ [€/MWh]	77
Plant economic life time n [y]	25	Sold electricity price (medium) $c_{el,s}$ [€/MWh]	44
Annual O&M cost ratio for CHP plant $r_{O\&M,CHP}$ [%]	4	Sold electricity price (low) $c_{el,s}$ [€/MWh]	21
		Purchased electricity price $c_{el,p}$ [€/MWh]	100
Annual O&M cost ratio for torrefaction unit $r_{O\&M,Torre}$ [%]	6	District heat price c_{DH} [€/MWh]	60
		Biocoal pellets price c_{bc} [€/MWh$_{LHV}$]	40

Considered co-located and integrated scenarios have the incoming cash flows from the sold products: electricity, district heat and biochar. The outgoing cash flows are represented by the expenses on the boiler fuel and torrefaction feedstock, purchased electricity and the operation and maintenance cost. Assuming no residual value for the investment, the NPV of a project is determined as the total sum of the present worth of future cash flows during the project economic life time of *n* years discounted at an interest rate of *i*, subtracting the value of total capital investment TCI:

$$NPV = \frac{(1+i)^n - 1}{i \cdot (1+i)^n}\left[E_{\mathrm{el,s}}\, c_{\mathrm{el,s}} + Q_{\mathrm{DH}}\ c_{\mathrm{DH}} + Q_{\mathrm{bc,LHV}}\, c_{\mathrm{bc}} - Q_{\mathrm{chips,LHV}}\, c_{\mathrm{f}} - E_{\mathrm{el,p}}\, c_{\mathrm{el,p}} - C_{\mathrm{O\&M}}\right] - TCI \tag{5}$$

where the annual energy streams *E* and *Q* are shown in Table 3 and the corresponding prices *c*.

The internal rate of return is calculated with Eq.(5) by solving it iteratively for such interest *i* that the NPV becomes zero. The PBP is found similarly by setting the NPV to zero in Eq.(5), and solving for the number of years *n*.

The annual operation and maintenance cost $C_{O\&M}$ is determined as a fraction $r_{O\&M}$ of the total capital investments. For a small-scale biomass-fired CHP plant the value for $r_{O\&M,CHP}$ = 4% was assumed based on another investigation [37]. Since the torrefaction is a developing technology, slightly higher O&M fraction of $r_{O\&M,Torre}$ = 6% was set in the current study. The overall cost for the operation and maintenance in all scenarios should include the corresponding expenses of the CHP plant and torrefaction, thus the combined value of the cost for operation and maintenance $C_{O\&M}$ was applied. The value was calculated with the mean $r_{O\&M}$ weighted with the fractions of the purchased equipment cost of the CHP plant and torrefaction unit:

$$C_{\mathrm{O\&M}} = \left(r_{\mathrm{O\&M,CHP}}\, \frac{PEC_{\mathrm{CHP}}}{PEC_{\mathrm{CHP+Torre}}} + r_{\mathrm{O\&M,Torre}}\, \frac{PEC_{\mathrm{Torre}}}{PEC_{\mathrm{CHP+Torre}}} \right) \cdot TCI \tag{6}$$

Table 7 summarizes the annual cash flows for the considered cases in conditions of the investment amortization in equal annual payments within the project economic life time. Sold electricity is calculated with medium price of 44 €/MWh. The relation between interest rate value (15%, 10% and 5%) and annual net cash flow was investigated. With the interest rates of 15% and 10%, the stand-alone torrefaction reactor is unprofitable. On the other hand, interest rate of 5% improves the performance of all studied cases, and even the stand-alone torrefaction unit becomes profitable. Among the integrated cases, the highest cash flow is observed in Case 5 yielding 62% increase of the net cash flow over the co-located plants. The integration Case 6 results in more moderate changes: cash flow is 39% higher than that of Case 0 (*i* = 5%). At the baseline interest rate of 10%, the integration options increase the annual cash flow by 8 – 11 times compared to the stand-alone CHP plant. With the higher level of interest rate (15%), only Case 5 results in positive annual cash flow value, thus making this integration option more beneficial than the stand-alone CHP plant or simple co-location.

Table 7.
Annual cash flows of different cases.

	CHP	Torrefaction	Case 0	Case 5	Case 6
Investment amortization (*i* = 15%) [M€]	-4.19	-3.20	-7.39	-5.90	-5.90
Investment amortization (*i* = 10%) [M€]	-2.98	-2.28	-5.26	-4.20	-4.20
Investment amortization (*i* = 5%) [M€]	-1.92	-1.47	-3.39	-2.71	-2.71
Operation and maintenance [M€]	-1.08	-1.65	-2.32	-1.75	-1.75
Boiler fuel [M€]	-3.15	-1.03	-4.17	-4.18	-3.84
Torrefaction feedstock [M€]	0	-4.61	-4.61	-4.29	-4.07
Purchased electricity [M€]	0	-0.66	-0.16	-0.13	-0.14
Sold electricity [M€]	1.71	0	1.49	1.39	0.89
Sold district heat [M€]	5.69	0	5.69	6.21	6.11
Sold biocoal [M€]	0	9.69	9.69	9.05	8.59
Annual net cash flow (*i* = 15%) [M€]	-1.01	-1.46	-1.78	0.40	-0.11
Annual net cash flow (*i* = 10%) [M€]	0.19	-0.54	0.35	2.10	1.59
Annual net cash flow (*i* = 5%) [M€]	1.25	0.27	2.22	3.59	3.09

Three different scenarios for the total capital investment of the studied cases are investigated: base level (TCI value from Table 5), optimistic (-25% from the base scenario) and pessimistic (+25% from the base scenario). The main results of IRR, NPV and PBP calculation in terms of concerned economic scenarios are illustrated in Fig.6. In addition to the variation of the TCI (characterized by lines' colours), the effect of three different price levels of sold electricity is considered (indicated by the different line patterns).

As could be expected, the integration Case 5 shows the best results within all three investigated metrics for profitability evaluation due to its longer operating time and increased electricity and DH production. Compared to Case 0, both studied integration options improve the profitability in all considered schemes.

The main economic drivers which have an impact on the project performance can be identified from their effect on the internal rate of return. A sensitivity analysis of the project IRR to the range of parameters (with ±20% change) is presented in Fig.7 with baseline investment costs and medium electricity cost assumptions.

The IRR of the stand-alone torrefaction unit is particularly sensitive to the price of wood chips. The investment cost is the second important factor which defines the profitability. The changes in other two parameters - purchased electricity price and O&M costs - result in variations of the IRR in a quite narrow range (2%). The profitability of CHP plant is mainly defined by the district heat price and the capital investment cost. While district heat constitutes the main product, the effect of sold electricity price appears to be limited. The electricity price is likely to be far more volatile than any of the other prices. The variation of 20% is a relatively large for most of the parameters, but the electricity price can in fact be subjected to uncertainties of even several times greater magnitude. The effect of the wood chips price is considerably smaller in comparison with the torrefaction plant due to the higher conversion efficiency of the generated products.

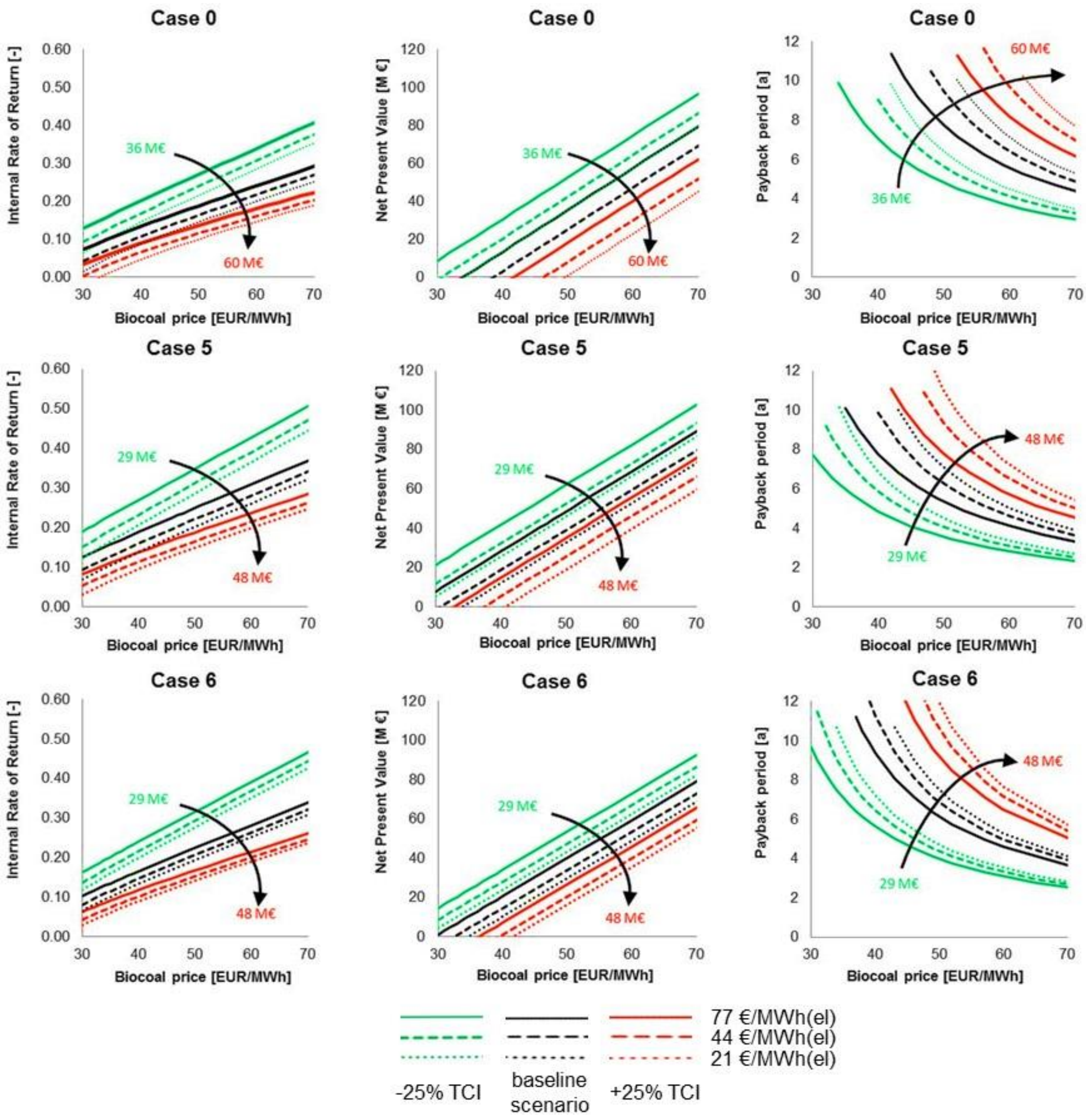

Fig. 6. Studied cases compared in terms of IRR, NPV and PBP. Line colour indicates the investment cost scenario (green – optimistic, black – base and red – pessimistic). Line pattern corresponds to the price level of sold electricity.

The integrated cases show practically identical results. The effect of the investment cost followed by the feedstock and district heat prices cause the highest impact on the project profitability. This dependence is relatively similar to the case of co-located plants (Case 0). The small effect of the purchased electricity price is a result of the need to augment the CHP plant's own production with purchased electricity to cover the total plant power demand during full-load periods. The IRR in Case 5 with the highest power generation among all the integration cases is slightly more sensible to the sold electricity price than in Cases 0 and 6 due to the increased power generation.

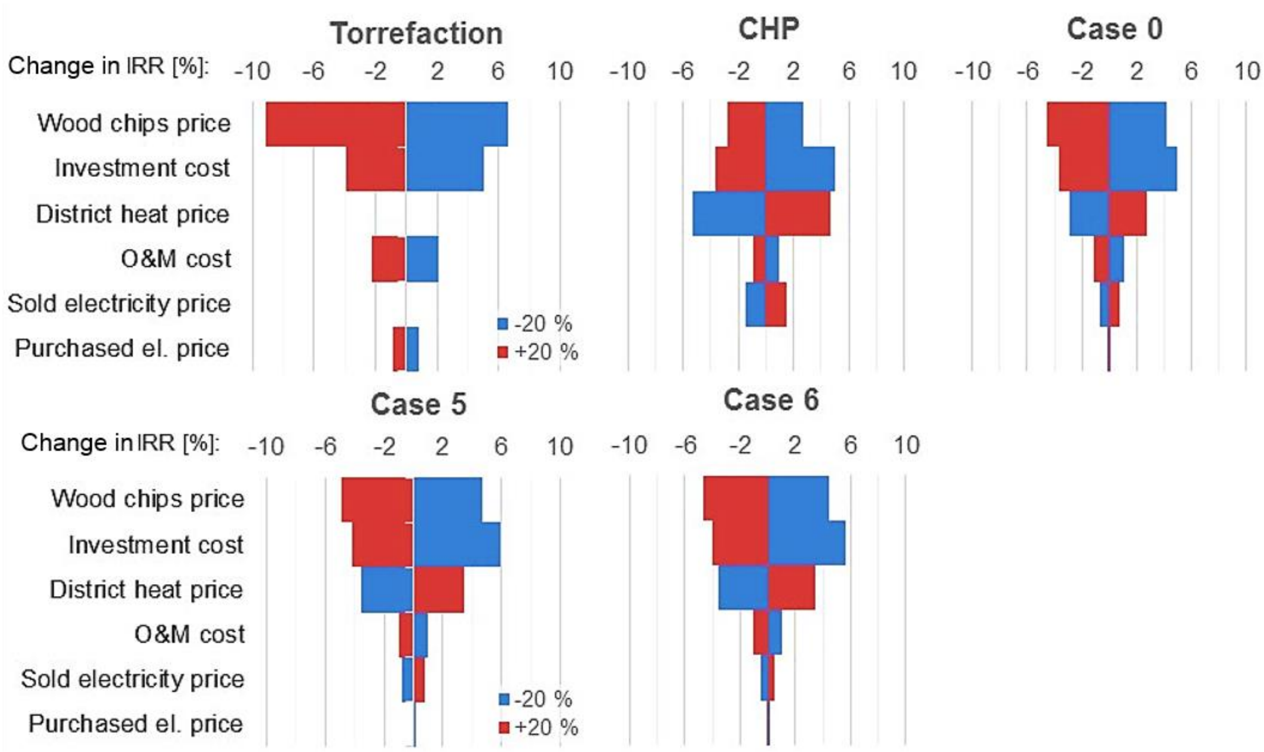

Fig. 7. Sensitivity analysis of IRR with ±20% change of parameters.

5. Summary and conclusions

This study has shown that the heat integration of a torrefaction process into a CHP cycle could be economically profitable over the co-located plants under certain circumstances. While the previous investigation revealed important benefits of the integration with CHP at reduced district heating load, the analysis of the integrated cases considering seasonal operational changes brings a more complete understanding of the annual operation for each scenario. The typical backpressure CHP plant that was analysed in the present work fulfils the district heating demand and, as a result, follows all the annual variations of the DH network (both qualitative and quantitative). The operational analysis of the current study takes into account all major changes that affect the plants performance in order to evaluate the potential of possible integration.

Three scenarios to cover the heat requirements of a torrefaction unit (30.3 MW_{LHV} production capacity) were initially evaluated: drum water (Case 1), live steam and low pressure steam (Case 5) and only live steam (Case 6). The analysis showed that integration options using live steam to cover the torrefaction demand have significant benefits. Within the frames of the considered capacity levels and the limitations for the plant operation, the integrated scenario of Case 1 cannot be operated during full-load periods. Reducing the capacity of the torrefaction unit may result into certain improvements, but for purpose of keeping the cases comparable, only Cases 5 and 6 were considered in the current work.

The energy efficiencies of the integrated cases are comparable with those of a stand-alone co-generation plant: in this respect, integration offers no clear benefits. The possibility to increase the annual operation of the CHP plant, on the other hand, makes integration advantageous over the stand-alone operation or the simple co-location of the plants. For both integrated cases studied in this work, the torrefaction unit acts as an additional and relatively constant heat consumer, thus enabling the CHP plant to operate at a lower DH load than would be possible otherwise. This allows the annual operation time and district heat output be increased. Fulfilling the significant heat demand of the dryer by low pressure steam provides the important benefits to the plant overall performance: with increased live steam mass flow through the turbine, the electrical power output is higher than in case of the stand-alone CHP plant at all load points except full load, when the turbine has to be mostly bypassed.

The economic assessment indicated that the share of the torrefaction equipment in the total purchased equipment cost of integrated plant accounts for approximately 30%. On the whole, the integration options require about a 40% more capital investment than a stand-alone CHP plant. The torrefaction products should thus bring a significant additional revenue from the sale to justify this investment. On the other hand, the integration options need ca. 20% less investments than co-located torrefaction and CHP plants. The relation between interest rate value and annual net cash flow for all studied cases was investigated. The integration options result into an annual cash flow increase by 8 – 11 times over the stand-alone CHP plant with the baseline interest rate of 10% and biocoal price of 40 €/MWh. With a more realistic value of 5% interest rate, all integrated cases together with stand-alone torrefaction unit become profitable.

The profitability was evaluated with three commonly applied methods: net present value, internal rate of return and payback period. Different scenarios for sold electricity price and total investment cost helped to obtain a comprehensive assessment of the integrated options within different economic situations. The integration case with the longest operation time (Case 5) resulted into higher values of profitability in contrast to the other options: both integration and co-located. The investment cost and the wood chips price are the main economic factors influencing the profitability of the integrated options, while the IRR value of the stand-alone torrefaction unit is particularly sensitive to the price of wood chips.

The results confirm the importance of a detailed operational and economic analysis in order to evaluate the future potential of the torrefaction integration and to choose the most suitable configuration. Sustainable and economically efficient combination of the torrefaction process and co-generation plant has a lot of potential. Modelling and comprehensive analysis of available data from the pilot plants and other torrefaction facilities are necessary and important steps towards the development of torrefaction, and implementing it into real applications. The analysis of the present paper provides a basis for further more detailed evaluation that can be done for any existing co-generation plant of similar type. At the same time, the relatively high uncertainties over the future energy prices for electricity, district heat and biocoal make accurate evaluation of the economic perspectives difficult. The market price for electricity is subject to fluctuations due to a number of factors, such as renewable energy subsidies, and changes in the level of supply and demand. The investment costs for the torrefaction unit equipment are expected to decrease in the near future as this technology becomes more commercial. It was found from the operational analysis that the integration of torrefaction with a combined heat and power plant can be advantageous, particularly when using live steam for the high-temperature demand of torrefaction, and the lower-grade heat in the form of backpressure steam to fulfil the significant demand of the drier. The effect of torrefaction on a CHP plant is clearly determined by the torrefaction unit capacity, and more detailed investigation is necessary for the determination of the optimum size.

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