

APPLICATION OF ORC UNITS IN THE PELLET PRODUCTION FIELD: TECHNICAL-ECONOMIC CONSIDERATIONS AND OVERVIEW OF THE OPERATIONAL RESULTS OF AN ORC PLANT IN THE INDUSTRY INSTALLED IN MUDAU (GERMANY).

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ABSTRACT: Over the last 10 years the ORC (Organic Rankine Cycle) technology applied in small size (0.5–2 MW_{el}) decentralized CHP biomass plants has demonstrated to be a well proven industrial product with excellent results in terms of reliability, ease of operation, low maintenance together with good conversion efficiency which allows to implement cost effective plants.

In conventional heat only plants for pellet production, belt or rotary dryers are used to perform drying process of sawdust, in order to reach the moisture content required by pellet process. In this paper heat only pellet production plants are compared with CHP solution based on a biomass combustion system, an ORC unit and a belt dryer fed by hot water coming from the ORC condenser. The results of the differential feasibility study show that CHP plants can be economically competitive with an electricity value above 0,16 Euro/kWh_{el} starting from a pellet production capacity of 4 t/h. Plants with a capacity above 8 t/h may be competitive also with electricity values around 0,10-0,12 Euro/kWh_{el}.

The experiences from the 10 ORC plants installed in the pellet industry confirm the assumptions of this study. The measured data from the 1 MW_{el} ORC unit installed in Mudau plant (Germany) are presented.

Keywords: Organic Rankine Cycle (ORC), Combined Heat and Power generation (CHP), Pellet, economic feasibility

1 ORC UNITS IN BIOMASS COGENERATION

Over the last 10 years the ORC technology has demonstrated to be a well proven industrial product for application in small decentralized biomass CHP plants (0,5 – 2 MW_{el}).

Typical systems are based on the following main steps:

- biomass fuel is burned in a combustor made according to the well established techniques also in use for hot water boilers. These combustors with their set of accessories (filters, controls, automatic ash disposal and biomass feed mechanism etc.) are nowadays safe, reliable, clean and efficient;
- hot thermal oil is used as heat transfer medium, providing a number of advantages, including low pressure in boiler, large inertia and insensitivity to load changes, simple and safe control and operation. Moreover, the adopted temperature (about 315°C) for the hot side ensures a very long oil life. The utilization of a thermal oil boiler also allows operation without requiring the presence of licensed operators as for steam systems in many European countries;
- an Organic Rankine Cycle turbogenerator is used to convert the available heat to electricity. Thanks to the ORC, that is thanks to the use of a properly formulated working fluid and to the optimization of the machine design, both high efficiency and high reliability are obtained. The condensation heat of the turbogenerator is used to produce hot water at typically 80 – 120°C, a temperature level suitable for district heating and other low temperature uses (i.e. wood drying and cooling through absorption chillers etc.).

The ORC unit is based on a closed Rankine cycle performed adopting a suitable organic fluid as working fluid. In the standard units for biomass cogeneration developed by Turboden silicon oil is used as working fluid [1]. The first ORC adopting this fluid was tested in 1986 by Turboden.

The thermodynamic cycle and the relevant scheme of components are reported in **Figure 1**.

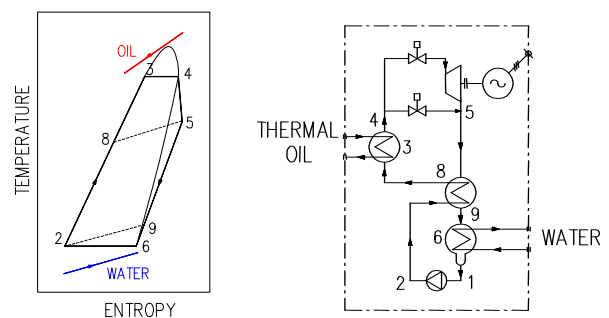


Figure 1 : Thermodynamic cycle and components of an ORC unit

The turbogenerator uses the hot temperature thermal oil to pre-heat and vaporise a suitable organic working fluid in the evaporator (8→3→4).

The organic fluid vapour powers the turbine (4→5), which directly drives the electric generator through flexible coupling.

The exhaust vapour flows through the regenerator (5→9) where it heats the organic liquid (2→8).

Finally, the vapour is condensed in a water cooled condenser (9→6→1).

The organic fluid liquid is then pumped (1→2) to the regenerator and then to the evaporator, thus completing the sequence of operations in the closed-loop circuit.

An evolution of this conventional cycle is the “Split system”, introduced by Turboden for the first time in 2004, within the CHP biomass plant installed in Pösing (Germany).

The “Split system” allows to use an additional heat input at lower temperature level, via a non-completely regenerative cycle. This allows to recover additional heat from hot combustion gas, hence increasing the thermal oil boiler efficiency, through a second thermal oil cycle at a lower temperature level (usually between 150 and 250°C), with limited influence on cycle efficiency. Therefore, the overall electric plant efficiency (generated electric power / biomass fuel power) is increased about 8%. This more efficient solution has gained in the last years an increased market share despite the higher investment costs. Therefore in this paper only ORC units with split system will be considered.

Compared to other competing technologies (i.e. steam turbines), the main advantages obtained from the ORC technology are the following:

- high cycle efficiency (especially if used in cogeneration plants);
- very high turbine efficiency (up to 85%);
- low mechanical stress of the turbine, thanks to the low peripheral speed;
- low RPM of the turbine allowing the direct drive of the electric generator without reduction gear;
- no erosion of the turbine blades, thanks to the absence of moisture in the vapour nozzles;
- very long operational life of the machine due to the characteristics of the working fluid that, unlike steam, is non eroding and non corroding for valve seats, tubing and turbine blades;
- no water treatment system as in steam plants is necessary.

There are also other relevant advantages, such as simple start-stop procedures, quiet operation, minimum maintenance requirements and good partial load performance [2]. The main advantage of ORC technology is that no particular qualification or know how is required for the personnel operating the CHP plant. This means that also customers without any background in electricity generation can easily evaluate an investment in a CHP plant.

Due to these main reasons the standard range of ORC units developed, produced and marketed by Turboden Srl. Brescia is considered an optimal solution for small biomass cogeneration systems in the power range up to 2 MWe1 per unit. This is confirmed by more than 70 Turboden ORC plants in operation for a total installed power of more than 65 MWe1 that are showing very good results in terms of reliability (average availability of the ORC units > 98% over more than 1.000.000 hours of operation) and in terms of reduced operational and maintenance costs.

2 SAWDUST DRYING TECHNOLOGIES FOR PELLET PRODUCTION

In this paper, different configurations of wood pellet plants based on biomass combustion are described.

The biomass fired combustion system of a typical pellet production plant is usually fed with raw material such as bark and low quality wood chips coming from sawmill and wood processing industry close to the pellet plant.

Wood pellets are manufactured from untreated wood wastes, mostly sawdust and shavings, without any addition of chemical gluing agent.

After a preliminary sorting process, only wood material which respects tight quality standards and with a suitable granulometry flows into the dryer, where evaporation of sawdust water content takes place.

From a technical point of view the different drying technologies are usually based on the generation of a hot drying air or gas stream which comes in contact directly with the wet material, drying it up to the optimal moisture content required by the following stages of pellet pressing process.

As sawdust usual moisture content we shall take into account a value between 40 and 50% for initial wet sawdust and about 10% for final dried sawdust.

Within the different technologies for sawdust drying that are available on the market, in this study rotary dryers and belt dryers are considered.

Herewith, some different pellet plants configurations are described with the respective sawdust drying technologies adopted.

2.1 Direct rotary dryer

In a pellet production plant based on a biomass combustion system and a direct rotary dryer, hot gas coming from the combustion chamber are diluted with an ambient air stream in a suitable mixing chamber, in order to obtain gas temperature compatible with the highest inlet temperature acceptable in the dryer (usually around 300°C). Higher gas temperatures at dryer inlet would lead to lower pellet quality, increasing risk of possible sawdust firing as well.

A feed system supplies the drum dryer with the wet biomass which comes into direct contact with the hot drying gas, thus evaporating the excess water content up to the process requirements.

A typical pellet production plant based on a biomass combustion system and a rotary dryer usually includes the following items:

- Biomass burner (hot gas generator)
- Mixing chamber including hot gas distribution device
- Wet biomass feed device
- Drum dryer
- Dried product discharge system
- Drying gas cleaning unit
- Fire detection and sprinkler system
- System Control device.

In **Figure 2** a block diagram of the process performed in a biomass plant for pellet production based on rotary drying system is shown.

2.2 Indirect belt dryers

As an alternative to rotary dryers, indirect belt dryers are often adopted for in pellet production plants. This technology requires to install a hot water boiler, generally biomass fuelled.

Within the belt dryer the produced hot water is utilized to generate a hot air stream that flows into a special web belt, thus evaporating the water content of the sawdust.

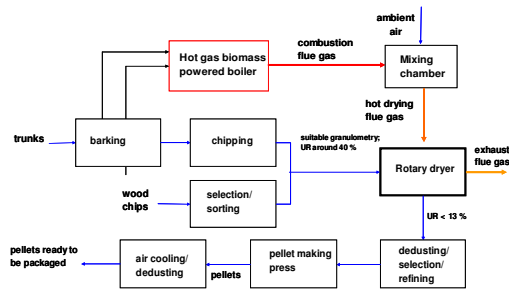


Figure 2 Schematic diagram of a biomass heat only plant for pellet production based on direct rotary dryer.

Therefore, within the belt dryer, there is no direct contact between hot combustion gas and wet biomass, since the hot air stream used as drying medium has not been mixed with hot combustion gas. Therefore within the dried product, any content of dust, particle and ashes usually coming from combustion gas, is avoided. Furthermore, due to lower drying air temperature (usually between 70 and 110°C), risk of possible sawdust firing is also strongly reduced.

A typical pellet production plant based on a belt dryer usually includes the following items:

- Hot water biomass boiler
- Wet biomass feed device
- Hot air generation (hot water/drying air heat exchanger).
- Drying web belt
- Dried product discharge system
- Drying air cleaning unit (if required by local regulations)
- Fire detection and sprinkler system
- System Control device

In **Figure 3** a block diagram of the process performed in a biomass heat only plants for pellet production based on belt drying system is depicted.

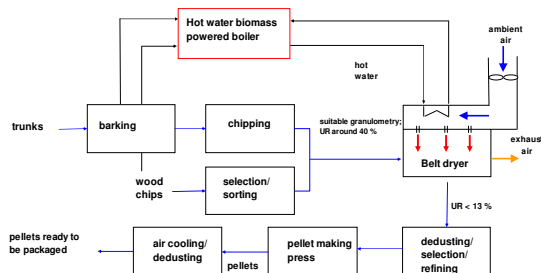


Figure 3 Schematic diagram of a biomass heat only plant for pellet production based on a belt dryer.

2.3 Indirect rotary dryers

In addition to direct rotary and belt dryers, indirect rotary dryers are below outlined as well. This is an intermediate solution between direct rotary and belt dryer, in which hot combustion gas from the biomass burner flow through a surface heat exchanger directly heating ambient air, which is then used as drying medium in a rotary drum. This heat exchanger replaces the mixing chamber.

Thus, as it happens for the belt system, there is no direct contact between hot combustion gas and wet material, leading to a better quality of pellet and reducing the risk of possible firing within sawdust.

2.4 CHP plant with ORC units coupled to belt dryers

Depending on market boundary conditions, a CHP solution within a pellet manufacturing plant can be profitable. In the following part of this study a CHP solution based on biomass ORC unit and belt dryer is described.

A typical pellet production plant based on a biomass combustion system and an ORC unit does not lead to significant changes to conventional heat only plan for pellet production with belt dryer.

This means that, in addition to the new installation of CHP biomass pellet plant, retrofitting of already existing pellet plant based on hot water boiler coupled to belt dryer can easily be implemented as well, just replacing hot water boiler with thermal oil boiler feeding ORC unit. Hot water will be actually available downstream the ORC condenser.

In **Figure 4** a block diagram of the process performed in a CHP biomass plant for pellet production based on belt drying system and ORC unit is shown.

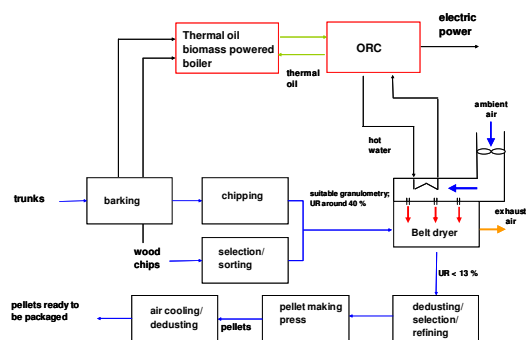


Figure 4 Schematic diagram of a CHP biomass plant for pellet production based on belt dryer coupled to an ORC unit.

2.5 Technical features assumed for the different plants configurations

The different technical solutions for sawdust drying described in the previous paragraph are characterized by different efficiencies (both thermal and electric) and different specific electric own consumptions. In the case of the CHP plant, additional fuel consumption for the electric power generation has also to be accounted for. The resulting additional energy flows need to be accurately accounted for in the economic analysis. The necessary assumptions, based on the average data of

standard technology solutions available on the market, are reported in the following tables:

PLANT TECHNICAL FEATURES	PLANT CONFIGURATION		
	Direct Rotary	Belt	CHP
Combustion system			
Thermal oil boiler efficiency (including Split system)	-	-	90%
Hot water boiler efficiency (including water economizer)	-	90%	-
Hot gas boiler efficiency	100%	-	-
Thermal oil boiler own consumption [kWel/MWth]	-	-	25
Hot water boiler own consumption [kWel/MWth]	-	15	-
Hot gas boiler own consumption [kWel/MWth]	15	-	-

Table 1 Technical assumptions: Combustion system.

PLANT TECHNICAL FEATURES	PLANT CONFIGURATION		
	Direct Rotary	Belt	CHP
Drying process			
Inlet wet biomass moisture	50%	50%	50%
Outlet dried biomass moisture	9%	9%	9%
Drying efficiency	65%	65%	50% (*)
Drying own consumption [kWel/t/h pellet]	20	40	40
Hot water temperature inlet belt dryer (about) [°C]	-	115	90
Hot drying gas/air temperature inlet dryer (about) [°C]	300	105	80
Electric power generation	Direct Rotary	Belt	CHP
ORC net electric efficiency (c.a.)	-	-	17% (*)

Table 2 Technical assumptions: Drying process, Power generation system.

(*) With hot water feed temperature of 90 °C. For drying efficiency and ORC electric efficiency at different hot water temperature, see **APPENDIX 1**.

As shown in **Table 2**, in the first part of this study, every ORC unit is assumed to supply belt dryer with hot water at constant feed temperature of 90°C; this leads to a fix value for belt drying efficiency equal to 50%. Therefore, with these assumptions, every ORC unit can be related to only one amount of pellet production capacity.

In the following table, pellet production capacity for all the ORC sizes are resumed:

Turboden ORC unit	Pellet capacity (t/h)
T200-CHP Split	1,1
T500-CHP Split	2,6
T600-CHP Split	3,1
T800-CHP Split	4,0
T1100-CHP Split	5,3
T1500-CHP Split	7,7
T2000-CHP Split	9,4

Table 3 Hp: hot water supplied by ORC unit to belt dryer at constant temperature (90°C).

3 DIFFERENTIAL ECONOMIC FEASIBILITY OF A CHP PLANT BASED ON ORC TECHNOLOGY

In this paragraph the opportunity to install a CHP plant based on ORC unit for supplying the heat necessary for drying sawdust to produce pellet is investigated.

An differential feasibility study comparing CHP biomass plants (based on ORC unit and belt dryer) with conventional biomass heat only plants is performed. In this economic analysis only the additional “revenues” and “costs” (both capital and consumption/operating costs) that result from the addition of an ORC system for cogeneration (that is to say only the revenues and the costs which would not exist if a heat-only system was implemented) are accounted for.

3.1 Selection of the reference case for heat only plant

The following technical solutions have been considered as reference cases, with the same pellet capacity output:

- heat-only plant based on a directly heated rotary drum dryer (see par. 2.1)
- heat-only plant based on an indirectly heated belt dryer (see par. 2.2)

Both the previous different reference cases have been considered because, although the direct drum dryer is economically more advantageous, there is a relevant part of the market that adopts belt dryer in heat only drying plants.

The advantages of the direct drum dryer are mainly reduced investment costs, higher thermal drying efficiency and lower electric own consumption

The reasons for adopting a belt dryer solution within pellet production plants are normally related to the possibility to burn lower quality fuel without contamination of the dried sawdust. In particular, according to several operators and engineering companies [3], in case of adopting a direct contact dryer some problems may occur in keeping the ash content of the pellet under the value of 0,5% required by the DINplus norm regulating pellet quality certification, when lower quality fuel is used.

The solution with indirect rotary dryer has not been considered in the present feasibility study, but intermediate economic results between the two boundary drying solutions (direct rotary and belt systems) are

expected to occur.

Summarizing, a direct contact dryer may be often preferred when:

- high quality fuel is available at reasonable prices;
- there are no stringent requirements concerning the quality of pellet.

On the other hand, indirect dryer may be usually preferred when:

- the operator intends to have a higher fuel flexibility;
- there are stringent requirements concerning the quality of pellet (i.e. pellet according to DINplus norm).

3.2 Discussion of main economic parameters and assumptions

The main economic parameters which influence the differential economic feasibility of a CHP plant are the following:

- Additional investment costs of CHP plant

Different pellet plant configurations adopted for drying, combustion and power generation (in the case of CHP plant) imply different overall plant investment costs.

In this study, the assumptions for investment costs of all the components of the plant have been defined as ratio between cost of the various components of the plant and cost of ORC units. This means that the same scale effect of Turboden ORC units investment costs, is assumed for all components.

In the next tables, the parametric costs assumed for the different components of the plant have been resumed:

Component of the plant	Overall Investment Cost CHP plant	Overall Investment Cost Only Rotary	Additional investment Cost CHP - Only Rotary
Turboden ORC unit	1	0	1
Boiler	1,8	0,7	1,1
Civil work + Engineering	1,3	0,65	0,65
Dryer	0,7	0,3	0,4
Total	4,80	1,65	3,15

Table 4: Assumed investment costs for CHP and heat only plants based on a rotary dryer as multiplier of ORC costs.

In addition to costs considered for all the items mentioned in the previous tables, for the whole range of ORC sizes an extra cost of 100.000 Euro due to necessary equipment for connection to the electric grid has been considered.

Component of the plant	Overall Investment Cost CHP plant	Overall Investment Cost Only Belt	Additional investment Cost CHP - Only Belt
Turboden ORC unit	1	0	1
Boiler	1,8	0,7	1,1
Civil work + Engineering	1,3	0,65	0,65
Dryer	0,7	0,6	0,1
Total	4,80	1,95	2,85

Table 5: Assumed investment costs for CHP plant and heat only plant based on a belt dryer as multiplier of ORC costs.

The actual additional investment costs assumed are reported in the table below for 3 different ORC sizes:

Turboden ORC unit	Overall Investment Cost [k€] CHP plant	Overall Investment Cost [k€] Only Rotary	Additional Investment Cost [k€] CHP - Only Rotary
T500	4.800	1.600	(*) 3.200
T1100	6.500	2.200	4.300
T2000	9.300	3.100	6.200

Table 6: Assumed investment costs for CHP plant and heat only plant based on a rotary dryer

Turboden ORC unit	Overall Investment Cost [k€] CHP plant	Overall Investment Cost [k€] Only Belt	Additional Investment Cost [k€] CHP - Only Belt
T500	4.800	1.900	2.900
T1100	6.500	2.600	3.900
T2000	9.300	3.700	5.600

Table 7: Assumed investment costs for CHP plant and heat only plant based on a belt dryer

(*) Example of calculation: $3200\text{k€} = 3,15 * 985\text{k€}$ c.a. (investment cost of T500 ORC unit) + 100k€ (grid connection).

- Size of the plant

The figures reported in **Table 6** put in evidence that the size of overall plant influences significantly the feasibility results since it influences specific investment costs of the various components of overall plant due to the economy-of-scale effect.

For example, additional investment cost of 6200k€ for a CHP plant based on T2000, is less than two times 3200k€, but the ORC size is four time larger.

- Value of electricity

One of the most significant parameter influencing the economic feasibility of a cogenerative plant is of course the value of the electric energy generated by the plant. The differential approach adopted in the present study implies that only additional energy flows of the

cogeneration plant compared to the reference heat only cases have been considered.

The additional electricity flows considered in this paper are the following:

- ORC gross power production;
- ORC own consumption;
- additional power consumption in boiler;
- additional power consumption in dryer.

The economic value of these additional electric energy flows strongly depends on the frame conditions and in particular on the specific type of regulation applied for green energy subsidy.

According, for example, to German renewable energy law, it is allowed to sell the gross electricity production to the grid at a subsidized rate and buy back the own consumption of the plant at market value. Under different regulations valid in countries such as Italy, for instance the additional consumption directly connected with electricity production or even the whole plant own consumption of the cogeneration plant are detracted from the gross electricity production and the remaining part may be sold to the grid at subsidized tariff.

Thus, in order to avoid the analysis of all specific different cases and to show results with general validity, an “Equivalent Electricity Value” has been defined.

In Appendix 2 this parameter is defined in detail and a calculation example is reported.

- Cost of biomass

The cost of biomass is another very significant parameter influencing the feasibility of a cogeneration plant in the pellet industry.

Within a CHP plant the belt dryer has lower thermal efficiency than in the reference cases, due to the selected hot water temperature available downstream the ORC condenser. This fact leads to have an additional biomass consumption that is relevant leading to a strong influence of the biomass cost on the feasibility of the plant.

Furthermore, in the case of the CHP plant, an extra fuel consumption of about 20% has to be taken into account for the electric power generation as well.

- Yearly full load operation hours

Due to the high investment costs, pellet plants are usually run at constant output during the whole year. Therefore, in all calculations of this study, a safely assumed full load operation time of 7500 h / year has been assumed. The sensitivity of the economic results depending on the variation of this parameter has not been investigated.

- Discount rate

In addition, the figure assumed for discount rate in the feasibility study also influences financial results. The present economic analysis has been based on the assumption to consider a constant value of discount rate equal to 5%.

3.3 Influence of electricity value and plant size on economic feasibility of the CHP unit (Fuel cost 10 Euro/MWh)

The Financial results are calculated in terms of discounted Pay Back Time of the additional investment required by the cogenerative solution. In this paragraph the sensitivity of the results to variations in plant size and electricity value is investigated.

The following boundary conditions are assumed:

- constant fuel cost (biomass) :10 Euro/MWh;
- Equivalent Electricity Value variable between 0,10 and 0,24 Euro/kWh_{el};
- ORC size: from T200 to T2000 (about 1 – 10 t/h pellet production);
- constant hot water feed temperature to belt dryer: 90°C.

The assumed biomass costs (10 Euro/MWh) can be considered as a moderate fuel cost which may be common for countries with low electricity value markets or for low quality fuel (for instance bark) in high electricity value markets.

The comparisons show that the payback time is strongly influenced both by the Equivalent Electricity value and by the size effect, due to higher specific investment costs for small units. The financial results are significantly better if a belt dryer is used as reference case for the heat only plant but, for several actual market conditions, a good feasibility is also obtained if a direct rotary dryer is used as reference case.

First of all, the differential economic feasibility for equivalent electricity values above 0,16 Euro/kWh_{el} is discussed. This scenario corresponds to markets where regulations for supporting electricity production from biomass are applied.

This is actually the case of Belgium, Germany, Italy, United Kingdom and Spain (for certain types of burned Biomass). New laws providing for an electricity value above 0,16 Euro/kWh_{el} are expected soon also in Austria and Switzerland.

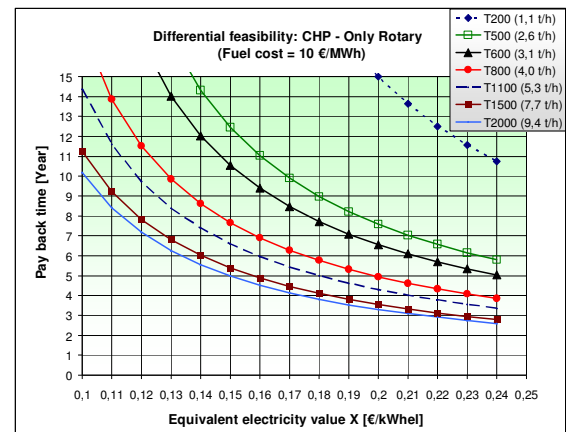


Fig. 5 Discounted Pay Back Time of the additional investment cost of a cogeneration system compared to a direct Rotary dryer as a function of electricity value and plant size

Under these conditions, cogeneration plants with a power range starting from 800 kW_{el} (pellet output > 4 t/h) are feasible regardless of the technical solution considered as reference case for drying energy supply (discounted PBT under 7 years and IRR > 15% for 15 years compared to direct rotary dryer). Plants in the power range of 600 kW_{el} (pellet output about 3 t/h) might be interesting for electricity values around 0,20 Euro/kWh_{el} (i.e. in Italy, Germany or Belgium) or if indirect air drying with a belt dryer is assumed as reference technology for a heat only plant.

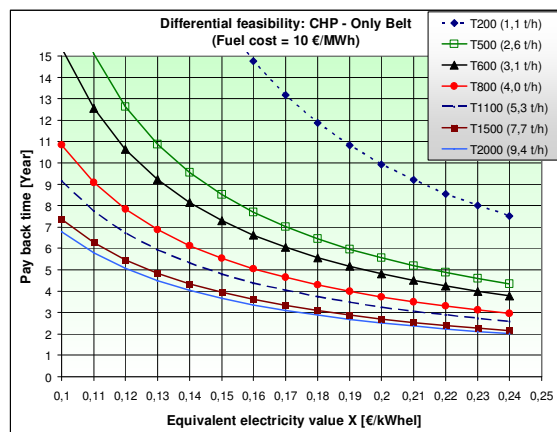


Fig.6 Discounted Pay Back Time of the additional investment cost of a cogeneration system compared to an indirect Belt dryer as a function of electricity value and plant size

Larger plants, with an installed power above 1500 kW_{el} (pellet output > 7,7 t/h), can be an economically interesting solution starting from an equivalent electricity value of 0,11 – 0,12 Euro/kWh_{el} depending on the technology considered as reference case for the heat only plant. This means that this solution can be considered profitable also in countries with lower support for electricity production from biomass.

The solution based on the Turboden T200 unit (about 200 kW_{el} and pellet production about 1 t/h) is not economically competitive under any realistic frame condition to the relevant economy-of-scale-effect.

Thus, in the following charts, T200 solution has not been considered.

3.4 Influence of electricity value and plant size on economic feasibility of the CHP unit (Fuel cost 20 Euro / MWh)

In the countries where electricity value is high due to relevant support schemes for green electricity generated from biomass, fuel cost tends to become much higher. For this reason the previous analysis has been repeated with higher fuel cost (20 Euro/MWh).

The following boundary conditions are assumed:

- constant fuel cost (biomass): 20 Euro/MWh;
- Equivalent Electricity Value variable between 0,10 and 0,24 Euro/kWh_{el};
- ORC size: from T200 to T2000 (about 1 – 10 t/h pellet production);
- constant hot water feed temperature to belt dryer : 90°C.

In **Fig.7** and **Fig.8** only data limited to equivalent electricity values for which this scenario can be realistic (equivalent electricity value above 0,16 Euro/kWh_{el}) are depicted. It has to be noted that biomass costs at this level will strongly impact the economic feasibility of the biomass based heat only solutions assumed as reference case.

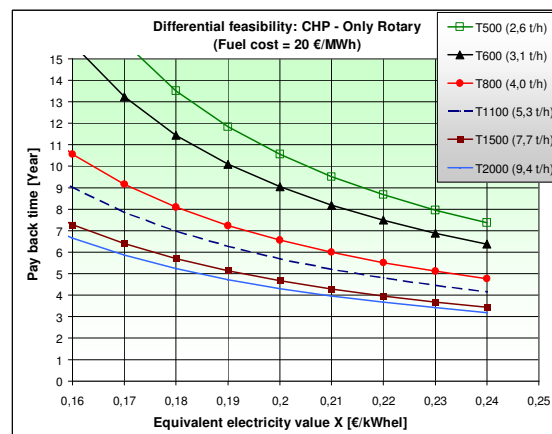


Fig. 7 Discounted Pay Back Time of the additional investment cost of a cogeneration system compared to a direct Rotary dryer as a function of electricity value and plant size

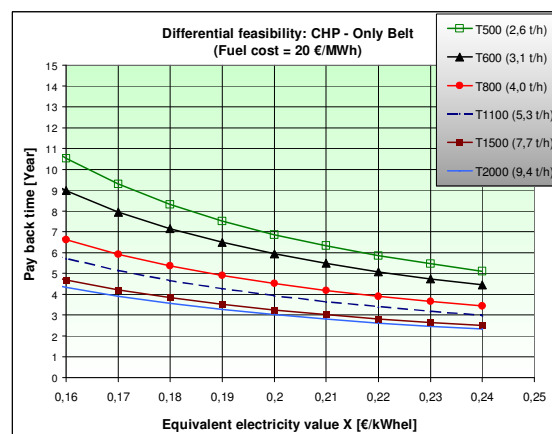


Fig. 8 Discounted Pay Back Time of the additional investment cost of a cogeneration system compared to an indirect Belt dryer as a function of electricity value and plant size

The results show that also in this difficult scenario plants with installed power above 1500 kW_{el} exhibit a good feasibility regardless of the technical solution for the dryer considered as reference case for the heat only plant (discounted PBT about 7 years and IRR about 15% for 15 years compared to the direct rotary dryer).

For equivalent electricity values around 0,20 Euro/kWh_{el} also plants in power range starting from 800 kW_{el} remain economically competitive. The higher fuel price has a strong impact on smaller plants in the power range around 500-600 kW_{el} that can be considered competitive only if indirect air drying with a belt dryer is assumed as reference technology for the heat only plant.

3.5 Influence of electricity value and biomass cost on economic feasibility of a T1500 - CHP unit

The previous analysis has shown that starting from a pellet output of about 8 t/h (installed power above 1500 kW_{el}) the installation of a cogeneration plant based on ORC technology becomes an economically interesting choice for a wide range of frame conditions. Therefore the sensitivity of the economic results to variations in fuel cost is analyzed more in depth for a system based on the T1500 – CHP unit.

The following boundary conditions are assumed:

- Fuel cost (biomass) variable between 0 and 20 Euro/MWh;
- Equivalent Electricity Value variable between 0,10 and 0,24 Euro/kWh_{el};
- ORC size: T1500 (7,7 t/h pellet production)
- constant hot water feed temperature to belt dryer: 90°C

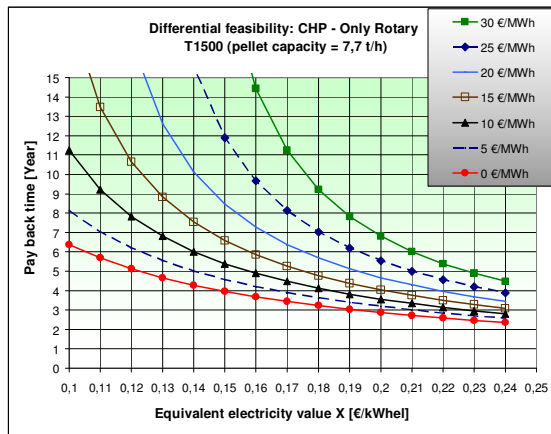


Fig. 9 Discounted Pay Back Time of the additional investment costs of a cogeneration system compared to a direct Rotary dryer as a function of electricity value and fuel cost

The table shows clearly that the differential economic feasibility of is very sensitive to the fuel costs at low equivalent electricity values, while the impact is relatively limited at high equivalent electricity values.

It is interesting to note that, at an equivalent electricity value of about 0,20 Euro/kWh_{el} (i.e. German or Italian frame conditions) the feasibility is excellent for a high fuel cost of 20 Euro/MWh (discounted PBT of the additional investment under 5 years and IRR > 23% for 15 years). Even in case of a fuel cost increase of 50% (from 20 Euro/MWh up to the very high value of 30 Euro/MWh), feasibility remains acceptable (discounted PBT of the additional investment under 7 years and IRR > 15% for 15 years). Fuel costs in this range are comparable to the costs of natural gas in many European countries; therefore, this would lead to negligible additional cash flow of the direct contact dryer based on biomass as fuel compared to the less expensive system based on a natural gas burner. The CHP unit exhibits a good pay back also under this frame conditions and, therefore, it can be considered a good solution for limiting the plant owners risk connected with fluctuations of biomass costs in countries with high electricity value.

At equivalent energy values of 0,10–0,12 Euro/kWh_{el}, a reduction of fuel cost below the average value of 10 Euro / MWh typical in low electricity value markets has a very positive impact on the feasibility of a cogeneration system. For example at an equivalent electricity value of 0,10 Euro/kWh_{el} the discounted payback time of the additional investment is of about 8 years for a fuel cost of 5 Euro/MWh. If fuel with no cost can be used the feasibility is even better with a discounted PBT of about 6,5 years (IRR > 16% for 15 years). This values could be obtained by using lower quality fuels as for example recycled wood, green cuttings or dried sewage sludge.

In fact the results in this case would be influenced by two variations in economic parameters that have not been accounted for. This solution is depending on the availability of suitable biomass boilers with reliable operation and good emission levels. For this type of boilers higher investment costs have to be considered that will have a negative impact on the feasibility of the CHP unit.

On the other hand the assumed reference case with direct dryer is limited to the use of higher quality fuels in order to avoid contamination of the dried sawdust. This different costs fuel costs for the reference case would lead to a better feasibility of the CHP unit. From this point of view the comparison with a reference case based on a hot water boiler and an indirect belt dryer that has the same capabilities in terms of possibility of burning lower quality fuel as reported in Figure 10 more correct.

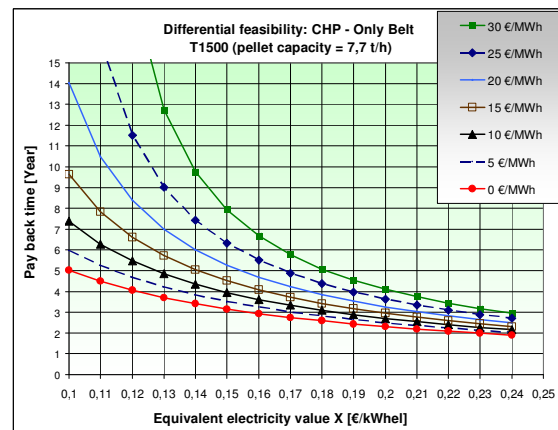


Fig. 10 Discounted Pay Back Time of the additional investment costs of a cogeneration system compared to a Belt dryer as a function of electricity value and fuel cost

For example comparing to an indirect belt dryer the discounted PBT is under 6 years (IRR > 18 % for 15 years) for a fuel cost of 5 Euro/MWh and an electricity value of 0,10 Euro/kWh_{el}.

In fact, according to the recent trend for electricity rates, in a medium term scenario market rates of 0,10 – 0,12 Euro/kWh_{el} for electricity bought from the grid by an average industrial user are realistic. Therefore, for a cogeneration system based on the T1500 unit and designed in order to cover the electrical own consumption of the pellet plant, the profitability of the investment can be good also in countries where

electricity production from biomass is not subsidized.

3.6 Influence of hot water feed temperature on economic feasibility of different CHP units with the same pellet production

A very important parameter in the technical and economic optimization of the cogeneration system is the hot water feed temperature to the belt dryer. This parameter has been fixed at 90°C in the previous calculations as reported in the paragraph resuming the assumptions.

This parameter directly influences the temperature of the drying air (thus the dryer efficiency) and the electric efficiency of the ORC unit. Higher water temperatures cause higher drying efficiency but lower electric efficiency. Lower water temperatures cause the opposite. The assumptions concerning the influence of hot water feed temperature on the electric efficiency of ORC and belt dryer are reported in Appendix 1 .

Therefore, this parameter is very effective in changing the ratio between electric power generation and pellet production. This means that the electric power at constant pellet production can be changed to a certain extent depending on the frame conditions. This can be useful in plants operated under market conditions in order to cover mainly the own consumption of the plant with the cogeneration system. This means that the average value of the produced electric energy is higher due to the that the buying rate from the grid is significantly higher than the selling rate to the grid. Another criteria for the optimization of the water temperatures can be the relative importance of electric and thermal efficiency depending on the value of electricity and fuel cost.

An example of the possible design conditions of ORC units, varying hot water temperature, is resumed in the following table (Fig. 12) where two family of curves are represented:

- The first one is characterized by the thermal power supplied by different sizes ORC units to belt dryers at different water feed temperatures, considering to keep the thermal input power constant at the nominal values of standard Turboden units;
- The second family of curves represents the thermal power required by the drying process for different pellet production capacities, at different water feed temperatures.

Any match between these different families of curves represents a possible working point in completely heat driven operation. For example, in the following table the red circles highlight the operating points assumed in previous calculations with hot water temperature 90°C, for ORC units with frames from T800 to T2000.

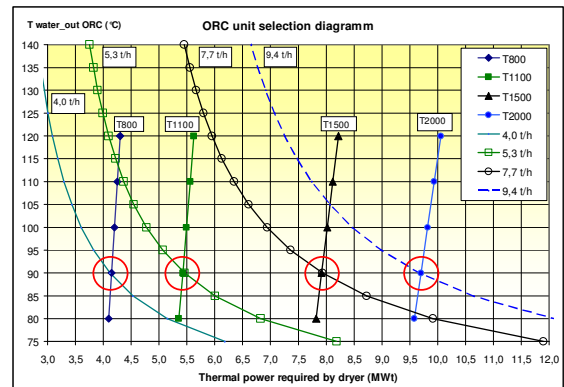


Fig. 11 Design points of cogeneration systems based on Turboden standard ORC units at 90°C water temperature (sizes from T800 to T2000)

The influence of changing water temperatures on the electric power production of a heat driven plant coupled to a pellet production process with 7,4 t/h pellet production is shown in the following table.

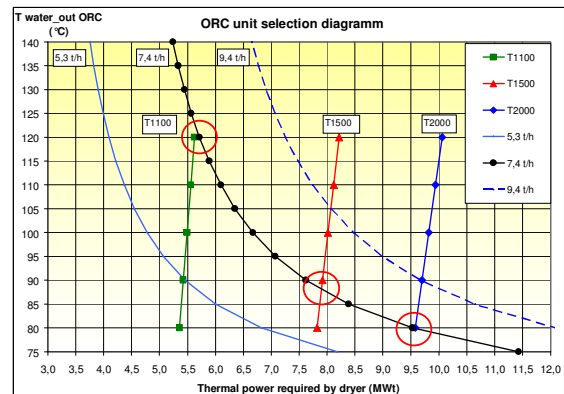


Fig. 12 Possible design points of a cogeneration plant with 7,4 t/h pellet production coupled to different frames of standard Turboden ORC units

The figure shows that, for a pellet capacity of 7,4 t/h, standard ORC units with frames between T2000 (at hot water feed temperature of 80°C) and T1100 (at hot water feed temperature of 123°C) can be used for this plant. In fact due to the fact that the efficiency of the ORC unit is strongly influenced by the water feed temperature (see Appendix 1) the net electric power from the selected ORC units at nominal thermal input power varies as follows:

- T1100 (at 123°C feed temperature) = 930 kWel c.a.
- T1500 (at 88°C feed temperature) = 1695 kWel c.a.
- T2000 (at 80°C feed temperature) = 2200 kWel c.a.

This means that, varying the temperature of hot water supplied by ORC units, the electric power of the cogeneration system can be adjusted during the engineering phase in a ratio of more than 2 in order to be adapted to the specific frame conditions of any single project.

The overall thermal efficiency of the drying process can also be varied approximately in a range between 40 % (@80°C water feed temperature) and 68 % (@123°C water feed temperature) .

From an economic point of view the solution with higher water feed temperatures has the advantage of lower biomass costs caused by the higher thermal efficiency of the drying process. Solutions with lower hot water feed temperatures have the advantage of higher revenues from electricity production as a consequence of the higher electric efficiency.

The economic feasibility of the solutions reported above at different values of fuel cost and average electricity value. The following boundary conditions have been assumed :

- Fuel cost (biomass) 20 Euro/MWh (Figure 13) and 10 Euro/MWh (Figure 14);
- Equivalent Electricity Value variable between 0,10 and 0,24 Euro/kWh_{el} ;
- ORC size: T1100 – T2000
- Hot water feed temperature to belt dryer 80°C (T2000) – 123°C (T1100)
- Pellet production 7,4 t/h

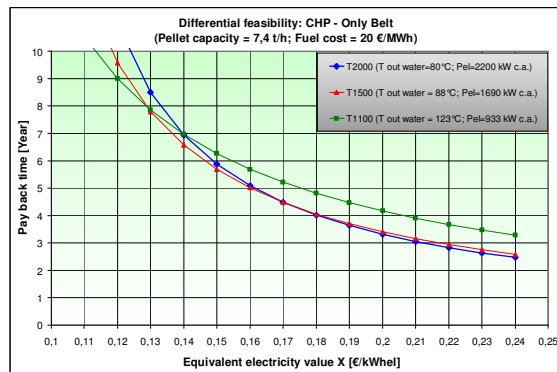


Fig. 13 Pay Back Time of the additional investment costs of a cogeneration system compared to a Belt Dryer as a function of electricity value and hot water feed temperature (Fuel cost = 20 Euro/MWh)

For fuel cost of 20 Euro/MWh typical for high electricity value countries the system based on a T1100 unit with 123°C hot water feed temperature has the best feasibility for electricity values under 0,13 Euro/kWh_{el}. Between 0,13 and 0,17 Euro/kWh_{el} the solution with about 90°C hot water feed temperature prevails. For electricity values above 0,17 Euro/kWh_{el} the solution based on the T2000 unit with 80°C water feed temperature has slightly better pay back time.

In Figure 14 the same comparison is repeated with a moderate fuel cost of 10 Euro/MWh . In this case the influence of the thermal efficiency is much lower. This leads the solution with 80°C to be the best from economic point of view for all electricity values above 0,09 Euro/kWh_{el}.

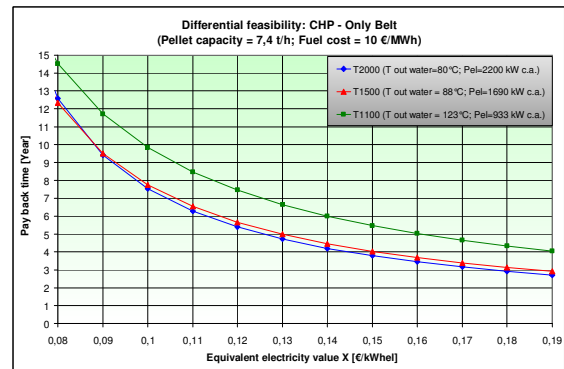


Fig. 14 Pay Back Time of the additional investment costs of a cogeneration system compared to a Belt Dryer as a function of electricity value and hot water feed temperature (Fuel cost = 10 Euro/MWh)

This results are in good accordance with the experience of the existing reference plants where a hot water feed temperature in the range around 90°C is the historical standard. In Germany, where the electricity value is particularly high, a tendency towards lower hot water feed temperatures is observed. The last chapter of this paper is dedicated to the operational experience of the first ORC plant in the pellet industry operated with 80°C feed temperature.

4 THE REAL CASE OF THE PLANT IN MUDAU

In Autumn 2005 decision to build a new pellet plant in Mudau (Germany) was taken. The company investing in the pellet plant is a newco founded by 3 partners that were running different business activities and wanted to diversify with an investment in the Bioenergy sector. The plant buys most of the sawdust and fuel (mainly bark) for the energy plant from a sawmill located just beside the pellet plant under a long term purchase agreement. It was decided to use a belt dryer and a cogeneration plant based on a thermal oil boiler and Turboden ORC unit for drying the wet sawdust up to the moisture content of about 10% required for the pellet production process. The investment cost for the complete plant was about 11 Million Euro. The maximum design pellet production is 6t/h. According to the local renewable energy law (Erneuerbare Energien Gesetz) the feed in tariff is about 0,16 Euro/kWh_{el}.

The plant optimization regarding the hot water temperatures under the local frame conditions led to selection nominal temperatures of 60/85°C in the hot water loop supplying the process heat to the belt dryer .

The nominal Data of the ORC unit are the following:

- Total input power from Thermal oil : 6570 kW
- Gross electric power : 1187 kW_{el}
- Net electric Power : 1124 kW_{el}
- Thermal power to hot water : 5335 kW
- Hot water temperatures : 60/85°C
- Net electric efficiency : 17,1 %

After the startup of the plant, a further optimization during actual operation of the plant has shown that it is economically more advantageous to operate the plant at

lower hot water temperatures (feed temperature at about 80°C) [4]. An overview of the main operational data of the cogeneration plant, as recorded by the local supervision system during the period between January and April 2008, is reported in the following table together with some calculated figures [5].

	Jan.	Feb.	Mar.	Apr.
Operation hours Max.	744	696	744	720
Operation hours ORC	731	675	738	718
Overall availability plant	98,3%	97,0%	99,2%	99,7%
Electricity production ORC [MWh _{el}]	914	843	923	905
Thermal energy production ORC [MWh]	3.642	3.332	3.641	3.553
Average gross electric power ORC [kW _{el}]	1.251	1.250	1.250	1.260
Average own consumption [kW _{el}]	50	50	50	50
Average net electric power ORC [kW _{el}]	1.201	1.200	1.200	1.210
Average thermal power from ORC [kW]	4.982	4.936	4.935	4.948
Average gross electric efficiency ORC	19,8%	20,0%	20,0%	20,1%
Average net electric efficiency	19,0%	19,2%	19,2%	19,3%

The recorded Data show that the cogeneration unit has operated in a very satisfactory way with an overall cogeneration plant availability (ORC + Boiler) that has exceeded 98%. The average net electric efficiency of the ORC unit has been 19,2 % which is substantially higher than both the contractual data (17,6%) and the assumptions of this study (18,1%), corrected taking into account the difference in cooling water temperatures (assuming an electric efficiency variation of 1% for every 10°C change water feed temperature, as described in Appendix 1: Electric Power Generation) .

Also the main technological data of the belt dryer have been continuously logged. The plant is operated with the following main technological data :

Water feed temperature to dryer: 80° - 81° C
 Water return temperature from dryer: 60° - 61° C
 Hot air temperature after heating zone: 71° - 73° C
 Hot air temperature after drying zone : average 35° C
 Wet sawdust moisture content : 35% - 55%
 (average about 45 %)
 Dry sawdust moisture content : 10 – 11%
 Material flow : 35 – 60 m³/h
 Average electricity consumption dryer: 127 kW
 Average electricity consumption feed system: 24 kW

The main recorded monthly energy flows are the following:

	Jan.	Feb.	Mar.	Apr.
Thermal power to dryer [kW]	3.596	3.808	3.606	3.534
Dry material output [t]	3.600	3.597	3.861	4.102
Average dry material production [t/h]	4,9	5,3	5,2	5,7
Average heat consumption for drying [MWh/ton dry material]	1,00	1,06	0,93	0,86

The variation in the average heat consumption per ton dry material can be easily explained with a seasonal variation of the humidity of the wet sawdust. According to the data the highest average moisture content was in February and the lowest in April. Assuming an average moisture content of the wet sawdust of 50% in February and of 45% in April and an average outlet moisture content of 10% the calculated average energy consumption per ton of evaporated water is 1,17 MWh/t in April and 1,18 MWh/t in February. Also this drying efficiencies are substantially better than the values assumed in this study (1,2 MWh/t @90°C water feed temperature 1,57 MWh/t @80°C). This is mainly due to the air temperature at drying zone outlet that is much lower than the value assumed in this study (35°C compared to 50°C). The assumptions on the moisture content are confirmed by measurements taken in the relevant periods by the operator of the plant. On the 23th of May the cogeneration plant had reached a total of 13.550 operation hours since startup of the plant in October 2006 corresponding to an annual operation time of more than 8.500 hours per year.

The results of this first period of operation show the feasibility and reliability of the proposed concept based on a thermal oil boiler and Turboden ORC unit for cogeneration of electricity and heat and on a belt dryer for sawdust drying with 80°C hot water feed temperature. The average operation data exceed the technical performances assumed in this study .

5 Conclusions

The economic analysis performed in this paper shows that the installation of cogeneration units based on thermal oil boilers and Turboden ORC units coupled with indirect belt dryers as heat suppliers for pellet plants is an economically interesting option under a broad range of frame conditions.

Plants starting from 4 t/h pellet production can be economically competitive starting from an electricity value of 0,16 Euro/kWh_{el} (see Figure 6) Even more important is the fact that, due to the additional incomes from electric energy generation, this solution reduces the risk connected with increased biomass costs, being able to generate positive cash flows at much higher fuel costs than the heat only solution. These frame conditions are actually present in many European countries where new pellet production capacity is under construction

(Germany, Austria, Italy, Belgium and UK , etc) .

For a pellet plant size above 8 t/h, a cogeneration plant may be a good solution for covering the own consumption of the pellet plant also in countries where no support schemes for renewable energy production are implemented, especially if fuel at negligible cost can be used. In this case the feasibility is good starting from electricity values in the range of 0,10 Euro/kWh_{el} which can be considered a long term average buying rate for industrial customers in many countries in the world. In particular, this gives excellent medium term application opportunities for new plants in Eastern Europe, Russia and North America.

The frame conditions described above apply to a big share of the new production capacities planned worldwide both concerning economical conditions (electricity value and biomass cost) and plant size.

The available operational data confirm that the actual process efficiencies are even higher than the figures assumed in this study.

6 Acknowledgments

The Authors wish to thank Mr. Grimm from Bioenergie Mudau for his collaboration in sharing the experience and operational data of the pellet plant in Mudau (Germany).

7 References

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APPENDIX 1: Definition of technical features.

In addition to the figures resumed in previous **Table 1** and **Table 2**, the main technical features are following defined:

(1) Combustion system

Thermal oil boiler efficiency: ratio between thermal power at thermal oil and thermal power at biomass furnace.

Hot water boiler efficiency: ratio between thermal power at water and thermal power at biomass furnace

Hot gas boiler efficiency: ratio between thermal power at flue gas and thermal power at biomass furnace.

Specific boiler own consumption : ratio between electrical own consumption of Boiler and thermal power supplied to dryer (in form of thermal oil/water or flue gas depending on boiler type)

Boiler own consumption: this figure takes into account electric power necessary for boiler operation such as:

- biomass feed device
- combustion vibrating grate
- combustion air fans
- exhaust gas extractor group
- heat transfer medium pumping (i.e. hot water, thermal oil)
- automatic ash disposal etc.

(2) Drying process

Drying efficiency: ratio between thermal power required by a theoretical evaporation and actual thermal power required by dryer.

Considering the specific heat capacity of the drying air to be constant during the drying process and neglecting the heat losses during the drying process, the drying efficiency can be calculated by the following simplified formula :

$$\eta_{drying} \equiv \frac{T_{IN} - T_{OUT}}{T_{IN} - T_{amb}}$$

where :

T_{amb} : ambient air temperature

T_{IN} : air/flue gas temperature at drying zone inlet

T_{OUT} : air/flue gas temperature at drying zone outlet

In particular, since paragraph 3 of the present study has been focused on an economic optimization of the CHP system (based on ORC plus belt dryer) with different inlet belt dryer water temperature, herewith some specific assumptions concerning belt drying process are resumed:

T_{IN} = hot water feed temperature – 10°C

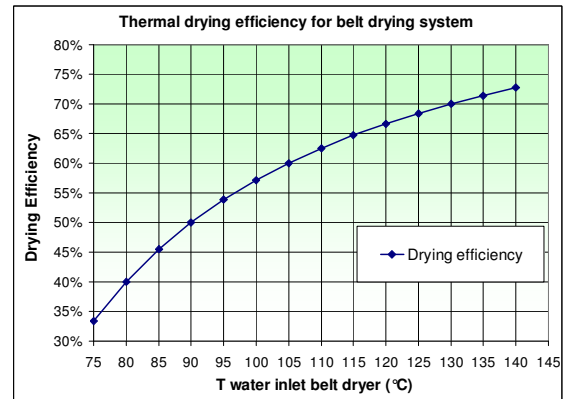
T_{OUT} = 50°C (constant)

T_{amb} = 20°C

The next Figure shows the drying efficiency, depending on water temperature at belt dryer inlet, calculated with the assumptions described above :

According to the adopted simplified calculation, a drying efficiency of 50% with hot water feed temperature of 90°C is obtained. This efficiency value is realistic if it is

compared to the technical data reported by belt dryer manufacturers.



(3) Electric power generation

ORC net electric efficiency: ratio between net electric power generated by ORC unit and thermal power inlet ORC from thermal oil.

The net electric efficiency of the ORC unit with water temperatures outlet ORC different from 90°C has been assumed to change according to the following formula :

$$\eta_{net_el}(T_x) = \eta_{net_el}(90^\circ C) - 1\% \times \frac{(T_x - 90)}{10}$$

Where:

$$\eta_{net_el}(90^\circ C) \cong 17\%$$

APPENDIX 2: Definition of the Equivalent Electricity Value (EEV).

The additional cash flow of a CHP plant compared to a heat only reference plant, considering only the additional energy flows which depend on electric power (due to CHP electricity production and additional plant own consumption) can be described by the following linear equation:

$$\Delta CashFlow_{el} = \sum_1^n (\Delta P_i \times V_i)$$

where:

ΔP_i = additional electric power flow

V_i = value of additional electric power flow [Euro/kWh_{el}]

In order to avoid the analysis of all specific cases depending on the different regulations applied in the various countries, thus with the aim to show results with general validity, an "Equivalent Electricity Value" has been defined as following (2):

$$\Delta CashFlow_{el} = \sum_1^n (\Delta P_i \times V_i) \equiv X \times \left[\sum_1^n (\Delta P_i) \right]$$

Therefore, the Equivalent Energy value X is defined as:

$$X \text{ [€/kWh}_{el}] \equiv \frac{\sum_1^n (\Delta P_i \times V_i)}{\left[\sum_1^n (\Delta P_i) \right]}$$

In the present paper, the previous formula has been actually applied in the following reduced form (n = 4):

$$X \equiv \frac{\sum_1^4 (\Delta P_i \times V_i)}{\left[\sum_1^4 (\Delta P_i) \right]}$$

or, in an equivalent way:

$$X \equiv \frac{(P_1 \times V_1) - \sum_2^4 (\Delta P_i \times V_i)}{\left[P_1 - \sum_2^4 (\Delta P_i) \right]}$$

where:

P_1 ORC gross electric power

P_2 ORC own consumption

P_3 Boiler own consumption

P_4 Dryer own consumption

V_1 Value of gross electricity produced by CHP unit
(including possible subsidy for renewable energy sources)

V_2 Value of CHP unit own consumption

V_3 Value of additional boiler own consumption

V_4 Value of additional dryer own consumption

$\Delta P_1 = P_1$

$\Delta P_2 = P_2$

$\Delta P_3 = P_3$ (CHP plant) - P_3 (Heat only plant)

$\Delta P_4 = P_4$ (CHP plant) - P_4 (Heat only plant)

Therefore, if a cogeneration plant for instance with a gross power of 1760 kW_{el} in Germany gets a feed in tariff of 0,18 Euro/kWh_{el} and has a overall additional own consumptions ($\Delta P_2 + \Delta P_3 + \Delta P_4$) of 330 kW_{el}, considering an average cost of 0,10 Euro/kWh_{el} for the energy bought from the grid, the equivalent electricity value will be: $X = 0,197$ Euro/kWh_{el}.