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Computational Tool for Techno-Economical Evaluation of Steam/Oxygen Fluidized Bed Biomass Gasification Technologies

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Abstract**—**The paper presents a computational tool developed for the evaluation of technical and economic advantages of an innovative cleaning and conditioning technology of fluidized bed steam/oxygen gasifiers outlet product gas. This technology integrates into a single unit the steam gasification of biomass and the hot gas cleaning and conditioning system. Both components of the computational tool, process flowsheet and economic evaluator, have been developed under IPSEpro software. The economic model provides information that can help potential users, especially small and medium size enterprises acting in the regenerable energy field, to decide the optimal scale of a plant and to better understand both potentiality and nits of the system when applied to a wide range of conditions.

Keywords**—**biomass, CHP units, economic evaluation, sification.

I. INTRODUCTION

BIOMASS, one of the renewable resources that could play an important role in the energy production, could be the asis of electricity generation and heating production for dustrial facilities and homes [1]. The main thermochemical omass conversion method is gasification [1], [2]. During the ears, a lot of gasification technologies have been developed, e differences arising from the type of reactor used: fixed bed, uidised bed, moving bed gasifier and reactor of special sign (two-stage-gasifiers, cyclonic reactors, vortex reactors, c.) [3]. Regarding technological performances, fix bed and oving bed gasifiers are producing a syngas with important antities of tar or/and char while product gas of fluidised bed sification systems is more suitable from both composition d environmental impact points of view.

In terms of successful industrial applications, CHP units sed on dual fluidized bed gasification (DFB) are in operation from the beginning of years '2000 (Gussing, Austria – 2002, Oberwart - 2009) [4], [5]. In the case of DFB process (known also as fast internally circulating fluidized bed – FICFB process), steam is used as fluidization agent in the gasification reactor and the necessary heat for the endothermic reactions is transferred through a circulating hot bed material coming from a second fluidized bed reactor where the bed material is heated up by the combustion of the residual char. An alternative to FICFB process in producing syngas of comparable quality is steam/oxygen bubbling fluidized bed process (BFB): in this case, both oxygen and steam are used as gasification agents, heat for the endothermic reactions being obtained by partial combustion of biomass.

A focal point in the improvement of fluidized bed gasification technologies is linked to gas cleaning systems used to reduce tar and particulate in the product gas. An innovative idea in this field was recently founded by EU through FP7 Framework Programme: catalytic ceramic candles are inserted in the freeboard of the fluidized bed gasifier for both particulate removal and hydrocarbons content drastic reduction in the product gas [6]. FP7 UNIQUE project ("Integration of particulate abatement, removal of trace elements and tar reforming in one biomass steam gasification reactor yielding high purity syngas for efficient CHP and power plants", www.uniqueproject.eu) aims to a compact version of a gasifier by integrating the fluidized bed steam gasification of biomass and a hot gas cleaning and conditioning system in one reactor vessel. One of the outputs of the project is the set-up of a computational tool developed to help potential users to evaluate technical and economic advantages of the UNIQUE technology. A comprehensive simulation tool based on process flow sheet calculation was set up for describing the gasification process. The tool is on-line available (via link through Unique homepage) with open access for potentially users. The process flow sheet tool involves the case of dual fluidized bed gasification (DFB) and bubbling fluidized bed process (BFB), the latter is available for the economic calculator. Both major components of the computational tool, process flowsheets and economic calculator, have been developed under IPSEpro simulation software (SIMTECH, Simulation Technology – Graz, Austria).

II. PROCESS FLOWSHEETS

For implementing product gas cleaning and conditioning system developed through UNIQUE project, an internally circulating fluidized bed gasifier (based on steam/oxygen gasification, 1 MWth fuel power) located at Trisaia research centre of ENEA is intended to become novel technology prototype. A compact version of the gasifier will be obtained by integrating the fluidized bed steam gasification of biomass and UNIQUE project hot gas cleaning and conditioning

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system into one reactor vessel (fig. 1).

This is possible by:

- placing a bundle of catalytic ceramic candles that operate at a temperature as high as the gasification temperature (800-850°C) in the gasifier freeboard;
- using a catalytically active mineral substance for primary tar reforming;
- optimising the addition of sorbents into the bed for removal of detrimental trace elements.

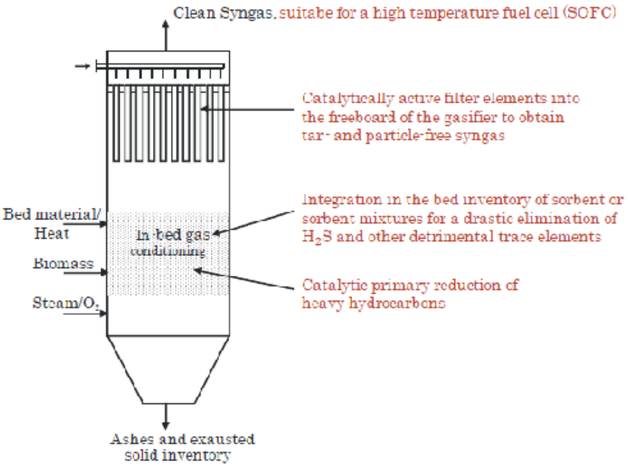


Fig. 1 UNIQUE gasifier

In the modeling of the prototype gasifier and the velopment of CHP units flowsheet, the new PGP_Lib yrolysis and Gasification Process Library) of IPSEpro ftware has been used. In this library, models for the basic it operations usually involved in the biomass conversion to ngas/energy chains are available [7]. As for other IPSEpro raries, Unit models can be edited/modified by the user and w models can be included in the library through the Model evelopment Kit, an independent application for editing and eating models. Process flowsheets are created using Process mulation Environment (PSE), a graphical interface for ilding-up process schemes, entering data (settings, rameters), etc. Unit models equations and the structural formation from the PSE flowsheet are integrated into a stem of equations which is solved using a multi-dimensional ewton-Raphson algorithm with analytical determination of the Jacobian matrix [8].

The process flowsheet of UNIQUE prototype inside IPSEpro package is shown in fig. 2. Cleaning and conditioning system is modelled by using a separator and a new unit, a reformer, which has been added to the PGP_lib for accounting for tar and methane steam conversion taking place when raw product gas is passing through the candles system. Because of the endothermic reactions taking place in the reformer (catalytic candles), the temperature in the freeboard is different from the fluidized bed zone temperature. On the other side, heat exchange is taking place between gasifier zones: a shaft connection has been implemented between the two main units of the gasifier for allowing the tuning of simulation results for reaching plant data.

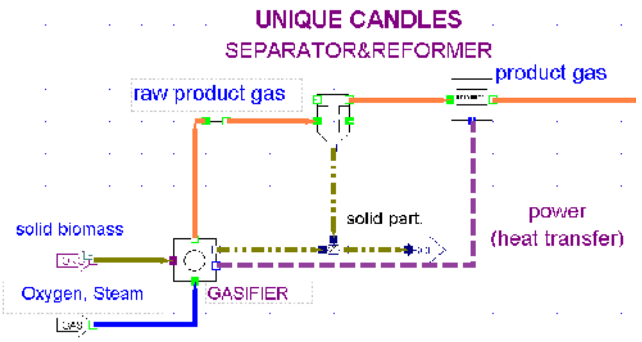


Fig. 2 Process flowsheet of UNIQUE prototype inside IPSEpro package

Gasifier outlet streams (raw product gas, ash, dust, tar) mass flow rates and compositions are calculated through mass balances and correlations for reaching experimental data. In the case of reformer, a quasi-equilibrium approach has been adopted for steam reforming reaction in order to meet product gas composition: reaction temperature (different from reformer real temperature), has been tuned to meet experimental data.It is to be mentioned that the results presented here are based on experimental data obtained at pilot plant scale (UNIQUE prototype is not yet in operation).For small and medium size capacities (below 10 MW fuel power), gasifier product gas conversion in energy can be realized using different equipments. As example, a process flowsheet incorporating a steam/oxygen gasifier, UNIQUE cleaning system and a gas engine is presented in the fig. 3.Because of low water content of the biomass (almond shell), biomass drying operation has been omitted. The flowsheet is available from UNIQUE project web page under the link:

- Gasifier – UCS – Gas engine (biomass – almond shells):

http://www.processweb.net/demos/UNIQUE/PSWeb_UNIQUE_GE.php

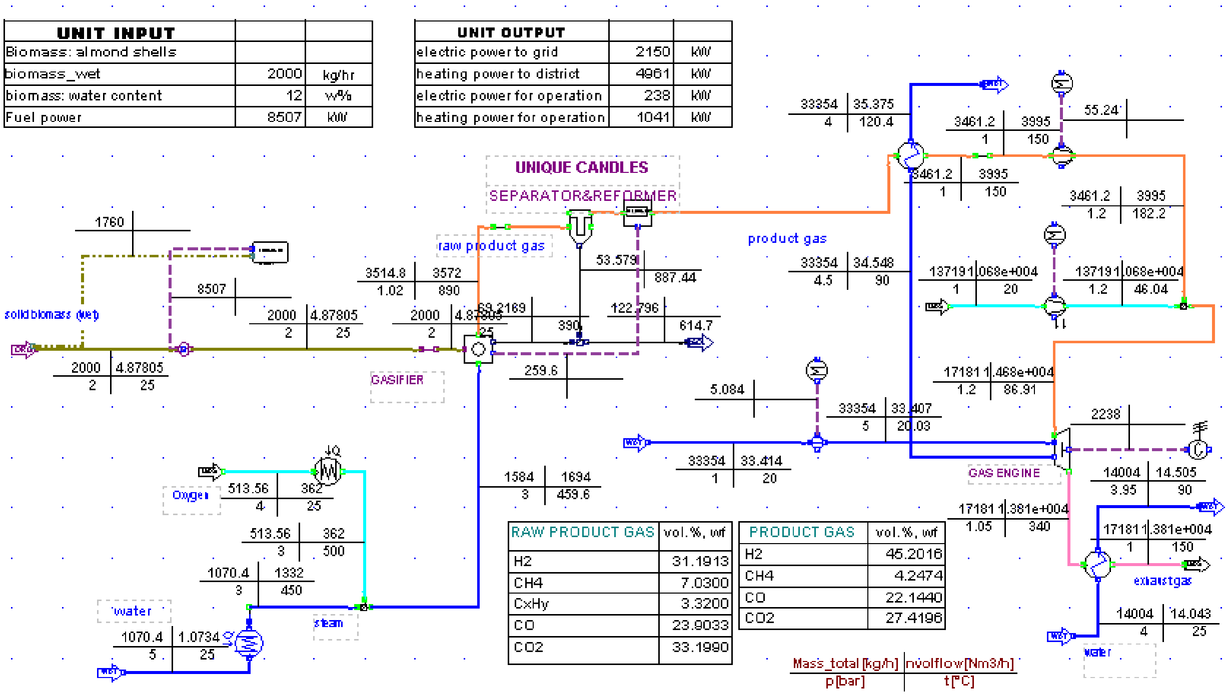
From the same page, a flowsheet including an Organic Rankine Cycle can be accessed and run:

- Gasifier – UCS – Gas Engine – Organic Rankine Cycle (biomass: almond shells):

http://www.processweb.net/demos/UNIQUE/PSWeb_UNIQUE_GE_ORC.php

III. ECONOMIC MODEL

For the commercialization of a new technology, it is essential to know whether the technology is economically viable or not. Therefore, in this study an economic model has been developed in order to make an economic analysis of UNIQUE technology.The economic model is based on the estimation of the following standard accounting items: *total plant investment costs*, *operating costs* and *annual cash flows.*



UNIT INPUT		
Biomass: almond shells		
biomass_wet	2000	kg/hr
biomass: water content	12	w%
Fuel power	8507	kW

UNIT OUTPUT		
electric power to grid	2150	kW
heating power to district	4961	kW
electric power for operation	238	kW
heating power for operation	1041	kW

RAW PRODUCT GAS	vol.%, wf
H2	31.1913
CH4	7.0300
CxHy	3.3200
CO	23.9033
CO2	33.1990

PRODUCT GAS	vol.%, wf
H2	45.2016
CH4	4.2474
CO	22.1440
CO2	27.4196

Fig. 3 Process flowsheet incorporating a steam/oxygen gasifier, UNIQUE cleaning system and a gas engine

Total plant investment costs are sum of all direct and direct plant costs. Total direct plant costs include total rchase cost of equipments, infrastructure costs, strumentation and controls costs and commissioning cost. otal indirect plant costs include project development costs d engineering and administration costs during construction.

In the literature, there are two ways of evaluating the total ant investment costs: on the basis of direct and indirect costs], [9], [10] or by using costs factor approach [11]-[13]. In oth cases, published costs vary greatly from a situation to other, even for plants of same size.

Due to these literature inconsistencies, in this work total vestment costs have been evaluated as the sum of direct and direct costs. The purchase cost has been calculated as the m of pieces of equipment that compose the main plant ctions (biomass storage and handling, gasifier, UNIQUE eaning system, gas engine). The cost of UNIQUE cleaning stem has been evaluated based on the information provided by the partners of UNIQUE consortium and for the others equipments, the literature data have been used. The infrastructure costs, instrumentation and controls costs, commissioning cost and all plant indirect costs have been calculated as a percentage of total purchase cost of equipments. Numerical values of these percentages have been derived from literature data.

To scale up the plant investment cost to another capacity, the data concerning total installed costs of various biomass CHP technologies, from several countries over a number of years, reported in [14], have been used. By processing these data, the scale cost is calculated on the basis of biomass fuel power according to the equation (1):

$$TPI_{CP} = TPI_{RP} \cdot (Pfuel_{CP} / Pfuel_{RP})^{0.74} \quad (1)$$

where: TPI_{CP} is the total investment cost of the computed plant (€); TPI_{RP} is the total investment cost of a reference plant , (€); $Pfuel_{CP}$ is the biomass fuel power of the computed plant (kW); $Pfuel_{RP}$ is the biomass fuel power of the reference plant (kW) and *0.74* is the scale factor.

In view of accounting for local investment conditions, the total investment cost has been adjusted by a tuning factor, whose value can vary between 0.7 and 1. The value “1” should be chosen for the countries where local costs (labour, land, etc.) are important.

On the other side, total investment cost incorporated in the economic evaluation has been calculated as for the 5th plant to be built (around 15% lower that the prototype cost [15]).

The mathematical equation taking into account all these considerations is (*f* - local conditions tuning factor):

$$TPI_{CP} = f \cdot 1/1.164 \cdot TPI_{RP} \cdot (Pfuel_{CP} / Pfuel_{RP})^{0.74} \quad (2)$$

The *operating costs* represent an annual outflow of cash from operating the plant (maintenance, consumables and utilities, waste streams disposal, labour and biomass cost).

Operating costs evaluation is based on plant annual operating hours (electricity and heat), biomass fuel costs, personnel and other (auxiliary) costs. The adopted equations are:

$$AN_{elect} = E_{grid} \cdot h_{elect} \quad (3)$$

$$AN_{heat} = H_{district} \cdot h_{heat} \quad (4)$$

$$C_{ME} = 0.04 \cdot TPI_{CP} \tag{5}$$

$$C_{lab} = N_{emp} \cdot C_{emp} \tag{6}$$

$$C_{fuel} = C_{biomass} \cdot h_{elect} \cdot BMflow / 1000 \tag{7}$$

$$C_{NF} = C_{ME} + C_{lab} + 0.03 \cdot TPI_{CP} \tag{8}$$

where: AN_{elect} is the annual net electricity generation (kW/year); E_{grid} is the electric power to grid, (kW); h_{elect} is the annual operating hours for electricity, (h); AN_{heat} is the annual net heat generation (kW/year); $H_{district}$ is the heating power to district, (kW); h_{heat} is the annual operating hours for heat, (h); C_{ME} represent the equipments maintenance cost, (€); C_{lab} is the labour cost, (€/year); N_{emp} is the number of employees, (emp); C_{emp} is the salary of one employee in a year, (euro/year/emp.); C_{fuel} is the fuel cost, (€); $C_{biomass}$ is the biomass (water free) cost, (€/ton_water free); *BMflow* is the biomass mass flow, g_total/h); C_{NF} represents the total non-fuel expenses, (€).

Annual cash flows consist of identifying and estimate the sh flows (cash outflows – expenses and inflows – revenues incomes) associated with a project.

The common expenses of a power plant are the fuel costs, e total non-fuel expenses and the annual debt payment for e case of a borrowed capital.

The main revenue sources of a power plant are electricity les to the national grid, heat supplied to customers via a strict heating network and the financial support instruments eed-in tariffs, premiums, green certificates, investment bsidies, tax credits, etc.). The premium paid for the green ectricity improves the economics by improving the plant onomics and reducing the investment risk.

In this study, the annual cash flows estimation relies on the bsequent information: electricity revenues; green certificates venues; heat revenues; financing plan (depreciation time; rms and conditions of investment financing: debt, equity nds or other sources – UE aid, local aid, country aid); debt terest rate, cost escalation and inflation.

The economic profitability of the UNIQUE technology has een evaluated on the basis of earned profit, calculated as the fference between the incomes and the expenses carried out during the entire life of the plant.

The equations used for calculation of annual cash flows are as follows:

$$I_{elect} = C_{elect} \cdot AN_{elect} \tag{9}$$

$$I_{GC} = C_{GC} \cdot AN_{elect} / 1000 \tag{10}$$

$$I_{heat} = C_{heat} \cdot AN_{heat} \tag{11}$$

$$C_{TD} = TPI_{CP} \cdot (1 - R_{OS} / 100) \tag{12}$$

$$C_{AD} = C_{TD} \cdot IR / 100 \cdot ((1 + IR / 100)^{EL} / ((1 + IR / 100)^{EL} - 1)) \tag{13}$$

$$\begin{aligned} E_T = EL \cdot C_{AD} + (C_{fuel} + C_{NF}) \cdot (1 + (1 + W / 100) + \\ + (1 + W / 100)^2 + \ldots + (1 + W / 100)^{EL-1}) \end{aligned} \tag{14}$$

$$\begin{aligned} I_T = EL \cdot I_{GC} + (I_{heat} + I_{elect}) \cdot (1 + (1 + W / 100) + \\ + (1 + W / 100)^2 + \ldots + (1 + W / 100)^{EL-1}) \end{aligned} \tag{15}$$

$$P_T = I_T - E_T \tag{16}$$

where: I_{elect} are the incomes from electricity sales, (€); C_{elec} is the electricity to grid price, (€/kWh); I_{GC} are the incomes from green certificates, (€); C_{GC} is the green certificates revenues, (€/MWh); I_{heat} are the incomes from heat sales, (€); C_{heat} is the heat to district price (€/kWh); C_{TD} is the total debt cost, (€); R_{OS} is the percent of total investment cost covered from other sources (EU, government, etc.), (%); C_{AD} is the annual debt payment, (€); *IR* is the interest rate, (%); *EL* is the unit economic life (years); E_T represent the total expenses during the entire life of the plant, (€); *W* is the inflation rate, (%); I_T represent the total incomes during the entire life of the plant, (€); P_T represent the total profit during the entire life of the plant, (€).

IV. CASE STUDY

The model, described above, has been applied for a case study that concerns the investment analysis of a UNIQUE plant developed in Romania. The main data used for this case study are reported in table I.

TABLE I
PARAMETERS FOR ECONOMIC EVALUATION OF THE BIOMASS PLANT

Parameter	Units	Value
Biomass type	-	Almond shells
Biomass mass flow	kg_total/h	1176
Biomass water content	kg/kg_total	0.12
Biomass ash content, water free	wt%	1.65
Biomass (water free) cost	euro/ton	70
Annual operating hours - heat	h	6000
Annual operating hours - electricity	h	7500
Unit economic life	year	10
Investment cost tuning factor	-	0.8
Percent of total investment cost covered from other sources	%	50
Interest rate	%	5
Inflation rate	%	3
Number of employees	Emp	10
Salary/employee/year	euro/year/emp.	20000
Heat to district price	euro/kWh	0.02
Electricity to grid price	euro/kWh	0.04
Green certificates revenues	euro/MWh	80

Depending on the evaluation purpose, the economic model can provide information for both first year and for the whole lifetime of the installation. The results of the economic model, for the entire lifetime of the plant are presented in table II.

TABLE II
UNIQUE PILOT PLANT ECONOMIC DATA

Parameter	Units	Value
Fuel power	kW	5000
Electric power to grid	kW	1264
Heating power to district	kW	2917
Total investment cost	€	4049762.59
Total debt cost	€	2024881.30
Cash flows – expenses for entire life of the plant	€	14393372.25
Cash flows – incomes for entire life of the plant	€	15102693.63
Cash flows – profit for entire life of the plant	€	709321.39

These results are showing that a 5MW UNIQUE plant could become financially attractive to Romanian market in case of a financial support (50% from total investment costs). UNIQUE technology profitability has been also investigated over a capacity range of 2 to 8 MW. The analysis has been carried out again by using the values of economic parameters listed in table I, including here the hypothesis that 50% of total investment cost has been loan. The results are presented in graphical form in fig. 4.

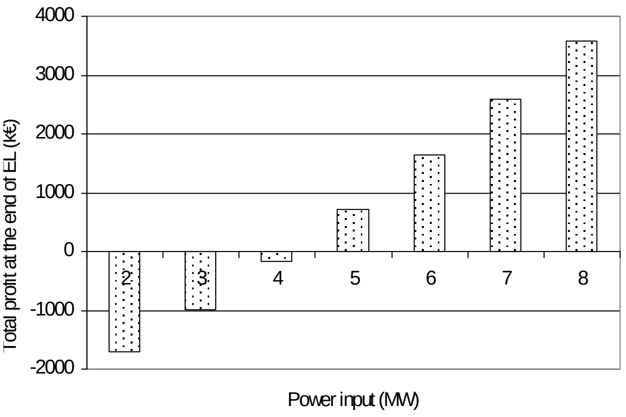


Fig. 4 Profit during the entire life of the plant for different sizes

The growth of the total profit is increasing as the capacity of the plant increase: no profit is obtained over a capacity range of 2-4 MW, while positive profit is associated to installed power in the range of 5 – 8 MW.

Finally, the effect of loan capital on UNIQUE profitability within 2 to 8 MW fuel power has been evaluated. The evaluations were made under the hypothesis that the borrowed capital is 25%, 50%, 75% and 100% of the total investment cost.

As resulted from fig. 5, UNIQUE technology, under the considered market conditions, can be economically feasible at small to medium scale only if investment subsidies are available. Just the financial support through green certificates (or other forms of support) does not guaranty the economic viability of the unit for a generally acceptable economic life of around 10 year.

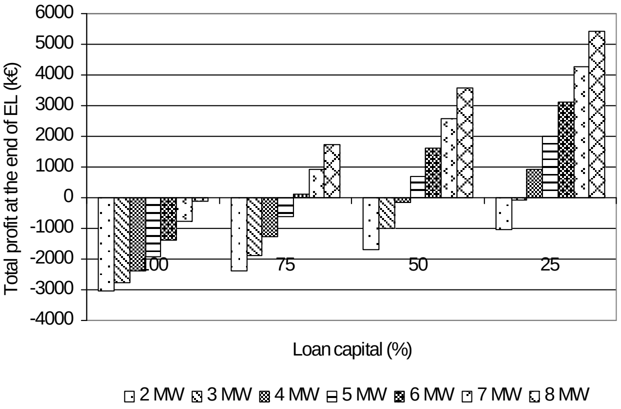


Fig. 5 Total profit trend for different percent of capital loan

Further investigations of the economic viability of steam/oxygen based fluidized bed biomass gasification in different market conditions and for different plant capacities can be done by accessing UNIQUE project website.

V. CONCLUSION

Through EU FP7 Framework Programme an innovative project (“Integration of particulate abatement, removal of trace elements and tar reforming in one biomass steam gasification reactor yielding high purity syngas for efficient CHP and power plants” – acronym: UNIQUE, www.uniqueproject.eu) was funded by the European Commision. The main objective of the project is to develop a compact version of a gasifier by integrating the fluidized bed steam gasification of biomass and the hot gas cleaning and conditioning system into one reactor vessel. The cleaning and conditioning system of the UNIQUE technology is expected to be able to deliver a high purity syngas suitable to assure a substantial share of power generation even in small to medium scale CHP and power plants and to increase the overall economic revenue in line with the energy new directives.

The computational tool developed inside the project is appropriate for the evaluation of steam/oxygen fluidized bed biomass gasification technologies from both technical and economic points of view. The economic model provides information that can help potential users, especially small and medium size enterprises acting in the regenerable energy field, to decide the optimal scale of a plant and to better understand both potentiality and limits of the technology.

The size of the CHP plant has a great influence on its economic viability. The general tendency is an increase of profit with increasing plant size but limits that arise due to logistic problems in biomass supply and in heat distribution should be also taken into account.

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