A hybrid optimization model of biomass trigeneration system combined with pit thermal energy storage

D. F. Dominković
Faculty of Mechanical Engineering and Naval Architecture
University of Zagreb, Zagreb, Croatia
e-mail: dominik6@gmail.com

B. Ćosić *
Faculty of Mechanical Engineering and Naval Architecture
University of Zagreb, Zagreb, Croatia
e-mail: boris.cosic@fsb.hr
address: I. Lučića 5, 10 000 Zagreb, Croatia
phone number: +385 98 168 81 49

Z. Bačelić Medić
iC artprojekt ltd, Croatia
Varaždin, Zagreb, Croatia
e-mail: z.bacelic@ic-group.org

N. Duić
Faculty of Mechanical Engineering and Naval Architecture
University of Zagreb, Zagreb, Croatia
e-mail: neven.duic@fsb.hr

ABSTRACT

This paper provides a solution for managing excess heat production in trigeneration and thus, increases the power plant yearly efficiency. An optimization model for combining biomass trigeneration energy system and pit thermal energy storage has been developed. Furthermore, single piping district heating and cooling network in the residential area without industry consumers was assumed. As a consequence, model is easy to adopt in different regions. Degree-hour method was used for calculation of hourly heating and cooling energy demand. The system covers all the yearly heating and cooling energy needs, while it is assumed that all the electricity can be transferred to the grid due to its renewable origin. The system was modelled in Matlab© on hourly basis and hybrid optimization model was used to maximise the net present value (NPV), which was the objective of the optimization. Economic figures become favourable if the economy-of-scale of both power plant and pit thermal energy storage can be utilized. Results shows that pit thermal energy storage was excellent option for storing energy and shaving peaks in energy demand. Finally, possible switch from feed-in tariffs to feed-in premiums was assessed and possible subsidy savings have been calculated. Savings are potentially large and can be used for supporting other renewable energy projects.

Keywords: trigeneration, seasonal storage, optimization, biomass, feed-in tariff, feed-in premium

1. INTRODUCTION

Worldwide demand for energy is increasing; as a consequence fossil fuel resources are becoming more and more expensive, in the same time making renewable energy resources more competitive. European Union has adopted 20-20-20 targets until 2020, which means increased energy efficiency by 20%, reduced greenhouse gas emissions by 20% and reaching 20% share of renewable in total energy generation [1]. In the EU's 2030 framework for climate and energy policies presented in January 2014, continuing progress towards a low-carbon economy is expected [2]. The most important objective by 2030 is to reduce the greenhouse gas emissions by 40% below the 1990 level, while increasing the renewable energy share to at least 27%. In order to achieve this target, improvements in energy efficiency are needed.

One good example in improving energy efficiency throughout the year is combined production of electricity, heating and cooling energy in trigeneration [3]. At the same time, using biomass as a fuel for trigeneration power plant increases the renewable energy share in the overall production mix. Rentizelas et al. [4] provide an optimization model for energy supply based on multi-biomass trigeneration, covering peak demand with a biomass boiler. Puig-Arnavat et al. [5] assessed different trigeneration configurations based on biomass gasification were shown. A. Borsukiewicz-Godzur et al. [6] calculated results for three variants of CHP biomass plants. A techno-economic assessment of biomass fuelled trigeneration system was made by Huang Y. et al. [7]. Recently, M. Wang et al. [8] published a paper dealing with multi-objective optimization of a combined cooling, heating and power system driven by solar energy. X. Zhao et al. [9] analyzed energy efficiency level for a station in China, which uses a trigeneration system. Although this is still a small-scale trigeneration system, used for s single building, interesting economic figures has been achieved, i.e. recovered year of the additional investment was in 5.47 year. There are also papers dealing with micro-trigeneration system such as G. Angrisani et al. [10], where a trigeneration system on a small-scale is assessed. Nevertheless, Ş . Kilkiş [11] developed a model for the net-zero exergy district development for a city in Sweden, which among the other units includes CHP plant with district heating and cooling system.

In simultaneous generation of electricity, heating and cooling energy, the system should be optimized to follow heating energy demand in order to achieve maximum efficiency of the energy being usefully utilized. Please note here that due to renewable nature of the biomass being considered, electricity generated has preference when supplying to the grid and thus, it is considered that all the electricity can be transferred to the grid in anytime. On the other hand, the feed-in-tariff for electricity is the most important income for investor in trigeneration power plant. In order to be eligible to receive feed-in-tariff, minimum overall yearly power plant efficiency has to be reached. One way of achieving high, relatively constant heat demand is to use dryers for reducing moisture content in biomass. Currently, legislative in Croatia allows this, but it is questionable if it will be allowed in the future as it is not the most efficient way of using the heat energy. According to Härkönen [12], after reaching the equilibrium moisture, which will happen naturally, after a required period of time when exposed to outside air, heat of desorption increases linearly as moisture content is getting lower. The biomass in Croatia is delivered to the power plant with up to 30% moisture, after which the heat needed for drying biomass increases significantly by reducing moisture content in biomass. Moreover, the increased size of wood significantly increases energy consumption in dryers and drying can become unprofitable as shown by Gebreegziabher et al. [13]. Thus, drying will not be considered as an option to utilize heat in this paper. As a consequence of not having a constant heat consumer, seasonal thermal energy storage will be incorporated in the optimization model in order to deal with peak demand as well as large differences in heating and cooling energy demand throughout seasons.

Currently in Croatia, for the system assumed, only feed-in tariffs for cogeneration power plants or biomass electrical power plants would be applicable, while feed-in tariff for the trigeneration systems does not exist. Both of them are at the same level for the capacities being considered in this paper. However, feed-in-tariff for PTES would be of great significance for economic feasibility of investment. G. Krajač ić et al. [14] provided an overview of potential feed-in-tariffs for different energy storage technologies. For the system being assessed, the triple tariff, as discussed in H. Lund et A.N. Andersen [15], would be significantly supportive towards the economic viability of the chosen system. Furthermore, neither a feed-in-tariff for district heating and cooling network is available in Croatia. As shown in B.Rezaie et M.A.Rosen [16], district heating in densely populated regions would be a favorable investment compared to low-density residential areas. However, in this case study, neighborhood consisting of family houses was considered.

Nevertheless, the importance of seasonal heat storage in future sustainable energy system in Croatia was assessed by G. Krajač ić et al. [17]. Without seasonal heat storage, critical excess in electricity production, as well as intermittency of wind power plants production, will be tough to handle with.

Up to now, most papers have dealt with the solar thermal energy coupled with the seasonal energy storage [18-22]. R.D. Raine et al. [23] optimized combined heat and power production for buildings using heat storage. However, storage volumes in two different scenarios had volumes of only 600m^3 and 350 m^3. Thus, these were not large-scale seasonal storages. B. Rezaie et al. [24] assessed exergy and energy efficiencies of seasonal hot water storage combined with solar collectors and boilers. When there is no instant need for heating energy, it can be stored in the large-scale pit thermal energy storage and used later when there will be need for the heating energy. In Mangold [25] it is shown that economy-of-scale is significant till water storage volumes of 50,000 m^3. Moreover, according to Energo Styrelsen's publication [26], economy-of-scale for the low capacity range is quite considerable.

The novel approach in this paper is a combination of large scale seasonal pit thermal energy storage and biomass trigeneration power plant. The model will be developed in order to make the most of economy-of-scale. Moreover, in order to develop the model which can be easily replicated, only residential buildings will be considered as a heat consumers. From the demand side point of view this is the worst case for covering the heating and cooling load throughout the year as there is no constant need for heating or cooling energy.

Furthermore, the guidance for the design of renewables' support schemes [27] has been issued by the European commission. Feed-in-premiums, variable or fixed, were given preference over feed-in-tariffs. As Croatia has implemented feed-in-tariffs as a renewable's support scheme, this paper will also estimate levels at which feed-in-premiums, both variable and fixed, should be set to in order to replace the current mechanism. At the end of 2013, 7 countries in EU28 were using feed-in premiums or combination of feed-in premiums and other supporting schemes [28]. Other common supporting schemes are green certificates and tenders. So far, feed-in systems proved to be more efficient than the green certificates [29]. It will be shown the potential savings in expenditure on subsidies if the power plants eligible for the supporting mechanisms would achieve one part of their income on the market.

2. METHODOLOGY

2.1. Problem definition

An investor who decides to invest funds wants to maximize profit. In a trigeneration power plant the crucial role for maximizing income is the generated electricity sold at a price set by feed-in-tariff. Consequently, economic the best way to maximize profit would be to produce as much as possible electricity. On the other hand, technically, the system is driven by heat demand in order to maximize efficiency. In order to satisfy both economic and technical targets, the feed-in-tariff eligibility is usually constrained by a minimum overall efficiency of the power plant. Thus, in order to have a constant electricity production, while still having overall efficiency above minimum allowed level, a relatively constant heat demand is needed. However, as it is shown that the heat demand has strong seasonal pattern, especially in housing dwellings [30][31], there is a need to develop a model which will offset high seasonality.

2.2. Model description

The model optimizes sizes of the seasonal thermal storage, the biomass power plant and the absorption units which are subject to different constraints. The decision maker can set the target overall efficiency of the power plant. The first target of the system is to fully cover the heating and cooling energy demand. As a consequence, seasonal energy storage, besides storing energy in periods with lower demand for periods with higher demand, shave peaks in heating energy demand which usually occur during the winter season. This means that a peak boiler is not necessary in the system. It is assumed that all electricity produced in the power plant can be sold to the network for the price specified by the feed-in-tariff. The produced heat can be used for district heating, district cooling by using absorbers, or stored in the energy storage. The three main system components are the biomass power plant, the absorbers and the seasonal energy storage.

2.3. Biomass power plant

The biomass power plant size is calculated, taking into account the heating and cooling demand. As the model is heat driven, the electricity generating capacity follows the heat consumption throughout the year. As an average biomass power plant has the availability of approximately 90%, the model calculates the part of the year with the lowest energy demand where the biomass power plant is shut down for maintenance. During this period heating/cooling energy is completely covered by seasonal energy storage.

2.4. Heating and cooling demand

Heating and cooling demand are calculated by using degree hours, based on hourly temperatures valid for the considered location. Yearly heating and cooling energy consumption per m^2 has to be assumed by the decision maker for the specific location. The district heating network cannot have both cooling and heating flow at the same time due to economic constraints. As this model does not predict industrial consumers, this constraint is not a problem for the system.

2.5. Absorbers

The absorbers in the system are driven by the heat generated from the biomass power plant. They can be driven directly by the produced heat in power plant or by the heat stored in the seasonal energy storage. Absorbers were preferred, compared to adsorbers, because they have a lower investment cost. As it is predicted that the water in the seasonal storage will be stored with a temperature between 85°C and 90°C, the predicted Libr-H_2O single effect absorbers are able to work properly [32][33].

2.6. Seasonal energy storage

Pit thermal energy storage (PTES) was chosen for the seasonal heat energy storage mostly due to low investment cost. Water as a storage media is a well-developed solution and so far, the only mature media for large volume storages. According to [34], PTES are the largest thermal energy storages being built. Typical efficiency of such storage is between 80 % and 95 % depending on the temperature level in the storage. As economy-of-scale after volume of 50,000 m3 does not apply, it is possible to build a few PTES instead of one if the storage volume becomes very large in the model.

3. OPTIMIZATION MODEL

3.1. Optimization variables

Three independent variables which are determined by the optimization model are:

- P_{el} - electricity generating capacity of the biomass trigeneration power plant in kW_e. The heat capacity (P_{el}) is proportional to the electricity capacity, following assumed fixed heat-to-power ratio.
- S_V - volume of the storage in m^3
- P_A - capacity of the absorber unit(s) in kW

3.2. Objective function

Maximizing net present value for the project lifetime, during which feed-in-tariff is assumed as guaranteed, was the objective in the optimization model. Although a biomass power plant has a much longer life time, this assumption was introduced in order to reduce vagueness about the future electricity price predictions. The optimization model also calculates the internal rate of return (IRR) and the simple pay-back period in order to provide enough inputs for the decision making process. The NPV function is:

$$\begin{aligned} NPV = &\left(I_h + I_c + I_{el} - E_{OM,Bf} - E_{OM,Bv} - E_{OM,DHCn} - E_{OM,S} - E_{fB}\right)\cdot D \\ &- Inv_B - Inv_A - Inv_{DHCN} - Inv_S \end{aligned} \tag{1}$$

where all the future annual income and expenditure values are multiplied by a discount coefficient D:

$$D = \frac{1}{(1+i)^t} \tag{2}$$

where i is the discount rate and t is the project lifetime.

3.2.1. Income

There are three income items in the model; revenues from electricity, heating and cooling energy sales. As the power plant needs to satisfy all the need for heating and cooling energy, it can be assumed that all the heating and cooling energy need for the district considered is sold from this power plant. Income from the heat sales during the one year I_h equals:

$$I_h = h_P \sum_{j=1}^{8760} h_j \tag{3}$$

where h_P is the price of kWh of heat, h_j is the hourly value of heat demand (kWh) throughout the year.

I_c is the income from the sales of cooling energy:

$$I_c = C_P \sum_{j=1}^{8760} c_j \tag{4}$$

where C_P is the price of kWh of the cooling energy and c_j is the hourly value of the cooling demand (kWh) throughout the year.

I_{el} is the income from the sales of electricity:

$$I_{el} = E_P \sum_{j=1}^{8760} e_j - e_{pp} \tag{5}$$

where E_P is the price of kWh of electricity, e_j is the hourly value of electricity production (kWh) and e_{pp} is the power plant own electricity consumption throughout the year.

3.2.2. Expenditure

There are five expenditure items, fixed and variable operating and maintenance cost of the biomass power plant, operating costs of district heating and cooling network and thermal energy storage and cost of fuel, which is biomass in this case.

$E_{OM,Bv}$ is the expenditure on variable O&M:

$$E_{OM,Bv} = V \sum_{j=1}^{8760} e_j \tag{6}$$

where V is the variable cost of O&M (€ /kWh$_e$).

$E_{OM,Bf}$ is the expenditure following fixed O&M cost:

$$E_{OM,Bf} = F \cdot P_{el} \tag{7}$$

where F is the fixed yearly O&M cost (€ /kW$_e$).

$E_{OM,DHCn}$ is the O&M cost of district heating and cooling network:

$$E_{OM,DHCn} = Z \cdot N \tag{8}$$

where Z is the number of dwellings in district considered and N is cost of yearly network maintenance (€ /dwelling).

$E_{OM,S}$ is the O&M cost of storage:

$$E_{OM,S} = U \cdot S_V \tag{9}$$

where U is the O&M price of the yearly storage maintenance (€ /m^3).

E_{fB} is the expenditure on fuel (biomass):

$$E_{fB} = B \cdot \frac{1}{h_d} \cdot \frac{1}{\eta_{el}} \cdot \sum_{j=1}^{8760} e_j \tag{10}$$

where B is the price of biomass (€ /ton), h_d is the lower calorific value of biomass (kWh/ton) and η_{el} is the electrical efficiency of the power plant.

3.2.3. Investment

The overall investment consists of four parts, investment in the biomass power plant, in absorption chillers, in district heating and cooling network and in the pit thermal energy storage. Investment in the biomass power plant Inv_B is calculated as follows:

$$Inv_B = B_{inv} \cdot P_{el} \tag{11}$$

where B_{inv} is the price of investment per power plant capacity (€ /kW$_{el}$).

Inv_A is the price of investment in absorption chillers:

$$Inv_A = A_{inv} \cdot C_{peak} \cdot \frac{1}{COP} \tag{12}$$

where A_{inv} is the price of investment per absorption capacity (€ /kW), C_{peak} is the peak demand for cooling energy (kW) and COP is the coefficient of performance of the absorption units. As mentioned before, the model predicted that all the cooling energy needs to be satisfied from this power plant, thus the needed capacity of absorption units is equal to peak cooling demand divided by the coefficient of performance, which was set in this model to 0.7.

Investment in the district heating and cooling network Inv_{DHCN} is calculated as follows:

$$Inv_{DHCN} = N_{inv} \cdot Z \tag{13}$$

where N_{inv} is the investment per dwelling (€ /dwelling). In this model N_{inv} was used from Ref. [35].

Investment in the pit thermal energy storage Inv_S :

$$Inv_S = S_{inv} \cdot S_V \tag{14}$$

where S_{inv} is the price of storage investment (€ /m^3), which was implemented in this model from Ref. [26].

3.3. Constraints

The heat demand in every hour *j* throughout the year needs to be covered, either by biomass power plant production, by heat stored in PTES, or by both sources of heat:

$$h_{B,j} + h_{S_V,j} \geq h_j \tag{15}$$

where $h_{B,j}$ is the hourly heat production in the biomass power plant and $h_{S_V,j}$ is the heat taken from PTES on an hourly basis.

Heat used in the absorption units needs to cover the cooling demand in every hour *j* throughout the year:

$$\left(h_{B,j} + h_{S_V,j}\right) \cdot \frac{1}{COP} \geq c_j \tag{16}$$

The sum of the heat production capacity of the biomass power plant and the heat from the storage that can be taken has to be larger or equal to peak heat demand:

$$P_{el} \cdot HTP + S_V \cdot \rho_w \cdot c_p \cdot \Delta T \cdot \frac{1}{3600} \cdot \eta_S \geq h_{peak} \tag{17}$$

where HTP is the heat-to-power ratio, ρ_w is the density of water (kg/m^3), c_p is the specific heat capacity of water (kJ/(kgK)), ΔT is the difference in temperature of stored water and the design temperature of the dwellings' heating systems (K), η_S is the efficiency of the PTES and h_{peak} is the peak heat demand (kW).

The cooling energy peak demand needs to be covered in the same manner as the heating energy peak demand:

$$P_{el} \cdot HTP \cdot COP + S_V \cdot \rho_w \cdot c_p \cdot \Delta T \cdot \frac{1}{3600} \cdot \eta_S \cdot COP \geq C_{peak} \quad (18)$$

Storage volume size has to be able to store all the heating energy which needs to be taken at certain time from the PTES:

$$h_{S_V,sum} \cdot 3600 \cdot \frac{1}{c_p} \cdot \frac{1}{\Delta T} \cdot \frac{1}{\rho} \cdot \frac{1}{\eta_S} \geq S_V \quad (19)$$

where $h_{S_V,sum}$ is the sum of heating energy which needs to be taken from the storage in the longest period of time where average biomass heat production rate is lower than heat demand (under the term "heat demand", "cooling energy demand" is also assumed, which is the same in this model except COP coefficient which needs to be taken into account).

$$e + h \geq P_{el} \cdot \frac{1}{\eta_{el}} \cdot B_{av} \cdot 8760 \cdot \eta_X \quad (20)$$

where *e* and *h* present the produced electricity and heat demand during one year of power plant operation, η_{el} is the electrical efficiency of the power plant, B_{av} is the availability of the biomass power plant and η_X is the minimum overall efficiency power plant needs to have to be eligible to receive subsidy.

3.4. Optimization method

A hybrid optimization method was used to optimize this problem. As this is a non-linear problem, a Genetic Algorithm and fmincon were used in Matlab©. The Genetic Algorithm has been recently applied in several papers for the optimization of the energy systems, such as in optimization of low-temperature district heating network [36]. It is a useful optimization method, which approaches to a global optimum very fast because it generates a population of points at each iteration, instead of a single point at each iteration in a classical algorithm [37]. However, it converges relatively slowly when it reaches a solution close to the global optimum. Thus, after Genetic Algorithm, fmincon starts and finds a minimum of the constrained nonlinear multivariable function [37]. However, fmincon needs to have a good initial point in order to end up in the global optimum instead of a local optimum. Thus, hybrid programming optimization method has proven to be very effective for this type of problem.

4. CASE STUDY: the City of Osijek

The model was applied to a district in the city of Osijek. Osijek is one of the four largest cities in Croatia. 2000 dwellings with 200 m^2, with average spacing of 10 meters between each of them were assumed. In Croatia, the yearly average heating energy consumption is rather high and 160 kWh/m^2 of heating energy per annum was assumed. In order to be eligible for the feed-in support, in Croatia, overall yearly efficiency of the power plant has to be above 50% [38]. Moreover, only usefully utilized heat by consumers is considered when calculating the yearly efficiency. Biomass moisture is considered to be relatively constant at 30% as this is a usual case in Croatia. Input data for the case study are presented in Table 1.

Table 1. List of data used in case study

	amount	unit
Power plant availability	0.9	
Biomass price	35	€ /ton
Lower calorific value (30 % moisture)	3,500	kWh/ton
η power plant total	0.88	
η_{el}	0.29	
HTP ratio	2.034	
B_{inv}	3,600	€ /kW_e
A_{inv}	400	€ /kW
N_{inv}	7,650	€ /dwelling
S_{inv}	60	€ /m^3
Plant own electricity consumption	6%	
Discount rate	7%	
Feed-in-tariff	0.156	€ /kWh_e
COP	0.7	
Design temperature for heating	21	°C
Design temperature for cooling	26	°C
F	29	€ /kW per annum
V	0.0039	€ /kWh
N	75	€ /dwelling per annum
U	0.1	€ /m^3 per annum
h_P	0.0198	€ /kWh
C_P	0.0198	€ /kWh
Project lifetime	14	years

Two case studies were done, with a minimum yearly average power plant efficiency of 55% and 75%, respectively. These efficiencies were chosen in order to assess possible increase in the minimum allowed efficiency for being eligible for feed-in tariff support. A sensitivity analysis was performed and the influence of the biomass price on overall results was investigated. The second parameter that was checked in the sensitivity analysis was the reduced heat and cooling demand due to increased thermal energy savings which resulted after applying better insulation. Many programs of improving insulation properties are being carried out in Croatia, where the government supports the investment up to 47% [39]. Thus, in this case a shift form *energy class E* to *energy class C* was assumed.

5. RESULTS AND DISCUSSION

5.1. Case study 1

In this case study, with the minimum yearly power plant efficiency of 55%, all economic indicators are good and this investment would be profitable for the investor. The NPV equals to 14,765,544 € , IRR is 11.5 % and the simple pay-back time is 6.85 years. Optimal capacity of the power plant is 8,950 kW_e. Results would be even better if a higher heat price could be achieved, but it was decided to use the cheaper than best alternative approach in order to be certain that customers would shift to a new heat supply option. The storage size in this case would be 17,397 m^3. The heat from the storage is mainly used while the biomass power plant is not producing heat due to regular yearly maintenance work. In Figure 3 usage of storage for peak energy demand can be seen.

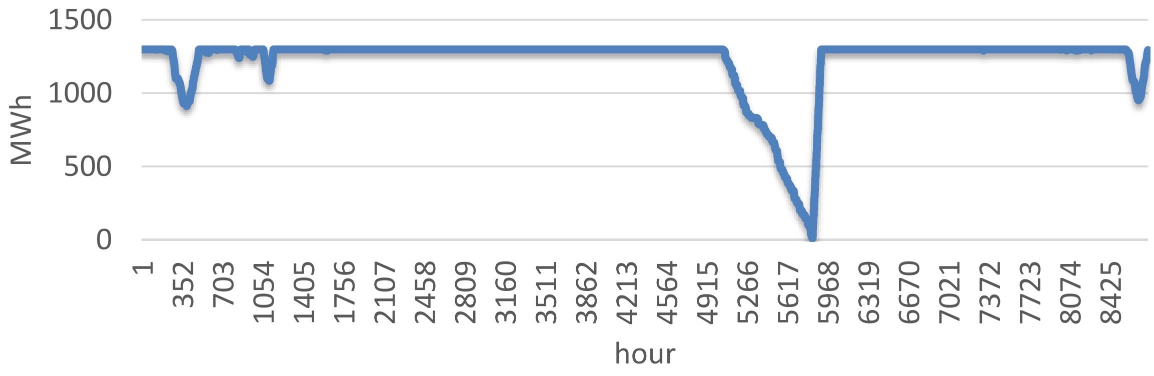

Figure 1. Usage of storage in case study 1

This case study shows that PTES could be used for shaving peak energy demands instead of the oversized cogeneration power plants that are now used in Croatia. Secondly, the economic indicators show that slight shift in legislative from minimum efficiency to be eligible for the feed-in-tariff from 50% to 55 % would not cause a risk to economic performance of a project.

5.2. Case study 2

In this case, with the minimum overall yearly power plant efficiency of 75 %, the economic indicators are not satisfying for an investor. The NPV is -9,211,370€ , IRR is 3.8 % and the simple payback time is 10.72 years. Optimal capacity of the power plant is 5,000 kW_e.

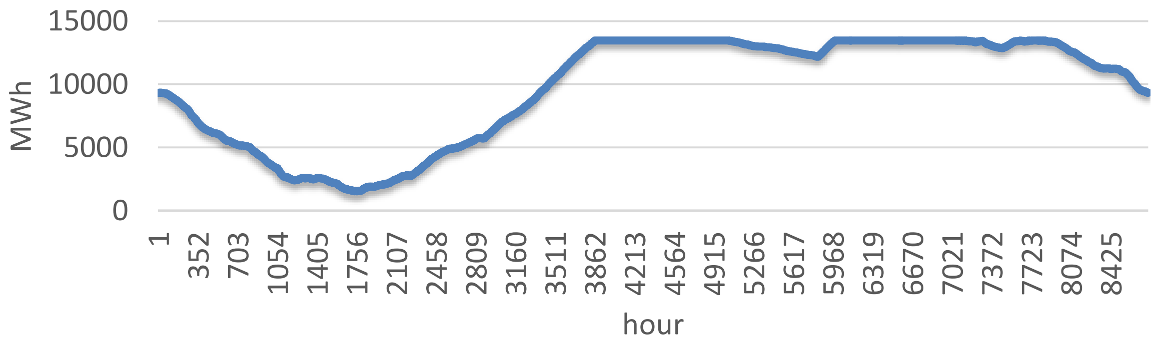

Figure 2. Usage of storage in case study 2

The storage size in this case is much larger and has a volume of 180,251 m^3. In Figure 4 can be seen that the storage is used more often than in the previous case. In some parts of winter, the total amount of heat taken from PTES is more than two and a half times larger than heat produced in the biomass power plant in the same time. Thus, in this case seasonal energy storage significantly contributes to overall power plant efficiency, as it significantly shaves a peak demand. During the regular yearly maintenance work, heat is provided from the seasonal energy storage in the same manner as in the case study one.

5.3. Comparison of the figures in two case studies

In Table 2 all important results are listed in order to be easier to compare case studies 1 and 2 optimization results.

Table 2. Results of case studies

	Case study 1	**Case study 2**
Power plant capacity	8,950 kW_e	5,000 kW_e
Storage size	17,397 m^3	180,251 m^3
Absorption units size	10,380 kW	10,380 kW
NPV	14,765,544	-9,211,370
IRR	11.5 %	3.8%
Simple pay-back time	6.85 years	10.72 years
Total investment cost	52,715,000 €	48,300,000 €
Share of storage in total investment	2%	22.4 %
Share of absorbers in total investment	7.9%	8.6%
Share of biomass power plant in total investment	61.1%	37.2%
Share of DHC network in total investment	29%	31.7%

As it can be seen from the results, the overall investment in the first case study is higher than in the second. This occurs because of a higher biomass power plant capacity in the first case; the biomass power plant in the first case has a 40% higher share in total investment than in the second case. It is interesting to see the shares of different parts in the total investment. The district heating and cooling network has a significant share in both cases, amounting to around 30% of total investment.

5.4. Comparison of fixed and variable feed-in-premiums

When comparing the feed-in-tariff and electricity prices on Nordpool for the year 2013 (because Croatia does not have its own electricity spot market), it was calculated that the fixed feed-in-premium should be set at 0.113 € /kWh in order to remain the same yearly subsidy level as it is the case now. In the case of the variable feed-in-premium (where total revenue per kWh of electricity would remain the same as with the feed-in-tariff), 76% of the electricity income would come from the feed-in-premium and 24% would be earned on the spot market. Thus, in the case of switching from feed-in tariffs to feed-in premiums, yearly subsidy expenditures

would decrease for 24%, as this funds would be obtained from the electricity market itself. This is a significant amount of savings that could be then used for further renewable energy subsidies.
Prices below zero, where the feed-in-premium could not be received, are very rare, while prices on the spot market above the feed-in-tariff did not occur at all during 2013. Thus, hours in which the power plant would not be eligible for the feed-in-premium do not play a significant role. For the case study 1, these two feed-in-premium options are showed in Figures 5 and 6.

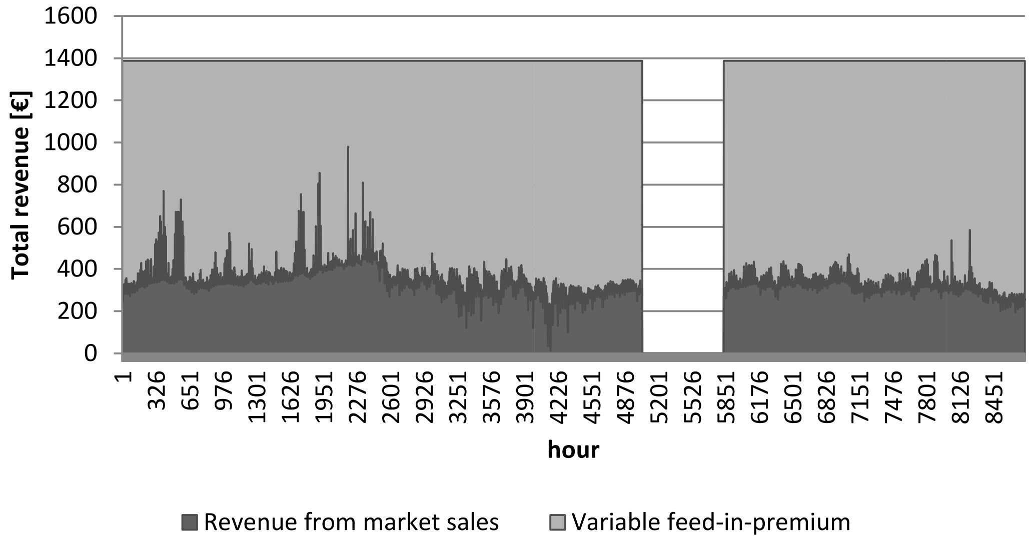

Figure 5. Hourly revenue with the variable feed-in-premium, case study 1

As it can be seen, for electricity market prices in the year 2013 on Nordpool, modelled biomass power plant would be eligible to receive premium in all hours except those when maintenance was in progress.

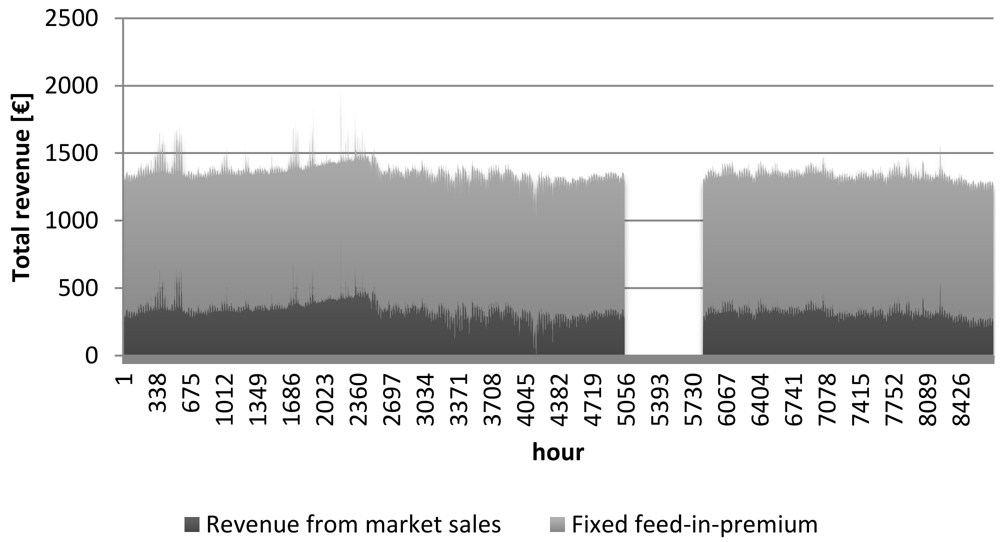

Figure 6. Hourly revenue with the fixed feed-in-premium, case study 1

Similarly to case with the variable feed-in-premium, power plant would be eligible to receive the premium in all hours except when maintenance work was in progress. Like in the previous case, subsidy funds account for 76% of the income from selling the electricity, while 24% of income is earned on the electricity market. However, in the case with the fixed feed-in-premium, risk for an investor would be higher than in the case with the variable feed-in-premium because of vagueness of the future electricity market price predictions.

5.5. Sensitivity analysis

In the sensitivity analysis, the impact of a significant increase in the biomass price was checked, as well as the impact of improved thermal insulation has been checked. Different biomass prices for the case of Croatia, according to difference in transportation distances, was assessed by B.Ćosić et al. [40].

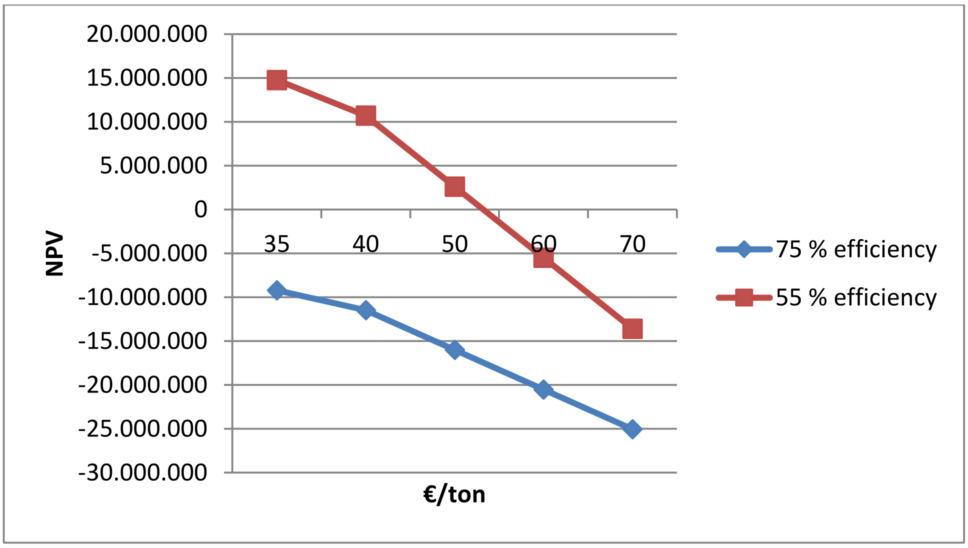

Figure 7. NPV change with biomass price increase

It can be seen in Figure 5 that the biomass price of 59 € /ton is a boundary price after which the NPV becomes negative in the first case study. As expected, in the second case, the NPV becomes even worse than in the original case study with an increase in the biomass. To sum up, an increase in the price up to 20% does not affect the overall economic result significantly.

In the second sensitivity analysis case, the improved thermal insulation reduced the cooling and heating energy demand from 160 kWh/m^2 per annum to 95 kWh/m^2 (Table 3.). T. Pukšec et al. [41] showed for the case of Croatia that significant energy savings can be expected if the policy measures already implemented are properly modelled in the future energy demand.

Table 3. Results in case of reduced heating and cooling energy demand

	Case study 1	Case study 2
Biomass power plant capacity	5 390 kW$_e$	3 010 kW$_e$
Storage volume	10 480 m^3	108 585 m^3
Absorption units capacity	5 350 kW	5 350 kW
NPV	4 406 950 €	-10 036 970 €

It can be seen that the NPV is lower than in base case studies, although a decrease is smaller in the second case study with an overall power plant efficiency of 75%. However, it is shown that careful planning should be carried out before deciding to invest in a power plant similar to this one because the impact of reducing heating and cooling energy demand is high comparing to economic indicators in two cases. If this change would be sudden, with the power plant already being built, the economic indicators would be much worse, as the power plant would be extremely oversized.

6. CONCLUSIONS

This model was developed in order to try to find a solution for problems of efficiency in the existing cogeneration power plants. Moreover, the model showed that a slight increase in legislative in terms of the overall power plant efficiency from 50% to 55% in order to be eligible for the feed-in-tariff would not present a problem on the economic side of a project. Additionally, following conclusions can be made:

- Increase in overall power plant efficiency reduces economic benefits for the investor
- PTES showed to be an efficient and cheap solution in combination with a biomass power plant by means of peak energy demand shaving and replacing the power plant supply during downtime
- PTES can significantly improve the overall yearly power plant efficiency
- Reducing the heating and cooling energy demand represents a great risk for the economic indicators of the whole project. Thus, a relatively secure energy demand should be envisaged at the beginning of the project in order to maximally reduce the risk for the investor.
- Price of the biomass plays important role in the overall economic indicators
- Economy-of-scale of both thermal energy storages and biomass power plants should be utilized in order to have an economic feasible project
- Switching from feed-in tariffs to feed-in premiums can obtain large savings in subsidy fund expenditures
- For the larger overall power plant efficiencies a different approach is needed in order to try to reach an economic feasible solution.

References:

[1] European Commission. Memo on the Renewable Energy and Climate Change Package. 23.01.2008, Brussels.
[2] European Commission. A policy framework for climate and energy in the period from 2020 to 2030. 22.01.2014, Brussels .
[3] Conolly D, Lund H, Mathiesen BV, Werner S, Möller B, Persson U, Boermans T, Trier D, Ostergaard PA, Nielsen S. Heat Roadmap Europe: Combining district heating with heat savings to decarbonize the EU energy system. Energy Policy 2014;65:475-489.
[4] Rentizelas A.A., Tatsiopoulos I.P., Tolis A. An optimization model for multi-biomass tri-generation energy supply. Biomass and bioenergy 2009; 33:223-233.
[5] Puig-Arnavat M., Bruno J.C., Coronas A. Modeling of trigeneration configurations based on biomass gasification and comparison of performance. Applied Energy 2014; 114:845-856.

[6] Borsukiewicz-Gozdur A, Wiśniewski S, Mocarski S, Bańkowski M. ORC power plant for electricity production from forest and agriculture biomass. Energy Conversion and Management 2014;87:1180-1185.
[7] Huang Y., Wang Y.D., Rezvani S., McIlveen-Wright D.R., Anderson M., Mondol J., Zacharopolous A., Hewitt N.J. A techno-economic assessment of biomass fuelled trigeneration system integrated with organic Rankine cycle. Applied Thermal Engineering 2013;53:325-331.
[8] Wang M, Wang J, Zhao P, Dai Y. Multi-objective optimization of a combined cooling, heating and power system driven by solar energy. Energy Conversion and Management 2015;89:289-297.
[9] Zhao X, Fu L, Li Feng, Liu Hua. Design and operation of a tri-generation system for a station in China. Energy Conversion and Management 2014;80:391-397.
[10] Angrisani G, Roselli C, Sasso M, Tariello F. Dynamic performance assessment of a micro-trigeneration system with a desiccant-based air handling unit in Southern Italy climatic conditions. Energy Conversion and Management 2014;80:188-201.
[11] Kilkiş Ş. Energy system analysis of a pilot net-zero exergy district. Energy Conversion and Management 2014;87:1077-1092.
[12] Härkönen M. Moisture of the wood. Forest power project, 13.09.2011, No 1016.
[13] Gebreegziabher T., Oyedun A. O., Hui C.W. Optimum biomass drying for combustion – A modeling approach. Energy 2013;53:67-73.
[14] Krajačić G, Duić N, Tsikalakis A, Zoulias M, Caralis G, Panteri E, Carvalho MG. Feed-in tariffs for promotion of energy storage technologies. Energy Policy 2011;39:1410-1425.
[15] Lund H, Andersen AN. Optimal design of small CHP plants in a market with fluctuating electricity prices. Energy Conversion and Management 2005;46:893-904.
[16] Rezaie B, Rosen MA. District heating and cooling: Review of technology and potential enhancements. Applied Energy 2012;93:2-10.
[17] Krajačić G, Duić N, Zmijarević Z, Vad Mathiesen B, Anić Vučinić A, da Graça Carvalho M. Planning for a 100% independent energy system based on smart energy storage for integration of renewables and CO_2 emissions reduction. Applied Thermal Engineering 2011;31:2073-2083.
[18] Pinel P, Cruickshank CA, Beausoleil-Morrison I, Wills A. A review of available methods for seasonal storage of solar thermal energy in residential applications. Renewable and Sustainable Energy Reviews 2011; 15:3341-3359.
[19] Sweet ML, McLeskey Jr. JT. Numerical simulation of underground Seasonal Solar Thermal Energy Storage (SSTES) for a single family dwelling using TRNSYS. Solar Energy 2012,86:289-300.
[20] Terziotti LT, Sweet ML, McLeskey Jr. JT. Modeling seasonal solar thermal energy storage in a large urban residential building using TRNSYS 16. Energy and Buildings 2012, 45:28-31.
[21] Xu. J, Wang RZ, Li Y. A review of available technologies for seasonal thermal energy storage. Solar energy 2014;103:610-638.
[22] Guadalfajara M, Lozano MA, Serra LM. A Simple Method to Calculate Central Solar Heating Plants with Seasonal Storage. Energy Procedia 2014; 48:1096-1109.
[23] Raine RD, Sharifi VN, Swithenbank J. Optimisation of combined heat and power production for buildings using heat storage. Energy Conversion and Management 2014;87:164-174.
[24] Rezaie B, Reddy BV, Rosen MA. Exergy analysis of thermal energy storage in a district energy application. Renewable Energy 2015;74:848-854.
[25] Mangold, D. Seasonal Heat Storage. Pilot projects and experiences in Germany, presentation at the PREHEAT Symposium at Intersolar 2007, Freiburg, Germany, June 2007.
[26] Energo Styrelsen. Technology Data for Energy Plants. May 2012

[27] European Commission. European Comission guidance for the design of renewables support schemes. 5.11.2013, Brussels.
[28] CMS. Renewables Support Mechanisms Across Europe. A comparative study, April 2013.
[29] Ragwitz M., Winkler J., Klessmann C., Gephart M., Resch G. A report commissioned by the Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). January 2012.
[30] Th. Frank. Climate change impacts on building heating and cooling energy demand in Switzerland. Energy and Buildings 2005;37:1175-1185.
[31] Isaac M, van Vuuren DP. Modeling global residential sector energy demand for heating and air conditioning in the context of climate change.
[32] Florides GA, Kalogirou SA, Tassou SA, Wrobel LC. Design and construction of a LiBr-water absorption machine. Energy Conversion and Management 2003;44:2483-2508.
[33] Gomri R. Second law comparison of single effect and double effect vapour absorption refrigeration systems. Energy Conversion and Management 2009;50:1279-1287.
[34] Lund, R., Linn, L.J., The Potential of Implementing Thermal Energy Storage in an Energy System with a High Share of Wind Power, 4th Semester Master Project, Sustainable Energy Planning and Management, Aalborg University, Spring 2013
[35] Pöyry, Faber Maunsell, Aecom. The potential and costs of district heating networks. A report to the Department of Energy and Climate Change, April 2009.
[36] Li H, Svendsen S. District Heating Network Design and Configuration Optimization with Genetic Algorithm. Journal of Sustainable Development of Energy, Water and Environment Systems 2013;1:291-303.
[37] www.mathworks.com (the latest access on the 25th of November 2014)
[38] www.hrote.hr (the latest access on the 25th of November 2014)
[39] Ministarstvo graditeljstva i prostornog uređenja, Program energetske obnove stambenih zgrada za razdoblje od 2013. do 2020. godine, November 2013.
[40] Ćosić B, Stanić Z, Duić N. Geographic distribution of economic potential of agricultural and forest biomass residual for energy use: Case study of Croatia. Energy 2011;36:2017-2028.
[41] Pukšec T, Vad Mathiesen B, Novosel T, Duić N. Assessing the impact of energy saving measures on the future energy demand and related GHG (greenhouse gas) emission reduction of Croatia. Energy 2014;76:198-209.