Abstract—In this paper, optimization of the location of biomass trigeneration power plant was considered for three case studies in the city of Petrinja, Croatia. The system combined biomass cogeneration power plant, absorbers and the seasonal pit thermal energy storage. In order to find optimal location of power plants several factors influence merit of potential locations. When the biomass availability, capacity of the power plant or the number of power plants changes the optimal location also change. Case studies have shown that significant amount of yearly spending on fuel (biomass) can be avoided, if the optimal location has been chosen for the power plant location. Furthermore, economic assessment of choosing optimal and non-optimal location was performed. Moreover, it was shown that while choosing the optimal location of the power plant, economic figures such as net present value (NPV) can be satisfying for the potential investor in the trigeneration power plant even in residential area.

Keywords—absorption, location optimization, net present value, pit thermal energy storage, trigeneration

I. INTRODUCTION

Renewable energy sources have become common topic nowadays. Modelling renewable energy systems was performed by the vast number of authors in the past time. Quick review of papers dealing with trigeneration systems, optimization and thermal energy storages will be showed here. Reference [1] showed that the number of articles using optimization algorithms applied to renewable energy systems is growing exponentially in the last 20 years. Authors in [2] used a mixed integer optimization method for optimal design of a trigeneration power plant in a hospital complex. Authors in [3] suggested solutions for sizing a trigeneration plant in Mediterranean areas. However they didn’t carry out economic assessment. Authors in [4] have made a techno-economic assessment of biomass fuelled trigeneration system integrated with organic Rankine cycle. Although solutions were technically feasible, economic results for investors wouldn’t be satisfying without subsidies, as the simple-payback time was 17 years. An energy and exergy analyses of a biomass trigeneration system using an organic Rankine cycle was done in [5]. They showed that significant improvement was obtained when trigeneration is used instead of only electrical power production. However, economic assessment hasn’t been done. Authors in [6] have also modelled biomass fuelled trigeneration system in buildings. They showed that the specific investment in trigeneration system is rather high for the small biomass fuelled system. Performance comparison of three trigeneration systems using organic Rankine cycles have been carried in [7]. They showed that in their configurations biomass fuelled trigeneration system has the highest energy efficiency, i.e. 90%. Multicriteria synthesis of trigeneration systems considering economic and environmental aspects was optimized considering specific demands of a medium size hospital in [8]. Authors in [9] tackled the issue of cost allocation when the system is producing different products. On the opposite from the other papers, they have assessed trigeneration system in the residential-commercial sector featuring highly seasonal and daily variable demands, which will also be the case in this paper.

Other authors were dealing with integration of trigeneration systems and different thermal energy storages. In [10] authors combined a trigeneration system and compressed air thermal energy storage. However, they didn't assess large-scale trigeneration system. Integration of trigeneration system and thermal storage under demand uncertainties has been analysed in [11]. They used a hybrid system which produces thermal energy via both electricity and town gas.

Authors in [12] showed that the thermal networks are financially beneficial for areas with high densities and industrial complexes, while for low-density residential areas the economic advantages are not completely clear.

There are also a lot of papers dealing with optimization of power plant location. In [13] authors used mathematical model suggested by Balinski. They have built a model consisting of 17,012 variables which resulted in optimal power plant location for sizes of 10 MW and 15 MW [13]. The linear programming (LP) optimization method was used. They achieved economic feasibility, but dealing only with electricity production from the biomass power plant. Authors in [14] optimized biomass fuelled systems using Particle Swarm Optimization (PSO). They were using profitability index as objective function. They have evaluated three different technologies and in every case, the optimal location was different. They have also evaluated genetic algorithm (GA) against PSO, but the PSO obtained better solutions with a lower number of iterations. Authors in [15] developed a transport cost model consisting of distance fixed and distance dependent biomass transport costs. They have used Euclidian distance for calculations. Among other conclusions they have noted that considering transport costs, installing a smaller
plant at three different locations would be less expensive than installing a single biomass plant. In [16] a mathematical model to optimize the supply chain of a forest biomass power plant was developed. The model considered supply, storage, production and ash management. The paper showed that the biomass purchase cost had the highest share in total cost. Thus, optimizing the biomass costs seem to be an obvious approach in reduction of overall costs.

The novel approach in this paper will be optimization of several factors in a large scale system, including power plant size, absorption unit size and the pit thermal energy storage size. Moreover, location of the power plant will be optimized in order to maximize Net Present Value (NPV). Moreover, the system considered will have to cover all of the heating and cooling energy demand in the city of Petrinja. The system will consist of the trigeneration power plant and seasonal pit thermal energy storage (PTES). The optimal location will be chosen depending upon the power plant size and the size of the distribution network system.

II. METHODOLOGY

A. Problem definition

Maximizing the profit is the key goal of most investors and all the other factors come afterwards. There are many factors influencing income side, as well as the expenditure side of the budget. The key element of the income side of the budget is feed-in tariff received per kWh of electricity produced. Other factors that contribute to the income side are revenue from sold heating and cooling energy. Thus, enlarging the power plant capacity will increase generation of energy rate, which will increase income if all the energy can be sold. On the other side, there are many factors which impact expenditure side such as operating and maintenance costs (both fixed and variable) of: biomass power plant, district heating and cooling network and seasonal storage. Depending on the chosen size of each of these parts of the system, operating and maintenance costs will differ. There are also many factors impacting investment costs. Generally, larger the parts of the system are, larger are the absolute investment costs. However, economy-of-scale can be quite significant when talking about relative investment, i.e. investment cost per kW of capacity. Thus, optimizing all of these factors is crucial in order to maximize profit for the investor.

Among the other factors, location of the biomass power plant is a significant factor that is contributing to the overall results. Choosing different location changes costs of the transportation of the biomass, as well as costs of distributing heating and cooling energy. Thus, optimizing these factors will be emphasized in this model.

B. Model description

The model consists of two major steps. In the first step, the model optimizes sizes of all parts of the system (power plant capacity, absorber unit capacity and seasonal storage capacity), taking into account constraints of the system. The system size is mostly constrained by the heat that can be consumed, and thus delivered, to the final consumers. Thus, this is a heat-driven model. Also, in order to be eligible for the feed-in-tariff, legislation of Croatia requests minimum yearly overall efficiency of the power plant of 50%. As a consequence, there is a finite amount of heating energy that does not need to be consumed by the end users. However, heating (or cooling) energy does not need to be consumed immediately after generation. Surplus of the heating energy production can be stored in the seasonal thermal energy storage and later used, when there will be shortage of the heating energy produced in the power plant. Also, considering the heating and cooling energy needs of the city modelled, the system has to cover all of the heating and cooling energy needs throughout the year on the hourly basis. It is assumed that all the electricity generated can be transferred to the grid due to guaranteed access of the renewable energy to the grid provided by legislation of Croatia.

Afterwards, in the second step the model optimizes the location of the biomass. In the first step biomass price, including transport is fixed and set to the 38 €/t. In the second step, transportation costs will be calculated taking into account the distance between the power plant and the locations of the forests. Price of the biomass at the forest road in Croatia, set by Hrvatske šume d.o.o., will be used for the biomass price. If there is lack of biomass for optimal power plant size, the model calculates additional costs of biomass that can be used from agricultural land that is not being used at the moment. However, on this land biomass has to be planted which increases costs of this type of biomass. For the purpose of this step, location will be divided into 361 quadrants, each with size of 1 x 1 km. Thus, the furthest quadrant will be distanced 12.5 km from the central point of the city considered. After this distance, it is assumed that heating and cooling energy losses in the distribution system are too large.

Optimization method used calculates the savings or losses comparing to the first step for the each quadrant. After positioning in the right quadrant the model calculates the distances of the forests taking into account available biomass. Furthermore, it calculates total costs from the nearest forests, which have sufficient amounts of biomass, including transportation costs from these forests. It also calculates the losses that are caused by increased distribution losses of heating and cooling energy, increasing the heating and cooling energy losses by 1% per kilometre, moving away from the centre of the city. Increased investment in the main pipe when moving away of the city centre is also taken into account. Finally, the model chooses the optimal location, i.e. location with the highest savings comparing to the first step. Moreover, the model van graphically shows changes in the savings or losses in each quadrant.

C. Biomass power plant

The size of the biomass power plant is calculated taking into account constraints of overall yearly efficiency that has to be satisfied in order to be eligible to receive the feed-in-tariff. Overall yearly efficiency, taking into account electricity produced and heating and cooling energy consumed by the
end-users, has to be above 50%. Availability of the power plant is set to 90%. Thus, the model calculates the period with the lowest heating and cooling energy demand and shuts down the power plant for maintenance. In this period, heating and cooling energy demand is covered solely from the seasonal storage. Biomass moisture is considered to be constant throughout the year and is set to 30%.

D. Seasonal thermal energy storage

Pit thermal energy storage (PTES) was chosen for the seasonal heat storage mostly due to low investment costs and well-known technology for building large-scale storages of this type. Water as storage is a mature media, and taking into account its large specific heat capacity, proves to be valuable choice for the energy storage. PTES are the largest thermal energy storages being built according to [17]. Typical efficiency of such storage is between 80% and 95% depending on temperature level in the storage. Significant economy-of-scale is present in this kind of storage, but only up to volume of 50,000 m³. After this size, economy-of-scale does not change significantly. Thus, building several storages can provide equal investment burden for the investor, but in the same time it facilitates maintenance and construction of these storages.

E. Heating and cooling energy demand

A degree hour is a method used for calculating yearly heating and cooling energy demand on an hourly resolution. Specific energy consumption per m² was set to 160 kWh/m² per annum, as insulation in Croatia is still not satisfying. As only single pipe was predicted, and the absorber units are centrally located, there is not a possibility of simultaneous flow of both heating and cooling energy in the same time. However, this shouldn’t be a problem as there are no large industrial consumers which need to have constant heating energy supply.

F. Absorbers

Absorbers in the system are centrally located and thus, cooling energy is distributed via piping. They can be driven by both heat produced from the biomass power plant, or by heat taken from the pit seasonal thermal energy storage. Absorbers should function properly, as the predicted temperature of media in seasonal thermal energy storage is between 85 °C and 90 °C. Due to lower investment costs, absorbers got preference comparing to adsorbers.

G. Location of the power plant

There are several forests which can provide biomass. Only forests owned by state company Hrvatske Šume d.o.o. were taken into account in this model as they can provide stable supply with long-term contract. Coordinates from central point of each of the forests was used for calculations. For the city of Petrinja, in total 52 forests in reasonable distance provide biomass that can be used to fuel the biomass power plant. For the case study of Petrinja, coordinates of additional agricultural land that could be used for planting biomass were unknown, as there is lack of systemized data available. Thus, although the model can calculate with this additional land, for this case study it won’t be used. After the optimal location has been chosen, results show names of forests that the biomass was taken from with associated amounts of biomass. For the transportation costs, price of 0.1 € / (km · t) has been used [18]. Nevertheless, Haversine formula has been used for calculation of distances between two points. Haversine formula calculates distances between two points on sphere. As distances in this model aren’t large, difference between the real shape of the planet Earth and sphere is not significant and thus, this formula can be used.

III. OPTIMIZATION MODEL

Optimization variables

Four independent variables exist in this model:

- \( L_{BP} \) - coordinates of optimal location of the biomass power plant (latitude, longitude)
- \( P_{el} \) - electricity generating capacity of the biomass trigeneration power plant in kWₑ.
- \( S_v \) - volume of the storage in m³
- \( P_A \) - capacity of the absorber unit(s) in kW

Objective function

Overall objective function is to maximize net present value. In the first step, the model calculates NPV using the fixed biomass price set to 38 €/t. In the second step model tries to improve NPV value by optimal positioning of the power plant in order to save some amount of funds that would be spent on transportation. Larger the savings are, better the improvement of NPV value is. NPV is calculated for the time of 14 years, as this is the time of guaranteed feed-in tariff in Croatia. The NPV function in the first step is:

\[
\text{NPV} = \left( l + l_A - E_{OM,B} - E_{OM,BO} - E_{OM,DKH} - E_{OM,ST} - E_{B} \right) \cdot D - \text{inv}_A - \text{inv}_B - \text{inv}_{DHC} - \text{inv}_{OM} \cdot (T_A - T_R) \cdot D - l_{ADD}
\]

where discount coefficient \( D \) is calculated as follows:

\[
D = \frac{1}{(1 + i)^t}
\]

where \( i \) is the discount rate and \( t \) is the project lifetime. In the second step savings (losses) are calculated as follows:

\[
S = \left( (T_A - T_R) - DHC_{YL} \right) \cdot D - l_{ADD}
\]

Where \( S \) are total savings (if comparing to the first step losses occurs, the result is negative) comparing to the first step, \( T_A \) are assumed transportation costs in the first step and \( T_R \) are real calculated transportation costs of biomass. \( DHC_{YL} \) are yearly losses [€] that occurs because of higher distribution network losses due to larger distance between the power plant.
position and the consumers. $I_{ADD}$ is additional investment cost in the main pipe due to larger distance between the power plant position and the consumers than in the first step.

Overall NPV is then calculated by adding savings (already discounted) to the NPV value from the first step:

$$NPV_0 = NPV + S$$

where $NPV_0$ is final net present value.

**Income**

Income consists of 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 $I_h$ equals:

$$I_h = h_p \sum_{j=1}^{8760} h_j$$

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:

$$I_c = c_p \sum_{j=1}^{8760} c_j$$

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:

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

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.

**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:

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

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

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

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

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

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

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

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:

$$E_{OM, S} = U \cdot S_f$$

where $U$ is the O&M price of the yearly storage maintenance (€/m³).

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

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

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

In the second step, real transportation costs $T_R$ has to be calculated in order to calculate savings (losses) comparing to the first step.

$$T_R = T_{coeff} \cdot \sum_{j=1}^{8760} DIS_f k$$

where $T_{coeff}$ is transportation cost per kilometer per ton and $DIS_f$ is the distance between the $k$-th forest and the power plant. Parameter $k$ is the number of forests the biomass is taken from.

**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:

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

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

$Inv_A$ is the price of investment in absorption chillers:

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

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:

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

where $N_{inv}$ is the investment per dwelling (€/dwelling). In this model $N_{inv}$ was used from Ref. [19].

Investment in the pit thermal energy storage $Inv_S$:
\[ Inv_S = S_{inv} \cdot S_Y \]

where \( S_{inv} \) is the price of storage investment (€/m\(^3\)), which was implemented in this model from Ref. [17].

In the second step additional investment \( I_{ADD} \) can occur because power plant is located further away then assumed in the first step. Thus, this additional investment cost has to be calculated:

\[ I_{ADD} = DIS_{add} \cdot S_{pipe} \]

where \( DIS_{add} \) is additional distance (km) of the power plant comparing to the first step, while \( S_{pipe} \) is the cost of the main pipe (€/km).

**Constraints**

1) **Constraints in the first step**

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:

\[ h_{B,j} + h_{S_{inv},j} \geq h_j \]

where \( h_{B,j} \) is the hourly heat production in the biomass power plant and \( h_{S_{inv},j} \) 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:

\[ \left( h_{B,j} + h_{S_{inv},j} \right) \cdot \frac{1}{COP} \geq c_j \]

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:

\[ P_{el} \cdot HTP + S_Y \cdot \rho_w \cdot c_p \cdot \Delta T \cdot \frac{1}{3600} \cdot \eta_S \geq h_{peak} \]

where HTP is the heat-to-power ratio, \( \rho_w \) is the density of water (kg/m\(^3\)), \( c_p \) is the specific heat capacity of water (kJ/(kgK)), \( \Delta T \) is the difference in temperature of stored water and the design temperature of the dwellings’ heating systems (K), \( \eta_S \) 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:

\[ P_{el} \cdot HTP \cdot COP + S_Y \cdot \rho_w \cdot c_p \cdot \Delta T \cdot \frac{1}{3600} \cdot \eta_S \cdot COP \geq C_{peak} \]

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

\[ h_{S_{inv},sum} \cdot 3600 \cdot \frac{1}{c_p} \cdot \frac{1}{\Delta T} \cdot \frac{1}{\rho} \geq S_Y \]

where \( h_{S_{inv},sum} \) 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).

\[ e + h \geq P_{el} \cdot \frac{1}{\eta_d} \cdot B_{av} \cdot 8760 \cdot \eta_X \]

where \( e \) and \( h \) present the produced electricity and heat demand during one year of power plant operation, \( \eta_d \) is the electrical efficiency of the power plant, \( B_{av} \) is the availability of the biomass power plant and \( \eta_X \) is the minimum overall efficiency power plant needs to have to be eligible to receive subsidy. Today, in Croatia \( \eta_X \) would be 0.50.

2) **Constraints in the second step**

In the second step, all the constraints are connected to the minimum/maximum distance from the central point of the city. The power plant has to be distanced minimum five kilometres from the central point of the city in order not to have heavy trucks carrying biomass through the city. Moreover, the furthest allowed distance of the power plant from the city centre will be set to 14 kilometres as it is assumed that losses after this distance will become too large.

\[ DIS_H(PP_p - C_{CO}) \geq 5 \]

\[ DIS_H(PP_p - C_{CO}) \leq 14 \]

where \( DIS_H(PP_p - C_{CO}) \) is the distance between the power plant position and the central point of the city calculated by Haversine formula.

**Optimization method**

In the first step of the optimization model hybrid optimization was used. In order to increase the speed of calculation the model firstly drives Genetic Algorithm (GA), which is a useful tool for fast approaching to a global optimum. Comparing to the classical algorithms, where a single point is created at each step [20], genetic algorithm generates a population of points at each iteration and thus, approaches global optimum fast. However, near the global optimum GA converges rather slowly, so fmincon is a useful and fast optimization method, when an initial point near the global optimum is known. Thus, in the first step Genetic Algorithm and fmincon were used as optimization methods.

In the second step, the model searches for minimum costs of transportation subtracted by increased costs of distribution network investment. The model searches for minimum transportation costs from every quadrant in the 10 x 10 kilometres network. Thus, the quadrant with the lowest transportation costs subtracted by increased investment cost in the main pipe is the optimum solution, i.e. the largest savings
compared to the first step are achieved. Optimization was programmed in Matlab®.

### IV. CASE STUDY DESCRIPTION

The model was applied to the city of Petrinja, Croatia. It has a total population of 24,671, living in 8,736 households. Average distance between the household was set to 10m. Average yearly heating energy consumption is 160 kWh/m². Input data is provided in Table 1.

#### Table 1. List of the data used in the case study

<table>
<thead>
<tr>
<th></th>
<th>amount</th>
<th>unit</th>
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<tbody>
<tr>
<td>Power plant availability</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Biomass price</td>
<td>36</td>
<td>€/t</td>
</tr>
<tr>
<td>Biomass price at forest</td>
<td>32</td>
<td>€/t</td>
</tr>
<tr>
<td>road</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower calorific value</td>
<td>3,500</td>
<td>kWh/t</td>
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<td>(30 % moisture)</td>
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<td></td>
</tr>
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<td>η power plant total</td>
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<td></td>
</tr>
<tr>
<td>ηel</td>
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<td></td>
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<tr>
<td>HTP ratio</td>
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</tr>
<tr>
<td>T_{conf}</td>
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<tr>
<td>S_{pipe} [21]</td>
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<td>€/km</td>
</tr>
<tr>
<td>B_{inv}</td>
<td>3,600</td>
<td>€/kW_{e}</td>
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<tr>
<td>A_{inv}</td>
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<td>N_{inv}</td>
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<td>S_{inv}</td>
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<td>Plant own electricity</td>
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<tr>
<td>consumption</td>
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<tr>
<td>Discount rate</td>
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<tr>
<td>Feed-in-tariff</td>
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<td>€/kWh_{e}</td>
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<td>COP</td>
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<tr>
<td>Design temperature for</td>
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<td>°C</td>
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<tr>
<td>heating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design temperature for</td>
<td>24</td>
<td>°C</td>
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<td>cooling</td>
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<td></td>
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<tr>
<td>F</td>
<td>29</td>
<td>€/kW per annum</td>
</tr>
<tr>
<td>V</td>
<td>0.0039</td>
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<td>N</td>
<td>75</td>
<td>€/dwelling per annum</td>
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<td>h_p</td>
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</tr>
<tr>
<td>C_p</td>
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</tr>
<tr>
<td>Forestry residue</td>
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</tbody>
</table>

Three case studies were performed in order to evaluate the importance of optimization of location of biomass power plant.

The first step of the optimization, the step that chooses the optimal size of the power plant is unique for all case studies. However, different case studies for the second step of optimization will be developed in order to show importance of optimizing location of the biomass power plant. Yearly available biomass equals 132,890 m³.

#### Case study I

In the case study I, construction of power plant with capacity of 5 MW_{e} was assumed (in this case, optimal size of the power plant from the first step of the model will be neglected). This relatively small size of power plant, will show how significant are the differences by choosing the right location for the power plant when biomass supply is significantly larger than the need.

#### Case study II

In the case study II, complete optimization model will be done in order to fully evaluate the developed model. After the optimal size of the power plant will be calculated, the model will search for the optimal location of the power plant. Moreover, differences between the most favourable location and the least favourable location will be shown. The data from the Table 1 will be used in this case study.

#### Case study III

In the last case study, several smaller power plants will be assumed. Each of three power plants will have equal capacity. The capacity of the single power plant will be calculated after the optimal size of the power plant will be calculated in the first step of the model. After the first step, optimal size of the biomass power plant will be divided by three in order to have equal final capacity, but in three different power plants.

It is assumed here that power plants will be built one by one, so the first power plant will be optimized according to all available biomass, then the location of the second power plant will be chosen according to remaining biomass and then finally, the location of the third power plant will be chosen from remaining biomass.

In this way, building several smaller power plants, step by step, can reduce capital intensity of the whole investment in the starting point. Moreover, in this case study growth of the price of biomass for each power plant will be observed and evaluated.

#### V. RESULTS

##### A. Case study I

For the power plant with total capacity of 5 MW, using in calculation the data provided in Table 1., yearly biomass consumption is 37,540 tons. For this type of power plant, south-west position is the most appropriate one with average yearly cost of biomass of 34.91 €/t.
Fig 1. Biomass price in different quadrants (from higher to lower average price: red, orange, yellow, green, blue, purple and pink; the black quadrant represents the optimal solution; white quadrants are subject to constraints and these locations cannot be chosen)

It can be seen from the Fig 1. that potential locations for small biomass power plant are generally better in the south than the north. The best location (coordinates: 45.3523, 16.2199) is located in the south-west (black quadrant). Nevertheless, it can be observed that the cheapest biomass cost and thus, larger the savings are, moving from the north to the south. Yearly savings comparing the best position (south-west) and the worst position (north-west) equals 18,640 €. This saving represents 1.5% of yearly spending on the biomass. The result shows that savings on the small scale are not significant.

B. Case study II

In case study II complete model was used. The results from the first step of the model showed that optimal size of the power plant for the city of Petrinja is 21.6 MW. The optimal size of absorber(s) is 15.9 MW as it needs to cover the entire peak cooling energy consumption. The optimal pit thermal energy storage size is 32,765 m³. The NPV value with the assumed parameters equals EUR 3,808,497.65. It should be noted here again that the assumed biomass price in the first step of the model was 36 €/t.

Yearly biomass consumption is large and equals to 162,182 tons. In order to obtain this amount of biomass forestry residue should be around 28%.

The lowest average biomass price equals 37.21 €/t. The optimal location is located in the south-east (coordinates: 45.3613, 16.3974). The most expensive average price equals 38.53 €/t which is a significant difference. It can be generally observed that average biomass prices reduce going from west to east and from north to the south. The yearly savings comparing the optimal location and the most expensive one is significant and equals 214,568 Euros. That is 3.6% of the yearly spending on the biomass. Comparing to the first part of the simulation, NPV is lower in both cases because assumed biomass price was set to 36 €/t which proves to be too low. NPV, when the optimal location is chosen, equals EUR 2,091,675, while on the least optimal location NPV equals EUR 218,777, which is a significant difference. These results show the significance of the right selection of the location, as the NPV value can soon become less favourable for the economic investment.

C. Case study III

In the third case study, three power plants, each with the size of 5 MWₑ was chosen to be built in the area around the city of Petrinja. Result for the first power plant can be seen in the results of the case study I (see Figure 1.).

Optimal location of the second power plant (coordinates: 45.5143, 16.3974) with capacity of 5 MWₑ can be seen in Figure 3.

Compared to the first power plant with the capacity of 5 MWₑ, the optimal location now is diametrically different. Optimal location for the second power plant is in the north-east, while the optimal location for the first power-plant was in the south-west. The average biomass price has also become more expensive and at the optimal location equals 35.99 €/t, while on the most expensive location equals 37.53 €/t. Thus, the yearly saving that can be achieved equals 57,830 EUR, i.e. 4.3% of yearly spending on the biomass.

The optimal location of the third power plant (coordinates: 45.3523, 16.3974) can be seen in Figure 4.
For the third power plant with capacity of 5 MWc, the optimal location is located in the south-east. It can be observed that the average biomass price reduces gradually from the north-west to the south-east. The average biomass price on the optimal location equals 38.92 €/t, while on the most expensive location equals 40.53 €/t. Thus, the yearly saving on biomass by choosing the optimal location can reach 60,698 EUR, i.e. 4.2% of the yearly spending for the biomass.

It is good to look again at the optimal locations of the three biomass power plants, each with capacity of 5 MWc. The first one was located in the south-west, the second one in the north-east and the third one in the south-east. It shows how the optimal location can be easily changed, if the biomass from the one location is reserved for some other purposes, and thus, not available for the power plant.

VI. CONCLUSIONS

In this paper, several case studies were performed in order to assess importance of choosing the optimal power plant location. Several conclusions can be made from this analysis:

- By increasing the power plant size, the saving in biomass costs increases significantly comparing to the smaller power plants
- Reserved biomass for other purposes and thus, unavailability for the current project changes the power plant optimal location dramatically
- Several smaller power plants will have quite different optimal locations than the one large scale power plant
- NPV value can significantly change by choosing non-optimal locations
- Choosing the optimal location of the trigeneration power plant can significantly improve the economic parameters and move the project towards economic profitability for the investor

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