Application of the minimum spinning tree (MST) approach to searching for an optimum location of biomass storage

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1. Introduction

The energy policy of European Union obliges member states to increase share of renewable energy in the overall energy balance. According to the climatic and energy package [1] Poland by 2020 is obliged to achieve such goals as growth of energy from renewable sources by 15%. The share of renewable energy comprises generation of electric power and heat as well as production of environment-friendly fuel. The use of energetic potential offered by biomass depends on many factors of both global and local magnitude. The most important factor is the economic one that is the key precondition for erection of power generating facilities fuelled with biomass [7]. Renewable energy sources are local ones and may improve the level of energy safety. The degree of the biomass utilization at the local scale, i.e. at the municipal or commune level substantially depends on accurate investigation of local opportunities for biomass production. Determination of the energy amount that can be generated from biomass is referred to an estimation of the biomass energetic potential [4, 5].

Usefulness of the energetic potential estimation may vary depending on the evaluation level. Nevertheless, whichever estimation method is applied and regardless its accuracy the knowledge about the potential size for specific types of biomass is not sufficient to take a decision about its utilization. Such a decision must be stemmed out from investigation of numerous conditions and economic factors that are only indirectly associated with the potential amount and opportunities for its utilization. The process of estimation how much of biomass is available should be only one component of a multistage and multi-criteria optimization analysis with where databases of statistical information and the GIS system are involved as well.

One of significant component of the optimization task for the process of acquisition and utilization of biomass for power generation consists in searching for the optimized solution for transportation tasks.

2. Characteristics of nature and climate in the Opole Province (voivodeship)

The province of Opole is situated in south-west part of Poland in the basin of the Odra river. It occupies the area of 9,412 km² of that about 60% falls to arable lands and 27% to forests. The Opole Province borders on the province of Lower Silesia, Great Poland (Wielkopolska), of Łódź and Silesia. In south the Opole region has the common border with the Czech Republic.

In terms of geographic location about 75% of the Province area fits within the Silesian Lowland, the remaining parts are in mountains. The Opole region is the province with the smallest area in Poland and is rated among the provinces with the lowest population. Typical inhabited regions within the Province are large villages that represent sizeable populated units and demonstrate high degree of urbanization. Rural areas occupy about 92% of the Province. With regard to economy, the Province is classified as a agriculture and industrial region, where agriculture is stimulated by beneficial natural conditions. The region boasts with the highest efficiency of agricultural production within Poland, which results from advanced culture of farming and favourable climatic and soil conditions (the vegetation period of plants lasts from 200 to 225 days). The agricultural production is substantially important for the south, western and north parts of the Province where, likewise the entire region, one can find high share of modern farms with high potential for further growth. With regard to size, farms in the Province of Opole are rated among the medium size ones within the country with the average are of a peasant farm amounting to 10.1 ha).

The Province area also comprises sections of nature conservation protected by law, such regions make up 28.38% of the Province area [2] (Tab. 1)

3. Renewable source of energy in the Nysa County, their utilization and expansion prospects associated with the biomass energy

The investigations covered all communes within the county of Nysa. The county is located in the south-west part of the province with the most area assigned for agricultural purposes. Considerations about selection of the area for investigations must be started from exclusion of lands of conserved nature and landscape. Figure 1 presents depicts such areas in the Nysa county. Each form of nature conservation is governed by specific legal regulations that practically disable implementation of many investment projects.

![Fig. 1. Areas of conserved nature and landscape in the Nysa county [2]](image-url)
The next phase of undertaken analyses shall comprise survey of places where basic sources of heat supply are located. Thermal energy for demands of town inhabitants is chiefly supplied by municipal heating systems. In addition, some boiler houses, mostly coal-fired, provide heat for clients in individual communes. The production of heat was evaluated on the basis of reports developed for communes of the Opole province [2]. Figure 2 depicts locations of individual sources of heat supply in the Nysa county. In total, the overall installed power of professional and industrial power plants amount to 8.3 MW with generation of 10.1 GWh/year.

Fig. 2. Locations of basic sources of supply with thermal power

In the Nysa county production from biomass is based on firewood, straw and products from farms of firewood plants for power engineering. Farms of such plants in the investigated region occupy about 3% of arable land. In the Nysa county such farms (i.e. woods of trees with short lifetime – willow) are located in such places as Włostowa and Nysa and occupy 29 ha of arable land altogether that makes up ca. 25% of all firewood farming in the province of Opole.

The primitive manner for utilization of biomass in the province of Opole consists in combustion. In the Nysa county predominantly straw is combusted with further utilization of generated thermal power for heating of greenhouse and for drying cereals. Straw and sawdust is also used of production of fuel – pellets or briquettes of wooden chips. Nowadays in the Nysa county there are five technological plants that use biomass to produce pellets and briquettes and their total output is about 660 t/month. Figure 3 depicts how biomass is used for heat generation in the Nysa county.

Fig. 3. Use of biomass for heat generation in the county of Nysa

4. Estimation of energetic potential offered by biomass – the methodical approach

In 2009 exactly 253153 TJ of energy was generated in Poland from renewable sources that makes up 9.0% of primary energy in total [7]. The most important item in the balance of renewable energy falls renewable sources that makes up 9.0% of primary energy in total generation in the Nysa county.

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In terms of practical utilization of the estimation results, the energetic potential of biomass can be classified in the following way [4]:

- theoretical potential – amount of energy that can be generated from biomass provided that efficiency of the generation plant is 100% (with no account for imperfection of the generation process) and also under the assumption that the total available potential is exclusively used for power generation
- technical potential – represents the part of the theoretical potential and reduced due to technical restrictions (limited efficiency of equipment available in the market, auxiliary needs of the power generation process)
- economic (market, business) potential – depends on fuel process, rates of taxes, economic indices and amounts of financial supports. It is the part of technical potential that can be reasonable utilized under cost-effective terms with consideration to economic criteria and tools (detailed analyses of profitability)

Evaluation of potential offered by energy sources can be carried out in many ways, where selection of an adequate method chiefly depends on the type of specific potential. To improve usefulness of the procedure applied to potential estimation it is first necessary to develop a suitable algorithm for estimation of the energy potential offered by biomass, such an algorithm should take account for gradual drop of the potential due to technical and economic restriction (Fig. 4).

Calculation of the potential on the theoretical and technical levels makes it possible to learn, in a simple and quick way, how to satisfy demand of a specific commune for heat and power. To calculate these types of potential one has to know a series of input data and the calculations themselves always need many simplifications and additional assumptions. The necessary information include, first and foremost, all available statistical data (acreage of crops and other lands in the commune, amount of animal breeding), information on yield of crops and availability of specific biomass types as well as information about physical and chemical properties of available biomass types as well as efficiency of equipment to be used for conversion of chemical energy to usable forms of power. Calculation of energy potential offered by biomass assumes unification of the power unit for both thermal and electric energy as GWh (per year) since such a solution makes much more easier to carry out quantitative balances and comparisons of energy potential for selected type of biomass [5].

Fig. 4. Diminishing of energy potential offered by biomass in pace with the level of its estimation

The way how to determine theoretical energy potential is explained on the example of the arbitrary selected biomass type – cereal straw. Calculations are always carried out for a confined territory, e.g. for the area of a single commune. The first phase of computations comprises adoption of assumptions, where a part of them is derived from statistical data. In case of cereal straw (similarly to any other type of green biomass) the following input information must be available:

- acreage or cereal planting A, ha
- availability D, %
- yield of drops (or annual growth) I, t/ha
- annual acquisition P, %
- calorific value of biomass $W_p$, GJ t⁻¹.
For each biomass type (e.g. cereal straw) the value of technical potential is calculated as a product of all foregoing parameters. When calculation of the technical potential is a point, the computations must consider efficiency of energy conversion, e.g. efficiency of a boiler for biomass combustion and generation of heat.

Anyway, as it was mentioned before, usefulness of such a procedure is rather low due to the need to rely on substantial simplifications and approximations during the initial phase when preliminary assumptions and input data are adopted for computations as well as due to the fact that results of such an estimation may be merely a starting point for further analysis and detailed investigations. Amounts of technical potential expressed in GWh/year for individual communes of the Nysa county are depicted in Figure 6.

![Figure 6: Technical potential of straw in the Nysa county, GWh/year][2]

The next step of the estimation procedure should consist in determination under the economic terms. Such a cost-effectiveness balance needs consideration to actual conditions for provision of financial resources for the investment as well as necessary expenses and possible incomes achievable during the plant operation. Thus, it is associated with detailed economic analyses, where the key component of such an analysis consists in optimization of costs, including expenses on transportation of biomass.

The further part of this study is devoted to application of an optimizing algorithm that is based on the theory of graphs and serves as the tool suitable to seek for the shortest transportation route.

**5. Application of the theory of graphs to seeking for the shortest route**

The theory of graphs is an independent mathematic discipline that has found broad application in many branches of science. It allows finding the shortest way between a set of points (graph nodes) with consideration to weight factors pre-assigned to graph edges. The task can be resolved with use of a number of tools, including the Kruskal’s algorithm, Prim’s algorithm, A algorithm or Floyd-Murdochland’s algorithm.

The graph $G = (V, E, w(e))$ can be considered, with a certain simplification, as a set of nodes $v_i$ that can be mutually connected with edges $e$, in such a way that each edge begins and ends in any of the nodes $[3]$. The characteristic feature of graphs is the possibility to assign weight coefficients to each edge of the graph by means of the $w(e)$ function that determines these weights. The weight coefficient of graph edges may be real or integer numbers and express, for instance, distances between the nodes. Searching for the shortest way consists in finding so called Minimum Spanning Tree (MST), i.e. such a tree that the total weight of all the edges in the tree is the least of all possible trees.

$$
\sum_{e \in E} w(e) \rightarrow \min
$$

For this study the Prim’s algorithm was applied to find out the MST for graphs that reflect locations where biomass is planted and where is used for energy generation (graph nodes) and the interconnecting road network (graph edges). The algorithm makes it possible to draw up the MST according to a predefined procedure. Construction of the Minimum Spanning tree begins from arbitrarily chosen node of the graph, for instance $v_i$. Then the edge with the minimum weight should be chosen from all graph edges that are incident to $v_i$. Let it be the $\{v_i, v_j\}$ edge. In each step of the algorithm the edge with the minimum weight is sought, where the edge must connect a certain node already included into the tree and a new node, i.e. the edge must be external to the set of graph nodes that is equal to the set of graph edges.

The Prim’s algorithm operation is explained on a simple example (Fig. 7). The notation $\{v_i, v_j, w\}$ was adopted, which stands for the graph edge that connects $(v_i, v_j)$ nodes and its weight is $w$.

Let us assume a connected weighted undirected graph as in Figure 7. The initial step consists in arbitrary selection of a node, for the presented example the procedure starts form the edge A.

![Figure 7: Searching for the Minimum Spanning Tree (MST) with use of the Prim’s algorithm.][4]

Then the sorted list is created, such that $L = \{[, A,E,1], [A,F,2], [A,B,6]\}$. Next, the edge with the minimum weight is chosen from that list – for this graph it is the $(A,E)$ edge. In the subsequent step the set of $L$ is supplemented with additional edges and the set adopts the content $L = \{[, A,F,2], [E,B,2], [E,D,3], [A,B,6], [E,F,7]\}$. This time the $(A,F)$ edge is selected. The procedure is repeated until the last edge is selected and that edge connected the spanning tree with the last node of the graph (for the example in place it is the node D).

The algorithm converts the initial graph that is subjected to the optimizing analysis into the graph in the form of the minimum spanning tree with the minimum possible total weight of edges (the calculated minimum distance for the presented example is $2 + 1 + 2 + 2 + 3 = 10$) (Fig. 8).
6. Procedure and results of searching for the shortest route of straw delivery

This section of the study outlines the course and results from the optimizing analysis carried out by means of the Prim’s algorithm described in the previous section. Computations were performed for elected communes of Nysa county and the already determined theoretical energy potential of straw sourced from farms located on the areas of the communes covered by the analysis served as the initial base. The values of calculated energy potential are summarized in Table 2.

<table>
<thead>
<tr>
<th>No.</th>
<th>Commune name</th>
<th>Adopted marking code</th>
<th>Theoretical potential of straw, GWh/year</th>
<th>Technical potential of straw, GWh/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Paczków</td>
<td>+PCZ</td>
<td>35.14</td>
<td>19–23</td>
</tr>
<tr>
<td>2</td>
<td>Otmuchów</td>
<td>+OT</td>
<td>65.56</td>
<td>30–34</td>
</tr>
<tr>
<td>3</td>
<td>Głuchołazy</td>
<td>+GŁ</td>
<td>52.16</td>
<td>23–26</td>
</tr>
<tr>
<td>4</td>
<td>Nysa</td>
<td>+NS</td>
<td>81.60</td>
<td>30–34</td>
</tr>
<tr>
<td>5</td>
<td>Kamiennik</td>
<td>+KM</td>
<td>38.81</td>
<td>19–23</td>
</tr>
<tr>
<td>6</td>
<td>Pakosławice</td>
<td>+PK</td>
<td>36.81</td>
<td>19–23</td>
</tr>
<tr>
<td>7</td>
<td>Skoroszyce</td>
<td>+SK</td>
<td>48.44</td>
<td>23–26</td>
</tr>
<tr>
<td>8</td>
<td>Łambinowice</td>
<td>+ŁM</td>
<td>36.70</td>
<td>11–15</td>
</tr>
<tr>
<td>9</td>
<td>Korfantów</td>
<td>+KF</td>
<td>71.62</td>
<td>23–26</td>
</tr>
</tbody>
</table>

Further studies were limited to six communes (+OT, +KM, +PK, +SK, +ŁM, +KF) where the determined energy potential exceeds the annual demand for municipal heat required by these communes. Selected communes and sites of straw harvesting are depicted in Figure 9.

The completed analysis in aimed to determination of the shortest route that connects locations where straw is harvested in individual communes and then one has to seek for the shortest route between sites where straw is stored in individual communes and the possible locations of a system for energy generation.

The completed analysis comprises two phases. During the first one the Minimum Spanning Tree was found out for the selected sites in communes from (Fig. 9) along with the associated sums of edge weights (the shortest routes that connect the selected sites). For the second phase one site on the area of each commune was selected from among all the places covered by the analysis and appointed as the destination where biomass (straw) should be delivered. Then the location for generation of energy from the gathered biomass was chosen and connected through the road network to sites of biomass storage. The optimization analysis was repeated for the graph drawn up in the foregoing way in order to find out the best (shortest) routes for delivery of biomass from individual communes to the site where is should be converted into usable form of energy.

Figure 10 explains course of the algorithm that finds the minimum route between sites in the commune of Otmuchów (+OT) with consideration to weight coefficients (distances) between individual inhabited places.

The minimum sums of weight coefficients calculated as the results of the optimizing analysis carried out for individual communes are summarized in Table 4.

<table>
<thead>
<tr>
<th>Commune</th>
<th>+OT</th>
<th>+KM</th>
<th>+PK</th>
<th>+SK</th>
<th>+ŁM</th>
<th>+KF</th>
<th>Σw_{min}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paczków</td>
<td>31.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nysa</td>
<td>15.7</td>
<td>14.9</td>
<td>20.3</td>
<td>20.9</td>
<td>39.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 11 depicts the graphical explanation how does work the algorithm for searching the shortest routes between the locations where biomass is gathered and stored in each commune and the site where it is converted into energy.

As one can see (Fig. 11, Tab. 5) the graph that is created by connecting individual sites with road sections has no edges between some nodes. It results from the fact that there is no direct road path between sites located at the ends of such edges where the connections would bypass other sites incorporated into the graph. Such direct connections, if any, would require assignment of very high weight coefficients and will be eliminated anyway by the Prim’s algorithms.
7. Final conclusions

The usefulness of potential from estimation at the theoretical and technical level is quite low since a substantial gap between the theoretical potential and respective economic and available (usable) potential.

Results that have been achieved as the result from estimation of biomass potential at the technical and theoretical level may serve as the kickoff points for further research studies that can be conducted by territorial units with use of tools developed for cost-effective, technical and business analysis of possible power engineering enterprises associated with conversion of biomass into usable forms of energy.

The theory of graphs can be applied to the algorithm of optimization procedure to determine the potential of energy production at the economic (business) level.

The Prim’s algorithm makes it possible to find out the shortest route between the selected points (e.g. sites) within the area under investigation, however more than single weight coefficients can be applied to find out the optimum route in terms of more than a single criterion.

The algorithm can be expanded and provided with tools suitable to seek for optimized sites (e.g. the site for conversion of acquired biomass into usable forms of energy).

References


Table 5 summarizes weight coefficient for individual edges of the optimized graph as well as the total value of the minimum weight \( \Sigma w_{\text{min}} \) (the shortest possible route that connects the sites covered by the analysis).

<table>
<thead>
<tr>
<th>Site name</th>
<th>Symbol</th>
<th>KM</th>
<th>G</th>
<th>P</th>
<th>M</th>
<th>MW</th>
<th>K</th>
<th>( \Sigma w_{\text{min}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karłowice Male</td>
<td>KM</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Grądy</td>
<td>G</td>
<td>6.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pakostawice</td>
<td>P</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Makowice</td>
<td>M</td>
<td>17.0</td>
<td>3.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Malżarzów Wielkie</td>
<td>MW</td>
<td>x</td>
<td>x</td>
<td>9.2</td>
<td>9.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Korfantów</td>
<td>K</td>
<td>x</td>
<td>x</td>
<td>20.3</td>
<td>16.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Złotogłów (miejsce produkcji energii)</td>
<td>Z</td>
<td>18.4</td>
<td>15.5</td>
<td>10.7</td>
<td>x</td>
<td>x</td>
<td>14.4</td>
<td>58.9</td>
</tr>
</tbody>
</table>

Fig. 11. Application of the Prim’s algorithm to searching for the minimum transportation routes for delivery of biomass to the site of energy production.

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