JJMIE

Jordan Journal of Mechanical and Industrial Engineering

*Volume 4, Number 1, Jan. 2010*
*ISSN 1995-6665*
*Pages 91 - 110*

# Comparison of Biogas Supply Chains Using the Example of the Conditions of a Municipality

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## 1. Introduction

Due to scarcity of oil fields and the constant rise of energy needs of the industrialized countries, alternatives of power supply must be found. In addition, the rising energy demand provides a drastic increase of CO2 emissions, which among other reasons are also responsible for the climatic change. In the climatic protection package valid since 2008 a reduction of up to 40% in CO2 levels is aimed by the year 2020 [1]. In order to achieve this objetive, an increase of the portion of renewable energies is intended for the energy and heat supply. In the past five years the portion of renewable energies of the total energy consumption in Germany has doubled and is now 8,6 percent [2]. Waste management carries also a large portion of CO2 emissions in Germany besides industry. So called biogenous waste from nearly all areas such as households, industry and the waste water treatment indicate a great potential for energy supply and reduction of CO2 emissions [3] (See Figure1).

Biogenous waste in Germany (liquid manure, sewage sludge, forestal debris, industrial waste and old timber, straw, bio green waste, biogenous portion of the domestic house waste, leftovers from commercial sources among other materials) are estimated to represent 80 millions Mg (Megagram) of dry matter per year [4]. In the case of complete energetic utilization from this matter, an amount of 400 $TWh_{th/a}$ (Terawatt hour, thermic per Year) could be generated, constituting an approximate of 24% of the current consumption of the Federal Republic of Germany[5].

Due to the substitution of coal with biogenic waste, approximately 160 Million Mg $CO_2$ would be saved with an emission factor of 0,4 Mg $CO_2$ /$Mwh_{th}$ (Megagram $CO_2$ per Megawatt hour, thermic) assumming for that, a closed $CO_2$-Cycle for the Bioenergy carriers and total utilization of biogenetic waste. With it the required emission reductions in both relevant sectors (Energy, and Waste management) will be by far surpassed[6]. With the prohibition of dumping of non pre-treated waste, which aim to strongly reduce a deposition of pre-treated biogenous waste and to prohibit the feeding of leftovers to animals in the entire European Union. New disposal ways for this waste fraction must be searched now.

The production of biogas in biological gas facilities or sewage purification plants represents a meaningful linkage between energy and waste management. The energetic use of biogenous waste opens possibilities of carrying out both the climatic protection and the power supply goals on a regenerative basis. Thus not only contribution is made to regenerative energy production, but also a new efficient utilization of biogenous waste is created. The climatic change and the discussion around the greenhouse effect moved the emission of $CO_2$ into the foreground. Transportation logistics importantly contributes to $CO_2$ emissions. In the past years optimization of transportation stood in focus for the minimization of costs. The mere adjustment of transport costs and posibilities without the consideration of the emission can no longer be justified. Route planning and transportation optimization are in the economy standard instruments for the improvement of logistics. In the area of the transportation of disposables, in particular during sewage sludge removal, this approach is rarely used. Large potentials for the disposal transportation due to successes in the past are therefore expected.

## 2. Objective

The efficient and ecological utilization of biogenous waste covers multiple logistic components such as points of collection, transportation, storage, drainage, hygienization, sterilization, cutting, and sorting, all of which are being part of the chain of valuable materials processing. The supply of the biogenous waste at the right time, with the correct quality and the proper place is associated with a large logistic effort because of cities with a high number of inhabitants where multiple sources of raw material are available. The costs, which are calculated for the supply of the biogenous waste, can be charged here against the yield from the production of biogas, so that profitability could be expected. Since there are multiple forms of biogenous waste, the collection of individual fractions is difficult to achieve efficiently. For example the waste fractions can belong to the food production, household, as well as that from hotel and restaurant industry combined. Therefore, it should be seeked for common disposal ways for the different waste fractions, in order to arrange more economical and more ecological forms of disposal and

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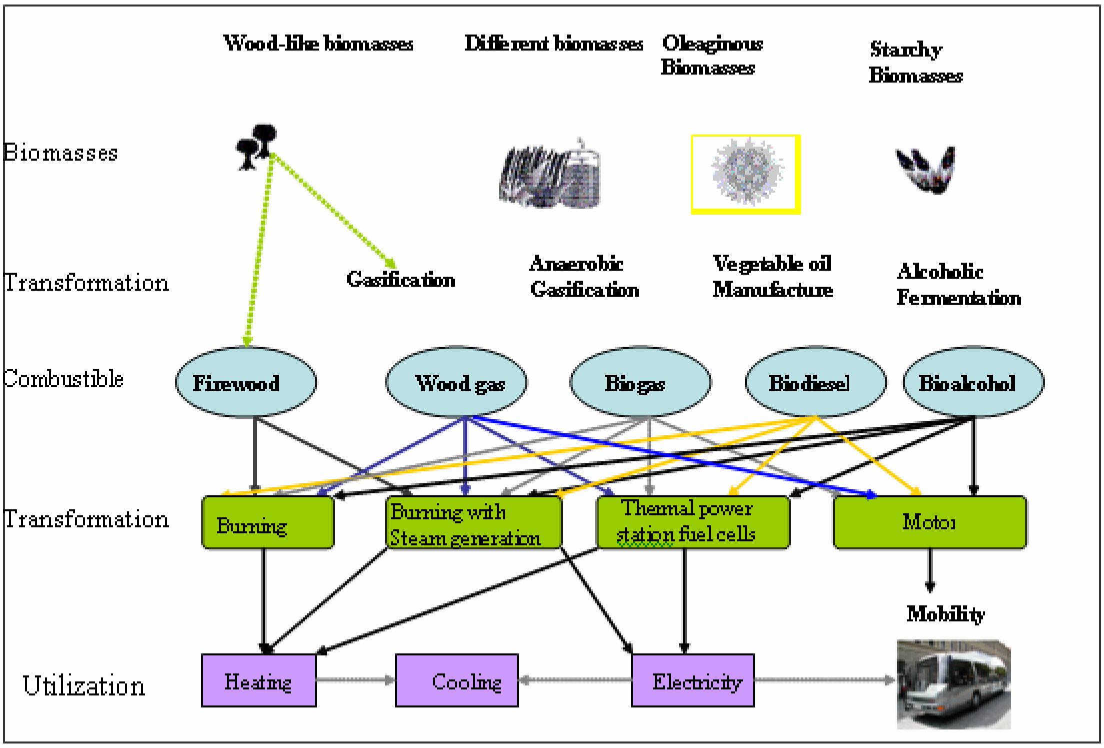


Figure 1.1 Energetic Utilization of Biomass.

utilization of organic resources. Consequently within the process chains in logistics, it is conceivable to collect the waste, mobilize it with large transportation units and bridging the spatial distance between waste deposits and reutilization points, according to the configuration of the technical components that aim to prepare the biogenous raw materials with the correct quality (pretreatment, e.g. to separate foreign matter, to adjust desired homogeneity). In this paper the biogenous waste fractions from “households”, “gastronomy” and “sewage sludge from the waste water treatment” are limited to the area in Duisburg, according to the demand of logistic and plant-technical components which are going to be examined and their optimization potentials evaluated in the chain of processes to be analyzed. It will be shown how the different types of waste with collective reutilization steps could be supplied, where cost of plant-technical and/or logistic components are aimed to be reduced. In addition a mathematical model is suggested for the costs calculation, which are costs for the required logistic and the use of the technical components. For the maximization of the objective function (profit) it is also necessary to minimize the distances between accumulation and reutilization points, to be bridged. Considering the very high number of sources of raw material, heuristic procedures are usually applied. For the determination of the optimal collection and transportation routes a simulation tool is also suggested where all transportation and collecting procedures are ought to be adjusted. With this contribution a new concept for an economically and ecologically optimal supply of different biogenous waste for biogas production is presented, considering the logistic and configuration-technical components.

## 3. The Biogas Supply Chain

The biogas supply chain covers the integration of sources with reloading stations and destinations. The sources that are mentioned in this paper are, households, hotel and restaurant industries, including snack stands and pensions, the food industry, meat industry and slaughterhouses and the waste water treatment as well. From all these areas large quantities of biogenous raw materials result and this must be supplied to an optimal reutilization. Depending on the condition of the biomass and distance to production centers direct transportation or transportation through reloading stations have to be considered. In the reloading stations the individual raw materials from the different sources are conducted to larger transportation units to be mobilized to production stations (biogas facility). In addition, it is meaningful to submit the collected biogenous raw materials in the reloading stations for a short pretreatment. This short pretreatment could involve weight reduction and/or volume reduction, drainage of the damp biowaste, so the transport to the biogas facilities can be arranged more efficiently. The biogas is then used as fuel for gas engines or directly for the energy and heat production. The compost produced tfrom the process can further be used as fertilizer and used in agriculture. Figure 3.1 shows the biogas supply chain.

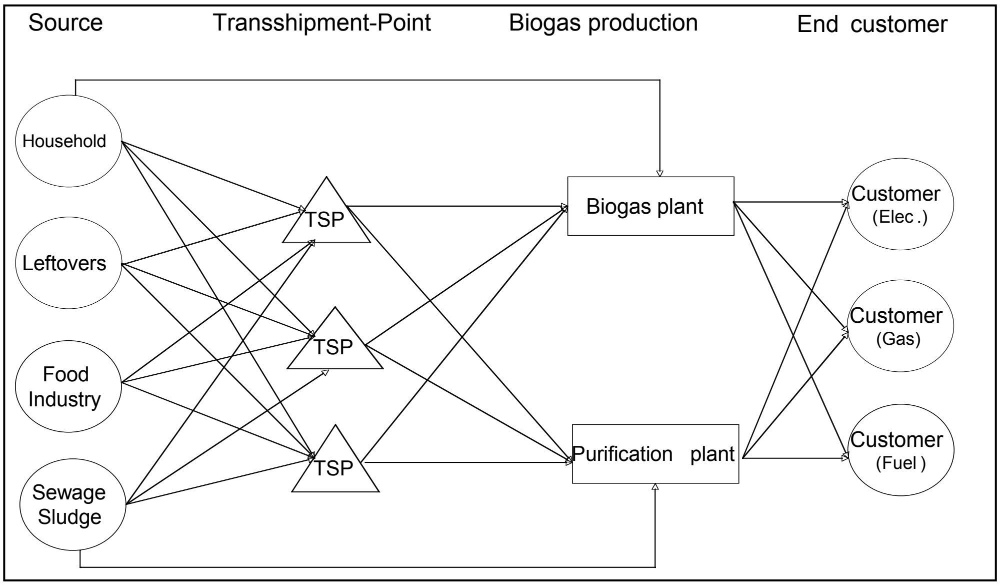


Figure 3.1. Biogas Supply Chain.

## 4. Area of Investigation

The area of investigation area is limited to the city of Duisburg. The city is divided into 48 urban districts, whereby identical postal zip codes are assigned to some districts. Therefore, only 25 different postal zip code areas with 492870 assigned inhabitants are considered [7]. Figure 4.1 shows the investigation area. Firstly, the waste fractions are separated, in order to differentiate their origins. Subsequently, the different sources of raw material and reutilization points in Duisburg are represented.

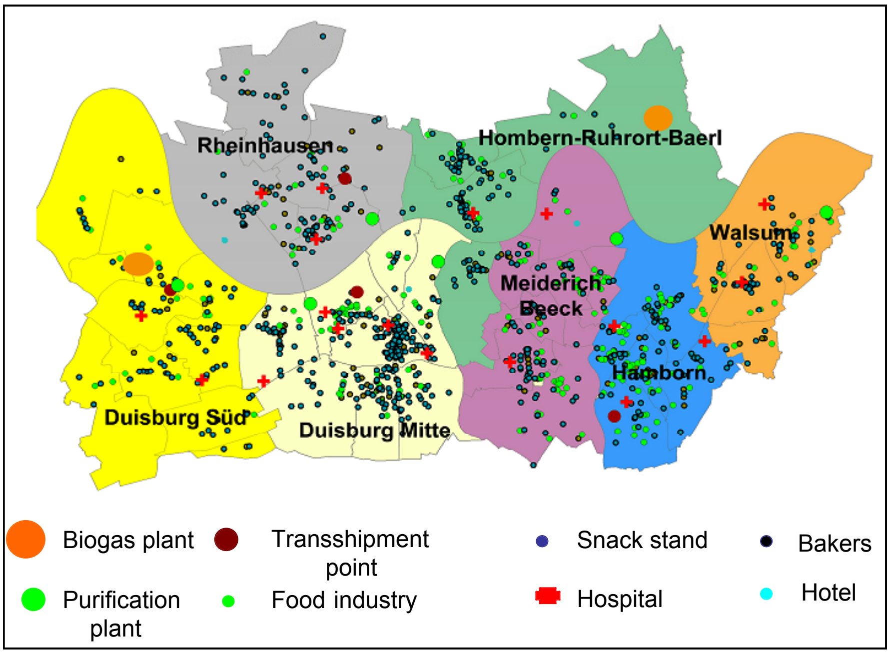


Figure 4.1 Map of the investigation area in Duisburg.

### *4.1. Database and Discussion*

The relevance of the investigation is further increased in this paper on the basis of three selected districts with assistance of the GIS software (geographical information systems).

### *4.2. Waste from households*

In 2006 36598.44 Mg (Megagram) of compostable waste was collected in Duisburg, where a third of the total was green waste that is accepted at the recycling points. This corresponds to about 11025 Mg of green waste in the year 2006. However this waste fraction is not considered in this paper. A small portion of 447.94 Mg was collected over the biowaste containers in the testing district. The rest of waste originates from two thirds of the total quantity from parks and cemetery maintenance as well as a small portion from Christmas tree collection. The collecting quantity from households is about 100 kg/inhabitant and year [8].

Waste from household in the three Districts

The number of inhabitants for each district and of the GIS derived number of houses is represented in figure 4.2.

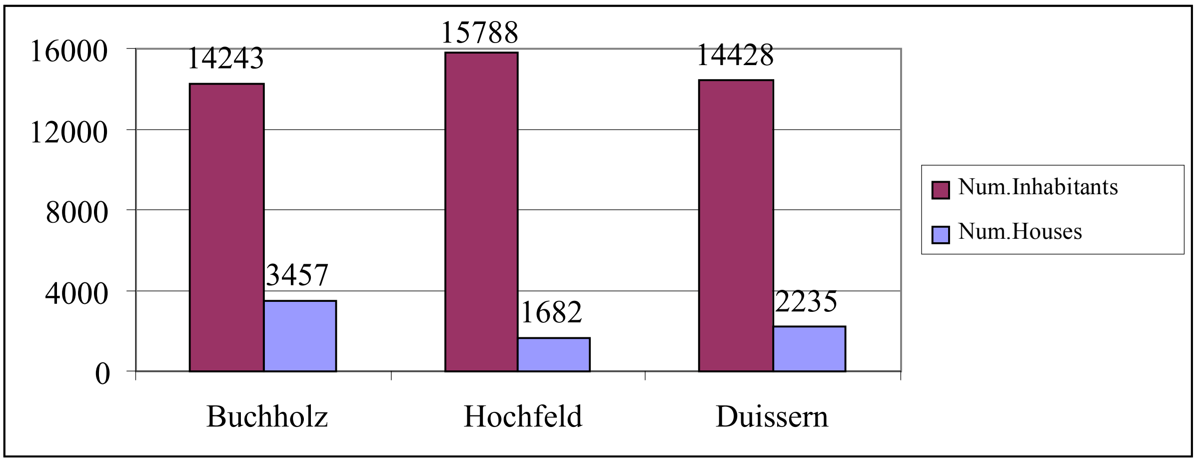


Figure 4.2. Number of inhabitants and houses in the districts of Duisburg.

The theoretical biowaste potential for the households from the three districts as provided by the Winzenhausen Institut is assumed to be 100 kg per inhabitant per year [8]. The quantity per house for a period of two weeks can be computed as following:

$$\text{Biowaste for each house in 14 days} = \frac{\text{Waste quantity per Inhabitant} \times \text{Number Inhabitants}}{\text{collect interval per year} \times \text{Number of Houses}}$$

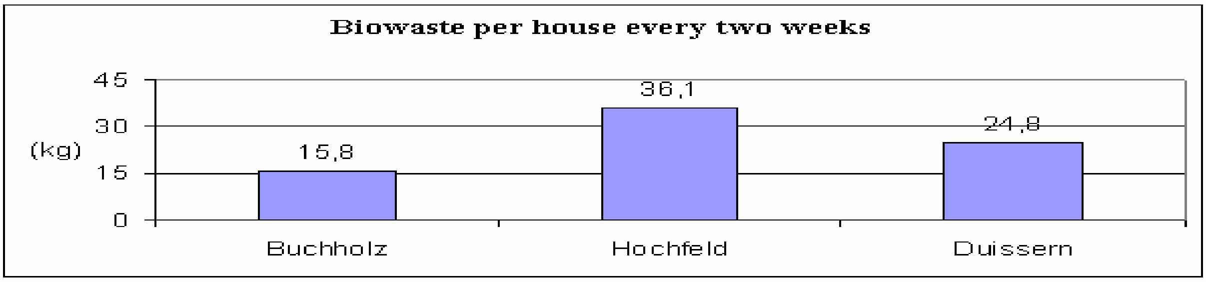


Figure 4.3. Biowaste of household per house every two weeks.

It is assumed that the biowaste of household is collected every two weeks. Thus it is represented with 26 collecting intervals per year and the biogenous quantities of waste for each house per district are represented in figure 4.3. After the computations it is to be determined that the quantity depends on each district. The reason for this is that there are more multi-family houses and buildings in Hochfeld. On the other hand although Buchholz holds more houses, fewer inhabitants per house are observed, thus this lowers the waste quantity per house. The entire quantity for the three districts is 170996 kg waste every two weeks.

### *4.1.2 Food Waste*

The amount of hospitals, hotels, baking shops and snack stands are gathered within the range of the food wastes. The information from surveys on hospitals, hotels and snack stands are taken over. The average waste disposed per hospital was around 300 kg every two weeks that means 26 Periods in year. The 16 hospitals in Duisburg produce up to 124.8 Mg per year. Additionally there are 22 hotels that produce 114.4 Mg per year. That corresponds to 200 kg per hotel every two weeks. For each baking shop results a quantity of 80 kg every two weeks is expected. Thus 243 baking shops produce 505.4 Mg per year. For small snack stand a quantity of 160 kg results every two weeks. Resulting in 2121.6 Mg of waste per year for 510 Snack stands. For Bars and Restaurants a quantity of 180 kg results every two weeks. So annually the waste production from 699 restaurants is 3271.3 Mg. Altogether the quantity of waste from the leftovers is approx. 6137,5 Mg/a.

Food waste in the three districts

The city of Duisburg has no information about the production of food waste, therefore the estimated value is derived from the number of gastronomic establishments. As an alternative to the estimated 25 kg/inhabitant·a [9], the production of waste can also be calculated from the number of inhabitants as follows:

$$\text{Waste per establishment}=\frac{\text{Waste quantity per Inhabitant}\times\text{Number Inhabitants}}{\text{collect interval per year}\times\text{Number of establishments}}$$

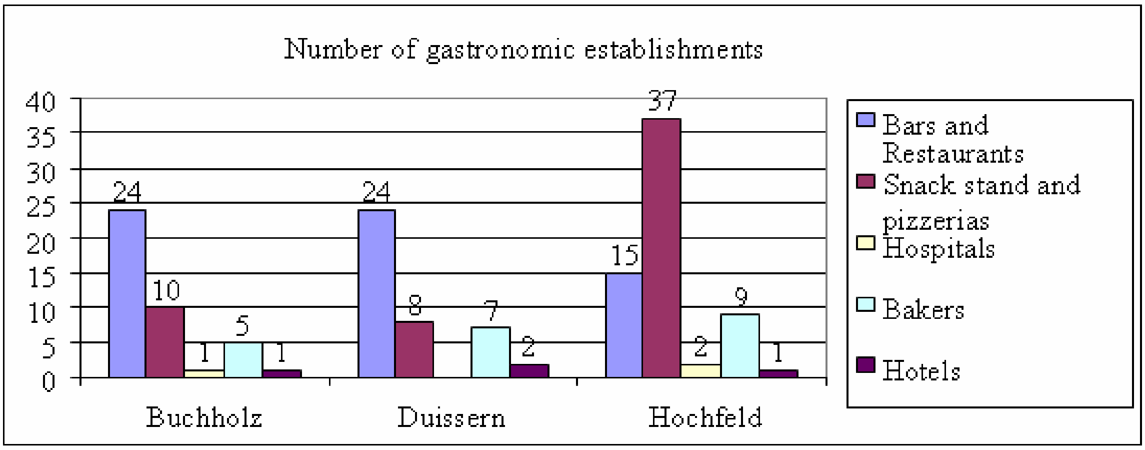


Figure 4.4 Number of gastronomic establishments in the three Districts.

The food waste is collected together with the household, therefore the geographic referencing uses only a node for each street section. Figure 4.8 shows the number of bars, restaurants, snack stands and pizzeria, hospitals, bakers shop and hotels. The entire collecting quantity every two weeks is 23520 kg.

### *4.1.3Waste from the food industry*

From the biogenous waste from the food industry, (grocery stores and other food producers), all organic rests originate from sell and production of food. Among them also baking rests from the production of pasta and also beer’s grains from the beer production are considered. Since no exact data for these quantities are available, the information from surveys on food industry is taken over. In relation to the individual food retailing a quantity of 80 kg every two weeks is estimated. The 912 food retailers produce annually approximately 1676.4 Mg. The grocery stores produce also a quantity of 80 kg every two weeks. The annually produced quantity of 261 stores is about 503.4 Mg. Thus the quantity of waste from the food industry is approx. 2179.8 Mg/a. The total quantity of produced waste from both fractions, food waste and waste from food industry, is then 8317.3 Mg/a. In the literature an amount of 20 kg per year per inhabitant is also considered and therefore the total quantity is about 9800 Mg/a [9]. This approximate value is determined by estimations, which is used as a comparative value in this paper.

Waste from the food industry in the three districts

The waste production is derived from the number of industries. As an alternative (20 kg/E·a) the waste production is calculated in relation to the quantity of inhabitants as follows:

$$\text{Waste per industry}=\frac{\text{Waste quantity per Inhabitant}\times\text{Number Inhabitants}}{\text{collect interval per year}\times\text{Number of industries}}$$

The waste of food industry like the leftovers is collected together with the waste of households. Figure 4.8 shows the number of food industries. The total collected quantity of 130 nodes every two weeks is about 10400 kg. A detailed representation of the quantity of the grocery stores is shown in figure 4.5.

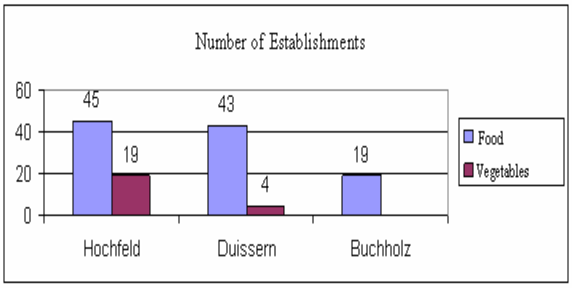


Figure 4.5. A detailed representation of the quantity of the grocery stores.

### 4.1.4Sewage sludge from waste water treatment

Sewage sludge is summarized under dredging from waste water treatment extracted in the Duisburger sewage purification plants. Six purification plants exist in Duisburg that are responsible for the waste water treatment of the city. The exact locations and produced quantities from these plants let themselve read off from the information platform in North-Rhine/Westphalia (AIDA) [10].

In this paper only the sewage sludge waste from waste water treatment plants is considered..

The well known Screenings and sand trap disposals were not included in the analysis. Sand trap disposals are washed in machines and used in the construction industry, for example in road construction. Screenings are washed likewise in machines and afterwards composted, deposited or incinerated [11]. For the total area in Duisburg an amount of 16644.06 (Mg/a) results from the waste water treatment plants [10].

In order to examine more clearly and transparently the transportation, inventory and distribution costs, only three districts in Duisburg are examined (Duissern, Hochfeld and Buchholz). These three districts were afterwards processed with assistance of the GIS software

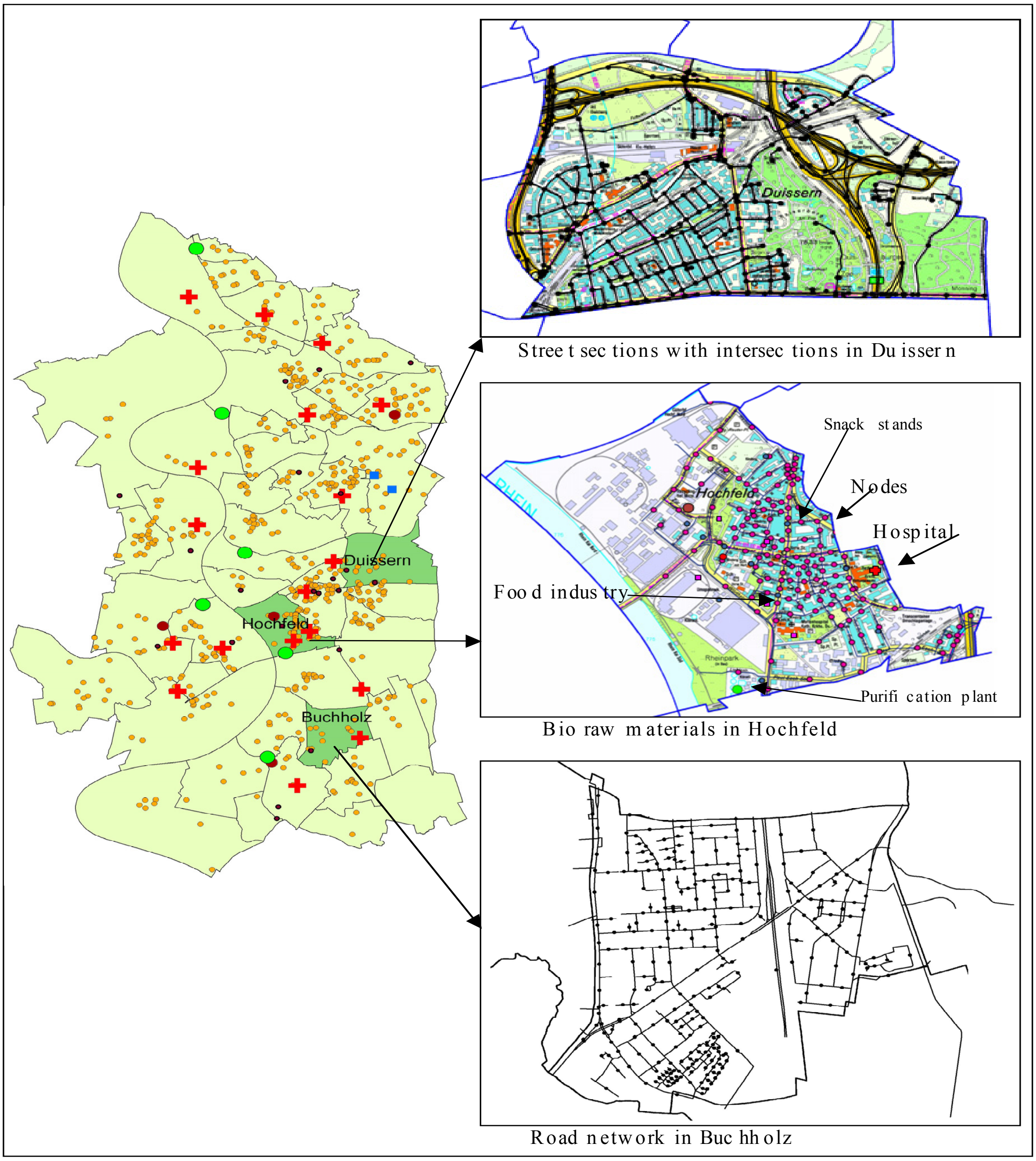


Figure 4.6 Investigation area.

*4.2Data preparation with GIS Software*

To increase the meaningfulness of the investigation, the model should have practical relevance where availability, actuality and accuracy of input data are required. The condition can be fulfilled and the production, administration and actualization of the data can be made possible by the application the digital information system. In order to calculate the biowaste quantity, two different methods are used in the literature, container-referred and inhabitant-referred calculations. Since the separate collection is accomplished only in four districts and no GIS data was made available, the investigation was accomplished regarding the number of inhabitants and surveys. To calculate the collecting costs and/or the covered driven distance, between two intersections (street section) they have to be represented as a node (in the middle of the road section) and the coordinates will be determined with assistance of the GIS software. Each house is assigned on a road section, which was labeled with a certain name. The data of the houses also contain the names of the road section, in order to avoid double allocation.

Duisburg has 6 purification plants and 4 recycling yards (transshipment stations). The investigation areas contain in total 666 nodes. The size of collecting surface is about 12.4 km² and has up to 44459 inhabitants [7].

*4.3GIS-aided route planning*

Three districts from Duisburg are selected for the investigation of the Biogas Supply chain (see Figure 4.14). Therefore 44459 inhabitants (9% of the total number of inhabitants of Duisburg), 12.4 km² surface (5% of entire surface), 7375 house, 63 bars and restaurants, 55 snack stands and pizzerias, 21 baker's shop, 4 hotels, 3 hospitals, and Grocery retailers are considered. The coordinates of nodes (in the middle of the road section) are determined with assistance of the GIS software and each house, hotel and hospitals were assigned to the nodes. A detailed representation of the Hochfeld district is shown in figure 4.6.

## 5. Analysis of The Process Chain

The 4 different process chains for biogenous wastes from the different areas are now considered.

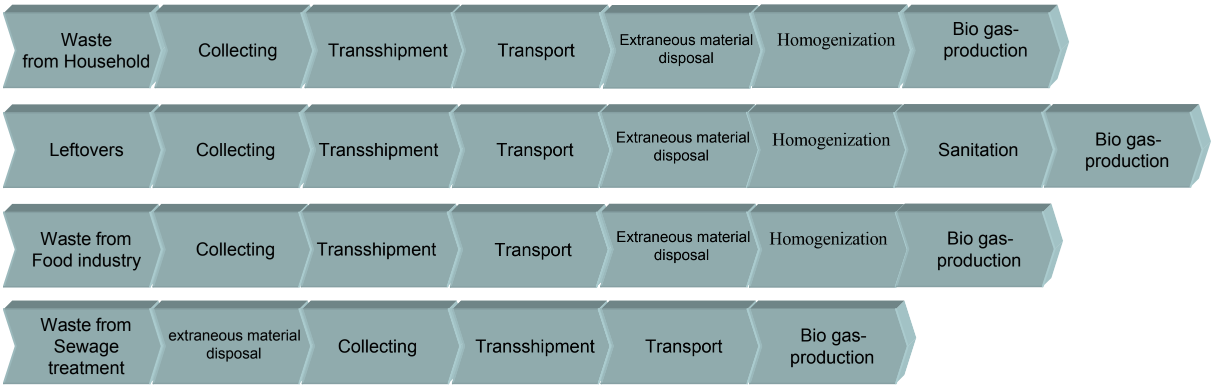


Figure 5.1 Biogas Process chain.

It should be seeked for optimization potentials for the collective utilization of waste. In addition different process chain scenarios are methodically run through to the end and in the observation of results regarding their cost-efficiency they will be compared one with another. If the four process chains are observed together, it is noticeable that those of the households, the hotel and restaurant industry and the meat industry are very similar. Only the pretreatment and processing of the biogenous waste materials from the hotel and restaurant industry and the meat industry are different due to legal regulations. There is no comparison between the pretreatment of sewage sludge from the waste water treatment with those of the other fractions and must always be observed therefore separately.

## 6. The mathematical model

For the computation of the entire process chains and the process chain scenarios a general mathematical model is suggested. This contains all collecting and transportation routes for transport over Transshipment stations (TSP) and direct transportation. The objective function is to maximize the net income from the disposal and utilization of waste. Some assumptions are done:

1. The Transshipment stations are temporarily limited. The material in the TSP stations should not be stored longer than two days, because if it is stored longer than two days, negative effects could occur. It could begin unpleasantly to smell for example.
2. The capacities of the TSP stations are equal in each point.
3. The production plant does not have a maximum capacity.
4. Each customer is served only by a vehicle.

The development of the mathematical model is based on an elaboration of Liu, Lin [12] and Liu, Lee [13], in which they solve a „Location Allocation problem" (LAP) with consideration from inventory factors. Even if they pursue another objective in their article, then the approach appears also interesting for the solution of „Capacitive Multi-Depot Location Routing Problem" (CMDLRP). Both articles were published in 2008 [14], [15].

## Notations

$M_s$ :Quantity of waste in the biological gas facility or purification plant s

$M_q$ :Waste collecting quantity of customer q

$E_{Biogas_s}$ :Fermentation gas yield per ton of biogas facility or purification plant s

$E_{Kompost_s}$ :Compost yield per ton of the biogas or purification plant s

$E_{Ent_q}$ : Income of the disposal fee of the customer q

$U$ : Number of the transshipment station

$Q$ : Number of customers

$S$ :Number of the biogas or purification plants

$R$ : Number of vehicles or route

$D$ :Number of final customers

$a$ : Vehicle capacity from source to the reloading station or biological gas facility

$b$ :Vehicle capacity from transshipment station to the biological gas facility

$\max Serv$ : Maximum service capacity of the vehicle

$C_{fix_j}$ :Fixed costs of transshipment station j

$c$ :Transport costs

$cm$ : Travel cost per distance unit

$C_{Lager}$ : Inventory carrying costs

$C_{\mathrm{hom}_j}$ :Costs of the homogenization in the TSP station/biological gas facility

$C_{\mathrm{h}yg_j}$ :Costs ofthe hygienization in the TSP station/biological gas facility

$C_{ster_j}$ :Costs of the sterilization in the TSP station/biological gas facility

$C_{st\square r_j}$ :Costs of the removal of extraneous materials in the transshipment station/biological gas facility

$C_{entw_j}$ :Costs of the drainage in the transshipment station/biological gas facility

$X_{ster_j}$ : 1, if the sterilization is needed, otherwise 0

$X_{entw_j}$ :1, if drainage is needed, otherwise 0,

$h$ :Index quantity of the TSP points or customers or biological gas facility

$g$ :Index quantity of the TSP points or customers or biological gas facility

$s$ :Index quantity of the biological gas facility

$i$ :Index quantity of the customers

$j$ : Index quantity of the transshipment points

$k$ :Index quantity of the route

$V_k$ :A row for route k with a transshipment point

$Dis_{kgh}$ : Entire distance for route k

$V_{Kap_{gh}}$ :Vehicle capacity

$UL_{kgh}$ :Average demand for route k

$D_{kgh}$ :Entire demand for route k

$Y_{ij}$ :1, if customer j is assigned to depot i, otherwise 0

$Z_j$ :1, if depot j is established, otherwise 0

$X_{kgh}$ :1, if g is a direct successor of h on the route k, otherwise 0.

$$
\begin{aligned}
\max P ={}& \overbrace{\sum_{s}^{S}\left(M_s \times E_{Biogas_s} + M_s \times E_{Kompost_s}\right)}^{\text{Biogas facilities revenue}} + \overbrace{\sum_{i}^{Q}\left(M_q \times E_{Ent_q}\right)}^{\text{Disposal fee}} - \overbrace{\sum_{j=Q+1}^{Q+U} C_{fix_j} x Z_j}^{\text{fixed costs}} \\
& - \sum_{k=1}^{K}\sum_{g=1}^{Q+U+P}\sum_{h=1}^{Q+U+P}\left(\overbrace{\left(c + cm + Dis_{kgh}\right)\times\frac{D_{kgh}}{V_{Kap_{gh}}}}^{\text{Collecting costs}} + \overbrace{\left(\frac{V_{Kap_{gh}}}{2} + R_{kgh} - UL_{kgh}\right)\times C_{Lager}}^{\text{Inventory costs}}\right)\times X_{kgh} \\
& \underbrace{- \sum_{j=Q+1}^{Q+U+P}\left(\left(C_{\mathrm{hom}_j} + C_{hyg_j}X_{hyg_j} + C_{ster_j}X_{ster_j} + C_{stgr_j} + C_{entw_j}X_{entw_j}\right)\left(\sum_{j=Q+1}^{Q+U+P} D_{gh} + \sum_{j=Q+1}^{Q+U+P} D_{gh}\right)\right)}_{\text{Pretreatment costs}} \\
& \underbrace{+ \sum_{k=1}^{K}\sum_{(g=Q+U+P+1)}^{(Q+U+P+D)}\sum_{(h=Q+U+P+1)}^{(Q+U+P+D)}\left(\left(c + cm + Dis_{kgh}\right)\times\frac{D_{kgh}}{V_{Kap_{gh}}}\right)}_{\text{Distribution costs}}
\end{aligned}
$$

$$V_{Kap_{gh}} \leq a, \qquad g = 1,\ldots,Q, \quad h = Q+U+1,\ldots,P \tag{1}$$

$$V_{Kap_{gh}} \leq b, \qquad g = 1+Q,\ldots,U, \quad h = Q+U+1,\ldots,P \tag{2}$$

$$D_{kgh} \leq \max Serv \tag{3}$$

$$\sum_{k=1}^{K} \sum_{h=1}^{Q+U+P} X_{ikh} = 1, \qquad i = 1,\ldots,N \tag{4}$$

$$\sum_{g \in v} \sum_{h \in v} \sum_{K=1}^{k} X_{ikh} \geq 1, \qquad \forall(\nu,\bar{\nu}) \tag{5}$$

$$\sum_{g=1}^{Q+U+P} X_{hgk} - \sum_{g=1}^{Q+U+P} X_{ghk} = 0 \qquad k = 1,\ldots,K, \quad h = 1,\ldots,Q+U+P \tag{6}$$

$$\sum_{j=1+Q}^{Q+U} \sum_{i=1}^{K} X_{ijk} \leq 1, \qquad k = 1,\ldots,k \tag{7}$$

$$\sum_{j=1+Q+U}^{Q+U+S} \sum_{i=1}^{K} X_{ijk} \leq 1, \qquad k = 1,\ldots,k \tag{8}$$

$$\sum_{h=1}^{Q+U+P} X_{ihk} + \sum_{h=1}^{Q+U+P} X_{jhk} - Y_{ij} \leq 1 \qquad i = 1,\ldots,N, \quad j = N+1,\ldots,Q+U+P, \quad k = 1,\ldots,K \tag{9}$$

$$X_{kgh} = \{0,1\}, \qquad g = 1,\ldots,Q+U+P, \quad h = 1,\ldots,Q+U+P, \quad k = 1,\ldots,K \tag{10}$$

$$Z_j = \{0,1\}, \qquad j = Q+1,\ldots,Q+U+P \tag{11}$$

$$Y_{ij} = \{0,1\}, \qquad i = 1,\ldots,Q, \quad j = Q+1,\ldots,Q+U+P \tag{12}$$

## Constraints

The constraints (1) and (2) restrict the capacity of the vehicle. The constraint (3) ensures the fact that the capacity of the transshipment station is not exceeded. In order to fulfill the acceptance of the model, the constraint (4) guarantees that each customer is assigned only to one route. Then constraint (5) guarantees that each route with the same transshipment station and/or biological gas facility supplies. With the next constraint (6) it is assured that the point of arrival of the vehicle should be also the point of departure. The constraints (7) and (8) serve for the fact that a route serves no more than one transshipment station and/or biological gas facility. The constraint (9) is responsible for the fact that a customer is assigned only to one depot, if there is a route, which passes near this customer. Constraints (10), (11) and (12) secure that the decision variables take either the value 1 or 0.

## 7.Proposed Biogas Facilities in Duisburg

Two different biogas production scenarios are examined in this paper. In the first scenario, surrounding biogas plants are considered to be used as production locations. And in the second scenario, Duisburg's purification plants are used as production locations (see figure 7.1). The city of Duisburg had 492870 inhabitants in 2008. Since 1975 the number of inhabitant in the city has decreased by approximately 100000. The current inhabitant density is 2124 inhabitants/km². The total area is 232 km² and the agricultural area without grassland is about 21 km². In this area grain is cultivated predominantly [16]. Besides, in four districts inside the Duisburg-South region, biowaste is collected separately. And in 2006, the amount of collected biowaste was approximately 447.94 Mg. [17].

### *7.1 Possible plants*

Agricultural biogas plant

The agricultural surfaces and raw materials are mostly located in the south region of Duisburg. Moreover, according to the area structure, it is possible that biowaste potential is higher, the biowaste containers have less extraneous materials and an agricultural biogas facility would be much more meaningful.

Since 1999, biowaste has been collected separately in four districts; Huckingen, Hüttenheim, Ungelsheim and Mündelheim. In these four districts, 22362 inhabitants are distributed to 10800 households. A possible plant is supposed to operate with not only renewable materials but also up to 49 % biowaste. Apart from the heat and electric energy which are utilized from the biogas, this biogas may also be fed into the local gas network [10]

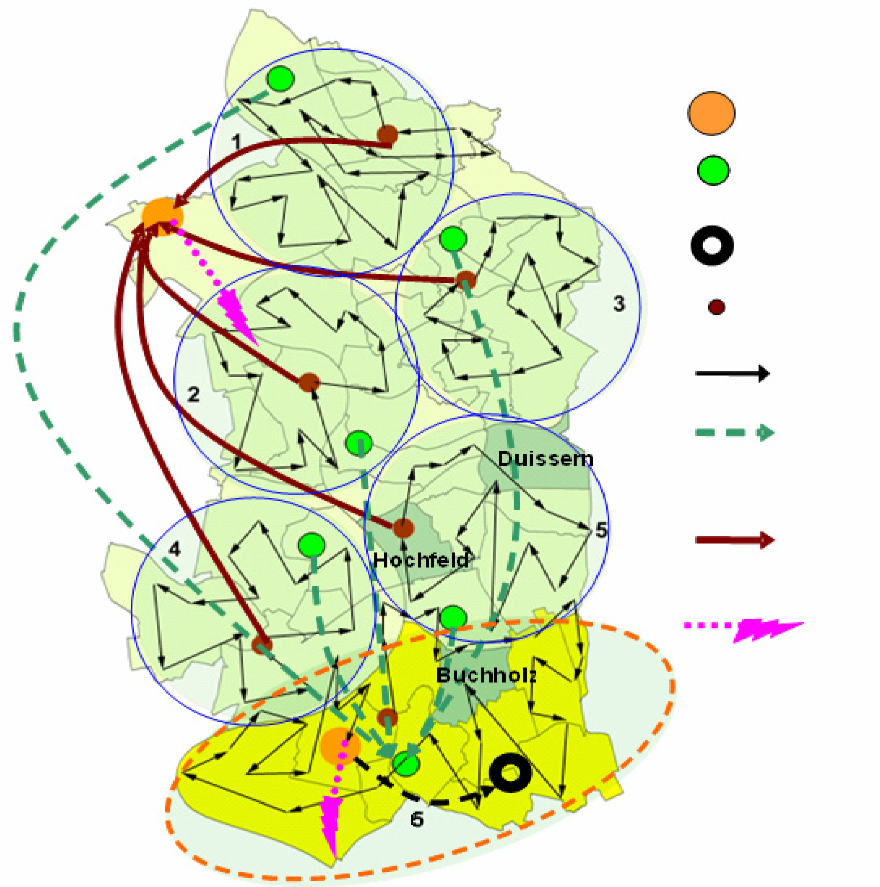


Figure 7.1 Proposal of biogas production models for Duisburg

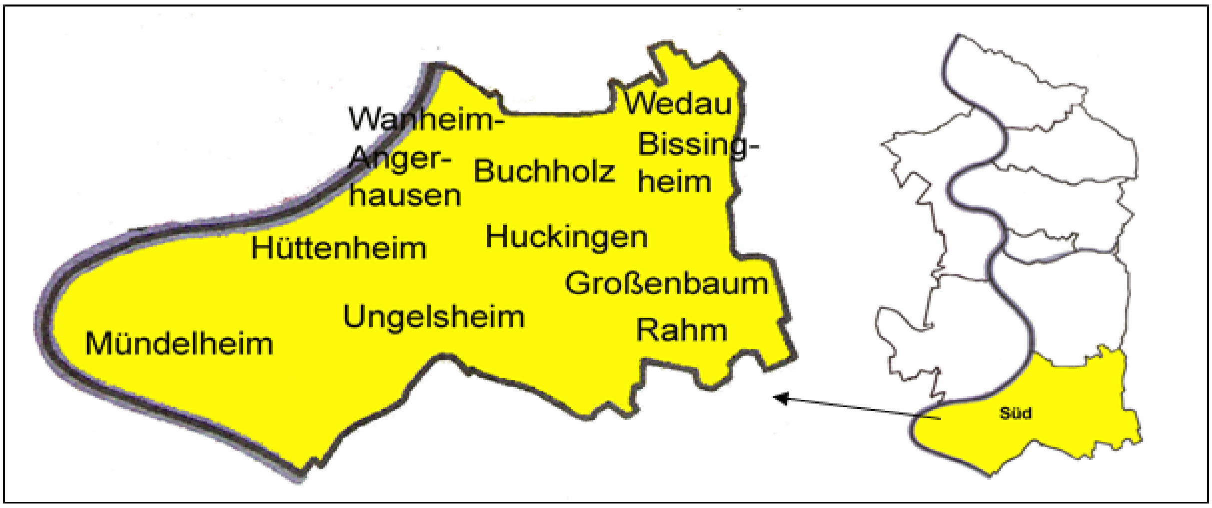
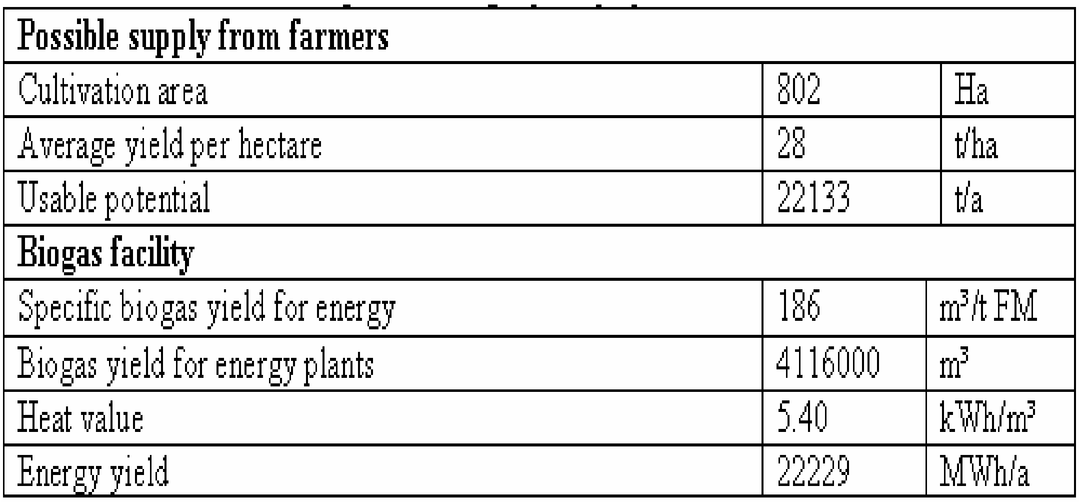


Figure 7.2 Overview of the district Duisburg south

Agricultural biogas facility has a cultivation area of approx. 801.5 hectares for the energy plants. These energy plants are corn, grass silage and rye. Besides, an annual harvest for these available plants is 22133 Mg/a. A substrate mixture, which is produced from these three plants, provides approximately 186 $m^3$/Mg FM (fresh mass) of biogas. From this estimation, it is seen that a great amount of biogas production of 4116000 $m^3$ can be achieved. The crop and its biogas yield are given in the table 7.1.

Table 7.1 overview of the crop and its biogas yield [16]



| **Possible supply from farmers** | | |
|---|---|---|
| Cultivation area | 802 | Ha |
| Average yield per hectare | 28 | t/ha |
| Usable potential | 22133 | t/a |
| **Biogas facility** | | |
| Specific biogas yield for energy | 186 | $m^3$/t FM |
| Biogas yield for energy plants | 4116000 | $m^3$ |
| Heat value | 5.40 | kWh/$m^3$ |
| Energy yield | 22229 | MWh/a |

Industrial biogas facility

The fermentation would be a possibility to use the bio waste which can be collected in Duisburg. The methane gas, which comes out during the fermentation, can be used for either heat or electric production. According to the other researches, the average amount of biogas can be 120 $m^3$ /Mg [16]. A possible industrial biogas facility can be planned in Duisburg Baer, because the population density of Duisburg Bear is smaller than the other urban districts. Another reason is that it is very close to a natural gas net, so that the produced biogas can be fed into the natural gas network.

Purification plants

The purification plants can be used as an alternative for the biogas production. Although the production cost of purification plants are higher than those of biogas plants, there are savings possibilities with the transport costs.

7.2. Agricultural and industrial biogas plants model

In the first model, two biological gas plants for entire Duisburg are suggested. These plants are located in the south (agricultural) and in the northwest (industrial) area of Duisburg. In the agricultural biogas plant, renewable resources may be used with biowaste, which are collected in Duisburg south, in order to produce biogas. For the purpose of transport cost reduction, either the existing TSP stations can be used or after a cost analysis, any additional TSP stations may be built.

7.3 Biogas-purification plant model

As mentioned for the second alternative; Duisburg is divided into six areas, because six purification plants are available. Like in the first model, an agricultural biogas facility is placed in the south area and all biowaste is used in this plant. Subsequently, the biowaste in other districts are distributed to five different purification plants. For this purpose, the purification plants for biogas production (sewer gas production) are assumed to be suitable. In case of insufficient capacity, the 6th purification plant can be also used as a spare disposal option.

## 8. Development of a simulation tool

In the investigated areas, the biowaste is planned to be collected every 14 days. It means that the collecting vehicle visits at least once all nodes in every two weeks and afterwards it brings the collected raw materials to a TSP point or a purification plant. In order to determine a route, the following criteria could be considered:

- TSP point´s or purification plant´s capacity,
- Capacity of the collecting vehicle,
- Driver´s and collection personnel`s working hours,
- Unloading time per biowaste source (house, snack stand, etc.),
- Preparation time and driving time

The routes are planned with the developed software, which connects the customers, TSP points and biogas facilities. The operation sequence of the used algorithm is given in the Figure 8.1.

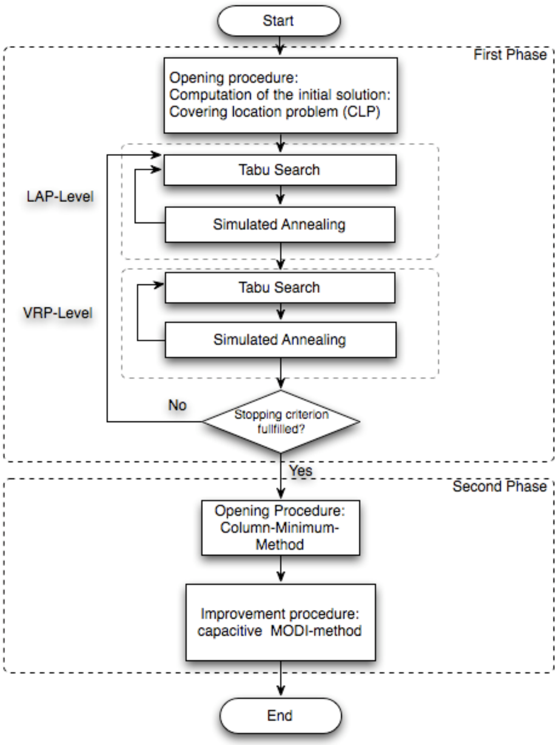


Figure 8.1 Process flowchart of the proposed heuristic approach

With the help of this process flowchart, the program can define the required TSP points (LAP) and compute the shortest route (VRP). In the second phase, the transport between transshipment points and biogas plants are handled. According to this phase some assumptions are done:

- All transshipment stations have the same capacity.
- All production plants have the same capacity.
- All collecting vehicles have the same capacity.
- All transport vehicles have the same capacity.
- All collecting vehicles have maximal three tours per day.
- The total capacity of the transshipment stations is equal to the whole capacity of all sources.
- The total capacity of the production plants is equal to the whole capacity of all sources.

*8.1 First phase: Location and route planning*

*8.1.1 Constructive procedure:*

*„Covering location problem “The heuristic „Covering problem“ possesses the following characteristics:*

- Distances (and/or travel time) of nodes cannot exceed a fixed value.
- A minimum number of nodes and transshipment points must be specified, which ensure the service level.
- The distances between the biogenous raw materials sources and the TSP stations cannot be larger than 10 km (see Figure 8.2).

The distances between customers and transshipment points or biogas facilities will be first determined by using a shortest path method. Dijkstra’s algorithm can be given as an example for this method. For each node, the reachability radius is given, it means that, there is a transshipment points set of $U_i$, which customer can reach.

$$U_i = \{ j \in V : d(j,i) \leq S_i \}, i = 1,\ldots,n$$

V is the set, which is the shortest path between i and j, can also be less or equal to the maximum distance $S_i$. It means that, the node is supplied by the transshipment point $j \in U_i$. The objetive function minimizes the total number of fixed nodes as transshipment points under the constraint that each Customers is served at least by a transshipment point.

8.1.2 Improvement procedure: Hybrid metaheuristic for the combined location and route planning

Step by step, it is tried to improve the initial solution from the constructive heuristics, with assistance of metaheuristics [18]. Hybrid metaheuristic consists of two subproblems; the location allocation problem (LAP) and vehicle routing problem (VRP). LAP problem is composed of location arrangement and customer assignment for the necessary location. Besides, VRP provides solution for customer-vehicle assignment and optimal sequence. The improvement method can be classified in two different procedures; special and general search methods. However, the special search methods are used for certain optimization problems. The general procedures, which are also called metaheuristics, are used for all problems [31]. In order to solve the NP-hard problems, numerous efficient procedures were developed; e.g. Simulated Annealing (which is based on a physical process in metallurgy) and Tabu Search (which was developed with assistance of artificial intelligence) [18]. In the Figure 8.3 it is shown, how the routes are generated by the simulation model for the three districts.

Possible transformation strategies are the following:

- Swapping: Two nodes are swapped between different routes.
- Insertion: A node is removed from one route and inserted into another.

In order to improve the solution of constructive heuristic, a hybrid heuristic, which consists of Tabu Search and Simulated Annealing, is used on both problem levels (LAP and VRP). With it both procedures share the same tabu list, whereby short cycles will be avoided and the search for better solutions can be arranged more effective.

8.2 Second phase: Transportation problem

The second phase of the model is a transportation problem which represents a single-step problem. The goal of the model is to keep the transport costs as low as possible. For this purpose, which TSP stations will satisfy which biogas or purification plants, should be determined by taking capacities into account.

*8.2.1 Constructive Heuristics: Capacitated Column Minimum Method*

In contrast to the simplest methods used to solve transport problems, the column minimum method considers not only the quantities but also the transport costs. The columns (transshipment stations) of the transport matrix are cyclically examined in the given order. If the biogas facility still exhibits demand, the most favorable feed connection from a still supplyable TSP station is arranged and the largest possible transportation quantity is planned.

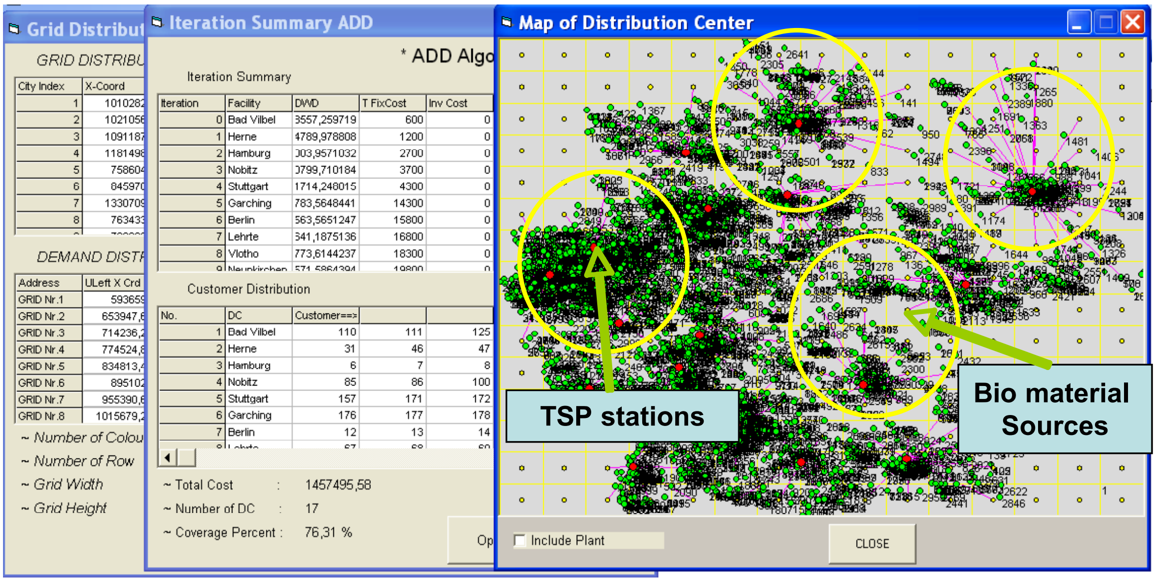
8.2.2 Improvement procedures: capacitated MODI-method

The MODI method, also known as modifying distribution method, is a numeric procedure, which can solve a standard transportation problem (with a given initial basic solution).

The MODI method reduces the total costs iteratively by exchange of one non-base variable with a base variable. If no more improvements can be achieved than an optimal solution was found..

### *8.3 Results of the simulation*

With the aid of heuristic procedures, this simulation tool optimizes the entire route length so that the $CO_2$ emission will be reduced and the transport costs will be minimized



GRID DISTRIBU

| City Index | X-Coord |
|---|---|
| 1 | 1010282 |
| 2 | 1021056 |
| 3 | 1091187 |
| 4 | 1181498 |
| 5 | 758604 |
| 6 | 845970 |
| 7 | 1330709 |
| 8 | 763433 |

DEMAND DISTR

| Address | ULeft X Crd |
|---|---|
| GRID Nr.1 | 593659 |
| GRID Nr.2 | 653947,6 |
| GRID Nr.3 | 714236,2 |
| GRID Nr.4 | 774524,8 |
| GRID Nr.5 | 834813,4 |
| GRID Nr.6 | 895102 |
| GRID Nr.7 | 955390,6 |
| GRID Nr.8 | 1015679,2 |

~ Number of Colou
~ Number of Row
~ Grid Width
~ Grid Height

Iteration Summary

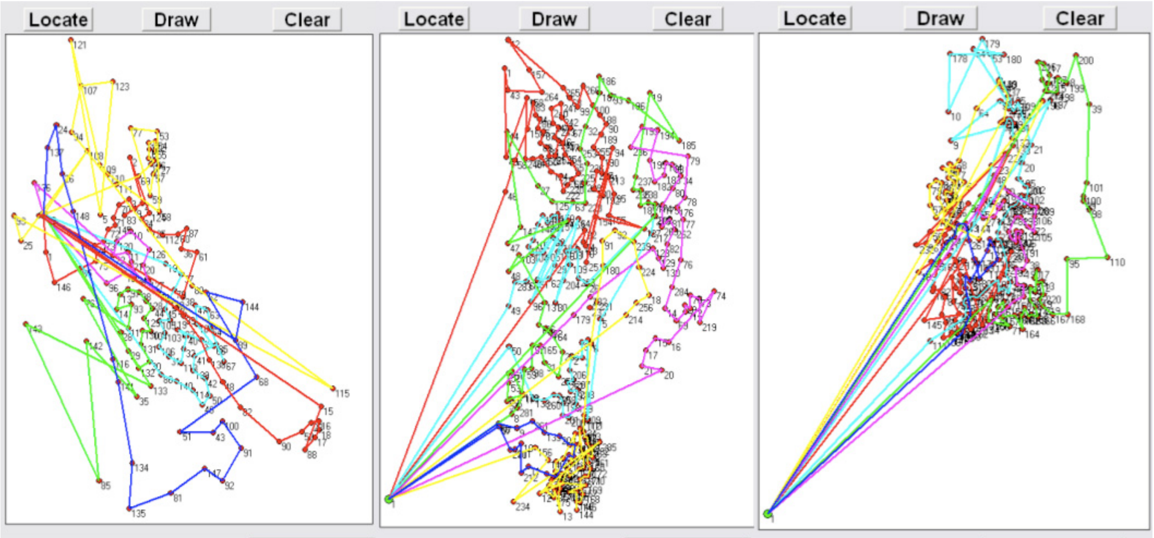
| Iteration | Facility | DWD | T FixCost | Inv Cost |
|---|---|---|---|---|
| 0 | Bad Vilbel | 3557,259719 | 600 | 0 |
| 1 | Herne | 4789,978808 | 1200 | 0 |
| 2 | Hamburg | 303,9571032 | 2700 | 0 |
| 3 | Nobitz | 3799,710184 | 3700 | 0 |
| 4 | Stuttgart | 1714,248015 | 4300 | 0 |
| 5 | Garching | 783,5648441 | 14300 | 0 |
| 6 | Berlin | 563,5651247 | 15800 | 0 |
| 7 | Lehrte | 541,1875136 | 16800 | 0 |
| 8 | Vlotho | 773,6144237 | 18300 | 0 |
| 9 | Neunkirchen | 571,5864394 | 19800 | 0 |

Customer Distribution

| No. | DC | Customer==> | | |
|---|---|---|---|---|
| 1 | Bad Vilbel | 110 | 111 | 125 |
| 2 | Herne | 31 | 46 | 47 |
| 3 | Hamburg | 6 | 7 | 8 |
| 4 | Nobitz | 85 | 86 | 100 |
| 5 | Stuttgart | 157 | 171 | 172 |
| 6 | Garching | 176 | 177 | 178 |
| 7 | Berlin | 12 | 13 | 14 |
| 8 | Lehrte | 67 | 68 | 69 |

~ Total Cost : 1457495,58
~ Number of DC : 17
~ Coverage Percent : 76,31 %

Figure 8.2 Distances between Sources and TSP stations.



Hochfeld Buchholz Duissern

Figure 8.3 . Generated routes for the three districts.

In the simulation, three districts are considered. In these three districts, up to 206 Mg bio raw materials are collected every two weeks. Thus in these districts, up to 5376 Mg of bio raw materials can be collected annually (see figure 8.7). Maximum transportation distance of 114 km is calculated for a period of every two weeks. Due to the improvement procedures, the transportation distance is reduced to 103 km for a period (see fig 8.4). It is assumed that the bio waste is collected with a truck of 12 Mg collecting capacity.

In figure 8.5, Diesel consumption per 100 km is given for the whole year.

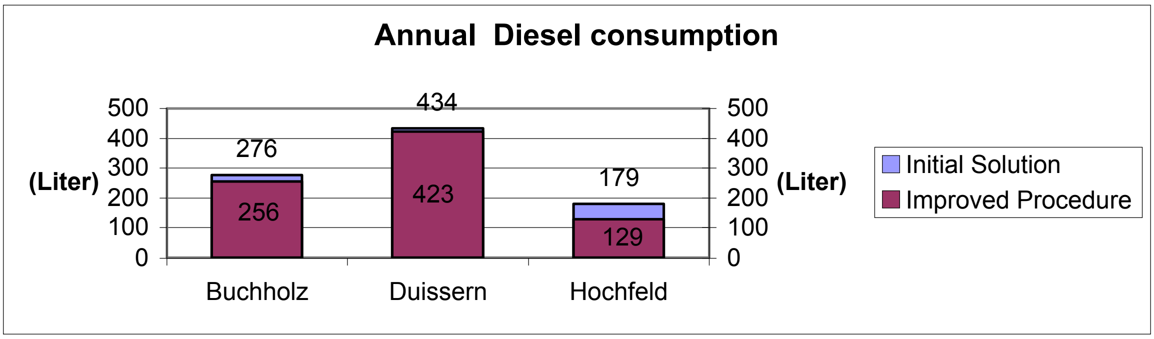


Figure 8.5 Annual consumption

Concerning the $CO_2$ emission, it is assumed that 1.138 kg $CO_2$ emission per kilometer is discharged in one year [19]. This results in total to 3365 kg of $CO_2$ emission per year. With the improvement procedures, the $CO_2$ emission is reduced to 307 kg (see figure 8.6).

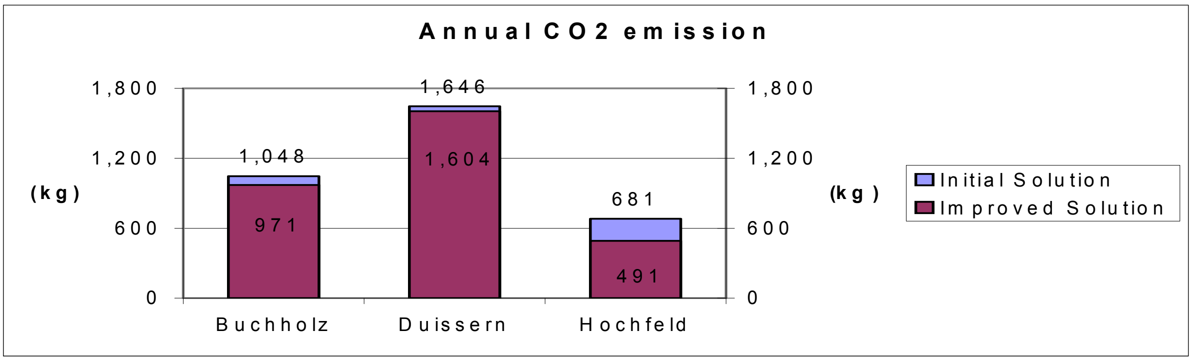


Figure 8.6. Discharge of $CO_2$ emissions

5376 Mg of bio waste collection results in a biogas potential of 537600 $m^3$. This quantity corresponds to 424704 kg (biogas). A truck with a capacity of 12 Mg, consumes 30 kg of biogas per 100 km. The total collecting distance, in the three districts per year, is about 2964 km. In order to cover the energy consumption of the truck, up to 889,2 kg of biogas will be needed.

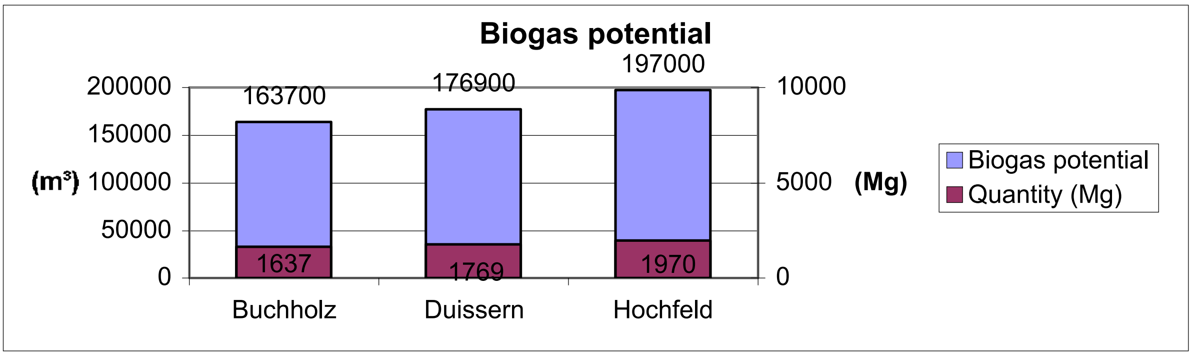


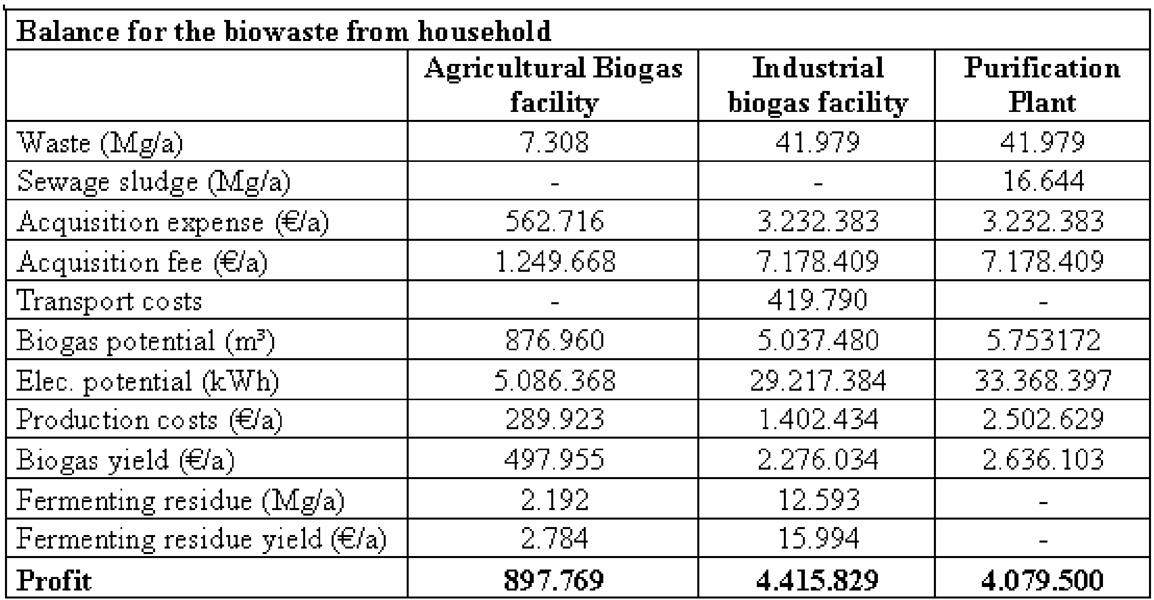
Figure 8.7 Biogas potential.

A gas-fueled waste collecting vehicle costs more than 15000 € to 30000 € in comparison with any vehicle with diesel engine. These price differences correspond from 4 to 9 % of the acquisition costs [20] [21]. However, the gas-fueled vehicles have fair fuel costs. If 20.25 € is saved for 100 km, it results a total saving of 5062.5 € per year for a covered distance of 25000 km. Therefore, the extra acquisition costs of 15000 € will be amortized after approximately 3 years. The average diesel price which is referred in this paper belongs to 2008. If a diesel price of 1.509 €/l is taken as a reference (this was the Diesel price before the economic crisis), 50.91 € per 100 km could be saved. In this case, the extra costs of 15000 € would have been already amortized after 1.2 years. So that 35.95 kg/100 km of $CO_2$-emission can be saved and the total saving results would become 135 Tons of $CO_2$ for a covered distance of 25000 km per year and a life span of 15 years.

## 9. Economical Efficiency

The collecting costs are derived from the waste quantity. In the literature, the collection costs are estimated to 77 € /Mg·km with an average population density [22]. The transport costs of 10 €/Mg·km are assumed in accordance to a declared information by a waste management service provider. The yield of fermenting residues from the purification plants is not considered. The tables 9.1, 9.2 and 9.3 show detailed balance information of biowaste.

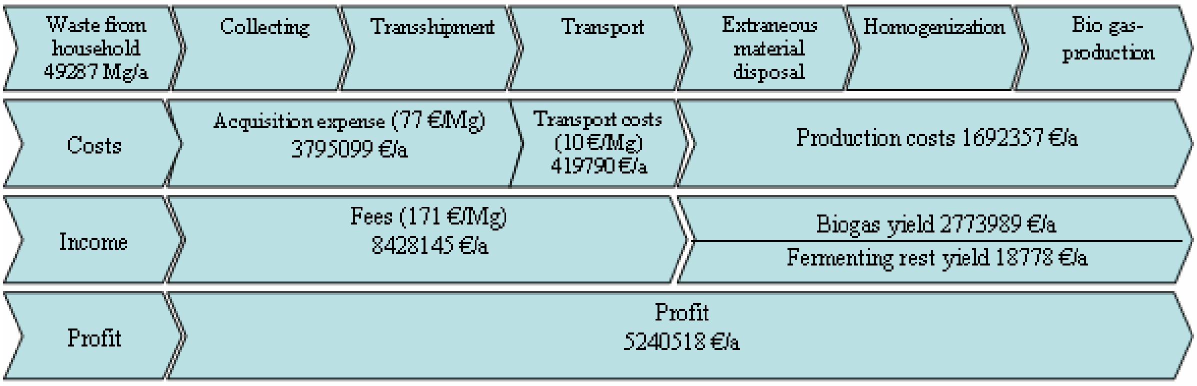
Table 9.1 Balance for the biowaste household.



| **Balance for the biowaste from household** | | | |
|---|---|---|---|
| | **Agricultural Biogas facility** | **Industrial biogas facility** | **Purification Plant** |
| Waste (Mg/a) | 7.308 | 41.979 | 41.979 |
| Sewage sludge (Mg/a) | - | - | 16.644 |
| Acquisition expense (€/a) | 562.716 | 3.232.383 | 3.232.383 |
| Acquisition fee (€/a) | 1.249.668 | 7.178.409 | 7.178.409 |
| Transport costs | - | 419.790 | - |
| Biogas potential ($m^3$) | 876.960 | 5.037.480 | 5.753172 |
| Elec. potential (kWh) | 5.086.368 | 29.217.384 | 33.368.397 |
| Production costs (€/a) | 289.923 | 1.402.434 | 2.502.629 |
| Biogas yield (€/a) | 497.955 | 2.276.034 | 2.636.103 |
| Fermenting residue (Mg/a) | 2.192 | 12.593 | - |
| Fermenting residue yield (€/a) | 2.784 | 15.994 | - |
| **Profit** | **897.769** | **4.415.829** | **4.079.500** |

Production costs are 5.7 ct/kWh for the agricultural biogas facility, 4.8 ct/kWh for the industrial biogas facility and 7.5 ct/kWh for the purification plant [23]. From this information, the costs for an agricultural biogas facility are 1,72 million €, for an industrial biogas facility 1,88 million € and for the purification plant 3,25 million €.

Agricultural and industrial biogas facility model



Biogas- and purification plant Model

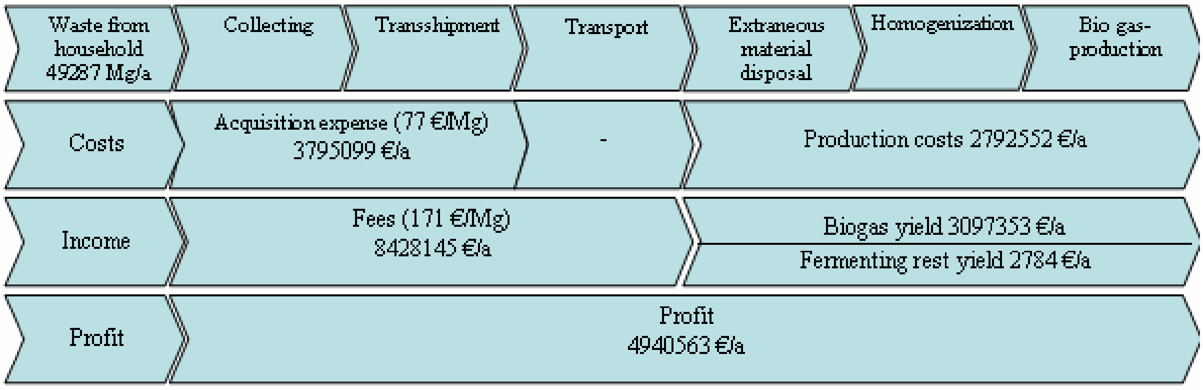
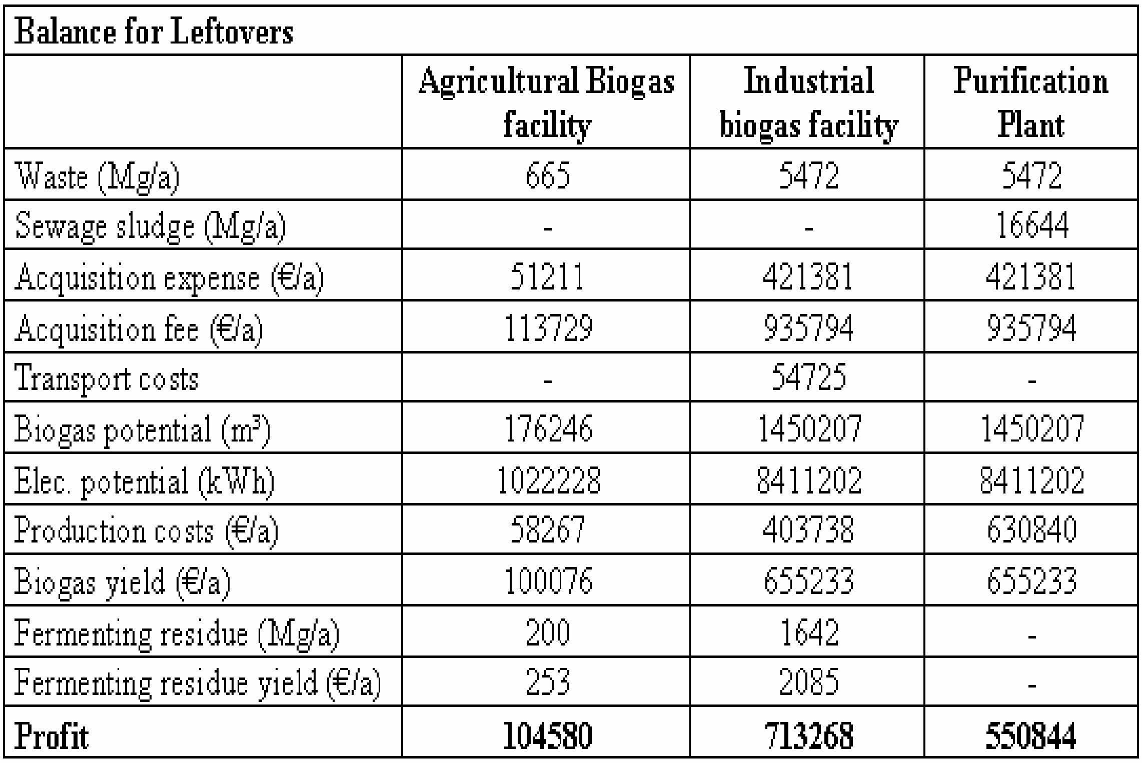
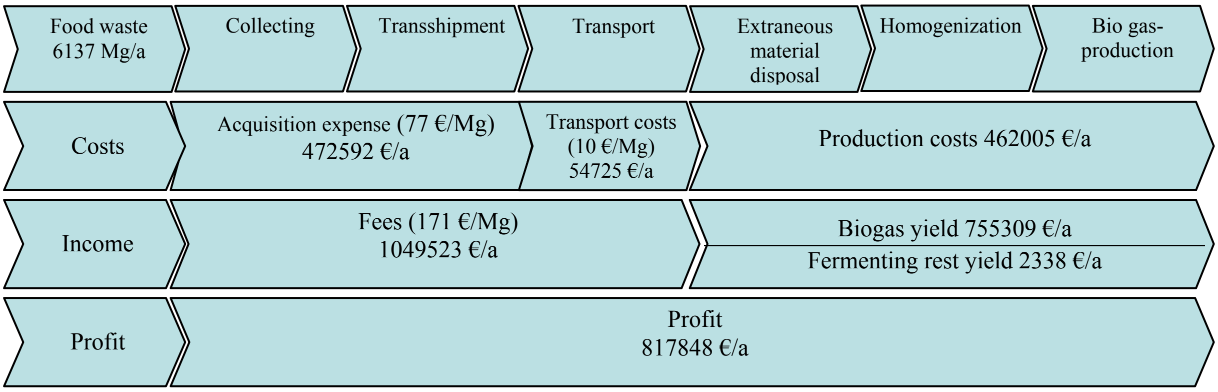


Table 9.2 Balance for Leftovers.



| Balance for Leftovers | | | |
|---|---|---|---|
| | **Agricultural Biogas facility** | **Industrial biogas facility** | **Purification Plant** |
| Waste (Mg/a) | 665 | 5472 | 5472 |
| Sewage sludge (Mg/a) | - | - | 16644 |
| Acquisition expense (€/a) | 51211 | 421381 | 421381 |
| Acquisition fee (€/a) | 113729 | 935794 | 935794 |
| Transport costs | - | 54725 | - |
| Biogas potential (m³) | 176246 | 1450207 | 1450207 |
| Elec. potential (kWh) | 1022228 | 8411202 | 8411202 |
| Production costs (€/a) | 58267 | 403738 | 630840 |
| Biogas yield (€/a) | 100076 | 655233 | 655233 |
| Fermenting residue (Mg/a) | 200 | 1642 | - |
| Fermenting residue yield (€/a) | 253 | 2085 | - |
| **Profit** | **104580** | **713268** | **550844** |

Agricultural and industrial bio gas facility model



Bio gas- and purification plant Model

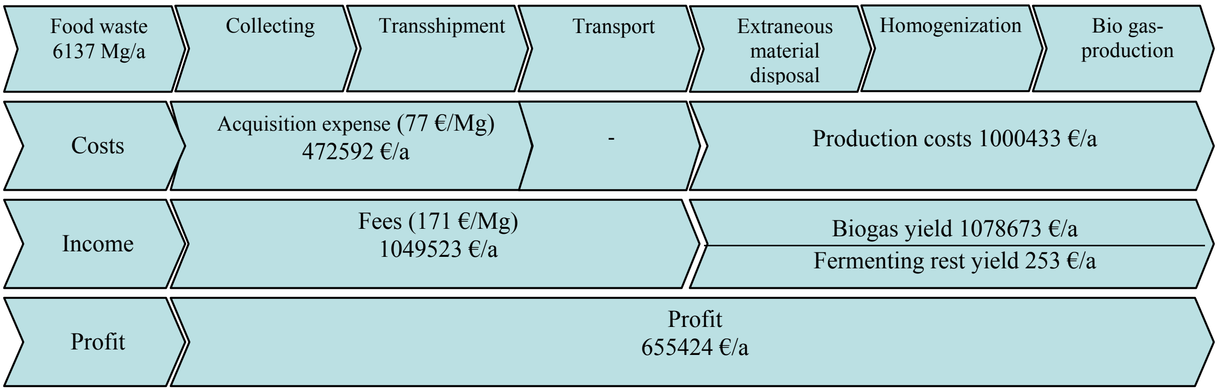
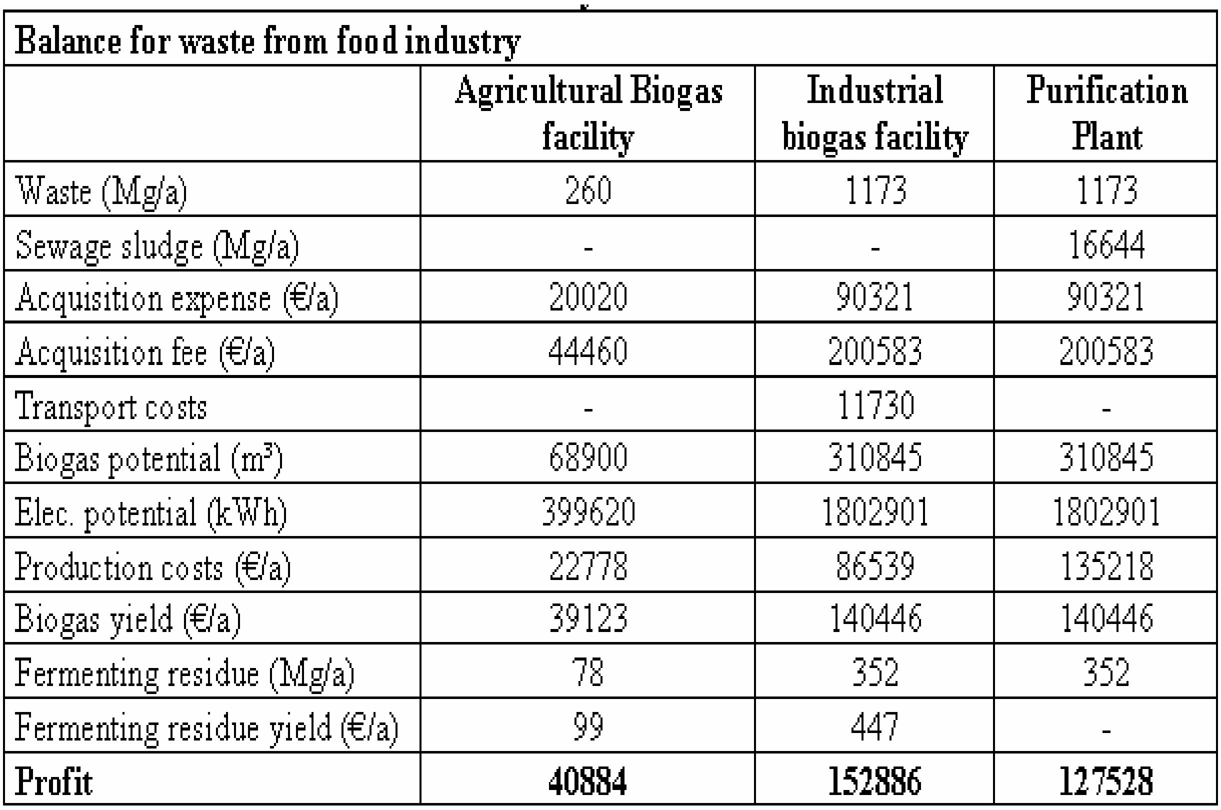
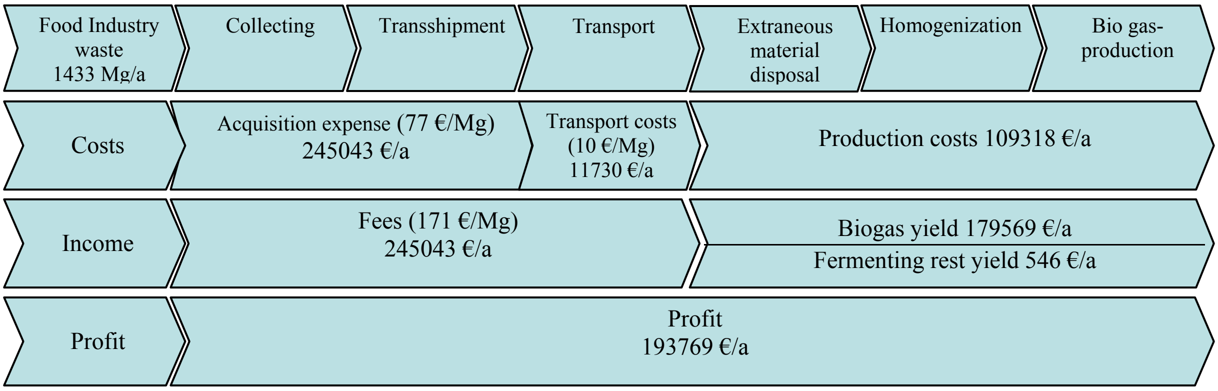


Table 9.3 Balance for waste from food industry

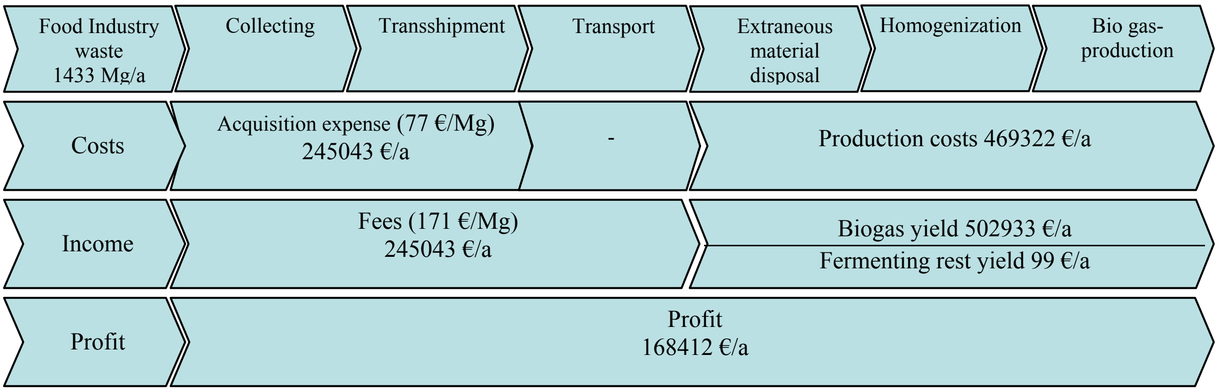


| Balance for waste from food industry | | | |
|---|---|---|---|
| | Agricultural Biogas facility | Industrial biogas facility | Purification Plant |
| Waste (Mg/a) | 260 | 1173 | 1173 |
| Sewage sludge (Mg/a) | - | - | 16644 |
| Acquisition expense (€/a) | 20020 | 90321 | 90321 |
| Acquisition fee (€/a) | 44460 | 200583 | 200583 |
| Transport costs | - | 11730 | - |
| Biogas potential ($m^3$) | 68900 | 310845 | 310845 |
| Elec. potential (kWh) | 399620 | 1802901 | 1802901 |
| Production costs (€/a) | 22778 | 86539 | 135218 |
| Biogas yield (€/a) | 39123 | 140446 | 140446 |
| Fermenting residue (Mg/a) | 78 | 352 | 352 |
| Fermenting residue yield (€/a) | 99 | 447 | - |
| **Profit** | **40884** | **152886** | **127528** |

Agricultural and industrial bio gas facility model



Biogas and purification plant Model



## 10. Summary and Outlook

The investigated waste quantity provides a theoretical biogas quantity of 863330 ($m^3/a$) for Duisburg. For the reality, it should be considered that raw material quantities can deviate clearly. The submitted paper suggests a total concept for the process chains simulation with logistic and plantspecific components for the biogenous waste materials supply. At the same time, the logistic components (collection, transport or storage) and the plantspecific components (drainage, cutting, sorting, hygienization and sterilization plants) are observed. It is possible to calculate the entire supply chain between the collecting points and the processing plants by using the extended mathematical model. The direct route between sources and processing plants are considered. The $CO_2$ emission which is caused by transport collecting process can be determined with the entire covered distance. The production of biogas in the water purification plants is extremely important, since the transportations of the sewage sludge would be omitted. With an appropriate pretreatment of the other three fractions in the transshipment stations, no new technical components in the sewage purification plants should be installed. Sludge from the waste water treatment is only suitable for one waste combination from the observed fraction. Thus, it can be seen that the preparation and pretreatment costs can deviate strongly from those of the other fractions. For this reason, it appears more economical, the biogenous wastes from the household, the leftovers and waste from the food industry, to transport collectively with the waste from the water treatment plant to the digestion towers of the sewage purification plants to produce biogas. The main idea is to observe the identification of the technical and logistic processes, which are necessary for the supply process. Meanwhile, the laws for treatment of biogenous waste materials are taken into account. However, the collective pretreatment of the different waste fractions comes along with some problems. So no hygenic conditions are needed to be fulfilled for the wastes from the household, while leftovers must be sanitized. In order to submit these, as a collective pretreatment, it must be ensured that the hygienc regulations are further observed.

This quantity of biogas is calculated with the assumption that 1 m³ biogas produces approximately 5.8 kWh electrical energy and supplies a theoretical electrical output of 50090716 kWh per one year production [24]. It is to be noted that, some part (20%) of the produced energy from the biogas is used for the pretreatment and preparation processes in the production plants. According to the North-Rhine Westphalia Energy Agency, the annual electric consumption per household per person is 2000 kWh without heat consumption [25]. With an electric potential of 40072573 kWh per year, up to 20000 inhabitants’ electric consumption can be covered per year.

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