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BIOGAS PRODUCTION

Development of a biogas station in the infrastructure of Severodvinsk city

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Declaration of Authorship

I, Svetlana Chetckaia, hereby certify that this thesis has been composed by me, that it is the record of work carried out by me and that it has not been submitted in any previous application for a Bachelor's degree. This project was conducted by me at the Ostfalia University of Applied sciences from 03/2017 to 07/2017 towards fulfillment of requirements of Ostfalia University of Applied Sciences and Tampere University of Applied Sciences for the degrees of B.Eng. in Environmental Engineering & Bio and Environmental Engineering under the supervision of Prof. Thorsten Ahrens.

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ABSTRACT

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This project represents development of the idea for biogas production in Severodvinsk city on the Northern-West part of Russia. It includes research of important issues of the city infrastructure, opportunities for biogas production and application, economical evaluation and optimal scenario development.

In Arkhangelsk region where Severodvinsk city is located, biogas production is not implemented, therefore current project is innovative. Challenging aspects of German experience transfer to a new region with different economical, legislative and climate background were defined and affected strategy adaptation. Based on the collected information, preliminary strategy of the project was created. Results from planning of technical aspects, substrate availability calculations and economical evaluation advanced the whole scenario. Conclusions for further steps for the project development were made and requirements for additional research were stated.

Key words: biogas station, substrate, fermentation, Severodvinsk

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ABBREVIATIONS AND TERMS

B.Eng	Bachelor of Engineering
CHP	Combined heat and power
CNG	Compressed natural gas
Dr.	Doctor
Dr.-Eng.	Doctor of Engineering
LNG	Liquefied natural gas
NVG	Natural gas as a vehicle fuel
TAMK	Tampere University of Applied Sciences
PFW	Produced food waste
Prof.	Professor
PSA	Pressure swing adsorption

1 INTRODUCTION

Modern world highly depends on products manufacturing and energy generation. Supply of goods and energy in cities is a crucial issue that is a basement of any infrastructure. Every production site causes harm to the surrounding environment without implementation of technologies to mitigate environmental risks. In Russia the most important problem in cities and villages is waste management. Technologies for waste recycling and utilization are mostly represented in big cities of central regions, when in other regions major part of waste goes to landfills. Decomposition of organic fraction in waste causes emissions of greenhouse gases to the atmosphere. Estimation for methane emissions from landfills varies from 30 to 70 million tons per year. Level of air pollution from landfills can be decreased by collection of methane from landfills or extraction of organic waste fraction. Implementation of waste separation makes it possible to utilize organic waste for production of compost, bioethanol or biogas (Sources of Methane, 2017).

The focus of the current project is to develop a plan for installation of biogas station and its successful implementation in the infrastructure of Severodvinsk city in Arkhangelsk region of Russia. Biogas production is not presented in Russia on a large scale; only few companies provide customers in Sothern areas with small biogas stations to supply houses with heat and electricity. The general level of biogas implementation is experimental. Therefore, biogas station in Arkhangelsk region will be a representation of a new technology application. The main challenge for utilization of biogas is a very well developed system of energy supply. Availability of energy resources leads to relatively low prices for electricity and fuel. Current energy infrastructure is reliable and efficient. Therefore, investing into new systems for biogas production will not be very sensible from the point of view of authorities.

The main idea of the project is to promote biogas station as the way of waste treatment with the benefit of energy production. Implementation of new technologies in the stable infrastructure is always challenging. It requires investments, changes in logistic aspects and the whole structure. For development of any innovation, feasibility and reliability of a project have to be proven. The new technology should have obvious benefits for the current situation, good perspective for the future and interest for authorities and local population. Biogas station will utilize biowaste and green waste as a substrate, and produced biogas will be used for generation of electricity and heat. Since the project is capable of covering waste treatment and energy production, station will be able to compensate required investments for its building.

In Arkhangels region the problem of air pollution and ozone layer depletion takes place. Nowadays environmental situation is improving, since power stations switch fuel from coal and oil to natural gas. Implementation of biogas production from organic waste can be a good addition to environmental policy of the region, that is especially developing in 2017. Every year country has a program for developing of different strategies. 2017 is the year of environmental focus and each region creates program for improvement of environmental situation.

For the future perspective, more biogas stations can be implemented to work with household waste as a substrate. Nowadays in Arkhangelsk region the project for waste separation and treatment plant is on developing stage. Current target of that project is to create new landfill and enhance recycling of paper, cupboard, glass and metal. Collaboration with biogas production can be very beneficial. Addition of biogas facility can help to supply the whole waste treatment station and local areas with energy and decrease amount of waste for storing on a landfill. Also similar projects of biogas station can be implemented in neighbor cities and other regions of Russia. Problem of waste disposal exists all around the county and 2017 is the best time for implementation of new environmental technologies.

2 BACKGROUND INFORMATION

2.1 Biogas application

Biogas is a mixture of gases with major parts of methane and carbon dioxide. Biogas may also include oxygen, nitrogen, hydrogen, ammonia, hydrogen sulfide and water content. Composition of biogas is presented in the Table 1 below (Ahrens, 2017).

TABLE 1. Composition of biogas

Chemical component	Ratio of volume (%)
Methane (CH_4)	45 – 70
Carbon dioxide (CO_2)	25 – 50
Water (H_2O)	0 – 10
Nitrogen (N_2)	0 – 5
Oxygen (O_2)	0 – 3
Hydrogen (H_2)	Less than 1 (in a range of ppm)
Ammonia (NH_3)	
Hydrogen sulfide (H_2S)	

Since methane is a gas that combusts with oxygen and forms thermal energy, biogas can be utilized as a fuel. Nowadays most common applications of biogas are energy generation and fuel production. Electricity can be produced by burning biogas in steam generators or gas turbines. This process usually creates excess of thermal energy that can be also utilized. Combined heat and power (CHP) units are able to work on biogas even with low percentage of methane and supply customers with electricity and hot water. Scale of energy generation at CHP units is rather large; size of the unit depends on the available fuel and energy demand.

Application of biogas as a fuel for automotive combustion engines is more challenging. Natural gas is already implemented as a fuel for vehicles. There are two types of gas fuel: liquefied natural gas (LNG) and compressed natural gas (CNG). According to the fuel quality demand of engines, methane concentration should be 95% or higher. Biogas production process cannot fulfil such requirement. Therefore upgrading of biogas to biomethane will be necessary. Nowadays different types of upgrading technologies are available: pressure swing adsorption (PSA), absorption, waster scrubbing, liquefaction, etc. Biogas upgrading technologies demand huge investments and large volume flow of incoming biogas for successful fuel production. Production of fuel from biogas in Russia will not be feasible due to several factors. First of all, CNG vehicles are not very common nowadays. Majority of private customers use gasoline or diesel fuel for cars, and investment into CNG engines will not be a trend in the near future. The second point is that CNG fuel is already available on the market. It is produced by the famous Gazprom company, that supplies different regions with natural gas. Competition would be extremely challenging and investment would be unlikely to pay off in a sensible period of time (NVG fuel, 2017).

2.2 Severodvinsk city

Severodvinsk is the city in Arkhangelsk region in Russia. It is located in the Northern-West part of Russia. Severodvinsk was founded in 1936 as a village for workers of shipbuilding industry and in 1938 it got the status of the city. In 2016 population of Severodvinsk was 185 075 people. Major part of the city is located on the coast of the White sea and island Yagry also belongs to the city. It is situated close to the coast and connected with the continent by bridge. Map of Severodvinsk is presented on the Picture 1 below (History of Severodvinsk, 2017).

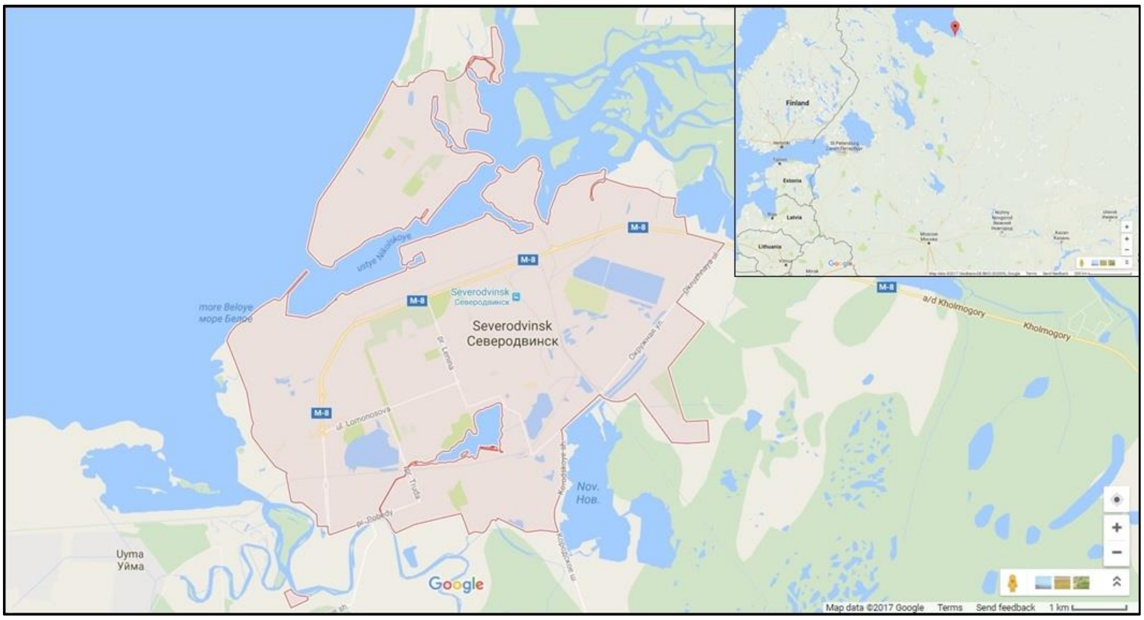

FIGURE 1. Map of the Severodvinsk city (googlemaps.com).

Energy production is one of the most important fields of industry in Arkhangesk region. In Severodvinsk there are two thermal energy plants that supply city, housing areas and production in the region with electricity and heat. First plant started operating in 1941. Coal was the main fuel for energy production. Nowadays company implements reinstallation projects of generators for utilization of natural gas. The second plant was installed in 1976 and utilized black oil as a fuel. Since 2011 power plant operates on natural gas after the renovation, what has a very positive influence on the environmental situation. During the process of oil combustion various pollutants are released into the air. Even modern filtration systems are not capable to prevent emissions such as nitrogen oxides (NO_x), sulphur dioxide and particular matter. After the reconstruction of the second power plant and utilization of natural gas, emission rate significantly lowered. Fortunately, water pollution did not take place even before the reconstruction project, but air pollution was an important issue. After the renovation of the first energy plant (project started in 2016) environmental situation will be improved not only regarding air pollution but also waste generation from burning of coal. The main problems of coal combustion are presence of particular matter in exhaust gas, formation of dust during transportation and storing of coal and ashes from combustion processes. Renovation of the power plant and utilization of natural gas will solve all these problems and will significantly reduce negative environmental impact in Arkhangelsk region (Territorial generative company, 2017).

Waste management is not very well developed in Arkhangelsk region. Major part of waste generated in Severodvinsk is collected and stored on a landfill. Housing areas and apartment buildings do not have opportunities for waste sorting, therefore rate of recycling in the region is rather low. Private companies focus on several types of materials for recycling (paper, tires, glass, hardware and devices, batteries, mercury containing lamps and thermometers). Customers bring specific separated materials to the waste collection points. List of waste types stored on the landfill is placed in Appendix 2 (Spetsavtohozyaistvo, 2016).

All household waste stays unseparated and collected for storing on the landfill. The landfill that is currently operating was installed in 1967. It has an area of 287 399 m^2 and the total amount of stored waste for 2016 is 8 607 828 m^3 (1 807 644 tons). In a year amount of generated municipal waste in the city reaches 500 144 m^3 (57 513 tons) and amount of household waste – 285 345 m^3 (32 814,68 tons) per year. Monitoring systems of the landfill control air pollution and surface water bodies (Spetsavtoho-zyaistvo, 2016).

2.3 Idea of a biogas station

The major challenge for implementation of waste separation systems in Severodvinsk city is the lack of treatment opportunities. Biogas production is a potential way of organic waste treatment, that can help to develop waste management system in the city. The most optimal substrates for fermentation process will be food waste from cafes and canteens (schools, kindergartens, office buildings) and green waste from parks and agricultural production. In organisations, organic waste can be separately collected in kitchens. It will not require big changes, since nowadays majority of food preparation sites has separate containers for food waste. Also organic waste from agricultural production is available in Severodvinsk city. Major part of vegetables is grown in greenhouses during 8 months every year. Leaves and spoiled crops can be utilized as a substrate for biogas production, since currently is it just transported to the landfill. Amount of green waste from parking areas may vary throughout different years due to climatic conditions, but can create a good addition for a substrate.

In the city private houses are not common at all. Citizen live in apartment buildings of different sizes. Nowadays several projects of new apartment buildings are developing at local authorities. It creates an opportunity to implement CHP units and use biogas for energy supply with connection to the common electricity and heat grids. Energy demand significantly varies between winter and summer seasons, what would lead to overproduction of energy during summer. Of course, rate of biogas production can be regulated in different seasons, but emergency energy storages would be required in any case. Connection of CHP unit to the central electricity grid and hot water pipelines would also create opportunity for increase of biogas production if more substrate is available.

In 2016 the experimental program for waste separation in some apartment buildings was created in collaboration with specialists from Norway. Project focused on separation of plastic and glass and acceptance of waste separation idea by local population. Developing of waste separation in the city may lead to availability of household waste for utilization as a substrate. Elimination of major part of paper, cupboard, plastic, glass and metal from waste would make a great opportunity for biogas production. For collaboration with apartment building project, it can be possible to utilize household waste produced by citizen in that area as an additional substrate source. That would require classification of waste produced in apartment buildings and clarification of its compound, according to the legislative standards. Also additional permission would be required for waste treatment, since municipal and household waste usually belong to the category IV, when green waste and kitchen waste belong to the category V (waste categories are presented in the Table 2 below). All waste classes require certification for waste treatment except category V, which can be forwarded to other parties without special permission for waste handling. This issue is beneficial for the current idea with utilization of organic waste only, since it eliminates large part of documents collection for implementation of the biogas station in Severodvinsk city. For the future perspective biogas station can implement additional fermenters for household waste handling after acceptance of certificates by local authorities (The federal law №89, 1998).

TABLE 2. Waste classification

Class	Waste description
I	Extremely hazardous
II	Highly dangerous
III	Moderately dangerous
IV	Low-risk
V	Non-hazardous, practically harmless

2.4 Scenario development

For development of the biogas station project in Severodvinsk city, it is important to assume all possible options for substrate sources and ways of biogas utilization. The main requirement for substrate is presence of organic matter. Since the main target of biogas production is implementation of new opportunity for waste management, option with energy crops as a substrate is not relevant for the current project. In Severodvinsk city there are four waste options available for biogas production: agricultural waste from greenhouses, landfill waste, green waste from park areas and food waste from canteens and cafes. Produced biogas can be utilized as a fuel for CHP units or upgraded to bio-methane. In case of CHP units application, produced electricity and heat should be delivered to the area of apartment buildings. In case of biogas upgrading to the quality of natural gas, it can be transported to thermal energy plant or agricultural production that uses natural gas to support necessary temperature conditions greenhouses. From the digestate it is possible to extract nutrient fraction and utilize it as fertilizers and transport the waste fraction to the landfill. Fertilizers are most likely to be sold to citizens, since gardening in summer cottages is very common in Arkhangelsk region. It can be also possible to supply agricultural production with fertilizers, but the company has high quality requirements and mostly utilizes chemical components. List of fertilizers that agricultural production uses is presented in the Appendix 1. All important issues for development of the scenario are represented in the scheme on the Figure 2 below.

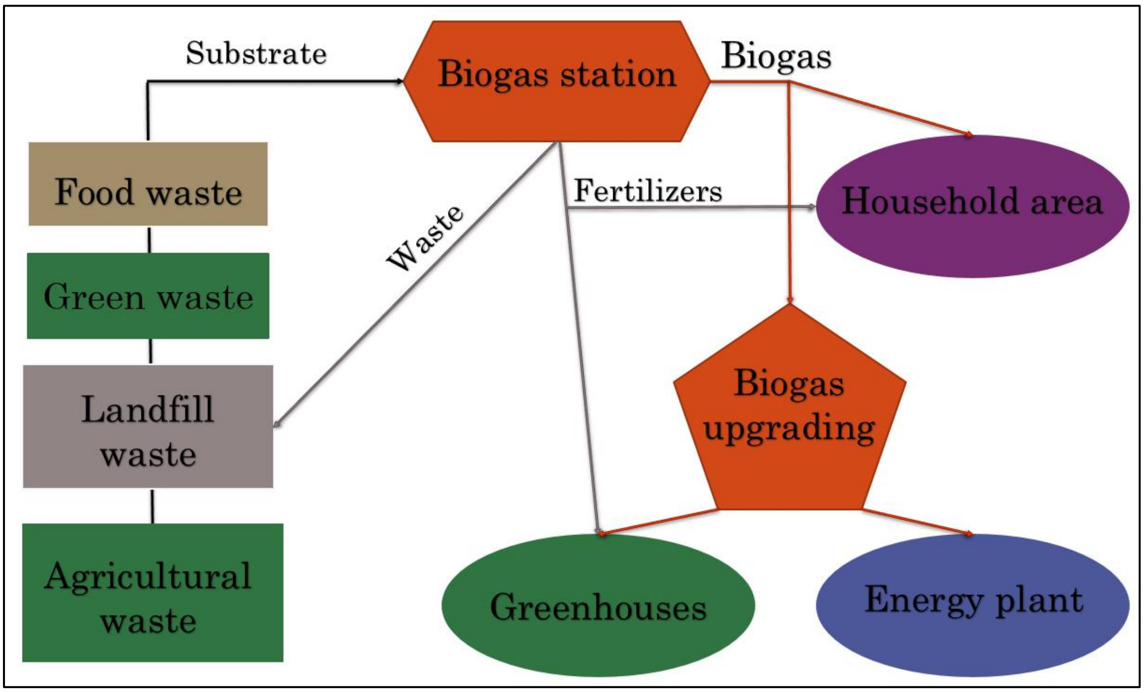

FIGURE 2. Scheme of potential substrate sources and biogas application.

Taking into account that the project is very unusual for Arkhangelsk region, it is important to focus on minimization of financial investments and optimization of logistical issues. First of all, biogas upgrading station would not be successful due to availability of natural gas, therefore biogas needs to be utilized for electricity and heat production at

CHP units. The most efficient way of energy delivery is with common CHP unit for housing area.

Landfill waste is not the best option for the substrate. Its composition is very complicated, even though organic fraction of municipal solid waste is rather high due to the lack of waste sorting in Arkhangelsk region. Utilization of landfill waste would significantly decrease efficiency of fertilizers production out of digastate. Also organic waste belongs to the non-hazardous waste category, as it was mentioned before. Utilization of organic waste only will make process of permit applications much more simple. Therefore, in developed scenario food waste from kitchens, agricultural and green waste from greenhouses and parks will be used as a substrate. Produced biogas will be supplying CHP unit at household area and probably agricultural production if construction of CHP unit at greenhouses' site is possible. Extracted fertilizers will be utilized to support small park in household area. They will be also sold to private customers and agricultural production if quality of fertilizers meets requirements. Waste from digestate will be transported to the landfill. The whole scheme is presented on the Figure 3 below.

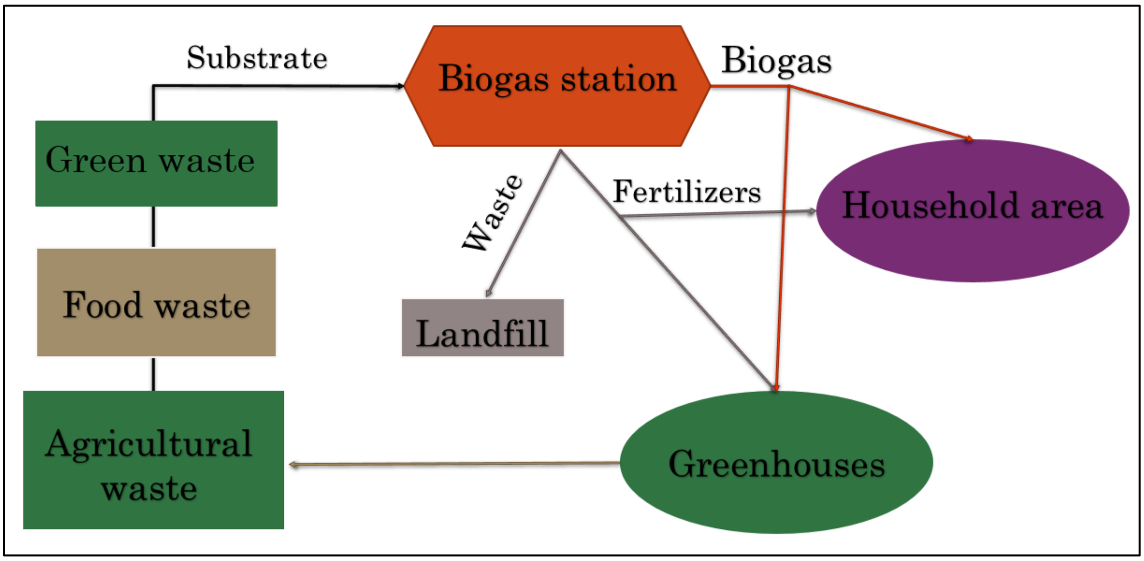

FIGURE 3. Developed scheme for the biogas station project.

3 SUBSTRATE ESTIMATION

3.1 Substrate types and sources

In the developing scenario, biogas will be produced from organic substances during the fermentation process, according to available types of biowaste. For the current project, target waste types are food waste from kitchens, agricultural waste from vegetable production and green waste from park areas. Nowadays in Severodvinsk city there are 32 schools, 65 kindergartens and approximately 300 cafes and restaurants. All waste from food production in canteens and kitchens belongs to a non-hazardous waste type (waste category V) and can be forwarded for further waste handling without special permissions and requirements, as it was mentioned in chapter 2. Waste from park areas and agricultural production consists of grass, leaves, plants and spoiled vegetables. Therefore, it also belongs to the waste category V. The only treatment that should be taken into account in the further project development is the storing of agricultural waste. Greenhouses produce 500-600 tons of green waste annually, but major part of it is formed in September. Amount of collected waste from park areas is 9000 m^3, mostly generated in summer and autumn (Ulyanova, 2017).

3.2 Calculations of green waste amount in the city

According to the data from Environmental department of Severodvinsk city, estimation of annual amount of green waste collected from park areas, grass from mawing lawns and fallen leaves from trees is 9000 m^3. Since green waste is a mixture of cut grass, fallen leaves and brunches, there is no information on exact density value available. Assumption that major part of formed green waste consists of grass and leaves was made. Therefore, density of 800 kg/m^3 was used for calculations (DairyNZ, 2017).

Due to the fact that several companies are responsible for collection of waste in different parts of Severodvinsk city, in the beginning of the project it can be complicated to arrange contracts with all of them. To prevent risk of substrate shortage, minimum and maximum amounts were estimated. For determination of minimum mass of green waste, assumption that 20% of collected waste from parks and lawns available for utilization in worst conditions was made. Calculations were done with the common Formula 1 of material density (The Physics Hypertextbook, 2017).

$$\rho = \frac{m}{V} \quad (1)$$

(where ρ – material density (kg/m^3), *m* – mass (kg), *V* – volume (m^3)

$$m_{min} = \rho \cdot V_{min} = 800\frac{kg}{m^3} \cdot 9000m^3 \cdot 0{,}2 = 1440000\ kg = 1440\ tons$$

$$m_{max} = \rho \cdot V_{max} = 800\frac{kg}{m^3} \cdot 9000m^3 = 7200000\ kg = 7200\ tons$$

3.3 Calculations of food waste amount from kitchens

The main source of organic waste that can be utilized for biogas production would be food waste from kitchens in cafees, canteens and restaurants. Amount of produced food waste can be calculated according to the standard “Production and consumption waste formation”. The Formula 2 below represents dependence of food waste formation from amount of produced dishes and working days of kitchens. For canteens and restaurants coeffiets of waste formation are different:

$$m_{restaurants\ and\ cafes} = 0{,}3\frac{kg}{dish}/day\ ;\ m_{canteens} = 0{,}1\frac{kg}{dish}/day$$

Due to the fact that kitchens at each cafe, resturant and canteen operate at different workload during the week, calculations for produced waste cannot be very precise. Estimation of produced food waste should be done with assumption of different conditions, what leads to calculations of minimum and maximum amounts of produced waste (Ecologicals.ru, 2017).

$$M_{\text{пищ}} = q \cdot N \cdot m \cdot 10^{-3} \quad (2)$$

(M – mass of food waste (t/year); q – amount of dishes in a day; N – amount of working days in a year; m – coefficient of waste production (kg/dish)

3.3.1 Estimation of food waste production at canteens in schools

For calculation of minimum waste production at canteens in schools, following conditions were taken into account: 150 students and 30 teachers; 1 dish per person; 24 working days in a month; academic year of 8 month.

$$M_{pfw} = 180\ dishes \cdot 192\ days/year\ \cdot 0{,}1 \frac{\frac{kg}{dish}}{day} \cdot 10^{-3} = 3{,}256\ tons/year$$

$M_{pfw} = 3{,}256 \frac{tons}{year} \cdot 32 = 104{,}192\ tons/year$ – minimum amount of food waste produced in 32 schools in Severodvinsk.

For estimation of maximum waste production 300 students and 40 teachers; 2 dishes per person; 24 working days in a month and academic year of 8 month were assumed.

$$M_{pfw} = 680\ dishes \cdot 192\ days/year\ \cdot 0{,}1 \frac{\frac{kg}{dish}}{day} \cdot 10^{-3} = 13{,}056\ tons/year$$

$M_{pfw} = 13{,}056 \frac{tons}{year} \cdot 32 = 417{,}792\ tons/year$ – maximum amount of food waste produced in 32 schools in Severodvinsk.

3.3.2 Estimation of food waste production at canteens in kindergartens

For estimation of minimum waste production at canteens in kindergartens the following values were assumed: 60 children and 15 teachers; 3 dishes per person; 20 working days in a month; academic year of 8 month.

$$M_{pfw} = 225\ dishes \cdot 160\ days/year\ \cdot 0{,}1 \frac{\frac{kg}{dish}}{day} \cdot 10^{-3} = 3{,}6\ tons/year$$

$M_{pfw} = 3{,}6 \frac{tons}{year} \cdot 65 = 234\ tons/year$ – minimum amount of food waste produced in 65 kindergartens in Severodvinsk.

The following conditions for maximum waste production were used for calculation of maximum amount of produced food waste in kindergartens: 100 children and 30 teachers; 5 dishes per person; 20 working days in a month; academic year of 8 month.

$$M_{pfw} = 650\ dishes \cdot 160\ days/year\ \cdot 0{,}1 \frac{\frac{kg}{dish}}{day} \cdot 10^{-3} = 10{,}4\ tons/year$$

$M_{pfw} = 10{,}4\,\frac{tons}{year} \cdot 65 = 676\ tons/year$ – maximum amount of food waste produced in kindergartens.

3.3.3 Estimation of food waste production in cafes and restaurants

Due to the very high variety of cafes and restaurants only average waste production can be calculated. Amount of customers per day may vary from 50 (restaurants) to 250 (fast food cafes), and significantly increases during the weekends. Therefore, calculations were done with the assumption of 100 customers and 2 dishes per person.

$$M_{pfw} = 200\ dishes \cdot 365\ days/year\ \cdot 0{,}3\,\frac{\frac{kg}{dish}}{day} \cdot 10^{-3} = 21{,}9\ tons/year$$

Currently in Severodvinsk city there are approximately 300 different cafes and restaurants. Estimation on minimum and maximum amounts of food waste that will be available for biogas production highly depends on amount of collaborations and contracts for waste disposal. The maximum amount of produced food waste is 6,5 tons per year. But in a real life this value will be significantly lower. For the estimation of range values of 300 and 50 cafes can be taken into account.

$M_{pfw} = 21{,}9\,\frac{tons}{year} \cdot 300 = 6570\ tons/year$ – maximum amount of food waste produced in cafes and restaurants.

$M_{pfw} = 21{,}9\,\frac{tons}{year} \cdot 50 = 1095\ tons/year$ – minimum amount of food waste produced in cafes and restaurants.

For estimation of the total amount of available food waste results from calculations for canteens and schools, kindergartens and cafes were combined. Simple calculations are placed below.

$M_{tot,min} = 104{,}192 + 234 + 1095 = 1433{,}192\ (\frac{tons}{year})$ – minimum food waste available.

$M_{tot,min} = 417{,}792 + 676 + 6570 = 7663{,}792\ (\frac{tons}{year})$ – maximum food waste available.

3.4 Range of total available waste

For estimation of the amount of total available substrate for biogas production, results from previous calculations were combined. Ranges of available substrates are presented in the Table 3. As it is possible to mention, values significantly vary for food waste and green waste; differences between maximal and minimal values are almost the same and can be rounded up to 6 000 tons of fresh mass per year. Such difference leads to the challenging problem of defining amounts of available waste and potential amount of biogas production. Design of biogas station depends on these factors. For development of such new project for Arkhangelsk region, key factor for determination of scale for biogas plant will be economical evaluation. Once the break-even production point is defined, optimum amount of organic waste for treatment can be estimated and it will be possible to design the biogas station for Severodvinsk city.

On the current stage of the project, only 2 types of organic waste can be assumed for utilization: food waste and agricultural waste. Green waste from park areas may contain high fraction of leaves, especially in autumn, what will lead to low gas potential. After research on the composition of green waste in different seasons and its gas potential, it will be possible to make conclusion on efficiency of its utilization. Since the difference between minimum and maximum amounts of green waste and food waste is very large, it can be risky to include organic waste with unknown composition and gas potential as a main source of substrate.

TABLE 3. Available organic waste

Substrate type	Amount (fresh mass), minimum (t/a)	Amount (fresh mass), maximum (t/a)
Food waste	1433	7664
Agricultural waste	500	600
Green waste	1440	7200

4 ECONOMICAL EVALUATION

4.1 B.E.A.T. tool

Estimation of the required investments and profit throughout time of operation of biogas plant were done with B.E.A.T tool provided by Ostfalia University. Calculation tool includes the system of excel tables and formulas that are able to combine all data required for calculations and give the final result. During previous Ostfalia research projects regarding biogas production, B.E.A.T. tool was developed by Silvia Drescher-Hartung and has confidential terms. Therefore, only results from B.E.A.T. tool without presentation of formulas can be included into the current thesis work. As an expert in economical evaluation, she developed the system of formulas that include all important factors for estimation of investment costs, production rate, sales of energy or biogas, substrate prices and profit or prices for digestate disposal. B.E.A.T. tool prepares economical evaluation of the project for 20 years, assuming such aspects as expenses for maintenance and increment rate.

4.2 Implementation of B.E.A.T.

First of all, fermentation type of the biogas station has to be considered. In case of Severodvinsk city, biogas will be produced during plug-flow fermentation, since the source for substrate is organic waste and extraction of digestate for possible utilization in agriculture is important for the region. For the next step, substrate types and their annual amounts have to be defined. Combined information is presented in the Table 3, chapter 3 but as it was mentioned, green waste was not included into economical evaluation due to the lack of information on its composition and gas potential. For estimation of gas potential for both types of organic waste, food waste was assumed to have middle fat content and agricultural waste to have same gas potential as grass silage. All coefficients were researched in Ostfalia laboratories. All of them are included in the B.E.A.T. tool. Information on methane yield, biogas yield, gas potential and methane concentration is presented in the Table 4 below for both types of substrates.

TABLE 4. Range of biogas production potential (B.E.A.T.).

Substrate type	Gas potential load, CH_4 per ton of fresh mass (m^3/t)	Methane yield at minimum load (m^3/a)	Methane yield at maximum load (m^3/a)	Methane concentration in biogas (%)	Biogas yield at minimum load (m^3/a)	Biogas yield at maximum load (m^3/a)
Food waste	57	81 681	436 848	60	136 135	728 080
Agricultural waste	112,32	56 160	67 392	54	104 000	124 800

Prices for waste disposal are assumed to be 0,34 EUR per ton (23 RUB/t). (Ulyanova, 2017). In the scenario this value may vary according to final calculations. If prices for waste collection and further utilization of organic waste for biogas production are lower than current prices for waste disposal, it will be easier to create more contracts with restaurants and cafes. It is also possible to make estimation on profit from digestate sales or expenses for its disposal in further development of the project. In the Severodvinsk scenario digestate can be utilized as fertilizers. Unfortunately, on the current stage of the project it is not possible to make any conclusions about the price. Laboratory tests with waste samples from potential sources are required for information on expected quality of fertilizers.

For the planning phase it is not possible to estimate expenses for construction of the whole biogas production site, due to the fact that biogas station should be installed along with construction of apartment building. Substrate does not create any expenses, since biogas production is the way of organic waste treatment. Profit from handling of organic waste is assumed with the price of 0,34 EUR per ton (23 RUB/t). Next important stage is statement of biogas application. In the current project, biogas will be utilized for CHP unit for electricity and thermal energy production. Since the B.E.A.T tool provides calculation for the 20 years period of time, increment rate is an important issue. In Russia increment rate is very unstable every year, therefore estimation with minimum (1,68%) and maximum (13,28%) values for the past 10 years were done.

Since the point of increment rate of 13,28% was critical, assumption of 3% as a maximum value for the next years was done (Increment rate, 2017).

Operational costs are formed by personnel fees, maintenance and repair. Average salary in Arkhangelsk region in 2016 was 31 900 RUB, what can be rounded up to 500 EUR per month (Echo Severa, 2017). Also assumption that 2 operators are required at biogas station was made. Price for maintenance and repair depends on the flow of produced biogas. The value of 0,025 EUR/Nm^3 is included into the B.E.A.T. tool.

Prices for electricity and heat vary during the year. The average value of 4 RUB/kWh (0,06 EUR/kWh) of electricity can be used for calculations. The save value of 0,06 EUR/kWh of thermal energy is assumed as the price for heat. (Energy Base, 2017)

Economical evaluation with B.E.A.T. tool shows that project cannot be profitable without sale of fertilizers that will be produced from digestate. Even though in conditions of maximum amount of organic waste available (7 664 tons/year), biogas station would not pay off even after 20 years of its operation. On Figures 4 and 5 that are presented below, curve for cumulative discounted flow reflects situations with minimum and maximum amounts of utilized organic waste.

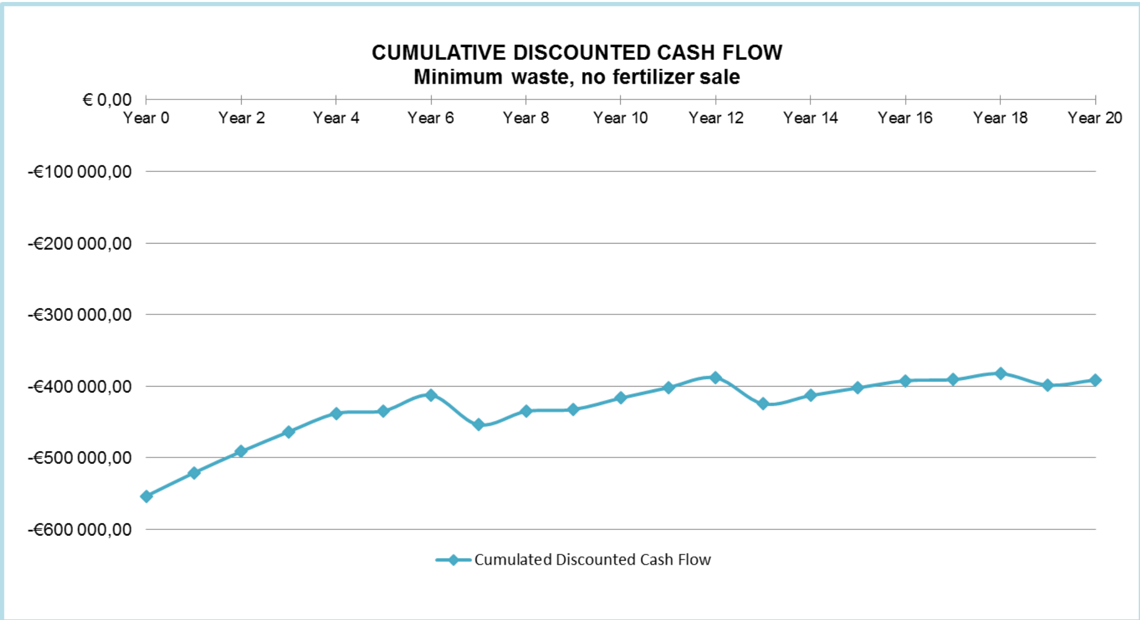

FIGURE 4. Cumulative discounted cash flow at the conditions of minimum organic waste amount application and no sales of fertilizers.

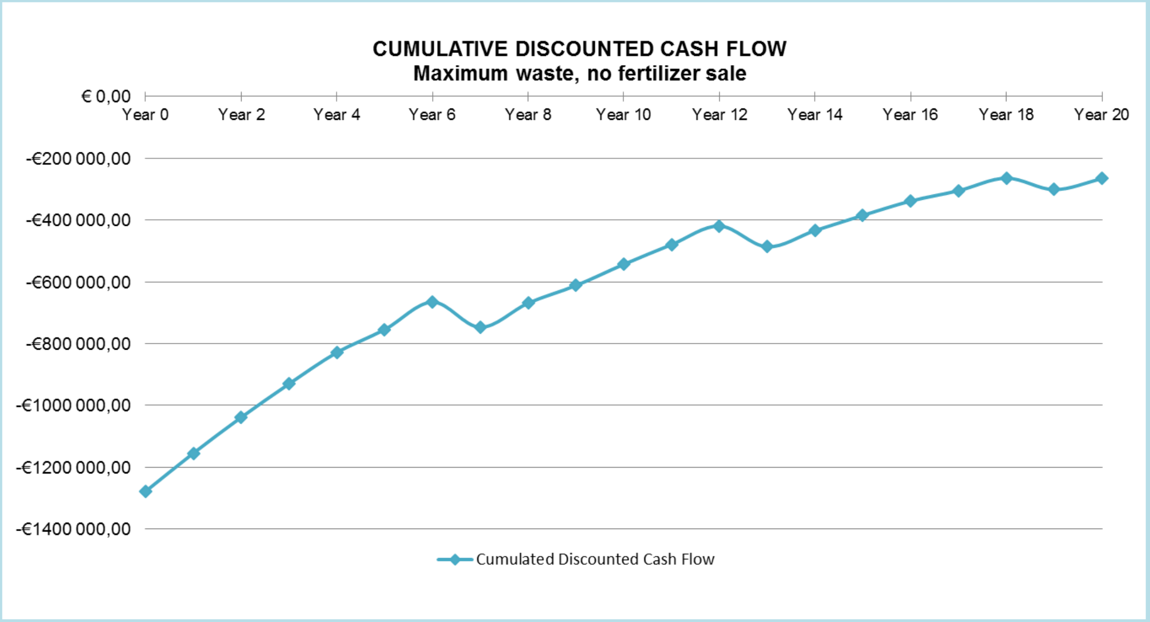

FIGURE 5. Cumulative discounted cash flow at the conditions of maximum organic waste amount application and no sales of fertilizers.

Once the price for fertilizers is taken into account, the whole situation looks much more optimistic. After several tests with B.E.A.T. tool it was possible to find the lowest value of 25 euros per ton for digestate sales when the project pays off within 20 years of operation. Figure 6 below represents cumulative discounted cash flow in conditions of minimal amount of substrate utilized and price for digestate of 25 euros per ton. As it is possible to mention, the project will become profitable after 18 years of operation. Figure 7 shows the dramatic change of situation in conditions of utilization of maximum amount of organic waste and the same low price for digestate of 25 euros per ton. According to the calculations with B.E.A.T. tool, the biogas production project would be profitable after 5 years of operation.

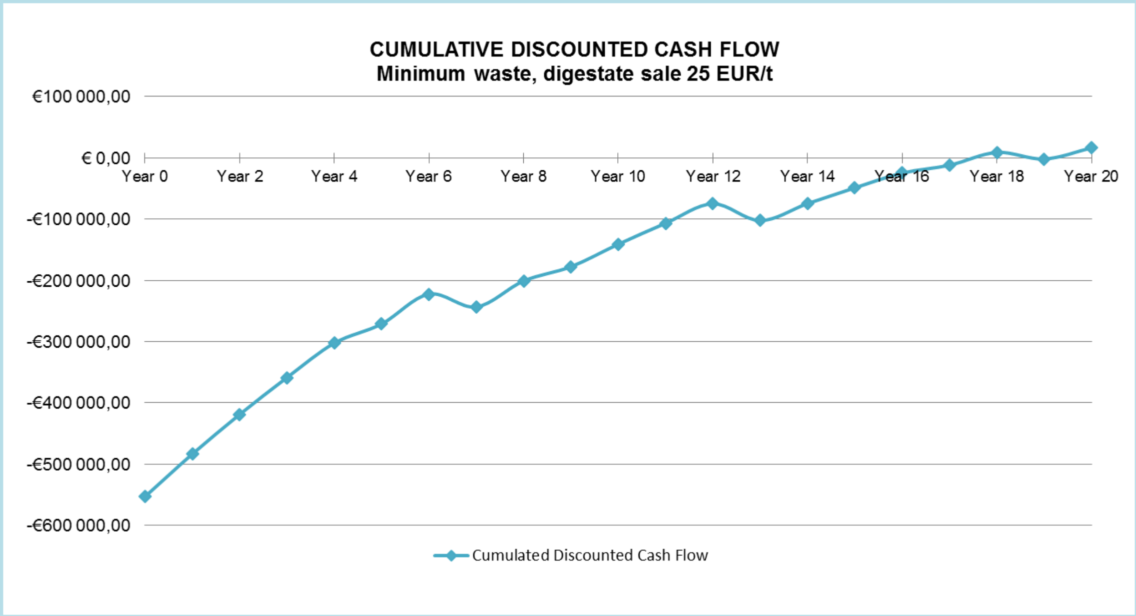

FIGURE 6. Cumulative discounted cash flow at the conditions of minimum organic waste amount application and sales of fertilizers with the price of 20 EUR/ton.

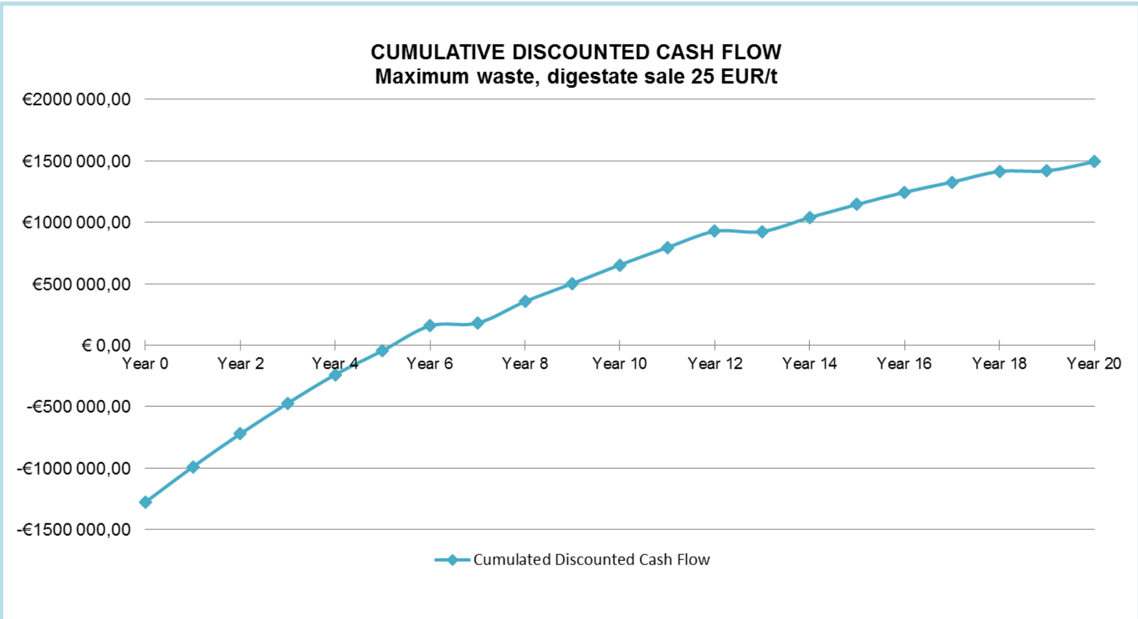

FIGURE 7. Cumulative discounted cash flow at the conditions of maximum organic waste amount application and sales of fertilizers with the price of 25 EUR/ton.

To define conditions of the perfect economical situation of the project, more tests with B.E.A.T. tool were done. On the Figure 8 below cumulative discounted cash flow for biogas production from maximum substrate utilization and digestate sales for 70 euros per ton is presented. In these conditions the whole project reaches break-even point after 2 years of biogas plant operation.

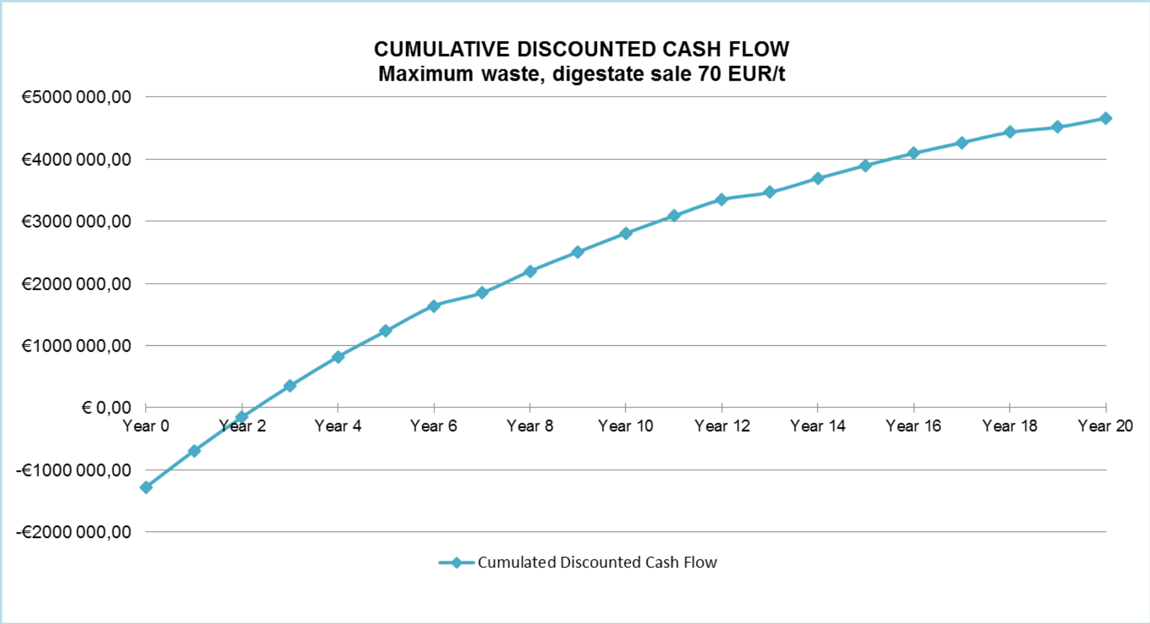

FIGURE 8. Cumulative discounted cash flow at the conditions of maximum organic waste amount application and sales of fertilizers with the price of 70 EUR/ton.

4.3 Problem of adaptation to different economical situation

Due to the fact that B.E.A.T. tool was developed with adaptation to German prices, it is rather challenging to implement it for estimation of required investments. Required construction costs in reality of Arkhangelsk region can be significantly lower than estimation with B.E.A.T. tool. At the moment it is not possible to make exact calculations of investments, since during implementation of project contracts with different companies for required supplies is an important issue. Such detailed information can be collected only at the stage of project implementation.

Fortunately, the main financial flow can be estimated with application of economical data such as prices for electricity, average salary and prices for waste disposal in Arkhangelsk region. All data that was inserted for economical evaluation is presented in the Table 5 in comparison with some values for Germany. Only values for ammonium nitrate fertilizers were added just for comparison of price levels. It is possible to mention that for most parameters there is a big difference, except the price for fertilizers that proves significance of fertilizer sales for economical evaluation of the biogas station project. Mostly the difference is caused by general price level in countries. Low prices for energy in Russia correspond with low average salary. The most dramatic difference is price for waste disposal, in Germany it is approximately 50 times higher than in Russia; when average salary in Germany 8 times higher and price for electricity is 5 times higher.

Even though actual investment will be less expensive than estimated value, the main tendency in case of fertilizer sales is very positive. In the situation presented on the Figure 6 the pay out time is very promising – 2 years for such pilot project is a good situation. After market and suppliers research amount of required investments can be calculated. At the current stage of the project it was important to make estimation on profitability rate. It allows to have an idea whether biogas station scenario can be successful or dramatic changes would be required.

TABLE 5. Comparison of data for economical evaluation in Russia and Germany

Parameter		Unit	Value in Russia	Value in Germany
Minimum amount of substrate	Food waste	ton	1433	
	Agricultural waste	ton	500	
Maximum amount of substrate	Food waste	ton	7664	
	Agricultural waste	ton	600	
Price for waste disposal (landfill)		EUR/ton	0,34	9 – 30 [1]
Increment rate		% (minimum)	1,68	0,6 [2]
		% (maximum)	13,28	2,7 [2]
Average salary		EUR	500	4 102 [3]
Price for electricity		EUR/kWh	0,06	0,617 [4]
Price for heat		EUR/m^3 (hot water)	0,44	-
Price for fertilizers (for ammonium nitrate)		EUR/ton	162	165

[1] – Costs for Municipal, 2017

[2] – Trading economics, 2017

[3] – World salaries, 2017

[4] – Clean energy wire, 2017

5 TECHNICAL IMPLEMENTATION

Biogas is usually produced during the biodegradation of organic substances. At the hydrolytic phase biomass is degraded into sugar, amino acids and fatty acids. On the next step metabolition of cracked products happens with formation of hydrogen, carbon dioxide, propionic acid and alcohols. During acetogenic phase fatty acids (propionic acid) and alcohol transform into acetic acid and hydrogen. At the final stage of methanogenesis formation of methane happens. Final biogas product consists of mostly methane and carbon dioxide with small amount of additional chemical components that were mentioned in Table 1.

In bioreactors fermentation happens under anaerobic condition throughout continuous, semi-continuous or batch operation. Methane can be produced with wet or dry digestion technologies, including mono-digestion or co-digestion at mesophilic (15°C – 43°C) or thermophilic (43°C – 78°C) conditions (Ahrens, 2017).

5.1 Biogas plant structure

For the current project the main principle of biogas production is a plug-flow dry fermentation, since only organic waste is used as a substrate. Biogas plant mainly consist of two storage tanks for substrate, two digesters, separator and storage tank for digestate and biogas. Both digesters have several mixers for homogenization of the substrate and protection covers for prevention of biogas leakages. During the typical biogas production process, substrate is delivered to the top of the first digester with an input device. It makes mixing easier and significantly decreases energy input for homogenization process, since transportation of substrate happens several times in a day, when mixing process is continuous. If density on the bottom layer is significantly higher than on top of the digester, energy input dramatically increases, while load of substrate from the top provides faster homogenization due to the effect from gravitational force. For operation of a biogas plant also heat exchangers for temperature regulation and pumps for material transportation are required. Typical plug-flow dry fermentation happens in thermophilic conditions at the temperature of 55°C. Separation of digestate allows to extract biomass with high concentration of nutrients. After 1 hour of sanitation at 70°C it is possible to utilize separated digestate as a fertilizer for agricultural production. Produced biogas is transported to CHP units for generation of electricity and production of thermal energy for household areas. (Ahrens, 2017).

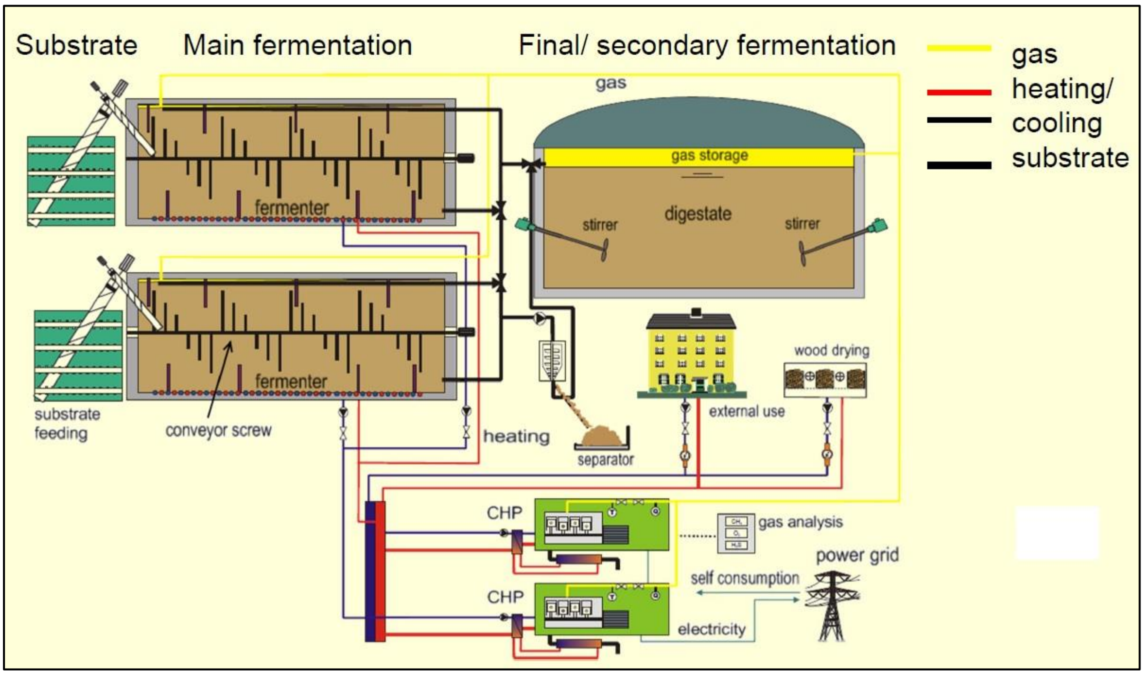

FIGURE 9. Main structure of biogas plant (Ahrens, 2017).

5.2 Estimation of digester volume

5.2.1 Calculations for daily feeding ratio

Some types of substrate available at different times of year. For estimation of required volume of digesters calculations on range of substrate volume were done. First of all, in cafes and restaurants food waste is produced throughout the whole year, when in canteens at schools and kindergartens it is formed only during 8 months. To conclude distribution of substrate daily rates of incoming waste were calculated. Density of organic waste was taken as 0,5 ton/m^3 and values of mass were used from the section 3 Substrate estimation (Environmental Protection Agency, 2017).

$V_{min} = \frac{1095 \frac{ton}{year}}{365\ days \cdot 0{,}5 \frac{ton}{m^3}} = 6{,}54 \frac{m^3}{day}$ – minimum volume of restaurant kitchen waste.

$V_{max} = \frac{6570 \frac{ton}{year}}{365\ days \cdot 0{,}5 \frac{ton}{m^3}} = 36 \frac{m^3}{day}$ – maximum volume of restaurant kitchen waste.

$V_{min} = \frac{104{,}192 \frac{ton}{year}}{192\ days \cdot 0{,}5 \frac{ton}{m^3}} = 1{,}09 \frac{m^3}{day}$ – minimum volume of kitchen waste from canteens at schools.

$V_{max} = \frac{417{,}792 \frac{ton}{year}}{192\ days \cdot 0{,}5 \frac{ton}{m^3}} = 4{,}35 \frac{m^3}{day}$ – maximum volume of kitchen waste from canteens at schools.

$V_{min} = \frac{234 \frac{ton}{year}}{160\ days \cdot 0{,}5 \frac{ton}{m^3}} = 2{,}93 \frac{m^3}{day}$ – minimum volume of kitchen waste from canteens at kindergartens.

$V_{max} = \frac{676 \frac{ton}{year}}{160\ days \cdot 0{,}5 \frac{ton}{m^3}} = 8{,}45 \frac{m^3}{day}$ – maximum volume of kitchen waste from canteens at kindergartens.

As it was mention in section 3 Substrate estimation, annual amount of agricultural waste is 500-600 tons. The period of waste generation lasts from March to September. Major part of agricultural waste is generated in September (approximately 70%). Annual volume of collected green waste from park areas is 9000 m^3. Available minimum of 1800 m^3 and density of 800 kg/m^3 were assumed for calculations.

$V_{min} = \frac{1440 \frac{ton}{year}}{214\ days \cdot 0{,}8 \frac{ton}{m^3}} = 8{,}41 \frac{m^3}{day}$ – minimum volume of green waste from park areas.

$V_{max} = \frac{7200 \frac{ton}{year}}{214\ days \cdot 0{,}8 \frac{ton}{m^3}} = 42{,}06 \frac{m^3}{day}$ – maximum volume of green waste from park areas.

$V_{min,Sept} = \frac{500 \frac{ton}{year} \cdot 0{,}7}{30\ days \cdot 0.8 \frac{ton}{m^3}} = 14{,}58 \frac{m^3}{day}$ – minimum amount of generated agricultural waste in September (harvesting period).

$V_{max,Sept} = \frac{600 \frac{ton}{year} \cdot 0{,}7}{30\ days \cdot 0.8 \frac{ton}{m^3}} = 17{,}5 \frac{m^3}{day}$ – maximum amount of generated agricultural waste in September (harvesting period).

$V_{min} = \frac{500 \frac{ton}{year} \cdot 0{,}3}{(214-30)\ days \cdot 0{,}8 \frac{ton}{m^3}} = 1{,}02 \frac{m^3}{day}$ – minimum volume of agricultural waste during the production season.

$V_{max} = \frac{600 \frac{ton}{year} \cdot 0{,}3}{(214-30)\ days \cdot 0{,}8 \frac{ton}{m^3}} = 1{,}22 \frac{m^3}{day}$ – maximum volume of agricultural waste during the production season.

TABLE 6. Daily feeding ratios for biogas station during the year.

Daily feeding ratio (m^3/day)	Kitchen waste (canteens)		Kitchen waste (cafes)		Agricultural waste		Green waste		Total amount	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
January	-	-	6,54	36	-	-	-	-	6,54	36
February	4,02	12,8	6,54	36	-	-	-	-	10,56	48,8
March	4,02	12,8	6,54	36	1,02	1,22	-	-	11,58	50,02
April	4,02	12,8	6,54	36	1,02	1,22	-	-	11,58	50,02
May	4,02	12,8	6,54	36	1,02	1,22	8,41	42,06	19,99	92,08
June	-	-	6,54	36	1,02	1,22	8,41	42,06	15,97	79,28
July	-	-	6,54	36	1,02	1,22	8,41	42,06	15,97	79,28
August	-	-	6,54	36	1,02	1,22	8,41	42,06	15,97	79,28
September	4,02	12,8	6,54	36	14,58	17,5	8,41	42,06	33,55	108,36
October	4,02	12,8	6,54	36	-	-	8,41	42,06	18,97	90,86
November	4,02	12,8	6,54	36	-	-	-	-	10,56	48,8
December	4,02	12,8	6,54	36	-	-	-	-	10,56	48,8

5.2.2 Retention time demand

As it was mentioned in chapter 3, it is challenging to make any assumption regarding biogas production from green waste from park areas. In spite of this fact, it can be a good potential additional source of organic matter. Therefore, it is assumed that maximum daily feeding ratios will exclude green waste.

It is possible to extract from the Table 5 above, that maximum daily feeding ratio is supposed to happen in September – 100,07 m^3/day, when minimum value is expected in January 6,54 m^3/day. If retention time is assumed to be 50 days, volume of digester at conditions of minimal and maximal substrate load can be calculated by following way (Ahrens, 2017).

$V_{d,min} = 50\ days \cdot 6{,}54 \frac{m^3}{day} = 327 m^3$ – digesters volume requirement at minimal load

$V_{d,max} = 50\ days \cdot 65{,}94 \frac{m^3}{day} = 3297 m^3$ – digesters volume requirement at maximal load

For estimation of digester volumes it is possible to use value calculated from maximum daily feeding rate. Even though, it is unlikely that all food waste and agricultural waste will be collected and 65,94 m^3 of substrate per day will be fed, there will be room for green waste. Potentially, grass part can be separated from leaves due to seasonal formation, it can be stored and evenly distributed for feeding of biogas digesters during the whole year. First digester usually includes 1/3 of total substrate volume. Therefore estimated volumes for digester can be calculated by following way:

$$V_1 = \frac{1}{3} \cdot V_{d,max} = \frac{1}{3} \cdot 3297m^3 = 1099m^3$$

$$V_2 = V_{d,max} - V_1 = (3297 - 1099)m^3 = 2198m^3$$

6 SIMULATION AND UPSCALING

One of the specifications of the current project for the development of biogas station in Severodvinsk city is the lack of opportunities for sampling of substrate matter and their transportation to Ostfalia laboratory. Another challenging issue is the requirement for data collection from potential stakeholders. Due to the fact that information on equipment prices or exact amount of available waste can be received only on the stage of real-life implementation of biogas plant project, preliminary calculations were done based on assumptions and estimations with the main purpose of strategy development.

On the current stage, the project includes only theoretical part of the biogas station development. In previous chapters, main purpose of calculations was to determine the scale of the project, estimate the range of available substrate amount. Major factor for the future development of the biogas station project was economical evaluation. Once important factors for successful implementation of biogas production as part of waste management were defined, it was possible to create a strategy with further tasks that will help to turn theoretical project into an actual biogas plant.

6.1 Waste management

First of all, it is important to get access to sampling of all types of waste that are planned to be utilized as a substrate for biogas production. Evaluation of the waste particles' size will create an idea of the requirement of preliminary treatment. Main risks of large particles in organic waste are stones and big branches from the waste collected in park areas; in the food waste from kitchens large plastic or cardboard particles from packages may be found. When large particles from collected food waste can be avoided by implementation of waste separation in kitchens, stones and branches can be challenging to eliminate from green waste at the moment of its collection. To prevent any damages to systems in biogas plant (digesters, mixing components, substrate transportation device) it is important to evaluate presence of potentially harmful large particles in organic waste. As it was mentioned in chapter 5, additional requirement for separation of grass part from green waste (since leaves usually have low gas potential) and its storing should be taken into account.

6.2 Biogas potential

Once samples of waste are available it is possible to perform laboratory tests for estimation of biogas potential. After running several batch tests it will be possible to get data on methane production from amount of fresh mass. It is important to assume seasonal availability such waste types as green waste and agricultural waste. Batch tests with different proportions of food/green/agricultural wastes will create the overall idea about methane production potential in different seasons. Continuous tests are required for estimation of biogas production in a long-term operation. Important factor for continuous testing is a sanitation phase. It can be performed by heating of substrate for one hour at 70°C (Freidank, 2014).

6.3 Substrate characteristics

Characteristics of substrate are also important for biogas plant design. Even though only organic waste is planned to be utilized as a substrate for biogas production, dry matter and organic dry matter contents can be determined by burning tests. One of the most important issue for the development of the current project is estimation of nutrients concentration and chemical compound of substrate and digestate. According to the results of economical evaluation from chapter 4, sales of fertilizer is a key point of the project expediency. Therefore, information on digestate composition is essential for determination of the price for fertilizers. The most important chemical components for fertilizer are nitrogen, potassium and phosphate. For the further development of the project it is crucial to test characteristics of digestate and estimate its price.

6.4 Stakeholders

One of the most important parts of further development of biogas station project is identification of independent parties for collaboration. For a more precise values in economical evaluation such aspects as prices for transportation of waste, construction investments, exact amounts of waste formation and potential customers of generated energy are very important to define. Nowadays the most efficient way of organic waste collection would be creation of a waste treatment company. In that way major factors would be organization of waste transportation, creation of customer base for waste collection, creation of agreement with authorities for entering energy grids, search for suppliers of materials or ordering of a biogas plant construction from one company. If biogas will be operated independently without registration as a waste treatment company, it will cause much more difficulties for collection of food waste and agricultural waste.

6.5 Market study

From the economical evaluation in the chapter 4 it was concluded that the key factor for successful implementation of biogas station is the price for fertilizers that will be produced from digestate. After several laboratory tests and gained data on digestate quantities and composition, it is necessary to perform a market research, especially if agricultural production will have different requirements for fertilizer quality. Important factors will be search for potential customers, range of prices, opportunities for organizing sales, transportation and packaging. Sales of fertilizers to stores is very unlikely, since it will lead to complicated process of additional company registration. In Severodvinsk city there is a market that is popular for sales of seeds, seedlings, vegetables, materials for greenhouses, gardening equipment, etc. It can be one of the options, since it is open during the whole year. The best option would be to arrange contracts for annual supply of fertilizers, since gardening season starts only in May and ends in September. Uneven distribution of sales can be challenging. Also requirement for advertisement has to be researched.

7 DISCUSSION

The main purpose of the current project was to create a theoretical scenario for biogas station for the infrastructure of Severodvinsk city based on the research, literature values and rough estimations. In Europe biogas is produced from various types of substrate and focused on providing energy to local citizens. For example, in Germany biogas plant can be very profitable due to the governmental support and relatively high prices for electricity, heat and fuel. In Russia situation is very different. Biogas production is presented on a small scale and the most efficient plants work along with animal farms, utilizing animal dung as a substrate. In the Northern regions biogas production is not presented at all. Research of the aspects of infrastructure in Severodvinsk city and creation of scenario showed interesting results and the most challenging aspects for the real-life implementation of biogas production.

Initial idea was application of biogas station as a waste treatment opportunity. In Severodvinsk city waste management is not developed. In 2016 an experimental project for waste separation took place. The main conclusion was that population will be willing to separate waste, but nowadays there are no opportunities for waste treatment. All collected waste in the region goes to the landfill. Therefore, biogas station can be a great way to implement opportunity for treatment of organic waste, since it will decrease amount of waste stored on the landfill and mitigate release of greenhouse gases to the atmosphere in the future.

Unfortunately, there are no governmental programs in Russia for biogas production. Therefore, no extra subsidies can be expected. For implementation of the project application for the grand from Environmental department in Moscow will be required. Due to the fact that this process if very complicated, feasibility of the project has to be proven. At first, the main source of profit from implementation of biogas plant was expected to be waste collection fee. There would be a high competition on the energy market and general level of prices for electricity and heat is rather low. After the research and economical evaluation, it appeared that prices for waste collection are also rather low and the main source of profit should be sale of digestate as fertilizer. Since the current stage of the project is theoretical, some investments into more detailed research and laboratory tests are required. One of the options would be the search for sponsors that support development of environmental technologies. Collaboration with ecological departments at universities or institutions can also be a good solution for further development of the project. The most complicated solution is application for a grand from Environmental department at local authorities.

At the moment implementation of biogas technologies in Arkhangelsk region may be rather questionable, but results from current project prove that biogas station can be a good option for waste management. Even with rough estimations, it is possible to find feasibility points. The target for the further research is to find opportunities for adaptation of investment costs to the Russian price level and potential ways to widen area of biogas production in Northern regions as a way of organic waste treatment.

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APPENDICES

Appendix 1. Information on current fertilizers of agricultural production

TABLE 7: List of utilized fertilizers.

Fertilizer	Required amount, t	Price RUB/t; EURO/t
KNO_3	20	35000; 539
KH_2PO_4	2	72300; 1112
$Ca(NO_3)_2 \cdot 4H_2O$	11	16950; 260
$MgSO_4 \cdot 7H_2O$	4	15750; 242
$Mg(NO_3)_2 \cdot 6H_2O$	1	26050; 400
K_2SO_4	1	39150; 602
$(NH_2)_2CO$	0,2	13250; 203

Appendix 2. Waste types acceptable for the landfill in Severodvinsk city

1. Dust (sandpaper) abrasive grinding; black metals with metal less than 50%
2. Waste of sand from wastewater treatment plants and sandblasting devices
3. Garbage with protective grills of economic and mixed sewerage low-risk
4. Unsorted municipal waste, excluding bulky waste
5. Unsorted waste from offices

6-11. Rubbish and dust from streets, production premises, stock premises, parking areas, filling stations, production sites' outdoor territories

12. Waste from kitchens and food production
13. Waste from cleaning of hotel rooms, motels and other places of temporary accommodation
14. Waste from cleaning of beauty salons, hairdressing salons, barbershops
15. Ashes and scobs from incineration
16. Construction waste from demolishing of buildings
17. Asphalt and concrete waste
18. Waste from construction and renovation works
19. Welding scobs
20. Brake pads with asbestos patches