RIGA TECHNICAL UNIVERSITY

Ģirts Kuplais

Modelling of climate technologies in landfill

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RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
Institute of Energy Systems and Environment

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Environmental engineering program

Modelling of climate technologies in landfill

PhD Thesis. Summary

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Riga 2010

PHD THESIS

PROPOSED FOR DR.SC. ING. DEGREE IN ENVIRONMENTAL ENGINEERING AT RIGA TECHNICAL UNIVERSITY

This study will be publicly defended at December ..., 2010 at the assembly room of Faculty of Power and Electrical Engineering, Kronvalda Boulevard 1, Riga.

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STATEMENT

I confirm that I personally developed this dissertation, which I submitted for consideration at Riga Technical University, for attaining the degree of the doctor of engineering sciences. This study has not been submitted to any other university for attaining a scientific degree.

Ģirts Kuplais ______________________

Date ________________________

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Overview

Actuality of the subject

Latvia has joined UN Framework Convention on Climate Change which puts an obligation to reduce a discharge of greenhouse gas (GHG) into the atmosphere. According to this document countries must achieve 8% GHG emission reduction till 2012 comparing to the level of 1990. In Latvia this task can be reached and opens new opportunities for surplus GHG emission sale and additional investment opportunities state fund set up for the joint implementation projects.

The EU member states have agreed on energy and climate package realization, within it Latvia has undertaken to promote energy efficiency for 20% but usage of renewable energy resources for 40% till 2020. In order to achieve this goal each energy sector representative, each energy farm plays an important role. It is a question of climate technology usage and operation allowing reducing an impact on global climate change.

In order to reduce greenhouse gas emissions, the climate technologies are widely used also into the management of landfills and play an important role in:

- Electricity consumption reduction used in all types of equipment;
- Reduction of greenhouse gas leakage from the landfill storage surface;
- The collection of biogas, which is formed into landfills storage, and appropriate use of it.

Latvia have made a choice for waste management at the end of the last century, in year 1997 developing and fulfilling municipal solid waste management strategy-programme "500-". The idea of the large regional landfill creation by closing small, sometimes non-organized parish and town dumps was incorporated into it.

Currently in Latvia are nine regional landfills in which special storages are created. The landfill site is a set of engineering systems, including piping, auxiliaries and water treatment technologies. The electricity is used for engineering equipment operation and lightening. The biogas is formed into landfills storage and it mainly consists of two greenhouse gases - methane and CO_2. It means that everything has to be done not only to reduce GHG release into the environment also to use them appropriately. Therefore the large landfill storages are equipped with biogas collection system and auxiliaries for biogas transportation.

In order to make possible for Latvia to move forward with a development of system for appropriate use and management of landfills energy resources, the research of factors impacting them is needed. Because of this reason this dissertation is focused on energy efficient management of landfills. Dissertation consists of two independent parts which is merged by the idea of the climate technology development.

1. A research of possibilities for energy efficiency increase at energy user side. Engineering data analysis for the major energy consumer leachate treatment.
2. Renewable energy resource - biogas, which is formed in landfill storages, energy efficient use feasibility research to get technical, economic and environmental friendly solution and to reduce an investment risk.

Objectives

The aim of researches described in the dissertation is to analyze landfill site management conception for energy efficient usage of climate technologies, in order to reduce greenhouse gas emissions by reducing electricity consumption for leachate treatment and appropriate use of the biogas formed in landfill storage.

Research tasks

Research challenges include solutions for the landfills energy efficient management optimization problems.

1. Landfill management model establishment using technology development approach, taking into account EU directives and legislative restrictions;
2. Analysis of energy consumers, paying attention to the major energy users, analysing energy usage of leachate treatment plant, defining dependent and independent variables and determining mathematical relation among them;
3. Development of methodology for optimal usage of landfill management energy resources, which is based on benchmark modelling for independent variables - electricity purchase price, cogeneration technology investments, mathematical description of heat load duration curves approximation graphic, tax and greenhouse gas emission limiting values:
    - 1.1. Analyses of renewable energy source - biogas usage possibilities in 2 climate technologies:
        - 1.1.1. The biogas purification and improvement for high energy efficiency use in Latvia;
        - 1.1.2. The use of biogas energy in power plants or in CHP equipment.
    - 1.2. Defining the goal function for energy resource use optimization.
4. Testing of usage optimization methodology within a one landfill in Latvia.

Scientific significance

In this work the renewable energy resources use optimization model is developed and it covers both horizontal and vertical modular systems. The optimization criteria are selected. Optimization goal functions are mathematically described for technological, economic and climate submodels.

Waste management energy resource optimization model is approbated for Daibe landfill conditions.

The energy consumption for leachate treatment is analyzed and empiric model for specific energy consumption of leachate treatment is obtained based on ongoing process in landfill and on analyze of leachate treatment technological equipment performance, and independent parameters are determined.

Practical significance

A methodology developed in the dissertation has large audience of users and the use of the results acquired in optimization model depends on the purpose for what a user is intended to use:

- In landfills - to evaluate landfills operation economic, technical and ecological parameters with a help of the criteria proposed in methodology and optimization methodology;
- Ministry of Environment – the results of research on the leachate management can be used in legislative document elaboration;
- Ministry of Economics - the methodology allows to evaluate a need for grants and subsidies for energy production using biogas in landfills;
- Investors - the methodology opens new possibilities for investors to perform investment performance analysis for CHP or other use of biogas.

Approbation

The results of the work are reported and discussed in:

1. Kuplais Ģ. The temper of solid waste landfill leachate and leachate cleaning facilities. RTU 48th international scientific conference. Riga, 2007, 11-13 October.
2. Kuplais Ģ., Liepiņš M., Prols J. Practise of leachate treatment in solid waste landfills in Latvia. RTU 49th international scientific conference. Riga, 2008, 13-15 October.
3. Blumberga D., Kuplais Ģ., Veidenbergs I., Dāce E., Guščа J. Modelling of the installed capacity of landfill power stations. RTU 50th international scientific conference. Riga, 2009, 12-16 October.
4. Kuplais Ģ., Blumberga D., Dāce E. System analysis for integration of landfill energy production in regional energy supply. 5th International conference "Waste management 2010", 2010, 12 – 14 July, Estonia, Tallinn.
5. Blumberga D., Kuplais Ģ., Romagnoli F., Vigants E. CHP or power station? Question for Latvia. The 12th International Symposium on District Heating and cooling. 2010, 5-7 September, Estonia, Tallin.
6. Kuplais Ģ., Blumberga D., Dāce E., Romagnoli F. Optimization model of biogas use in landfills in Latvia. 7th International conference "Organic resources in the carbon economy", 2010, 29 June – 3 July, Greece, Crete, Heraklion.

Publications

1. Blumberga D., Kuplais Ģ., Veidenbergs I., Dāce E. Benchmarking method for estimation of biogas upgrading schemes. Latvian Journal of Physics and Technical Sciences. - Nr. 4 (2009), pp. 23–35.
2. Blumberga D., Kuplais Ģ., Veidenbergs I., Dāce E., Guščа J. Modelling of installed capacity of landfill power station. The 50th International Scientific Conference of Riga Technical University, section „Environmental Engineering", 2009, 14 – 15 October, Latvia, Riga – Scientific Proceedings of Riga Technical University „Environmental and Climate Technologies", Volume 3, Series 13. – Riga: „RTU", 2009, pp. 19 – 26.
3. Kuplais Ģ., Liepiņš M., Prols J. Practise of leachate treatment in solid waste landfills in Latvia. The 50th International Scientific Conference of Riga Technical University, section „Environmental Engineering", 2009, 14 – 15 October, Latvia, Riga – Scientific Proceedings of Riga Technical University „Environmental and Climate Technologies", Volume 1, Series 13. – Riga: „RTU", 2009, pp. 52-60.
4. Blumberga D., Kuplais Ģ., Veidenbergs I. Analysis of use of biogas in cogeneration plant Daibe landfill. The 50th International Scientific Conference of Riga Technical University, section „Environmental Engineering", 2009, 14 – 15 October, Latvia, Riga – Scientific Proceedings of Riga Technical University „Power and electrical engineering", Volume 24, Series 4. – Riga: „RTU", 2009, pp. 68-76.
5. Kuplais Ģ. The temper of solid waste landfill leachate and leachate cleaning facilities. The 50th International Scientific Conference of Riga Technical University, section „Environmental Engineering", 2007, 11 – 13 October, Latvia, Riga – Scientific Proceedings of Riga Technical University „Power and electrical engineering", Volume 21, Series 4. – Riga: „RTU", 2009, pp. 19 – 26.
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7. Blumberga D., Kuplais Ģ., Romagnoli F., Vigants E. CHP or power station? Question for Latvia. The 12th International Symposium on District Heating and cooling.2010, 5-7 September, Estonia, Tallin.
8. Kuplais Ģ., Blumberga D., Dāce E., Romagnoli F. Optimization model of biogas use in landfills in Latvia. 7th International conference "Organic resources in the carbon economy", 2010, 29th June – 3rd July, Greece, Crete, Heraklion - Book of Abstracts of the 7th International Conference ORBIT 2010 – Thessaloniki: Grafima Publ., 2010, pp. 115.

Structure of the Dissertation

The dissertation consists of an introduction, 4 chapters and conclusions. It content of 120 pages, 49 figures and 81 references. The literature review is not included in this summary.

1. Experimental research of Daibe landfill leachate management

The leachate treatment management is the largest electricity consumer in the landfill and the main task of it is a reduction of the sites storages liquid phase pollution. In order to increase the technology efficiency the analysis of the parameters impacting electricity consumption has to be performed and quantitative coherence among dependent and independent variables has to be found.

The aim of this chapter is to obtain a coherence of electricity consumption change used for leachate treatment depending on operating modes and parameters characterizing them by the use of company operation data about several years.

1.1. Experimental research scheme and parameters

Daibe landfill leachate treatment is a two stage reverse osmosis (RO) plant. The energy consumption change analysis is done for leachate treatment in 2006, 2007 and 2008.

The personal reads data once in a day records them in a register and enters in computer. Due to the computer failures, not all data are available for equipment operation analysis.

In a way of measurement the following values are determined:

- amount of leachate G, m^3;
- purified water amount G_1, m^3;
- first level operating time t1, h;
- second level operating time τ_2, h;
- leachate conductivity C_1 mS/cm,;
- purified water conductivity C_2 mS/cm;
- electricity consumption W, kWh.

1.2. Empirical data processing method and results

In order to obtain equations for determination of electricity consumption the empirical data processing is performed using statistical data processing methods - correlation and regression analysis. The statistical analysis and empirical model development is performed with a software STATGRAPHICS Plus.

In dissertation for equipment operation analysis the correlation is considered among:

- Energy consumption W and independent parameter: amount of leachate G, purified water amount G_1, leachate conductivity C_1, purified water conductivity C_2, leachate treatment efficiency ΔC, water regeneration level r;
- Specific energy consumption w_i and independent variables: leachate flow m, leachate treatment efficiency ΔC, water recovery level r.

In the summary only a few graphics are shown where a correlation among dependent value and independent parameters can be observed.

The higher experimental data processing result generalization can be achieved by the use of specific indicators. The correlation analysis between specific energy consumption w_i and leachate flow m is performed. The results are shown in figure 1.1.

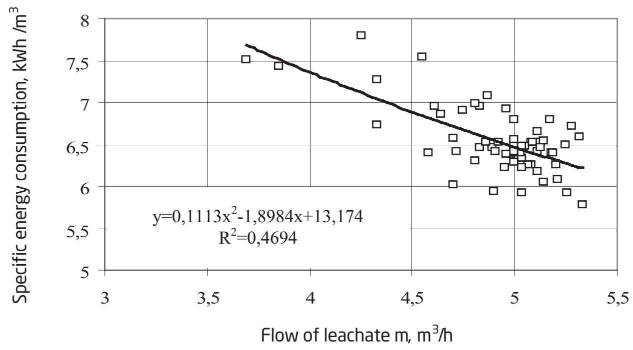

Figure 1.1. Specific energy consumption on leachate m3 changes depending on leachate flow

The disposition of data in figure is characterized by dispersion. It can be explained by specific electricity changes which can be determined with several independent parameters, and one factor models can show tendencies of changes depending only on one factor. The value of the correlation coefficient square determined by analysis is $R^2 = 0,47$ and correlation coefficient is $R = 0,69$. Connection between values is non-linear and it can be expressed by equation:

$$w_i = 0,111m^2 - 1,898m + 13,174 \quad (1.1)$$

Coherence between energy consumption used for leachate treatment and leachate treatment efficiency ΔC, which can be described by leachate pollution reduction related to initial pollution is week. Reaching cleaning efficiency 0.98 – 0, 99 important data dispersion is observed and it points out the need for additional research. For additional research the reverse osmosis equipment meter data was used.

The specific energy consumption is affected by water recovery level r. An increase of recoverable amount of water causes a growth of specific energy consumption.

The specific energy consumption changes depending on water recovery level are shown in Figure 1.2.

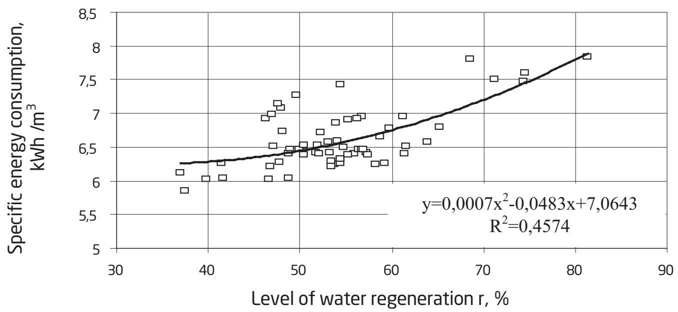

Figure 1.2. Specific energy consumption changes depending on water recovery level

Specific energy consumption changes depending on water regeneration level are characterized by considerable data dispersion. The value of the correlation coefficient square determined by analysis is R^2 = 0, 46 and correlation coefficient is R = 0, 68. There is decent correlation between the values. Connection between values is non-linear and it can be expressed by equation:

$$w_i = 00007r^2 - 0{,}0483r + 7{,}0643 \qquad (1.2)$$

The correlation analyses among specific electricity consumption and independent parameters shows that there is a correlation among specific energy consumption w_i, leachate flow m, and water recovery level r. It means that the parameters mentioned above have to be used in the further data regression analysis and regression equation can be found using two independent parameters - m and r.

With a help of the one factor correlation analysis the independent parameter set has been established that should be considered determining electricity consumption and specific energy consumption calculation multiple regression equations.

The objective of research performed in this chapter is to get multiple factor empiric equations which quantitatively describe the reverse osmosis leachate treatment plant energy consumption and specific consumption indicators and serve as a basis for operating regime result prognosis and review.

Creating empirical models in the form of regression equations there is always a need to solve several important questions - are all independent variables characterizing discussed fact included in model and does the model include redundant, insignificant variables making model unnecessary complex. Partial answers to these questions are given by data correlation analysis which is previously performed. It helped to point out parameters which need to be included into the model. However, for statistical significance assessment of parameters included into the model the process descriptive regression equation is needed.

During the investigation a regression equation is obtained which determines leachate management reverse osmosis equipment energy consumption:

$$W = 132{,}38 + 5{,}47G + 0{,}75r \qquad (1.3)$$

The correlation value of the empirical model R^2 is 0, 85 and it is determined as a result of data statistical processing. It means that created model (1.3) explains 85 % of analyzed data changes. Other 15% are related to variables which are not included into equation or independent variables which are not defined in this work or their mutual interaction effect. Equation (1.3) adequacy test is performed using Fisher criterion (F = 199, 5), which table value is $F_{tab.}$ = 1,4. It means that coherence $F > F_{tab.}$ is valid and the equation (1.3) is adequate and usable for analyzed data description within boundaries of their changes:

- Purified leachate quantity G changes from 30 till 340 m^3;
- Water recovery level r changes from 35 till 80 %.

Autocorrelation test. Using Durbin-Watson test in data statistical processing and data analysis process the DW criteria is defined. Its value is close to value 1,4 and it means that there is not significant residual autocorrelation and during the analysis performed with the least square method an assessment of values is not distorted.

Multicolinearity test is performed by analyses of correlations matrices of regression equation calculated coefficients: correlation among coefficients and that means also among independent variables are negligible and assessment is correct.

Heteroscedasticity test is performed by checking residue distribution depending on observed water recovery level. The study of residue distribution depending on other factors is performed in this work. In all cases there is a conclusion that heteroscedasticity cannot be observed and standard error is set correctly.

One of the regression equation verification types is connected with mark probation of its elements and fact about logical explanation on equation certain changes from the point of view of described processes. In the equation of electricity consumption determination regression (1.5) both element marks are positive. It shows that an increase of purifying leachate and purified water amount leads to increase of the electricity consumption in the process of treatment. This tendency corresponds to the nature of the process and can be logically explained.

One of the substantial questions of empiric equation usage is – do and how much the results calculated by regression equations correlate with empiric data.

Only in the case of satisfactory correlation it can be affirmed that model adequately describes a situation observed in practice and its usage for modelling of situation is correct. For the empiric equation adequacy control the empiric and calculated data are compared. The comparison of the data is shown in Figure 1.3.

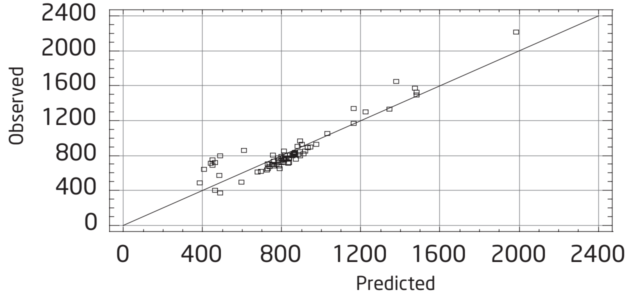

Figure 1.3. Comparison of empiric and calculated data

As it can be seen in Figure 1.3., a good correlation between both data sets can be observed. If calculated value corresponds to measured results, the points would be on the line what can be seen in the figure. The greater point dispersion is observed if energy consumption values are high and low.

During the investigation the regression equation which determines leachate treatment RO equipment specific electricity consumption is obtained and it is shown below:

$$wi = 5{,}17 - 1{,}62m + 0{,}057r \quad (1.4)$$

R^2 value determined in the result of developed empiric model data statistical analysis is 0,673. It means that the model (3.13) explains 67,3 % of analyzed data changes. Other 32,7 % are related to variables which are not included into equation or independent variable which are not defined in this work or their mutual interactions effect. Equation (1.4) adequacy check is performed using Fisher criterion and its value is F = 48. It means that coherence $F > F_{tab.}$ correspond and equation (1.4) is adequate and can be used for analyzed data description within boundaries of their changes:

- Purifying leachate flow m changes from 3,6 till 5,4 m^3/h;
- Water recovery level r changes from 35 till 80 %.

In autocorrelation test showed that assessment of values is not distorted. In the result of multicolinearity test it is found that an assessment of equation coefficient is correct.

In the result of heteroscedasticity test it is found that heteroscedasticity is not observed and standard error is determined correctly. For empiric equation adequacy verification the empiric and calculated data are compared. The comparison is shown in Figure 1.4.

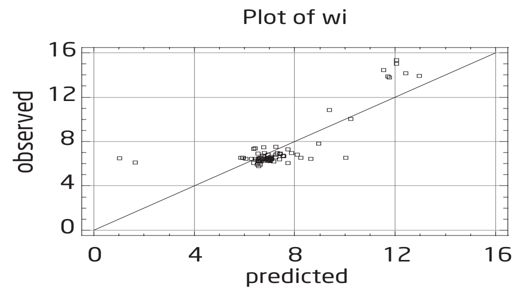

Figure 1.4. Specific electricity consumption calculated and experimental value comparison

It can be seen in the figure that the calculated and experimental data congruence is good in the middle part of the graphic and there are differences in a case of small and large specific values. The measurement accuracy can be one of the reasons for the differences.

Leachate reverse osmosis treatment plant operates with purification affectivity till 80% of clean water and the other part is concentrate sediment. Residues are returned back to landfills storage through penstock with existing leachate pumps. When concentrate is entering in the waste upper layer it is moistening waste and in the same time works as catalyst and take part in waste decomposition biological and chemical processes. It speeds up waste decomposition process. Leachate treatment equipment is always equipped with incoming raw leachate and outgoing purified water quality control devices. The pollution of purified water and leachate is determined by electrical conductivity measurements. The flow measuring devices record incoming leachate, sediment concentrate and purified water amount.

In order to determine long term changes of leachate pollution, data on leachate pollution changes in 2006, 2007 and 2008 was inspected. Estimated monthly average pollution is shown in Figure 1.5.

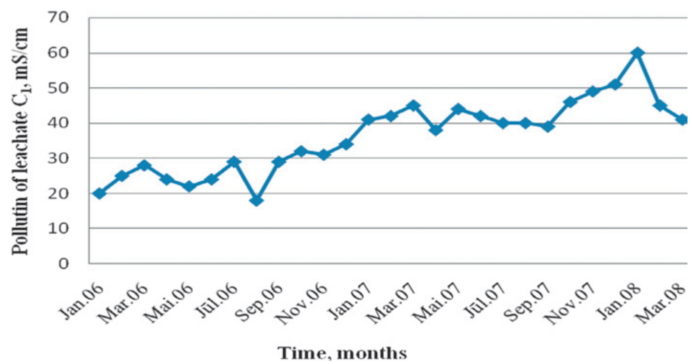

Figure1.5. Long term changes of leachate conductivity

The figure 1.5. shows that leachate pollution level is fluctuating each month but the pollution level is rising in long term. It means that storage is contamined with leachate treatment process concentrate, which according to scheme is returned back.

With the increasing pollution level the infiltrate osmotic pressure is raising proportionally and the difference in pressure between the pump pressure and infiltrate osmotic pressure is decreasing.

When the difference in pressure is decreasing the leachate flow through the RO plant is also decreasing. Since pump pressure in RO plant is constant - pressure regulator keeps it at 60 bar level, the leachate purification time is increasing and it leads to the increase of electricity consumption, which is needed for certain amount of leachate purification.

1.3. Uncertainty of reverse osmosis plants specific electricity consumption

A standard uncertainty of overviewed values, sensitivity coefficient and investment index calculations are performed for daily average leachate amount. In the current case the relative extended uncertainty for specific electricity consumption is 0,0383 or 0,64 %. It means that in this operating regime of landfill the specific electricity consumption is 6 ± 0,04 kWh/m^3.

The leachate amount measurement uncertainty index is 97% and for electricity consumption it is about 3%. It means that leachate amount measurement uncertainty is a significant contribution in uncertainty balance and for further reduction of total uncertainty this value should be considered firstly.

2. Optimization methodology for landfill management

Solutions for the use of unsorted waste landfill biogas differ by biogas quality, user target groups, investment volumes and other factors. It is possible to use unpurified biogas in households, power plants, boiler houses, CHP plants, purified and improved biogas right now is used in vehicles as well as for supply in natural gas system. In landfills of Latvia the most popular biogas usage type is connected with biogas use in cogeneration plant (with high energy efficiency) which is built close to landfill or in power plant (with relatively low energy efficiency) if there is no heat user.

2.1. Methodology for energy source operation calculation optimization

In the dissertation the most popular landfill biogas management organizational scheme in Latvia is developed in detail when an energy source with electricity production is installed in landfills territory and it is possible also to produce heat. It means cogeneration plants installation optimization variant for crude biogas usage.

Landfill is considered as closed system in which by performance of technical actions an environmental and climate impact is reduced and additional resources for landfill management are obtained.

Optimization model consist of modules and models which are combined in two planes:

1. Horizontal dimension, which covers calculation group models:
    - Calculation group for technological solutions;
    - Economic calculation group;
    - Climate calculation group;
    - Optimization calculation group;
2. Vertical dimension covers following module:
    - Current situation module;
    - After action module;
    - Data base module;
    - Graphic module.

Relationships among calculation groups and modules are illustrated in Figure 2.1.

Landfill can be defined as a complex process group situated in different mutual interactions. Changes in one system can affect others. The produced energy amount highly depends on all system interaction, therefore it is important to define factors which can affect system as well as to find out an influence of the factors on separated landfill management systems.

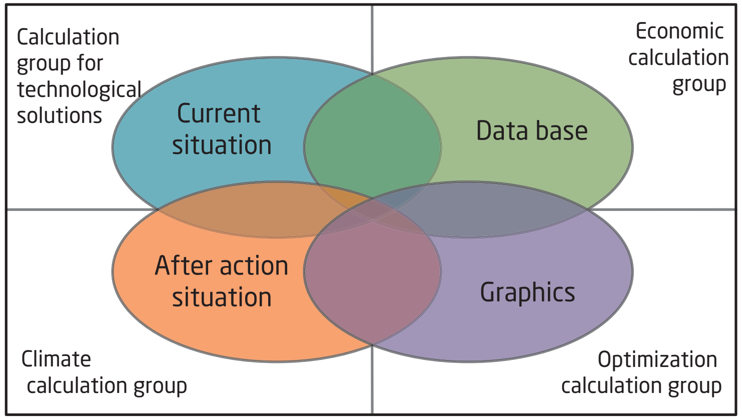

Figure 2.1. The interactions among calculation groups and modules

The main purpose of the optimization is to find solution, using energy production technical and economic criteria which are expressed by cost and CO_2 emission level, i.e., when economic gain and CO_2 emission level reduction is maximal.

Expenses connected with energy production are connected with biogas formation process, its amount growth and followed decrease in landfill, therefore these changes happen in one time period - that is existing as long as landfills storage is working. The expenses need a consideration taking into account the time factor, accordingly a current value method is used for optimization .

Assessing technological solutions, the output data, which are determined by mathematical equations or with empiric models, are used. Different assumptions have to be made and limits have to be set. The last one are also known as benchmarks establishing them the technological solutions differ with installed capacity, efficiency parameters, that is, all independent parameters used in optimization model are discrete values. Therefore variant screening method is selected as mathematical programming method for optimization performance.

2.2. Technical solution calculation group

The calculations are based on equation system which describes biogas production process and the produced energy amount in a cogeneration determination. In dissertation the main calculation correlation are described.

In the technological solution group are integrated 2 equation groups, which are connected to biogas obtaining and its use in cogeneration plants.

A groups technological parameters are connected with biogas obtaining and cogeneration plant operation.

1. Amounts of biogas which are possible to get in landfill storage are determined with LandGEM model based on first level waste decomposition equation:

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_0 \left(\frac{M_i}{10} \right) e^{-kt_{ij}}, \qquad (2.1)$$

where:

Q_{CH4} - the annual methane formation amount, (m^3/gadā);
n - calculation year (the initial waste acceptance year);
k - methane formation year, ($year^{-1}$);
L_0 - methane formation amount potential, (m^3/t);
M_i - in landfill tipped waste amount in i years, (t);
t_{ij} - waste cell age.

More information is given in literature review of dissertation.

2. Biogas usage parameter determination begins with biogas CHP plants input energy amount which is divided in 2 periods:

- In first period it will increase, defining time boundaries $0<\tau<\tau_{1/2}$,

$$dQ_{piev} / d\tau = k_3 * B_1 \qquad (2.2)$$

where

k_3 - energy production intensity ratio for the first period;
B_1 - biogas volumes in the first period, thousands m^3;

- In second period with biogas input energy amount decrease, defining time boundaries $\tau > \tau_{1/2}$,

$$dQ_{piev} / d\tau = k_4 * B_2 \qquad (2.3.)$$

where

k_4 - energy production intensity ratio for the second period;
B_2 - biogas volumes in the first period, thousands m^3.

Energy production intensity coefficient in first as well as in second period are dependent from methane composition in biogas, from waste composition, from chosen technology in CHP, from heat loads, CHP installed capacity, CHP operation efficiency, from plants electric and heat capacity relationships and from other parameters.

3. The biogas quality A depends on interrelated parameters from which in energy production case the most important role is playing Vobbe index or biogas combustion heat Q_z^d, which is dependent from biogas composition and it is determined by equation:

Qzd = (127CO + 358CH4 + 230H2S +0CO2)/ 3600, MWh/ thous m3 (2.4)

where

CH_4^{bg} - methane content in biogas, %;

CO_2^{bg} - carbon dioxide content in biogas, %;

CO^{bg} - carbon monoxide content in biogas, %;

H_2S^{bg} - sulphide content in biogas, %;

4. Biogas losses Bz (thous m3) from landfill storage surface is determined depending on the storing waste quality, cover material and landfill surface square.

B groups technological parameters. Technological equipment- cogeneration plants operation parameters which affect and are connected with equipments technological solutions, for example, installed electrical capacity Nuzst, MW, electrical and heat energy ratio α, energy production energy efficiency hkoģ, total electricity amount produced in cogeneration regime cogeneration E koģ, heat demand Qsa which includes following parameters: heat consumers optimal heat load Qsp , heat load duration – operating hour amount τ, curve of the heat load duration curve Qsig, degree days per year DGD.

5. Any cogeneration plants establishment starts with the consumer heat load assessment. Basing on consumer demanded heat load, the optimal cogeneration technology and its capacity is chosen. Heat load duration curve characterizes heat load values for heating system needs and the existing time-hours per year. The method for optimal cogeneration plant capacity determination is worked out in Institute of Energy Systems and Environment.

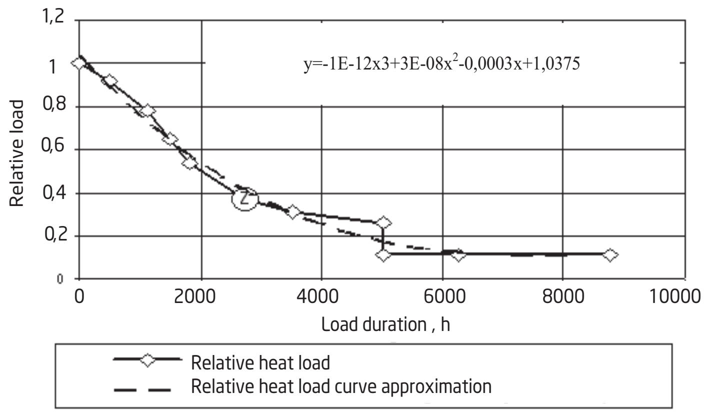

Figure 2.2. The relative heat load duration curve and its approximation

The optimal cogeneration plant will be the one which, basing on heat load duration curve will develop the maximal amount of the heat working on full capacity. It means that installation capacity will be determined by rectangle with maximal area, which is illustrated in load duration curve. Dividing each hours load values with load maximal value will get normalized or relative load duration curve. Example of the relative load duration curve is shown in Figure 2.2. In the figure the approximation curve is shown.

Graphic approximation is made to obtain descriptive equation in a way of continuous function which can be used for calculations.

The equation in example is given for approximation curve:

$$q_{sa} = -10^{-12}\tau^3 + 3\times10^{-8}\tau^2 - 0{,}0003\,\tau + 1{,}03 \quad (2.5)$$

The optimal heat load of cogeneration plant is determined by:

$$Q_{sp} = Q_{sp}^{max} * q_{sa}, MW; \quad (2.6)$$

where

Q_{sp} - optimal heat energy consumer heat load, MW;

Q_{sp}^{max} - heat energy consumer maximal heat load, MW;

q_{sa} - relative heat load.

The figure shows that in real life as well as in approximated load time schedule the maximal energy production ca be observed in the case of relative load 0, 3. It means, by choosing cogeneration plants heat load 0, 3 from maximal needed, it is possible to operate it with full load approximately 5000 h per year.

By choosing smaller capacity equipment it is possible to increase operation hours but then energy production amount decreases. By increasing installed capacity over optimal the operation hours decrease and in spite of larger capacity, the produced energy amount decreases.

6. Produced heat amount can be determined integrating area under the approximated heat load curve and can be determined by:

$$Q_{sig} = Q_{sp}^{max} * \tau * q_{sa}, \text{ MWh/year} \quad (2.7)$$

$$Q_{sar} = Q_{sig} / \eta_{term} \quad (2.8)$$

where

τ - heat load duration – operating hours, h/year;

Qsig - the heat amount determined in heat load duration chart, MWh/ year;

Qsar - produced heat amount, MWh/year;

hterm - thermal energy efficiency.

7. Installed electrical capacity can be determined with equation:

$$N_{uzst} = Q_{sp} * \alpha, \text{ MWe}, \quad (2.9)$$

where

N_{uzst} - installed electrical capacity, MWe;

α - electrical and heat ratio;

$E^{koģ}$ - total produced electricity amount in a cogeneration regime, MWh;

8. Cogenerations plants energy efficiency is heat and electricity produced in plant and passed to consumers in network, proportion toward heat energy input:

$$\eta_{koģ.} = \frac{W_{lietd} + W_{paš} + Q_{lietd} + Q_{paš} + Q_{s.zud}}{Q_{piev}} \quad (2.10)$$

where

hkoģ. - production energy efficiency, %;
W_{lietd} - electricity passed in network MWh_e;
$W_{paš}$ - cogeneration plants electricity consumption, MWh_e;
Q_{lietd} - the useful thermal energy for heat consumer, MWh_{th};
$Q_{paš}$ - heat consumption in plant, MWh_{th};
$Q_{s.zud}$ - heat loss, MWh_{th};
Q_{piev} - to cogeneration plant supplied biogas energy, MWh.

9. Electricity amount produced in the cogeneration plant can be determined depending on operating hours:

$$W = W_{lietd} + W_{paš} = N_{uzst} * \tau \quad (2.11)$$

where

W - electricity amount produced in cogeneration plant, MWhe.

10. It is important to determine real capital investments because equipment is installed to use all biogas which is produced in municipal solid waste landfill. On the basis of the consideration that smaller cogeneration plant will need to operate longer time period and will need to change them after every 15 operating year it is necessary to set up, how long the equipment will work. The equipment operating length can be determined with equation:

$$\tau_{bg} = B/B_g, years; \quad (2.12)$$

where

τ_{bg} - biogas utilization time, years,
B - biogas amount in landfill, m^3;
B_g - biogas annually amount in landfill, m^3.

2.3. Economic calculation group

Economic calculation with computer model gives chance to determine electricity and heat energy production cost as well as capital investment and to assess the economic feasibility. It is done by determining set of indicators.

1. Income for sold heat energy:

$$I_{se} = Q_{sp} * T_{se}, Ls/year, \quad (2.13)$$

where

T_{se} – heat tariff, Ls/MWh.

2. Income for sold electricity:

$$I_{ee} = W_{liet} * T_{iep}, Ls/year, \quad (2.14)$$

where

T_{se} – electricity procurement tariff, Ls/MWh.

3. Heat energy tariff

Heat energy tariff is determined according to the natural gas tariff. In the landfill the heat tariff could be agreement tariff which could not exceed 0,2 ... 0,3 from electricity purchase price.

4. Electricity purchase price

Electricity tariff is determined according to purchase politics of country. In order to make CHP choice optimization, in the dissertation the benchmarking was modelled for electricity purchase price depending on cogeneration plant installed capacity. The benchmarking chart example for compulsory purchase tariff depending on installed capacity is shown in Figure 2.3.

In the chart the graphical comparison of compulsory purchase tariff, cogeneration and power plant (producing only electricity) is performed, the tariff for first 10 years is taken much higher than after that. The electricity tariff value for first 10 years is predicted with benchmarking equation:

$$T_{iep}^{sāk} = 139{,}73N^{-0{,}0678}, Ls/MWhe \quad (2.15)$$

If cogeneration plant works more than 10 years then electricity purchase tariff value will decrease and after 10 years benchmarking equation will be:

$$T_{iep}^{vēl} = 111{,}79N^{-0{,}0678}, Ls/MWhe \quad (2.16)$$

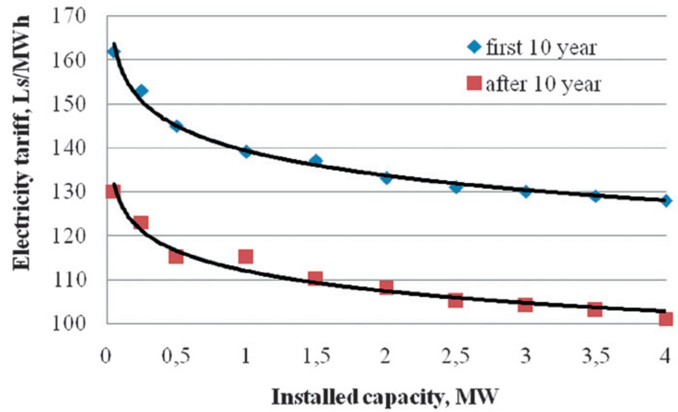

Figure 2.3. Electricity tariff benchmark depending on installed capacities

In benchmarking process few assumptions are made. One of the most important determines that compulsory purchase tariff is the same as generating electricity in cogeneration regime where energy efficiency is higher.

5. The capital investments for cogeneration equipment and installation costs:

$$K_k = K_{tehn} + I_{mont} \qquad (2.17)$$

where

K_k – total capital investments for cogeneration plant, Ls;

K_{tehn} – capital investment for cogeneration plant, Ls;

I_{mont} – cogeneration plants installation and launching cost, Ls.

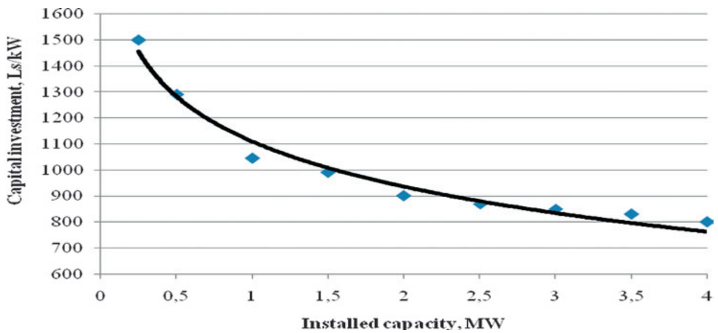

Figure 2.4. Cogeneration plants specific capital investments determination chart

Because of biogas and natural gas cogeneration plants technological solutions are uniform and always are installed internal combustion engines (more rare micro turbines), the total capital investments for this type of technology installation are well investigated and economic data are possible to get from implemented project practical experience.

The specific capital investments k_k can be determined by setting charts or with equation shown below:

$$k_k = 1050 - 182 \ln (N_{uzst}), \text{Ls/kW} \qquad (2.18)$$

Total capital investment can be determined by equation:

$$K_k = 1000 * k_k * N_{uzst}, \text{Ls} \qquad (2.19)$$

where

k_k -specific capital investments, Ls/kW.

6. Simple payback time:

$$p = K_k / (I_{se} + I_{ee}), \text{years} \qquad (2.20)$$

where

p - cogeneration plants simple payback time, years.

7. The present net value (NPV):

$$NPV = K_k \times \frac{1}{(1+R)^{T_1}} + (\text{Ise} + \text{Iee}) \times \frac{1-(1+R)^{-T_2}}{R}, Ls, \qquad (2.21)$$

where

R – real discount rate, %;

T_1 – the capital investment realization time, years

T_2 - the cogeneration plants operation time, years.

8. Adjusted annual net savings

Adjusted annual net savings is a characteristic which shows how large is annually average net savings if energy efficiency activities are implemented. Their determination is important precondition for energy efficient activity optimization. Energy efficient activity adjusted annual net savings are determined by equation:

$$ITGI = \frac{K_k \times \frac{1}{(1+R)^{T_1}} + (I_1 - I_2) \times \frac{1-(1+R)^{-T_2}}{R}}{\frac{1-(1+R)^{-T_2}}{R}}, Ls / gadā. \qquad (2.22)$$

2.4. Climate calculation group

The greenhouse gas emission calculations give possibility to investigate cogeneration plant contribution in environment change and climate change impact reduction. Ecological calculation group characteristics are connected with climate change effect causing emission absolute values and with emission reduction economic parameters.

In dissertation carbon dioxide emissions which are connected with landfill cogeneration plants installation and operation are calculated, based on consideration that all methane in biogas is used in cogeneration plant and is not emitted in the air basin thereby all amount is CO_2 emission reduction.

1. CO_2 emission reduction

Annually CO_2 emissions connected with cogeneration plant operation using waste landfills biogas can be expressed with equation:

$$CO_2 = (Qsp + W) * R * O / \eta_{koģ}, tCO_2/year \qquad (2.23)$$

where

CO_2 -annual CO_2 emission reduction;

R - emission factor, kg CO_2/MWh;

O -oxidation factor.

2. CO_2 emission reduction cost-effectiveness

In the dissertation the cost-effectiveness assessment is performed and it practically illustrates economic assessment of GHG emission reduction setting, how large investments are necessary to reduce environmental pollution for 1 ton CO_2. Cost effectiveness of each energy efficiency action can be express by:

$$E_{CO2} = K_k / (T_3 * CO_2), \text{Ls/t}CO_2; \qquad (2.24)$$

where

T3 - investment period length, years.

The cost-effectiveness practically shows climate technology usage effectiveness. The obtained results are possible to compare with emission trading CO2 values for Europe and global market.

3. GHG emission reduction values benchmark

For this time the benchmark can be determined for independent variables which can be - capital investments, technological equipment energy efficiency as well as other parameters. However, the most accurate benchmark method can be obtained from emission trading data.

2.5. Optimization calculation group

In optimization panel plan performance are unknown values, which numeric values are determined in exercise solving process. With these values the optimization goal function is defined. In dissertation the goal function is defined for most complex solution: for biogas cogeneration plant with stable heat consumer.

In the work are used 9 plan indicators: B, A, Bz, Nuzst, E koģ , hkoģ., α, Qsa, CO2.

Plan indicators determine independent constant and variable parameters. In optimization model all values which are constant for one particular landfill energy production characterization before and after technological solution implementation activities are considered as independent parameters.

Independent variable parameters characterize the technological solution realization actions in landfill - from technical, economic and impact on climate change perspective.

Performing optimization model condition system existing correlations between independent and dependent parameters have to be determined. These correlations determine simulation object economic and technical content. From this fact a requirement derives that plan indicators should be integers. For its part the plan indicator prevail independent fixable and variable values are discrete with certain values which are entered in optimization model data base.

The data base performs condition system formed by input data which base on empiric (heat load duration chart curve describing) and analytical equations (for example, Mendeleev equation for calorific value determination), computer program for calculation results (LandGEM model), assumptions (for instance, heat consumer load amplification) and restrictions (e.g. technological solution limit relation electricity/heat for cogeneration plant).

In order to compare different plans, plan effectiveness indicators have to be selected. Plan effectiveness indicator which is described as function from unknown values, calls as objective function. Objective function for each plan allows determining corresponding number, which in defined units characterize respective plan effectiveness. Thus, it is possible to compare different plans from view of selected effectiveness factor. The objective functions maximal (minimal) value is called as optimality criterion.

The optimality criterion characterizes the aim of optimization. The optimal plan is plan to which conforms objective functions maximal (minimal) value. Two values are selected as plans effectiveness factors: adjusted annually net savings, Ls/year and CO2 emission reduction, tCO2/year. Each factor is expressed by objective function.

Adjusted annual net savings, Ls/year

ITGI =f (Kk; Tiep; Tse; Ise; Iee; Idarb; CH4 bg ; A; CO2 bg; CO bg; Qzd; Nuzst; W; hkoģ.; α; Qsp; Qsa; Bz; τ; DGD) ® max, (2.25)

Where

CH4 bg; A; α ; Qzd; CO bg ; CO2bg – relatively constant values;

Kk; W ; Tiep; Tse; Idarb; Iee; Ise; hkoģ.; Nuzst ; Qsa; Qsar; Bz – variables.

CO2 emission reduction, tCO2/year

CO2 = f (R; O; Kk; Qsa; Nuzst; CH4 bg ; A; CO2 bg; CO bg; Qzd; Nuzst; hkoģ.; α; Bz; τ) ® max, (2.26)

where

CO2bg; CO bg ; CH4 bg; Qzd; A; α ; R; O – relatively constant values;

Kk; W ; hkoģ.; Qsar; Nuzst ; Qsa;Bz – variables.

2.6. Modules and sub-modules description

Each module and sub-module is made for special task performance and to provide results. Therefore it is important to clarify characteristics which are used in them.

Module "Actual situation" By using this module it is possible to determine landfills management parameters and biogas formation and to analyze factors which are impacting it. It consists from 10 till 20 sub-modules.

Module "Follow-up situation" By using these module different activities are analyzed which are possible to carry out in landfill. In addition to module "Follow-up situation" used sub-modules is added sub-module "Investments" in which the capital investments, present net value (NPV), adjusted annual net savings and carbon reduction cost effectiveness are calculated.

Module "Data base" In module are included all output data which are important for computer program use and running.

Module "Graphs" The Graphs module is developed to graphically illustrate mathematical module calculation results.

3. The biogas use optimization methods testing in Daibe landfill

Latvia is divided in 11 industry and municipal waste management areas from which North-vidzeme region is the second largest based on population level.

Daibe landfill is settled at Cēsu region in Stalbe parish and started to operate in 1st December 2004. Daibe landfill provides waste disposal from Cēsu, Limbažu, Valkas and Valmieras region. Landfill is built in accordance with European Union and Latvian Republic law and regulations requirements. The total area which is reserved, taking into account landfills future development prospects, is 49, 2 ha. The landfills area - 12,96 ha (4 waste disposal storages). First ordinal storage area is 3,6 ha (through wall) and maximal deposited waste mountain height is corresponding to surroundings landscape ~ 20 m.

At the moment in Daibe landfill occur landfills biogas collection and incineration in cogeneration plant, producing electricity because there are no heat consumers.

There are horizontal gas collectors deployed in landfills storage. Biogas utilization consists of gas discharge, cleaning system, and from small power plant.

3.1. Biogas volume forecasting

Biogas volume and compound modelling for Daibes landfill is carried out by LandGEM model for 3 different waste disposal scenarios:

- 1. scenario – the situation for the end of the year 2007 (after 3 year waste disposal);
- 2. scenario - the situation after first ordinal storage filling in the end of 2011 (after seven year waste disposal);
- 3. scenario – will include calculations if waste will be stored in bioreactor.

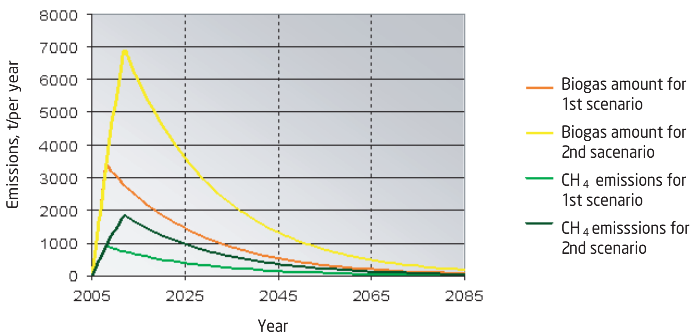

Figure 3.1. Biogas volume and methane emission reduction (for first and second scenario)

Comparing first and the second scenario (Figure 3.1.) it can be observed that gas production changes at the early stage are not important but they are significantly changing after five years and later what can be accountable with deposit waste amount increase two times. It proves that calculation for each year separately is not effective. Obtained results do not allow predicting total biogas volume in landfill stabilizations time as well to determine necessary waste gas collection systems capacity.

Third scenario calculations are carried out for bioreactor, assuming that each year in it will be concealed 10 thousands tons biodegradable waste (sludge from city water treatment plants, food residues, waste from animal recycling and other same treated waste). Modelling is made for 2005 till 2011 period.

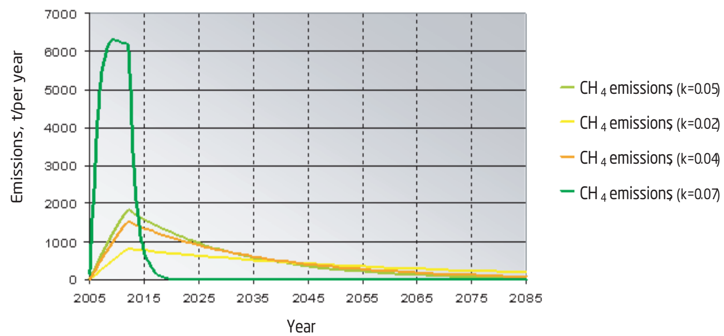

Figure 3.2. Methane emission changes depending on coefficient k values

Figure 3.2 illustrates CH_4 emissions depending on methane formation coefficient k value changes. In the traditional landfills (k=0.05 and k=0.04), where is no additional water supply, the maximal methane emission amount can be achieved in 2012, respectively 1842 tons and 1523 tons. But in dry landfill (k=0.02) methane gas amounts decrease average two times, reaching 815 tons in 2012. However the landfills stabilization time increases and important methane gas amounts are emitted also after 2085. In the bioreactor obtained methane amounts reach the maximal level already in 2009 – 6319 tons, this allows to come to conclusion that the highest coefficient k value provides faster biodegradation process decreasing waste decomposition time.

3.2. Daibe landfill operation data exploration

First level biogas collection tubes were installed in Daibes landfill in 2005. Landfill gas collection system costs are 281 000 lats. In landfill the horizontal gas collection system is built which includes pipe system for landfill gas collection almost in 3 km length, pump station and regulating station. In the next round (the second tube level) was realized in second part of 2010, but third round (the third tube level) is planned to realize together with first waste disposal storage recultivation works in 2011-2012.

In order to realize technological, economic and ecological assessment not only produced improved biogas quantity B, raw biogas income flow have to be determined but also methane percentage in biogas.

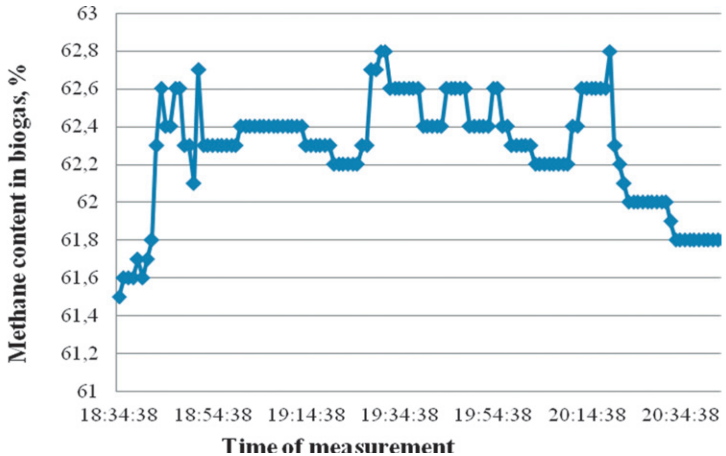

Figure 3.3. Methane concentration in biogas in landfill "Daibe"

In 2005 the biogas monitoring in Daibe municipal solid waste landfill started. The methane percentage in biogas is determined by performing continuous monitoring and processing data which are obtained in Daibe landfill. The monitoring date example is shown in Figure 3.3. Measured data showed that concentration is high, average more than 62%. However average date in a year cut in last 3 years evidence that average methane concentration in gas is approximately 60%.

At the moment in Daibe landfill is installed small cogeneration plant with installed capacity 0,175 MWe. Because there are no heat consumers (only heating of small administrative house in heating season) in landfill, the cogeneration plant will not work in cogeneration regime.

As it is possible to see in Figure 3.4. produced electricity amount is changing very fast. Mainly it depend on collected landfill gas volume, however it depend also on methane content in biogas.

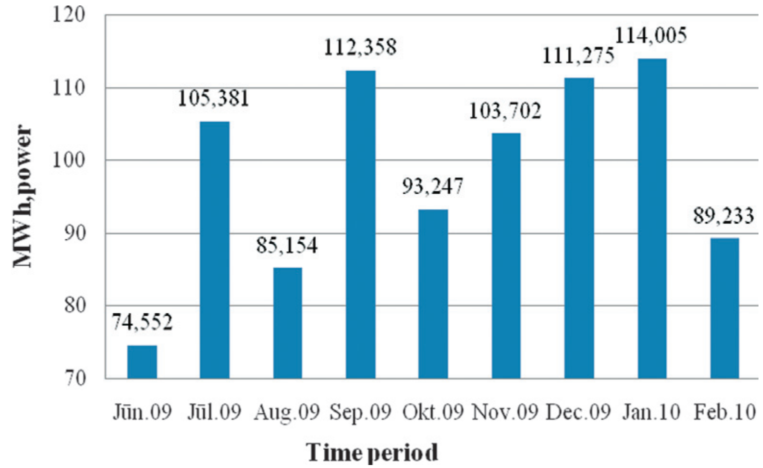

Figure 3.4. Electricity produced in Daibe landfill cogeneration plant

3.3. Optimization models approbation

The main aim of the optimization is to find values of variables which meet and provide the maximal or one or more minimal desired objectives. In other words, optimization is a process which is used to make some process more effective and more functional. Because there is no heat consumer in Daibe landfill, the cogeneration plant is working in power plants regime.

The electricity production can happen in power plants with different capacity and what kind of situation will depend on landfill gas volumes as well as from biogas quality. It is the task of optimization models approbation.

3.3.1. Data and assumptions

The data used in optimization model are obtained in Daibe municipal solid waste landfill in Cēsis region, Latvia.

The assumption is carried out using the fallowing inputs:

- Total biogas utilization for electricity production B = 42 millions m3/year;
- Biogas quality: calculation is carried out for 3 calorific values, for example, Qzd = 4 kWh/m3, Qzd = 5 kWh/m3, and Qzd = 6 kWh/m3;
- Cogeneration plants installed specific power range is n_{uzst} = 0.025 ... 1;
- Equipment operation time– 7000 hours/year;
- Cogeneration plants efficiency $\eta_{koģ}$ = 50%;
- There is no heat consumer heat load Qsa = 0;
- Total produced electricity amount in cogeneration plant is 105 TWh.

The calculation is made with the following assumption:

- Total landfills biogas amounts, what is formed in 15 year time in landfills manifold is constant;
- Biogas quality, composition and calorific value is constant;
- The cost for the installed capacity is determined using benchmarking and basing on information from technology producers and suppliers;
- The cogeneration plant will work in power plants regime because there are no heat consumer;
- In power plant is installed internal engines for biogas utilization;
- The cost for installed capacity is taken on the basis of information from technology producers and suppliers;
- The electricity procurement tariff is determined by benchmarking method;
- The efficiency coefficient is taken on the basis of information from technology producers and suppliers;
- The methane losses from landfills manifold is constant over the time;
- Operational cost for biogas equipment is accepted on the basis of information from technology producers and suppliers.

3.3.2. The optimization results for technological parameters

The higher capacity is installed, the faster biogas tank is emptied and via versa - the lower is capacity more slowly the reservoir is getting empty, but there is higher possibility to raise equipment efficiency coefficient. From other side, more slowly reservoir emptied the greater is the biogas losses through the coating. It means that greenhouse gas emissions will increase.

The analysis of the technological equipment is performed based on two main parameters for biogas use - biogas quality and equipment relative installed capacity. Results are shown in Figure 3.5.

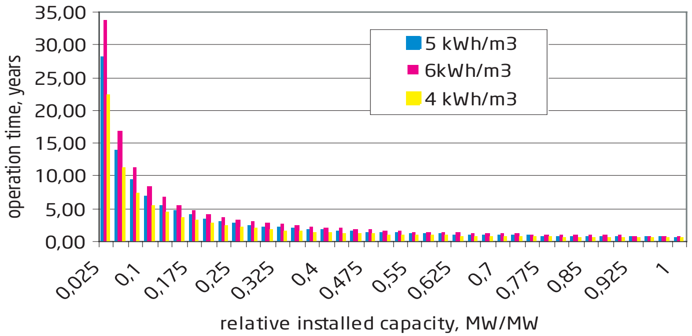

Figure3.5. Equipment operation time via versa relative installed capacity

As shown in Figure 3.5 the greater installed capacity, the shorter operation time. If it is assumed that operating time could be from 5 till 10 years, then installed capacity could be 0,125 and larger. In addition the calculation results show that the higher is the gas quality, the longer technological equipment time will operate. The analysis shows that operation changes depending on installed relative capacity have non-linear nature and there is not noticed optimum. It means that capacities optimal values are detectable by other optimization task, for example, through economic optimization.

3.3.3. The results of economic optimization

Evaluating total incomes, by installing various power stations (see. Figure 3.5.), largest incomes are possible at low capacities. Operating equipment for 187 years need to reckon that will need to change equipment for 14 times and also methane losses will be significant. Hence, this variant needs to be considered as theoretical possibility.

The results of economic optimization is assessed by using indicators which shows specific investment cost in tariff, as well as analyzing benefits which arising from the difference between electricity purchase tariff. Specific investment cost in electricity tariff is shown in Figure 3.6.

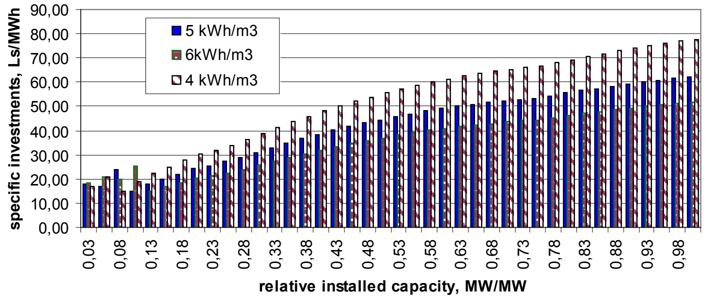

Figure 3.6. Specific investment cost in electricity tariff

The smallest specific investment costs are for higher quality biogas (6kWh/m3). The optimal specific investment cost could be in diapason with installed technology relative capacity from 0.045 till 0, 0625.

The economic optimization was carried out by searching maximal benefits depending on installed cogeneration or power station capacity and biogas quality. Figure 3.7. illustrates the results of economical optimization.

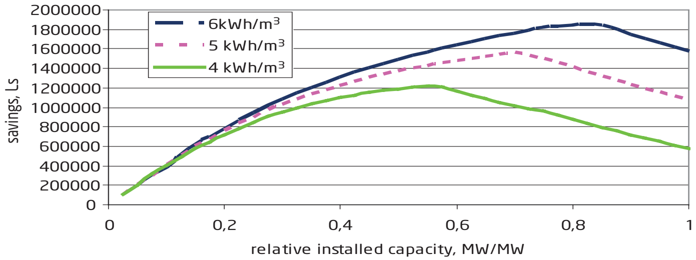

Figure 3.7. Economic optimization diagram

It is possible to see from the results of economic optimization in Figure 3.7. that if quality biogas is low (4 kWh/m^3) then optimal installed relative capacity is 0,55. If biogas quality is only 5kWh/m^3, then optimal installed capacity is 0,7, and 0, 85 respectively at the high quality biogas (6 kWh/m^3). It means that in landfills is possible to find the optimal capacity which gives the largest incomes depending on biogas quality.

3.3.4. The results of climate technology parameter optimization

The climate technology parameter calculation results show that with larger installed capacity it is possible to get larger greenhouse gas emission reduction (Figure 3.8).

The analysis shows that GHG emission reduction depending on installed equipment relative capacity has non-linear nature and there is no expressed optimum. It means that relative capacity optimal value can be determined with other optimization task, for example, performing economic optimization.

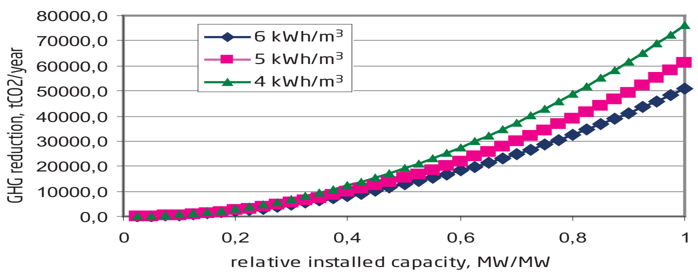

Figure 3.8. Impact on climate change reduction diagram

Conclusions

1. There is developed optimization model for biogas utilization.
    - The economic cost objective function was found, basing on technological solutions for biogas utilization for electricity and heat production;
    - The GHG emission optimization objective function was found, basing on technological solutions for biogas utilization for electricity and heat production.
2. The empiric model for determination specific electricity consumption (used for leachate purifying treatment) is based on reverse osmosis equipment experimental data statistical processing and analysis, using correlation and regression analysis method.
3. The analysis of the experimental data shows that leachate pollution in long term period increases. It means that storage is getting contamined with leachate purifying process concentrate which according to scheme is returned in storage. Increasing pollution level leachate osmotic pressure increases proportionally and pressure difference between pump pressure and leachate osmotic pressure decreases. Decreasing pressure difference in the reverse osmosis plant leachate flow through plant decreases, it increases infiltration purifying time and as a result the electricity consumption increases. The research shows that concentrate supply to the waste storage are connected with electricity consumption increase in the future, which increases landfill energy consumption and decreases the amount of electricity supplied in net.
4. The measurement uncertainty source identification is performed and there are analyses and determined type of uncertainties and examined specific electricity consumption determining uncertainty balance, as well as examined separate parameter uncertainty contribution in total uncertainty. In order to reduce specific electricity consumption determination uncertainty firstly the leachate amount should be considered because uncertainty balance is showing, that measures of leachate amount gives the larges input (around 97%) in the balance. The landfill specific electricity consumption determination expanded uncertainty was estimated, the amount of the leachate for average daily values are ± 0, 04 kWh/m3 or ± 0, 64 %.
5. With landfills gas emission model LandGEM version 3.02 there are calculated 3 scenarios for biogas production amount and contamination calculations in Daibe landfill, taking into account stored waste and moisture content, nutrients and its availability for anaerobes, waste mass pH, and temperature and region climate. Simulation results shows that in first 3-5 years biogas volume in Daibe landfill is small, the maximum will be reached after storage closure in a year 2012- 5.5 millions m3 from them 2.76 millions m3 methane. Thereby, the gas collection systems installation on the landfill in early stage is not economic efficient. The results prove that the economic and ecological research id needed for future operation planning and for technological plant selection.
6. The optimization calculations shows that the optimum can be reached and it is dependent from Vobbe index and cogeneration plants installed capacity. Increasing Vobbe index value increases optimal cogeneration plant capacity.

ZAAO

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