RIGA TECHNICAL UNIVERSITY
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Institute of Energy Systems and Environment

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SUSTAINABLE DEVELOPMENT OF PELLETS PRODUCTION

Summary of the Doctoral Thesis

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DOCTORAL THESIS
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To be granted the scientific degree of Doctor of Environmental Engineering (*Dr. sc. ing.*), the present Doctoral Thesis will be publicly defended on 23rd March 2017, at 14:00, Room 115, at the Faculty of Power and Electrical Engineering of Riga Technical University, Āzenes iela 12/1.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Environmental Engineering is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to other scientific degree.

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Date: ………………………

The Doctoral Thesis is written in the Latvian language and consists of an introduction, four chapters, conclusions, and a bibliography with 143 reference sources. It is illustrated by 59 figures and 3 tables. The total volume of the present Thesis is 97 pages.

Table of Contents

Research Background and Topicality

Sustainable development of industrial plants is possible combined with an efficient use of resources. Nowadays, production of products from bioresources with high added value is becoming an increasingly urgent matter. That is not only a matter of survival for plants, but also a solution to the development of a country's macroeconomics.

One of industrial plants that produces products with high added value is a pellets production plant, where the biomass – wood and other plant matters – are transformed into pellets, which is a widely used fuel for energy production. Unlike other bioresources, for example, firewood or woodchips, pellets have a high added value, which can be measured not only by price for one MWh, but also by environmental, climate, economic, and socioeconomic benefits.

Production costs for pellets are dependent on the price of the material and the investments for plant development. One of the most important questions from the point of view of the plant's economic stability is its operational costs, which are determined by the technological possibilities and parameters of the equipment and the professionalism of operation management.

Research Scope

The objective of the present Doctoral Thesis is to develop a methodology that can help evaluate and predict the pellet plants' sustainable development possibilities. To reach this objective, it is necessary to accomplish the following tasks:

- to form a group of the pellet plants' operation indicators, and to introduce and analyse the efficiency of benchmark methodology in a plant;
- to analyse the operational indices of a pellets' production plant, and to search for its weak spots;
- to develop a methodology for the implementation of energy management and the analysis of possible technological improvements;
- to predict the development of pellets' production, and to analyse its sustainability at local level with the system dynamics model.

Scientific Significance

The scientific significance of the Thesis is confirmed by a demand-side management scheme that is based on mutually integrated (nexus) analysis method for pellet plant factors, illustrated in Figure 1.

It is very important to maintain energy efficient plants that use energy management. Energy management in a pellets' production plant is important because of the following reasons:

- energy efficient energy production and use is the most significant sector for developments for production in European Union countries;
- the new international standard ISO 50001:2011 is made to help establish the energy management systems. Its integration in companies could "make a story for the road" to a low-carbon society;
- energy management in a company would give a chance to save up energy resources and money.

The decrease in energy consumption in a pellet plant can be made in several levels. Energy consumption analysis is based on internal energy management of a company:

- by monitoring: regularly following the operation parameters of a company;
- by development, choice and realization of improvement technologies: working by the international energy management standard ISO 50001:2011;
- by analysing the results after collecting and handling the data that describe the existing situation in a company.

The external factor analysis is based on government legislation regarding the development of power sector:

- by development of pellet market, which adds value to local biomass;
- by replacing fossil fuels because of economic reasons and effects on climate change;

- by using the different proportions of renewable energy sources with innovative technological solutions;
- by establishment of transport logistics, decreasing the mileage of empty vehicles;
- by economic situation in countries with developed forestry;
- by natural disasters.

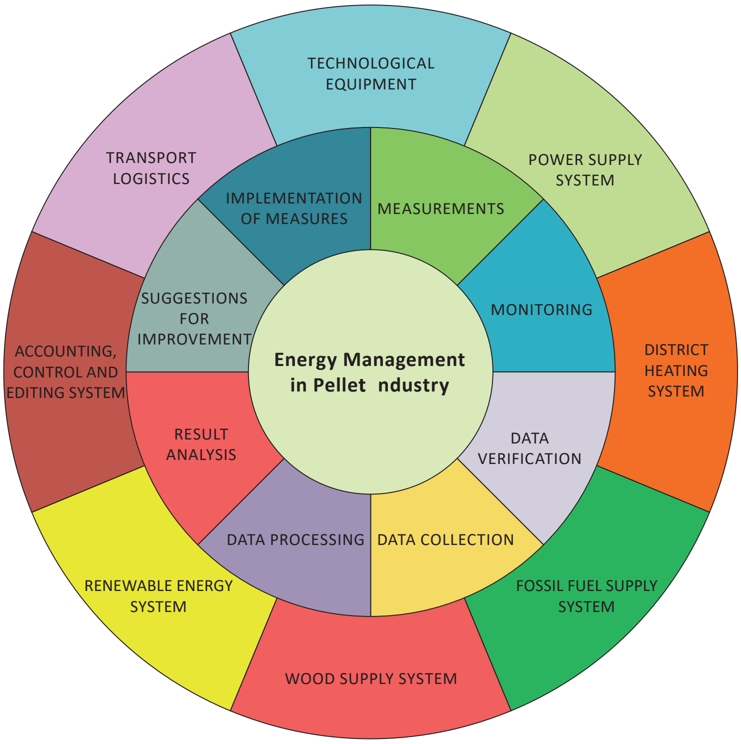

Fig. 1. Demand-side management scheme.

Practical Significance

The beginning phase of the scientific research was spent in contact with the lack of understanding from other Latvian companies for the necessity to establish benchmarking to analyse the consumption of energy, resources, water, and defined indicators with their boundary values.

The results of the Doctoral Thesis have been successfully tested and introduced in the company's "Graanul Invest" production plants. They are also included in Latvian legislation and are acceptable for the development of energy management models and use in the documents of governmental institutions, energy audit programmes, and energy management programmes for production companies.

Approbation of the Research Results

Conferences

1. Uuemaa P., Drovtar I., Vigants H., Blumberga D., Puusepp A., Industrial CHP optimal management in the energy market under incomplete information, *2014 IEEE Innovative Smart Grid technologies Asia, ISGT Asia 2014*, Kuala Lumpur, Malaysia, 20.05.–23.05.2014.
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Structure of the Doctoral Thesis

The Doctoral Thesis is written in Latvian. It consists of four chapters, conclusions, and a list of references. The introduction describes the topicality of the work, the goal of the research, the importance of the research results,and the possible applications of developed methods.

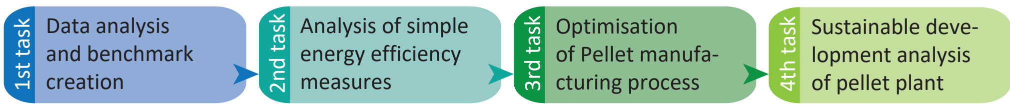


Fig. 2. From simple to more complicated task.

The first chapter of the Thesis gives an insight into a pellet production unit. There, pellet production process is divided into steps. The correlation and regression analysis is made for the data from a production unit. Benchmarking method is used to establish the possible optimisation level of the equipment.

The second chapter describes the analysis of the pellet production unit's performance indicators and sets out the weak spots of the equipment. Potential optimisation methods for a drum dryer are offered. Also, an option for the decrease in mill electricity consumption is set out. The importance and savings of pre-milling are studied.

The third chapter illustrates the optimisation of the drum dryer by decreasing the human factor and implementing an automatic control system. CO_2 emissions are analysed, and it is concluded that cogeneration plants are more suitable thermal energy producers for pellet production. An optimisation method for cogeneration plants is given.

The fourth chapter includes the development of the system dynamics model, which analyses the development of pellet production and its sustainability locally. The submodels consist of the amount of energetic wood, income and expenses, capital investments, electricity consumption, increase in energy efficiency, and workforce.

Finally, the conclusions section summarizes the main points of the research. The Doctoral Thesis consists of 97 pages, including 58 figures, 3 tables, and a list of references with 143 sources.

1. TASK. PERFORMANCE INDICATORS OF A PELLET PRODUCTION UNIT. ANALYSIS OF BENCHMARKING METHODS' USEFULNESS IN A COMPANY

Overall quality standards have to be considered to achieve pellet quality from wood sawdust, and to provide wood sawdust pellet plant productions' conformity to market conditions and consumer demand. Only clean sawdust without sand, abrasive particles and other additions can be used for pellet production. To achieve a high quality of production, sawdust has to be dry and pellets have to be mechanically solid, they cannot contain any foreign bodies. The residues from wood processing companies is the main source of materials to produce sawdust pellets.

All production processes and units' components can be divided into several steps, which are described by the author after attending a pellet production unit:

- materials and the preparation of materials for the operation of the equipment;
- preparation of the materials necessary for wood sawdust pellet production;
- drying of materials;
- preparation of materials – extraction;
- extruding of materials, granulation, pellet production;
- treatment and storage of production.

Before sending the production to storage tanks, the main quality-describing parameters such as moisture content (optimal moisture content for pellets is 8 %), density, tenacity and division of particles are defined for pellets. From storage tanks they are transported to a truck, weighed, and sent to consumers.

1.1. Generation and processing of necessary data

In order to evaluate the electricity consumption in processes, it is assumed that each unit is operating at a 100-% capacity, for a certain number of operating hours according to technical specification. In order to determine the efficiency of electricity consumption compared to production volume, the following equation (1.1.) should be used:

$$\eta_{\mathrm{el}} = \frac{P_{Pellet}}{Q_{\mathrm{el}}}, \quad (1.1)$$

where
P_{Pellet} – volume of produced pellets, t/h;
Q_{el} – total electricity consumption of appliances, kWh.

It can be used to make calculations about efficiency improvements, if the volume of produced pellets increases compared to the consumed electricity. If energy efficiency indicators are compared to the existing system, the energy efficiency indicator of the improved system is bigger, since the total system of a production unit operates more efficiently.

If electricity and heat energy is generated using a cogeneration unit, the following equation (1.2.) is used for the primary energy savings value. This equation includes the consumed fuel and heat energy and electricity:

$$\Delta Q_{PE} = Q_{el.ats} + Q_{Qats} - Q_{kur}, \quad (1.2)$$

where
ΔQ_{PE} – primary energy savings, MWh;
Q_{kur} – consumed fuel energy in a station, MWh;
$Q_{el\ ats}$ – energy consumption for electricity generation, MWh;
$Q_{Q,ats}$ – energy consumption for heat energy generation, MWh.

Fuel savings are dependent on primary energy savings and the lowest heating value of fuel. Cogeneration plants' efficiency is dependent on the produced heat energy and electricity, and the consumed primary energy.

The information about the maximum operational load of appliances is taken into account when processing the obtained data. However, the data about the periods of maintenance or the periods when an installed appliance is out of order is not taken into consideration. Simple software is used to carry out a simplified data analysis to determine the correlation of set parameters; data, which is not representative, is not included in data analysis.

The most important efficiency parameter in a wood pellets production unit is the volume of production; therefore, the outgoing data is the amount of produced pellets in tones. Data analysis from other variable parameters is carried out based on the volume of production.

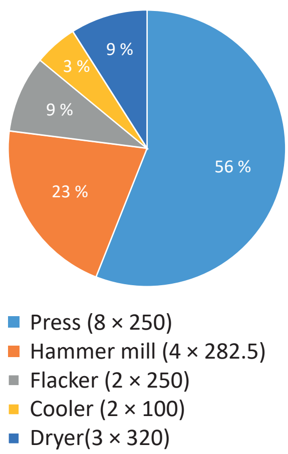
Correlation and regression analysis is used to describe mutual relations between variables. In case of mathematical models, correlation is expressed using the Pearson's correlation, which determines the correlation coefficient *r*. The determination of the value of the correlation coefficient with the help of mathematical models requires initial processing – normalization – of the data. Regression analysis was made by data using MS Excel environment.

Regression equation was determined using the method of least squares and the statistical analysis of obtained result. The coefficient square value R^2 indicates correlation between the parameters; it was used to express the correlation coefficient R thus determining the proximity of parameters. If correlation between parameters is very close, the correlation coefficient is 0.75. The value of correlation square is multiplied by 100, and the value expressed in percentage shows the percentage of incidental value change, which is characterized by a regression equation.

1.2. Analysis of data from a pellet production unit and correlation between parameters

1.2.1. Electricity consumption analysis

Pellet production units' data analysis was carried out based on the information given by the company – the data about the operation of a pellet production unit in 2014. The specific electricity consumption for each equipment in a pellet production unit applied to one ton of production is illustrated in Figure 1.1.



Machine	Energy consumption
equipment x power	kWh/ton
Press (8 × 250)	83
Hammer mill (4 × 282.5)	35
Flacker (2 × 250)	14
Cooler (2 × 100)	4
Dryer (3 × 320)	12.8
Total	148.8

Fig. 1.1. Electricity consumption of an equipment per ton of production.

As it can be seen from the Figure, the largest energy consumer in the production unit is the granulator – the wood pellets press. The second largest electricity consumer is the hammer mill, which uses 23 % of the total electricity consumption. Flackers and dryers indicate similar results in terms of electricity consumption.

Regression analysis should be carried out in order to assess the importance of electricity consumption in appliances and to determine if there is an interrelation between parameters and the volume of production (see Fig. 1.2.).

The figure demonstrates that there is close correlation between the electricity consumption of electrical motors and the volume of production. Correlation coefficient square value $R^2 = 0.944$ (94.4 %) and especially the correlation coefficient r = 0.97 indicate the closeness of interrelation between the parameters. Interrelation between the parameters is a linear regression that can be expressed by the equation (1.3.):

$$E = 136727 + 122{,}54\,P, \quad (1.3)$$

where
E – monthly electricity consumption, kWh/month;
P – monthly pellet production, t/month.

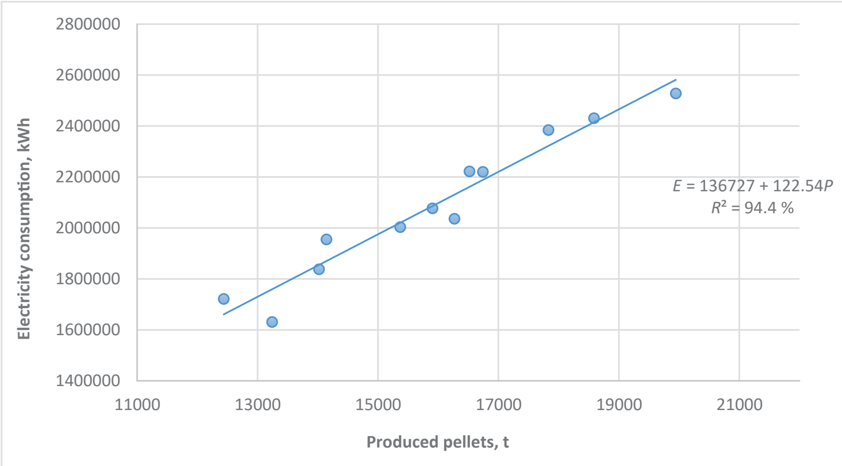


Fig. 1.2. Electricity consumption of an equipment per produced volume of pellets.

1.2.2. Analysis of heat energy produced in a cogeneration plant

An example of data analysis is made for heat energy produced in a cogeneration plant, with the use of different fuels. In order to determine if there is a correlation between such parameters as consumed fuel and its type, the amount of heat energy and the volume of production, data analysis was carried out using the data gathered during parameter monitoring in the production unit in 2014.

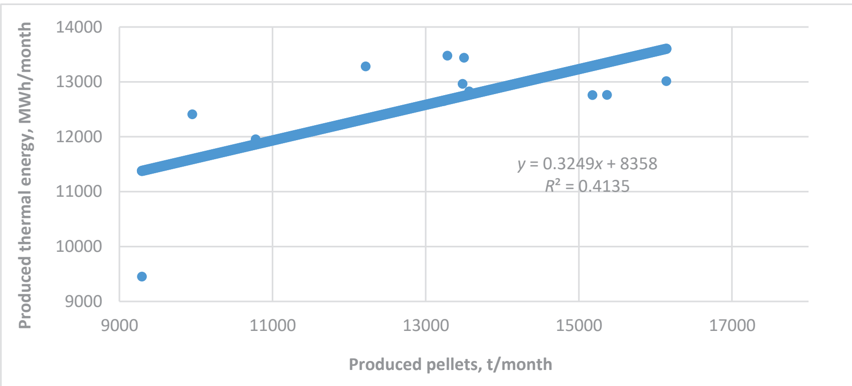


Fig. 1.3. Volume of production depending on the heat generated in a cogeneration plant.

The Fig. 1.3. shows that there is a linear correlation between such parameters as the amount of produced pellets and the heat generated in a cogeneration unit, because the correlation coefficient r = 0.64, which means that the correlation between these two parameters is average.

There are two different wood fuel types used in the cogeneration plant: barks, and woodchips. The heat generated when bark is used as a fuel is shown in Fig. 1.4.; but when woodchips are used as a fuel – in Fig. 1.5.

In the case when bark is used as a fuel, the correlation is small between parameters. The data set can describe 4 % of the changes in mutually dependent variables that are described and analysed with the regression equation. The data of the pellet production unit shows that the bark accounts for 30 % of all the fuels used there; therefore, this correlation is not statistically significant. To provide cleaner production processes, the amount of bark used in combustion processes should be reduced.

When determining the heat generated from woodchips, which accounts for 70 % of the fuel used, a linear correlation was obtained. It describes the generated heat amount depending on the consumption of woodchips (see Fig. 1.5.). The square value of the correlation coefficient demonstrates that the data describes 47 % of the changes in mutually dependent variables that are analysed by regression equation. As the correlation coefficient $r = 0.69$ shows very close correlation between the variables, it can be concluded that the independent variable – woodchips consumption – is statistically significant.

Differences in correlations are defined by the characteristics of the fuel: lowest heating value, moisture content, ash content, and other combustion efficiency-describing parameters.

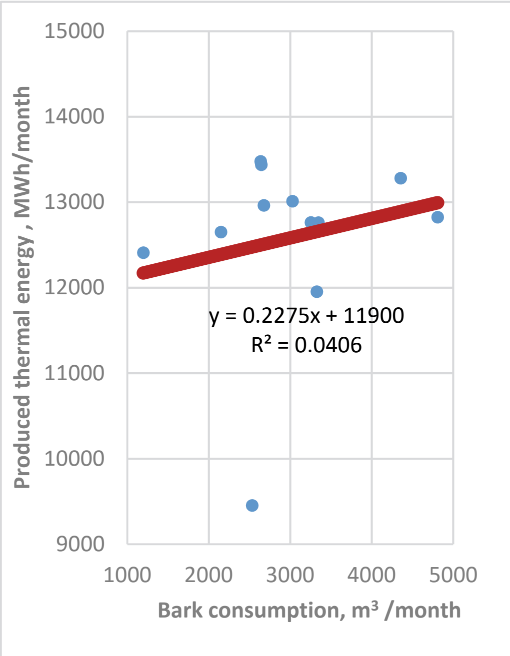


Fig. 1.4. Relation between generated heat energy and fuel type – bark.

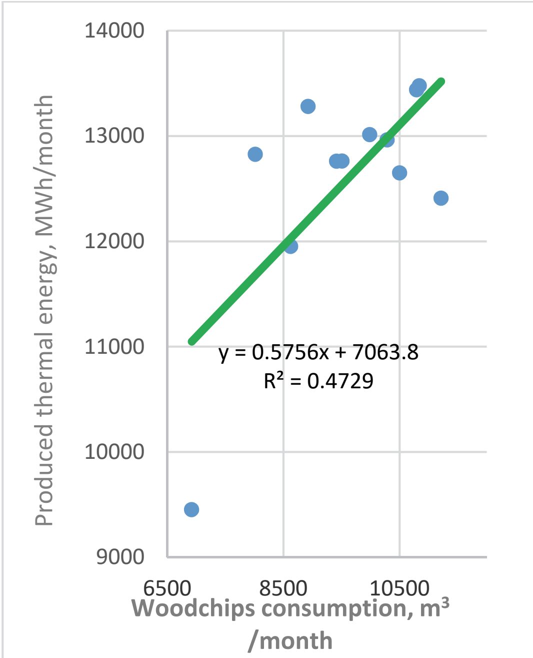


Fig. 1.5. Relation between generated heat energy and fuel type – woodchips.

This type of verification has economic nature, because wood chips as a fuel is more expensive than bark. With the current technological solution, if such actual verification takes place – if the fuel ratio 3:7 is changed –, it would reduce a cleaner production process and also the volume and price of production would be affected. The use of barks as a fuel cannot be considered as a sustainable solution for combustion because of the large ash content in it.

In order to determine the further relation of the parameters that influence the described primary relationship – between the volume of production and the amount of generated heat energy – , also the correlation between the volume of production and the fuel type was analyzed. If only bark is used as fuel, then there would be a very close correlation, because the correlation coefficient value is $r = 0.96$. If only woodchips are used as a fuel, then there would be very close correlation with the correlation coefficient value $r = 0.89$. Based on previous correlation data analysis, it can be concluded that production amount is directly dependent on the type of fuel used in the cogeneration plant.

1.3. Benchmarking method

European Union directive on energy efficiency is focused on energy efficiency measures on the energy end-users side. Visible reduction in energy consumption in industrial plant equipment can be achieved with the double helix technique and the introduction of energy management.

The use of double helix technique is connected with the rating of double-spiral connection field, which shows the link between energy efficiency measures and energy management: the bigger the overlap area of spirals, the bigger the gain. Methodology is based on in-depth use of benchmarking method.

Output data is the changes in a company's dependent variable y (production, generated energy, etc.) depending on the independent variable x (production, fuel consumption, etc.) before and after energy efficiency measures were made. Energy management always starts with the data analysis of energy consumption, which allows determining the existing situation in an industrial plant, obtaining the 1st benchmarking curve, and finding the solutions for the establishment of higher-priority energy efficiency measures.

2nd benchmarking curve is obtained after realizing the primary measures. This is followed by new energy efficiency measures until mathematical connection for energy consumption optimization is found. The final stage increases the overlap area of energy efficiency and energy management, making it innovative.

The method was tested out on a large wood processing company's by-product recycling plant. 1st benchmark begins with the generation and processing of electricity data (Fig. 1.6.). After data analysis, appropriate energy efficiency measures were found. The realization of these measures gave a new decrease in energy consumption and a new benchmarking curve.

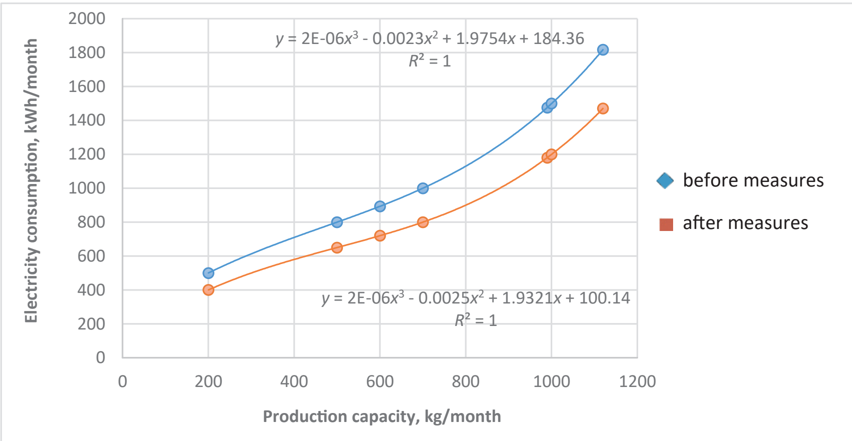


Fig. 1.6. Changes in company's operating parameters before and after the application of energy efficiency measures.

Changes in absolute values are typical to a particular company. To use the analyzed data for the establishment of energy management measures, indicators – relative values of data – are made. These values are obtained dividing the dependent variable y by the independent variable x. Operation indicator of the company after establishing the energy efficiency measures can be determined by the equation (1.4):

$$e_2 = \frac{E_2}{G} = 2 \cdot 10^{-6}\, G_2 - 0{,}002\, G + 1{,}932 + \frac{100{,}1}{G}, \qquad (1.4)$$

where

e_2 – operation indicator of the company after the establishment of energy efficiency measures;
E_z– electricity consumption after energy efficiency measures, kWh/month;
G – pellet production amounts before energy efficiency measures, kg/month;
G_2 – pellet production amounts after energy efficiency measures, kg/month.

The equation (1.4) is the 3rd benchmarking step of energy management, which is used for the further analysis of data and the operation optimization of the equipment. Industrial plants should be made, where benchmarking value is as small as possible; therefore, independent variable value at the minimum point can be read from the graph or, more precisely, by using indicator equations.

Independent variable x values for appropriate minimum indicator values match and are equal to the optimal production amount value $G_{opt} = 600$ kg/month. The optimization value gives possibility of rating the possibilities of production regulation in a way that a plant is working with minimum electricity consumption on a single production unit.

2. TASK. PELLET PRODUCTION UNIT'S OPERATION INDICATOR ANALYSIS. DETERMINATION OF WEAK SPOTS

Every producer must foresee and plan a moment when the plant is stopped and the maintenance of the equipment is carried out. Production amounts in that month will be relatively lower than the ones in the months with full operational capacity.

2.1. Drum dryers' possible improvements

Drum dryer is used in the studied sawdust pellet production unit. Correlation between production amounts and fuel amounts for drying is analyzed in the Doctoral Thesis. There is an average correlation between parameters, with the correlation coefficient $r = 0.67$. The square value of the correlation coefficient describes 46 % of changes between the mutually dependent variables that were described and analyzed by regression equation.

Manual air feed in the existing system creates incomplete combustion processes; therefore, the quality of materials for pellet production cannot be controlled. It means that materials have to be treated repeatedly, but this affects resource consumption.

Automatic air feed system would be an important improvement for this step of production, because it would help provide better combustion, decreasing the amount of products from incomplete combustion and providing a more balanced generated heat amount, which is the main element for drying functions.

Air amount in the furnace has to be in appropriate proportions and as hot as possible. When the air amount in the furnace is bigger than necessary, the combustion efficiency does not change but energy for air feed and heating is consumed. However, if the air amount is too small, the combustion will be incomplete, thus increasing the CO_2 emissions and the amount of unburned fuel.

Pellet production units' efficient energy management example includes the performance of tests to find the most efficient operation conditions.

2.2. Electricity consumption decrease for mill

Energy management system also consists of the performance of experiments to try and find the most economically efficient operation conditions. This subchapter looks at a part of pellet production process where dry sawdust is milled into smaller fractions. Pellet production process is displayed in Fig. 2.1. One of the pellet quality criteria is particle size, which is controlled by the sieves inside the mills.

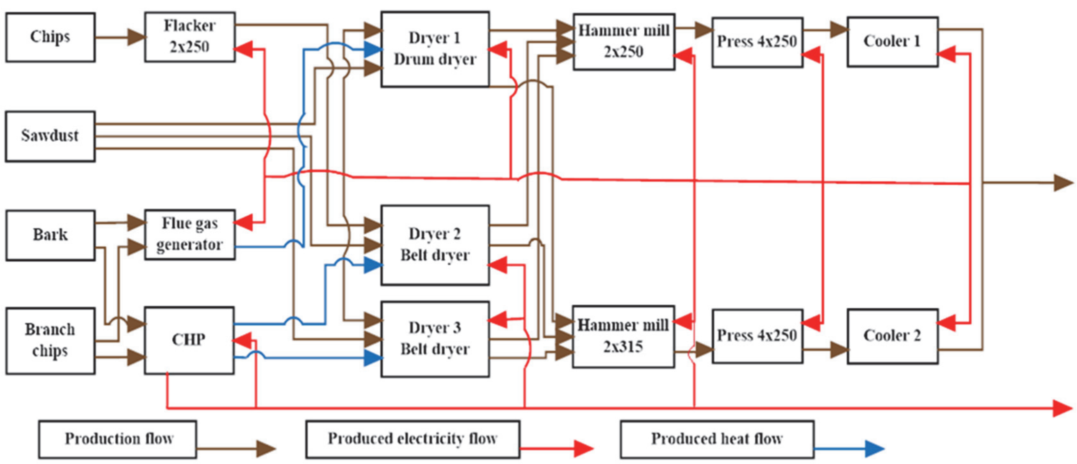


Fig. 2.1. Operational scheme of a pellet production unit.

The scheme of a hammer mill, usually used for dry sawdust milling, is displayed in Fig. 2.2. Operation principle of mills is that sawdust is fractioned by a 4–8 mm plate (hammers) rotating around the axis and sieves, with openings sized 5–20 mm, pushing the milled sawdust out. In this case, electricity consumption on one milled ton and produced amount is dependent on several factors: hammer thickness, size of openings in sieves, material size sent to the sieves, air flows through the mills, etc.

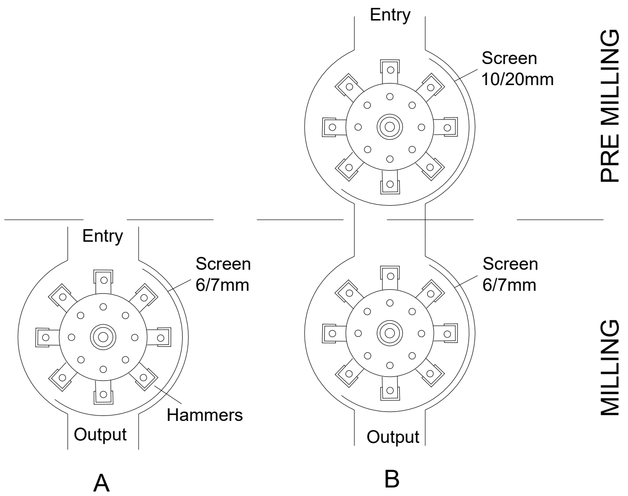


Fig. 2.2. Principal scheme of a hammer mill.

A chance to transform the production scheme is searched in the energy management system, to decrease the electricity consumption of the production unit. Pre-milling can be added to the milling process. Inlet and outlet points would be switched in hammer mills for pre-milling.

The experiments where milled production and consumed electricity were measured were carried out in the energy management system of the company to compare pre-milling and milling. In the first set of measurements, hammer mills were operating in pre-milling regime, two sieves were added, and the openings of the sieves were 10 mm for the first one and 20 mm for the second one. There, during 38 minutes, 10 500 kg of milled sawdust were produced. The average electricity consumption of the electromotor during measurements was 290 kVA.

In the second set of experiments, hammer mills were operating in milling regime, two sieves were added, and sieves openings were 6 mm for the first one and 7 mm for the second one. Pre-milled material was used in this experiment. There, during 16 minutes, 10 500 kg of milled sawdust were produced. The average electricity consumption of the electromotor during measurements was 311 kVA.

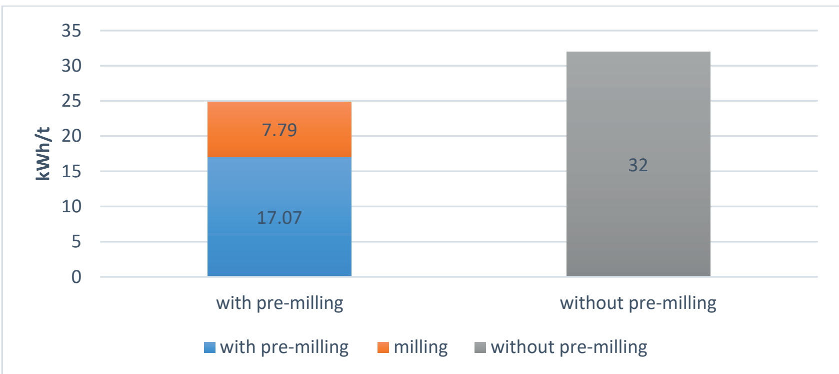


Fig. 2.3. Milling regime of electricity consumption, kWh/t.

Figure 2.3 provides a comparison of electricity consumption per tonne milled in each regime. Graphs demonstrate that in case of pre-milling electricity consumption per tonne produced decreases compared to the regime when pre-milling is not used.

3. TASK. ENERGY MANAGEMENT IMPLEMENTATION METHODOLOGY FOR TECHNOLOGICAL IMPROVEMENT ESTABLISHMENT. OPTIMIZATION

3.1. Drum dryer operation optimization

To promote the improvements of the system that apply to drum dryer operation and are used for sawdust drying in pellet industry, it is necessary to significantly reduce the effects of the human factor on energy efficiency – energy and resource savings.

The drum dryer system consists of several parts, including a boiler and a rotating or drum dryer that operate the equipment, to provide functionality of the dryer. The heat carrier in drum dryers is flue gas. During the process, the materials are sent to the drum dryer, but drying begins when materials get in contact with hot flue gases. This dryer is characterized by high efficiency, because, depending on its size, it can dry large amounts of sawdust in short periods of time. However, there are boundaries on the parameters of the end production.

The main fuel used in the boiler is either barks or woodchips, but it is possible to use other types of the biomass. The size and components of the boiler were adjusted using calculations, to provide effective fuel combustion.

Most important energy efficiency aspects are energy efficiency for furnace construction solutions, and the operating and maintenance efficiency. Air feed is one of the factors that is related to furnaces, effecting the heat generation energy efficiency. Improvements of the process means an automatic air feed in the furnace to increase the furnace efficiency, thus increasing the overall efficiency of the drum dryer, which is directly dependent on the flue gas temperature.

The energy efficiency coefficient η for the furnace is determined using a reversed heat balance equation (3.1):

$$\eta = 100 - q_3 - q_4 - q_5 , \tag{3.1}$$

where

q_3 – chemically incomplete combustion losses, %;

q_4 – mechanically incomplete combustion losses, %;

q_5 – heat losses in the environment, %.

To decrease the chemically incomplete combustion losses, the necessary air feed for combustion processes should be organized in appropriate proportions, the ash and slag amount on grates should be controlled, and a good mixing of fuel and air should be provided. All these conditions together with the existing equipment prototypes and the implementation of new appliances that rate production efficiency parameters in the system serves as a base for developing a new prototype. It includes the development of an automatic system and simplified technological solutions.

The automatic control system includes fuel feed and air feeder. It provides combustion processes with the highest possible efficiency thanks to the built-in system regulation block. Hot flue gases are formed during combustion processes. Afterwards, they are sent out through the flue gas outlet to the drum dryer. In the drum of the dryer, dump sawdust is dried in a hot flue gas environment – using built-in plates and a flue gas flow, the sawdust is moved from inlet of the dryer to outlet.

Flue gas with the dried material travels to the cyclone filter. Cyclone is used to remove the dry sawdust from flue gas and vapor that are sent out in the atmosphere through a chimney, but the dry sawdust travels down and makes its way to the sawdust bunker.

The air feeder valve before the furnace is regulated in accordance with the sawdust moisture parameters. Thereby, combustion process in the furnace is regulated and more complete combustion is provided achieving a hotter flue gas, which provides more efficient sawdust drying. Resulting from system improvements, the air feed could be provided automatically, thus switching out the effects of the human factor on air feed amounts. Monitoring of the equipment's control panel data would allow determiningand providing the conditions for effective combustion more precisely.

This is one way to optimize the existing system and, in a certain production phase, decrease the effects of the human factor, decreasing the amount of damaged products and the energy and resource consumption. This could lead to the increase in everyday production amounts, because resources would be used more effectively and material quality would be controlled.

The most effective optimization method is automatic control system that regulates the air feed at a certain pressure and temperature in the furnace. The algorithm of this system can be viewed and rated in Fig. 3.1.

The automatic control system consists of the following operational steps.

1. Material feed frequency is controlled (defined in steps 2 and 3).
2. If oxygen concentration exceeds 3 %, then material feed rate in furnace and bed movement speed are increased. Primary air feed is increased up to 10 %, and secondary air feed is decreased. After increasing all necessary parameters, step 4 follows.
3. If oxygen concentration is below 3 %, then material rate feed in furnace and bed movement speed are decreased. Primary air feed is decreased, and secondary air feed is increased up to 50 %. After increasing all necessary parameters, step 4 follows.
4. Motor operation speed is regulated (defined in steps 2 and 3).
5. Primary air feed rate is changed. In steps 2 and 3, it is changed in an interval of 10 %; in steps 7 and 8, it is changed up to the 90-% boundary.
6. Secondary air feed rate is changed in steps 2 and 3.
7. If pressure in the furnace is below 300 Pa, then primary air feed rate is decreased and step 1 follows; if not, then step 8 follows.
8. If pressure in the furnace exceeds 300 Pa, then primary air feed rate is increased and step 1 comes next; if not, then step 9 follows.
9. If pressure in the furnace is equal to 300 Pa, then no parameters are changed, and step 1 follows.

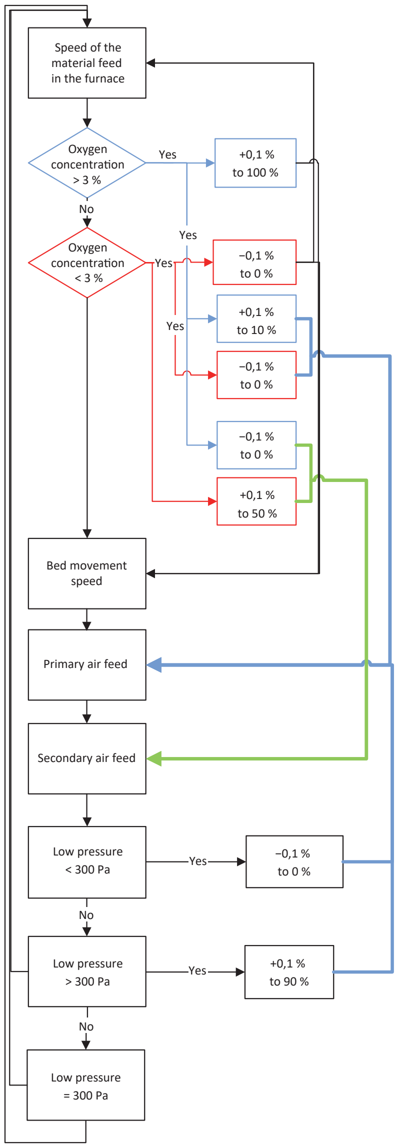


Fig. 3.1. Algorithm of the automatic control system.

To compare CO_2 emissions in the existing situation when the production unit uses two different thermal energy producers – a cogeneration plant and a drum dryer to dry necessary materials for pellet production – the graph displayed in Fig. 3.2. was made.

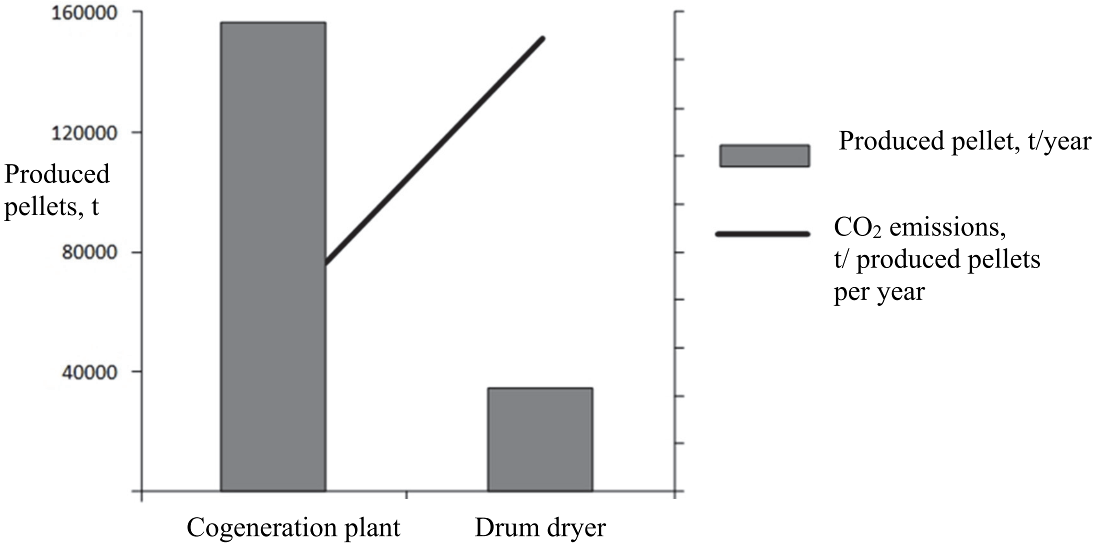


Fig. 3.2. CO_2 emissions on the pellet amount produced.

The equation (3.1.) was used to calculate the emissions. It was assumed that only one type of fuel – wood – was used. This assumption was made because, in the existing situation, it would better describe the emission amount, when specific parameter values are known:

$$M_x = 10^{-3} \cdot \mathrm{c} \cdot V_{d.kop} \,, \qquad (3.1.)$$

where
M_x – outflow of one emission component (CO, CO_2, or NO_x), g/s;
$V_{d.kop}$ – total flue gas amount from production unit, nm^3/s;
c – concentration of one emission component, mg/nm^3.

The calculations where CO_2 emission amounts on a cogeneration plant's and a drum dryer's production amounts were recalculated separately show that the emissions from the cogeneration plant are noticeably smaller at bigger production amounts.

The cogeneration plant produces more than 80 % of the total thermal energy produced, which clearly shows that this equipment is more efficient when compared to the older technological solution – the drum dryer. The drum dryer should be as automatic as possible to provide more effective operation with new technological solutions.

3.2. Suggestions for electricity consumption optimisation in a production unit

3.2.1. Optimal industrial cogeneration plant (CP) management in electricity market at insufficient information conditions

Traditional optimisation methods for an industrial CP use available heat storage in the production place. Liberalization of electricity market creates new possibilities for optimisation. Unstable price fluctuations in immediate delivery electricity market allows industry to optimise the electricity price using the elasticity of industrial production. This research is focused on finding a model of optimised production and decision acceptance for an industrial equipment that manages and controls the electricity production units on spot.

The different nature of a CP, which differs it from other traditional electricity plants, is its possibility of using generated heat to gain profit. Heat is sold to heating network or used on spot for industrial processes. The main criterion that differs industrial CPs and public district heating plants (DHP) is the thermal energy market. The thermal energy market is limited for an industrial CP and it is not connected to a bigger market. This means that thermal energy price is fixed for a long period of time, which makes electricity load planning (LP) and demand-side management (DSM) possibilities for industry even more attractive.

In this research, the industrial CP was studied together with industrial production to maximize the profit of all the equipment. The model has to take into account the optimization of industrial production to make it possible to monitor the effects of each equipment's input and output variables on the decisions. The main role in determining an optimal management point is to the division of different products according to the existing markets. In this research, it is assumed that the participant makes economically rational decisions.

Previous studies on optimal management of CPs. Several studies have proved that optimised operation of an industrial CP together with demand-side management (DSM) creates a positive effect on the profit and efficiency. Important place is taken by the development of optimisation methods at market liberalization conditions to increase profit from the production process. The consumer who finds himself in the territory of electricity producer has the freedom of choice to purchase electricity from the market, therefore choosing an optimal solution.

Biggest support for the optimisation of production process, using DSM activities, is electricity market where unstable price variations exist.

Industrial locally produced electricity producer approach based on market conditions. Fig. 3.3. illustrates the financial flows. The principal approach of this research is optimisation of the production process on the basis of the economical indices of the equipment. The precondition to achieve this is the existence of the market. This means that every product (except heat) should be sold or purchased freely at the market, without any limitations. If market prices are varying and the equipment has usable storage units, then it is necessary to make modelling of optimisation to maximize the profit.

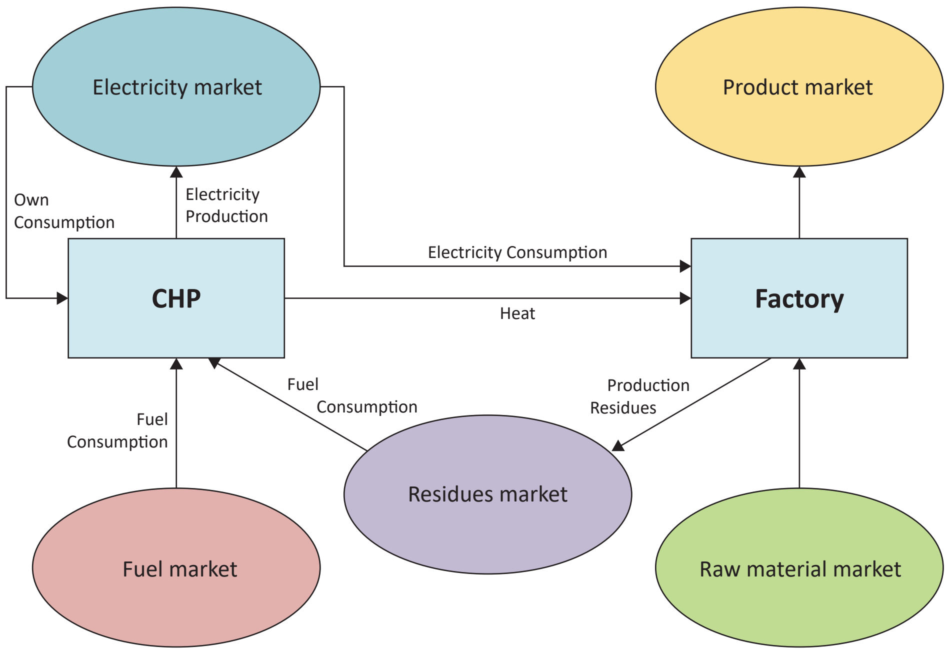


Fig. 3.3. Connections of industrial equipment to different markets.

Main describing indices studied at industrial CPs. Local CP is used at the studied wood industry, with biomass as fuel, the output electricity capacity of 6.5 MW_e, and the output thermal energy capacity of 15 MW_{th}. The average electricity consumption of the production unit is 3.2 MW_e. In this research, it assumed that, apart from electricity market, instability of other markets is very low and there are only long-term changes; therefore, it is not possible to optimise the market in accordance with the behaviour of other markets.

Electricity market is very unstable, and tendencies are slightly predictable. The prices of each next day are known only a day before. The production and consumption of electricity is controllable at certain boundaries. The ability to control the load at set boundaries and varying market allows achieving remarkable savings of expenses and maximizing the income from sales.

Wood industry – a case study. Studied equipment is one separate connection point with electricity network. It is equipped with smart metering, which allows the imported and exported electricity to be registered each hour. As electricity production capacity is larger than consumption, then the most of it is exported.

The task of optimisation is to maximize the gains from income. These optimisation tasks can be solved more effectively by using market price predictions. The analysis of equipment's electricity profile shows that it is dependent on three different components. As seen in Fig. 3.4., the drops in profile are caused by periodic decreases in electricity production and the rest of drops in profile are caused by changes in the production unit's consumed load.

Production variations of the CP were caused by regular soot blowing to keep the boiler surfaces clean and to provide the thermal efficiency of the production unit. Based on the information given by the employees of the unit, soot blowing interval is chosen by empirical experience; however, the blowing time can be changed at any moment, in a time span of 24 hours. Unstable consumption drops in a unit are caused by an unplanned stoppage of a separate appliance. The uxiliaries services of the CP are stable and are considered as inelastic load. Optimisation task can be focused on the optimisation of two profiles: electricity production, and electricity consumption of the production unit.

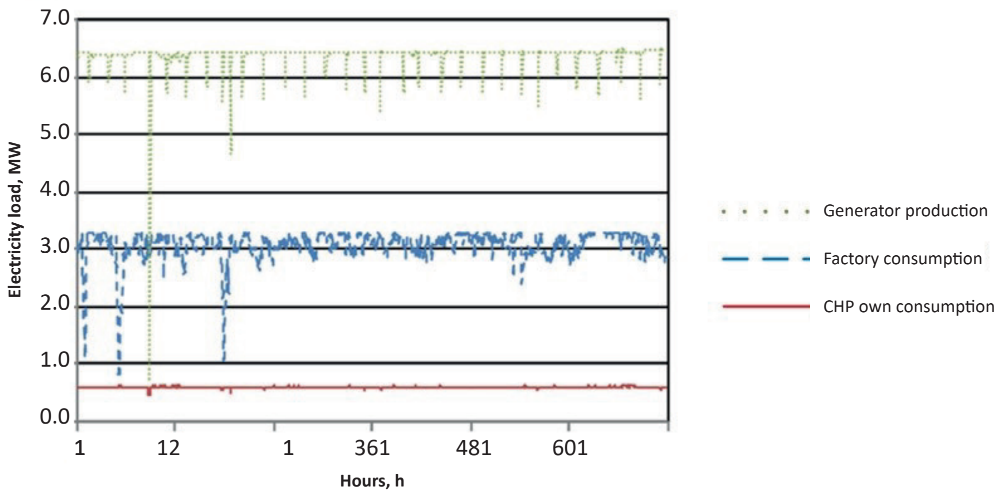


Fig. 3.4. Divided load profile according to different sources.

Production unit has production flexibility, which allows production at drop hours and consumption of produce at peak hours. It is calculated in a production unit that it can regulate 10 % of its consumption load, and the remaining 90 % is the base load that is impossible to control. The main criteria that allows for this kind of elasticity is the nominal capacity of motors, which is higher than average work load. Limits and assumptions are that it is not allowed to disturb the profit by using load switches. Based on inner calculations of the equipment, the income from industrial products noticeably exceeds any income from electricity production or load switches, which means that any losses caused by the actions of DSM are not allowed.

Optimisation calculations. The goal of optimisation is to maximize the exported electricity profit in the overall period, at each time of the given hour *t*:

$$\max_{C_t^O, M_t} \sum_t W_t^O \cdot P_t - \sum_t C_t^O \cdot P_t \qquad (3.2)$$

where

W_t^O – optimised electricity production in time *t*, including services, MWh;

M_t – electricity production service binary variable in time *t*;

C_t^O – optimised electricity consumption in time *t*, MWh;

P_t – instant delivery price of electricity market in time *t*, €/MWh.

Using this approach, the optimum is calculated for each hour separately because of the differences in electricity price, which were changing each hour of the study. In this case, soot blowing can be defined as a planned mandatory service. To switch electricity consumption loads, the load can be switched between the minimal and maximal capacity.

Optimised load profile can be approved if profit increase exceeds the load switch outer expenses C_{LS}. Electricity consumption amounts have to remain the same:

$$\sum_t C_t^o = \sum_t C_t^R. \tag{3.3}$$

The equality of limits means that industrial production has to remain the same.

Results. Developed optimisation model is solved using the hash integer linear programming method. Instant delivery prices are based on historical Elspot Estonia price range prices in November 2013. Modelling was made using elastic consumption of up to 10 % of the average consumption load.

Consumption was modelled with 10 different scenarios on load switch capacity from 1 to 10 % ($0.01 \leq L \leq 0.1$). The bigger switch elasticity for production unit, the bigger savings from it. Savings model between elasticity and savings is linear.

Load switch capacity is a part from the consumption load from the average full load that can be switched. A representative of the industry has approved that with few changes in production process, it is possible to achieve such elasticity without any considerable reconstructions and investments. The results are given in Table 3.1.

Table 3.1.

Results of optimisation

Actual instant delivery price	42.32 €/MWh	Original difference	Optimised load price	Difference after optimisation
Average income from generators	42.30 €/MWh	−0.04 %	42.37 €/MWh	0.13 %
Average consumption expenses	42.36 €/MWh	−0.10 %	41.59 €/MWh	1.72 %
Average income from export	42.22 €/MWh	−0.23 %	43.28 €/MWh	2.27 %

As seen in the Table, profit increase is much higher than separate results from each separate activity, which means that there is a cumulative profit effect. The results of modelling demonstrates that the increase in profit could be 2.5 % from the original “operation as usual” case, using the optimisation method. The representative of the industry has approved that the error of the used method is acceptable and represents the situation as good, as can be assumed, based on given data. The optimisation model shows an effective use of market situation, when market possibilities are used fully to maximize the profit.

3.2.2. Effective use of the remaining heat of an industrial CP for cooling

Maximal thermal energy production is limited in summer because of a lower demand of heat. As industrial CPs are working mainly with back-pressure turbines to maximize the thermodynamic efficiency, electricity production will decrease respectively in periods with lower heat demand. Therefore, finding solutions to increase the thermal energy load is an important factor for electricity production increase at the CP and for economical indices of the plant.

Technically, in summer, the CP can work in condensation mode if there is enough cooling equipment. However, the relatively low electrical efficiency and the market price of electricity does not cover the fuel price of variables. The use of remaining heat for local cooling allows CP to increase electricity capacity. Ideally, it can operate as a base electricity plant.

Absorption-based cooling is the most suitable cooling technology that is based on remaining heat. Therefore, in this research, the absorption cooler is chosen to produce industrial cooling energy. The research focuses on the increase in produced electricity and its wider use transforming the existing CPs to tri-generation plants. Transformation helps to improve the economic performance of all the equipment and increase the profit.

CP operation at open electricity market conditions. Most of CPs variable expenses are fuel expenses. CP is operating based on those. CP can be operating at condensation mode at normal operation if its income from electricity production exceeds the variable expenses of the plant.

Critical expenses of CP are the expenses to produce one extra electricity MWh. In this study, critical expenses are equal to short-term critical expenses. Electricity load increase from CP is expected for as long as critical expenses for it are covered. In the case when income exceeds the variable expenses of production, it is expected that the plant will produce electricity. Traditional plant operation criteria can be written as an equation (3.4.):

$$W_e \cdot P_e > W_f \cdot P_f, \tag{3.4}$$

where

W_e – electricity production, MWh;

P_e – electricity price for an hour at instant demand market, €/MWh;

W_f – fuel consumption, MWh;

P_f – fuel price, €/MWh.

Third commercial object – cooling energy production – is added in this research. Thermal energy use in commercially beneficial way differs the CP from a standard heat condensing electricity plant. It allows the producer to be competitive in electricity market and to save up the primary fuel in power sector. The implementation of cooling energy allows the CP to increase thermal energy production and produce extra electricity for market. Usually, the overall efficiency of biomass CP is 0.85–0.9. The main principle of a CP is: usually it works in accordance with the thermal energy load because it is not competitive enough for electricity market when operating at condensation mode.

Thermal energy market allows the CP to use full effectivity for the good of itself. With one and the same primary fuel, condensation electricity plants' electricity price is lower and can sell the produced electricity in instant-delivery market, but CPs' electricity supply is not accepted because of its high price. Price establishment in the instant-delivery market of electricity is dependent on several aspects; however, average electricity price from instant-delivery market is too low for a biomass CP. In a traditional condensation electricity plant, the production capacity for electricity is increased based on effective use of primary energy. To increase CPs' electrical capacity over one allowed-by-thermal-energy load, the criteria in (3.5.) have to come true:

$$W_e^{extra} \cdot P_e + W_h^{extra} \cdot P_h > W_f^{extra} \cdot P_f, \tag{3.5}$$

where

W_e^{extra} – extra produced electricity from increased heat load, MWh_e;

P_e – electricity price, €/MWh;

P_h – heat price, €/MWh;

P_f – fuel price, €/MWh.

The price of extra-produced thermal energy can be positive or negative depending on whether the extra thermal energy is commercially necessary or whether it is simply cooled down. If it is simply cooled down, then condensation creates negative expenses. If extra thermal energy is commercially necessary for cooling, then this extra heat has a positive price. The cooling demand, available at this study, is covered with extra heat that is produced at the CP. When a part of aCP's thermal energy is transformed into commercially necessary cold water, then a plant becomes a tri-generation plant.

The heat price that is consumed for commercially necessary cooling can be determined only after comparing the alternative expenses with the traditional cooler or after air conditioner expenses are made. Cooling energy price can be calculated using the savings that it gives to a plant when electric drive is changed to central cooling based on the remaining heat.

The consumers' purchased electricity has different price components, which has to be taken into account. These components vary in different countries and places, and they are dependent on legislation that is specific for a particular location. To determine electricity savings from the equipment, it is necessary to take into account the specific critical electricity price P_t for a location.

Absorption-based heat cooling has size-dependent expense effect, which means that the CP will operate with a higher electricity load if savings from the use of absorption coolers together with extra income from electricity are bigger than extra fuel expenses. Biomass plants that are common in European Union usually have several subsidies. Cooling with absorption coolers allows the CP to increase electricity production and receive extra income from subsidies, in addition to extra income from electricity sales price. As subsidies, based on the mandatory procurement component, do not require the producer to take part in electricity market, this type of subsidies is not taken into account in the present research.

There are no obstacles for operating a CP in condensation mode; however, in this case, the plant should be able to work in market conditions. This is not possible in the Baltic States, where the fuel prices are higher than the income from electricity. The use of options for heat-based cooling is strongly affected by local energy policies and changes in them. The total efficiency η_n for a standard biomass CP is higher than the required η_R by legislation, to receive subsidies. Therefore, plants can operate in partial condensation mode in a higher efficiency range for as long as a minimal total efficiency is maintained.

Possibilities for wood industry CPs. Estonian wood industry is studied in this case. The equipment requires heat for air cooling at the drying process to cool down the production. Extra cooling is necessary for household and office rooms, where cooling is performed by air conditioners now. A local CP that produces the heat required for the drying process is operating at the industry. Main parameters of the studied industry are displayed in Table 3.2.

The drying process requires less heat during summer because of the high outside temperatures, which leads to remaining heat. Fig. 3.6. displays the connection of the equipment's remaining heat amount with the outside air temperature, and the thermal energy production profile for the studied industrial CP. Studied CP uses a back-pressure turbine, which makes it impossible to control thermal energy production without losses in electricity production capacity.

Table 3.2.

Main parameters of studied industrial equipment

Input data	**Variable**	**Value**	**Unit**
CP electrical output capacity	W_e	6.50	MW_e
CP heat output capacity	W_h	18.00	MW_{th}
CP total efficiency	η_n	0.89	
Fuel price	P_f	12	€/MWh
Subsidy, feed in premium		53.7	€/MWh_e
Price (savings) for cooling	S_c	0.00	€/MWh
Process cooling airflow		90 000	m^3/h
Process cooling temperature		5	°C
Heat exchanger efficiency		0.85	
Air conditioners (AC) capacity		0.334	MW_{th}
AC load factor, $t > 10$ °C		1	
AC load factor, -10 °C $< t < 10$ °C		0.75	
AC load factor, $t < -10$ °C		0	
Absorption cooler efficiency	η_{ABS}	0.75	
t° below full heat load required	t_{max}	10.00	°C
Investment costs of absorption cooler		170 000	€/MWh_{th}

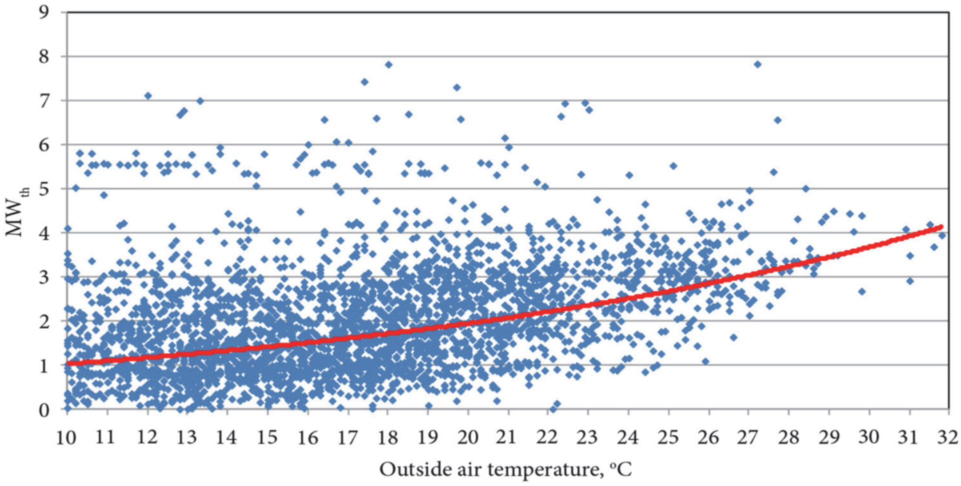


Fig. 3.5. Connection of the studied equipment's remaining heat production with the outside air temperature.

Fig. 3.5. includes the modelling results for cooling capacity, with which it is possible to increase the existing total thermal energy load. Remaining maximum points, where remaining heat is available, can be cooled down by dry coolers that are set up in a CP, at the same time keeping efficiency at the required 75 %.

At the time of high outside air temperature, less heat is consumed in the drying process. On the other hand, high outside air temperature requires much more cooling energy to cool down industrial production, which makes cooling demand a perfect replacement for thermal energy consumption decrease. Operation drops exist, which happen due to planned or unplanned maintenance. Modelling uses real historical data of the studied equipment where these drops are included, and they will not to be covered with cooling load. To maximize electricity production, it is necessary to cover the remaining thermal energy peaks that can not be covered by the cooling load with dry coolers.

As shown in Fig. 3.6., the largest part of heat is consumed by the drying machine, and thermal energy drops in summer are covered by the cooling energy demand. The combined thermal energy load makes production profile closer to base load plants profile. This, therefore, allows more stable operation. The fluctuations of the remaining thermal energy at the same interval of outside air temperatures create different operational effects. Extra cooling equipment could improve the reliability of the system.

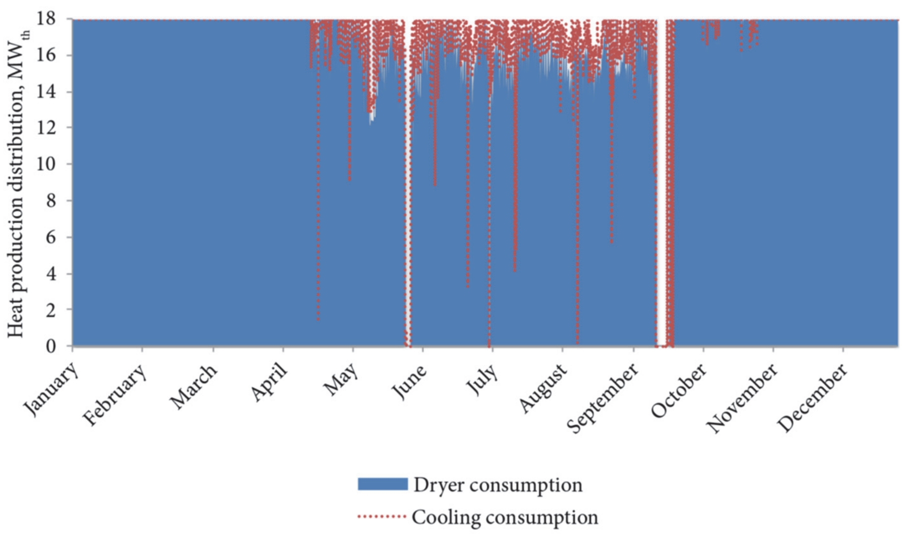


Fig. 3.6. Actual thermal energy consumption profile, when extra cooling load can help even out the thermal energy consumption in summer for the studied case equipment.

Wood industry – a case study. *Nord Pool* instant delivery market in Estonian region, a small-range CP, cannot operate at condensation mode at market conditions because fuel prices exceed the electricity market price. In accordance with Estonian statistical database and country's forest sales prices, the average biomass fuel price was 12 €/MWh in 2012. In the same year, average electricity market price was 39.2 €/MWh. If the CPs total efficiency η_n is 89 %, the fuel consumption at full load is 27.5 MW, which created electricity efficiency η_e = 24 %, which in its turn means that 24 % of primary energy is transformed into secondary energy – electricity. With this electricity efficiency, the plant's short term critical price would be 50 €/MWh_e. Traditional biomass CPs would not operate in these conditions.

At present, the plant has an 0.3-MW_{th} cooling load for household and office buildings that are cooled with electrical air conditioners. Wood processing requires a 0.8 MW_{th} cooling load to cool down the production. Production is cooled with the air from outside, and no coolers are used. However, if a heat exchanger is used, fan electricity consumption would be lower. The company loses a part of the product's quality during summer because of the lack of the cooling load. Total existing cooling load is 1.1 MW_{th}. To transform this cooling capacity from the thermal energy network taking into account transformation factors, the total cooling load in thermal energy network would be 1.7 MW_{th}. As seen in Fig. 3.6., the remaining heat production can reach up to 7.8 MW_{th}, which covers and exceeds the cooling demand.

The studied industry operates a CP with the output capacity of 6.5 MW_e and 18 MW_{th}, stopping operation for yearly maintenance. In all, 100 % of thermal energy is used in the company's drying processes. Thermal energy demand for drying decreases in summer because of the high outside air temperature, but cooling load increases. The system offered for the developed industrial tri-generation is displayed in Fig. 3.7.

The process diagram in Fig. 3.7. is made for the certain studied case equipment. Instead of using all thermal energy in a drum dryer and being dependent on the dryer's thermal energy, the CP can be operated by using the remaining heat for cooling. To transform thermal energy into cold water and cover the cooling demand, the absorption cooler is necessary. In the case when cooling load is not sufficient to maximize the electricity production, dry coolers will start to work to cool down the rest of remaining heat and maximize the electricity production, and thus also the profit.

Results. Calculation results for cooling energy production in the studied case industry are displayed in Table 3.3. The payback period for the absorption cooler is less than six years, as shown in the table. A positive effect on the environment is achieved through a decreased consumption of primary fuel.

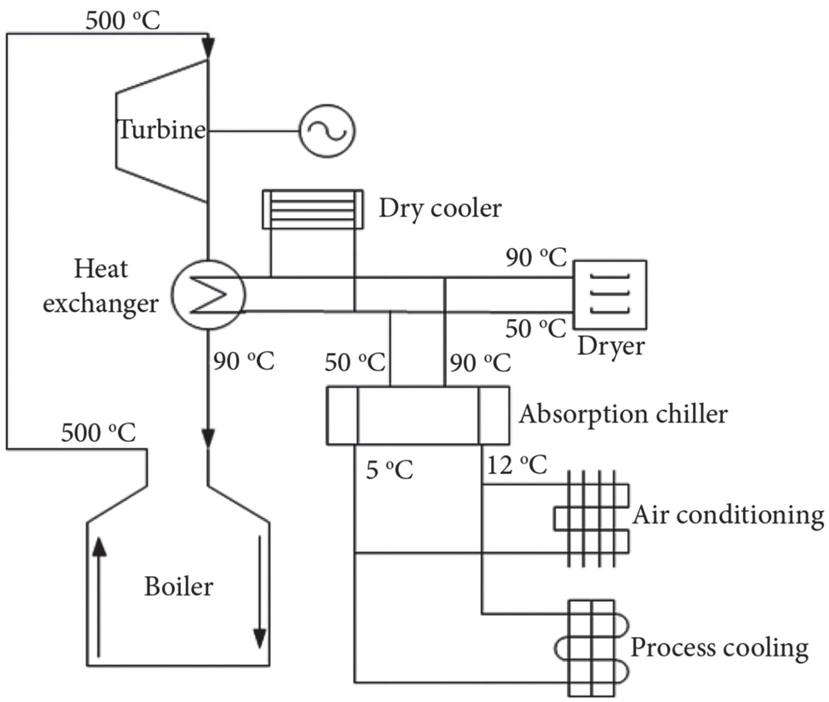


Fig. 3.7. Offered technological solution for the industrial CPs' cooling system.

Table 3.3.

Calculation results of the studied case of industry

Output data	Variable	Value	Unit
Required process cooling		1 346	MWh_{th}
Process cooling load	W_{PC}	1 583	MWh_{th}
Air conditioners load	W_{AC}	2 491	MWh_{th}
Total cooling load		4 074	MWh_{th}
Heat demand for cooling	W_h^C	5 432	MWh
Heat demand for drying	W_h^H	147 507	MWh
Excess heat		6 180	MWh
Excess heat peak		7.8	MWh_{th}
Heat for cooling		2 927	MWh
Cooling load peak		1.7	MW_{th}
Additional condensation need		3 254	MWh
Condensation peak		6.8	MWh_{th}
Additional electricity production		1 057	MWh_e
Additional electricity income		105 478	€
Additional fuel consumption		4 476	MWh
Additional fuel cost		53 708	€
Additional profit		51 770	€
Payback period		5.6	Years

The previously mentioned case studies calculations were made assuming that there are no heat losses or condensation. The payback period for the absorption cooler is calculated by the extra efficient thermal energy load that it creates. These saving are counted as 0 because, due to small cooling demand, there is no volume effect and the operational costs of absorption coolers are the same as expenses for the existing equipment. The main profit in this study comes from the increased electricity production in the CP.

To simplify calculations, capital expenses and interest rates were not taken into account. If extra field experiments are made, they can be taken into account in future research. In the case when operational savings come up, it will make the probability better.

It should be pointed out that this research was done taking into account the existing subsidy mechanisms; therefore, the results are dependent on energy policy. Developed methods are suitable in any case, even when subsidy mechanisms do not exist because the equation can be used in probability studies. Developed methods can be used at any CP for conversion calculations. This research focuses on the producer's aspect and does not take into account the indirect effect on other market participants or national energetic variety aspects.

4. TASK. PRODUCTION DEVELOPMENT AND SUSTAINABILITY ANALYSIS AT COUNTRY LEVEL USING SYSTEM DYNAMICS MODEL

In the market of energy commodities, one of the fastest-growing markets worldwide is pellet production and consumption. Pellet production amount has grown from 1.7 million tons in the year 2000 to 28 million tons in the year 2015. The major pellet net importer is European market, whereas the largest net exporter is USA market. The European Union (EU) is responsible for 74 % of the world's wood pellet consumption. The two main wood pellet uses are heating and power production. Pellet production increase is expected in all markets, with the highest rise predicted in China market.

The current situation in the pellet and woodchip export at the Baltic sea region's countries gives proof that Latvia differs from other countries because it exports the bio-product with low added value – woodchips. This means that the resources that could strengthen the macroeconomic development of the country travel away from it. In the recent years, the wood logging amount in Latvia is nearly 12 million m^3 per year, of which 53 % are from private forests and 47 % are from state forests. Most of the wood fuel is used in the form of firewood.

Also, in the recent years, the woodchip manufacturing amounts have increased rapidly. Since 2008, they have doubled almost twice. Manufacturing amounts increase because of the increasing interest of local consumers. Firewood and the forestry residues are used in woodchip manufacturing, the wood from overgrown agricultural land is used. The largest part of the produced volume of woodchips consists of industrial fuel woodchips that are manufactured from firewood and low quality wood, and, for the present, only a small part of produced woodchips are manufactured from forestry residues. The woodchips from forestry residues is mainly used in the power sector, and their increase can be explained by the growing number of biomass boiler houses and cogeneration plants.

Pellet production strongly effects the fuelwood market, because not only the pellets that are used in the power sector are produced but also the competition for the purchase of fuelwood resources takes place. According to the currently installed capacities, Latvia is considered as one of the leading pellet manufacturers in Europe. Although pellet production in Latvia is developing rapidly, the demand for pellets in local market is low. About 90 % of produced pellets are exported.

Any industry's product value is made up from separate different positions that can be divided into intermediate consumption and added value.

4.1. Methodology of system dynamics model

The theory of system dynamics is based on studying the relationships between the behaviour of the system and its structure. It allows better understanding of the causes of a certain system behaviour, thus allowing to solve and eliminate the problematic behaviour of the system. Modelling method allows understanding the structure and dynamics of complex systems. Computer software is used, as it is the easiest way of how to illustrate and work with complex systems. There are three main elements that make up the system dynamics concept. If these elements are used correctly, it is possible to obtain adequate results:

- stocks, flows, and feedback loops;
- precisely set system boundaries;
- causal relations not correlations.

Stocks and flows are the basic components of the system that help create the basic structure of the model. Stock is the accumulation of resources, information, or any other value. Stock can have both incoming and outgoing flows. Often systems have feedback loops, which means that the values of the flows are determined based on the value of the stock.

An essential concept element of the system is precisely defined boundaries of the system. When creating the model, the maker must be able to define and understand which components of the system should be included in the model development.

The last important condition that must be considered during the development of the system dynamics model is determination of causal relations, not searching for correlations.

System dynamics modelling consists of multiple steps:

- investigated problem and goal are formulated;

- development of dynamic hypothesis, during which the main stocks and flows of the model are identified and defined. Their mutual interaction is described;
- development of the model structure in computer software (structure and formulas);
- validation of the model, when it is determined whether the structure and behaviour of the model corresponds to the operation of the real system.

During the model development phase, it can be necessary to go back to previous steps to correct the errors or to update the model with previously unidentified elements. Other times, the identified problem and the developed dynamic hypothesis have to be reviewed. The goal of the system dynamics modelling is not to make precise "point" predictions, but to determine what kind of dynamic development of the system could be expected in a particular period of time; therefore, the results must be treated as a possible direction of the development.

4.2. Dynamic hypothesis

To plan and define the future perspectives of energetic wood, it is important to include all basic parts in the modelling process that determines how the choice in favour of the use of a particular wood type will form. Three usage types of energetic wood are compared in the Doctoral Thesis: firewood, woodchips, and pellets. To display the most important components of the system and their mutual connections, a causal loop diagram of the system is used (Fig. 4.1.). It helps to understand and characterise the behaviour of the system.

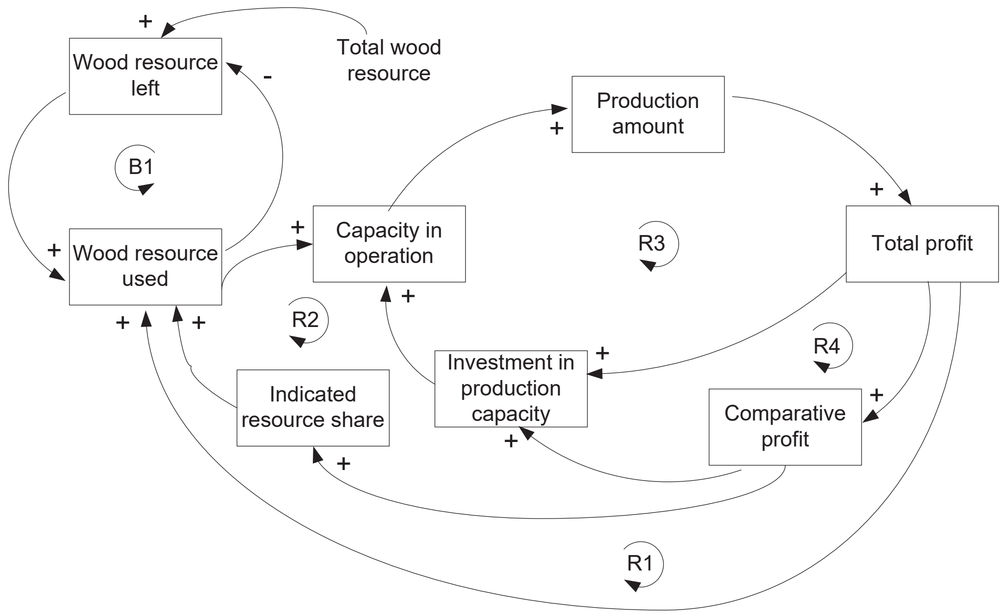


Fig. 4.1. Causal loop diagram.

The causal loop diagram in Fig. 4.1. shows four reinforcing processes R1–R4 and one balancing process B1. The first reinforcing loop R1 shows: the more forest resources are used for production of a particular product (firewood, woodchips, or pellets), the larger production capacity should be installed, which promotes larger production amounts. With the increase in production amounts, the profit from sales increases, the relative profit is larger, and the use of forest resources for production of a particular product will be increased.

The second reinforcing loop R2 is similar to R1, i.e., larger amount of resources means larger installed capacity, larger production amounts and total profit. Larger profit means additional resources for research, increasing the relative profit due to a decreased consumption of raw materials. Time is needed for research, therefore the increase in relative profit will occur with a delay, which means that a larger part of total resources will be used for the production of a particular product thus increasing the amount of resources provided for the production process. This process also occurs with a delay.

The third reinforcing loop R3 works from the installed capacities. The larger is the installed capacity, the more products will be produced, which leads to larger profit. If the relative profit is larger than that for other products, then a part of the profit can be used for building of new capacities. If the relative profit is smaller than that for other products, then the profit will not be used for building of new capacities, because the resources will be used for the production of other products and the current capacities will not work at a full load. Delay exists between the investments assigned for building new capacities and the currently operating capacities, because time is needed to make decisions and to carry out the purchase and installation of capacities.

The fourth reinforcing loop R4 works similarly to R3, but in this case, like in the case of R2, a part of the profit is given to research, promoting the increase in relative profit and thus increasing the competitiveness with other products, which allows investing a part of the profit in installing new capacities.

The infinite growth of forest resources use is delayed by the balancing loop B1. The total amount of forest resources for power industry is limited. If more resources are used, for example, in woodchips production, the less resources will be left for firewood and pellets. The amount of resources used for the production of one product cannot exceed the total available amount of resources. Initially, the reinforcing loops will promote a rapid increase in production, but coming closer to the limit of available resources, the effect of the balancing loop will increase and the production rate will decrease.

Basing on historical data, a prediction was made that the usage of firewood will decrease significantly until 2030, which would stimulate the growth of the woodchip and pellet production. Historical data testify that in the last 10 years, significant increase in the woodchip and pellet production rate is observed, while firewood production amounts are already strongly decreasing. The decrease in firewood and increase in woodchip production can be explained by the growing demand for woodchips in cogeneration plants and boiler houses. Woodchip production from forestry residues is evolving. The decrease in firewood is connected with the increase in pellet production.

4.3. Model structure

4.3.1. Obtainable wood amount

System dynamics model is developed in “Powersim Studio 8” software. There are several assumptions included in the model:

- increase speed of heat energy pricing rate is 1.5 % per year;
- increase speed of electrical energy pricing rate is 1.5 % per year;
- salary increase for workforce is 2.5 % per year;
- price increase for end product is 2.5 % year.

The model is based on the acquisition of wood resources. Wood logging amount depends on the demand of various wood industry sectors and the demand of power industry. Maximum logging amount is controlled by the forest law and related order of the Cabinet of Ministers. The type of requested wood determines how much wood goes to each sector and for the production of a certain product. Attention is focused on the use of energetic wood, studying the production amounts of firewood, woodchips and pellets; therefore, a part of logged wood resources that is used out of the power sector is determined based on the existing consumption.

Logged wood is used in various ways, therefore the structure of the model for the resource acquisition part is made as a stock that describes the total amount of felled wood in the main clearing (FTS), and it is regulated by four flows. The incoming flow describes the amount of harvested wood (HR), but three outgoing flows describe the further uses of wood. All obtained wood resource is included in the harvested amount – firewood, paper logs, and logs. The total amount of harvested wood is determined by the amount from both the government and private forests.

The amount of obtained wood for use in power industry (EWS) is introduced as an additional stock that is regulated by four flows. Two incoming flows describe the obtained wood from the main clearing and the amount obtained from forest cleaning (FCR). Forest cleaning includes residues, such as branches, stumps, and crests. Outgoing flows show the division between export (EXR) and use in local market (LR). The use amount of energetic wood is dependent on the demand from the power sector.

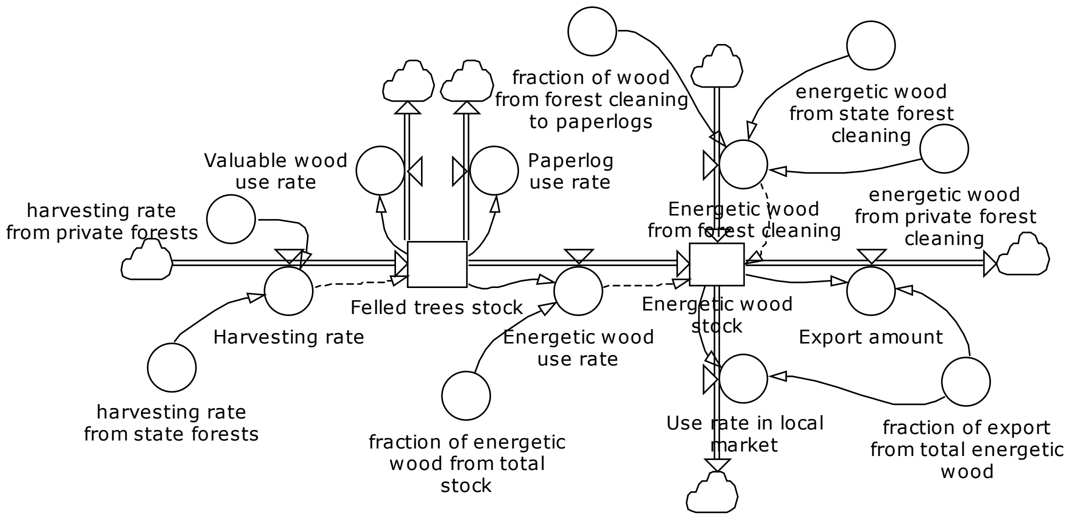


Fig. 4.2. Obtainable wood amount.

The amount of wood obtained from forest cleaning comes both from private and government forests. A part of the wood resources obtained in forest cleaning are used for pulpwood; the remaining part is used for energetic wood stock. Branches, stumps and crests are not included in this amount. Energetic wood flows used for export and local market are determined by the export part from the total energetic wood amount that is based on statistical data.

4.3.2. Logical function

The economical factor is an important condition for the choice of the product to be produced. A logical function is included in the model that compares the profit of firewood, woodchips and pellets on one used m^3 of wood to determine the amount of energetic wood resources to be used for each product. Share given for each product is described with the equation (4.1.):

$$f_1 = e^{\alpha P1}/(e^{\alpha P1}+e^{\alpha P2}+e^{\alpha P3}) \,, \tag{4.1}$$

where

f_1 – share of wood for each product (firewood, woodchips, or pellets);
α – coefficient, which indicates how frequent is the change from one product to another;
$P1$, $P2$, $P3$ – profit from firewood, woodchips and pellets, EUR/m^3.

The amount of wood given for other products is calculated by the same principle, only changing the profit number of the product, stated in the numerator, to the profit of the particular product.

4.3.3. Sub-model of energetic wood

A part of energetic wood is equal to the firewood production amount. Produced firewood amount divides into firewood for consumption, woodchips, and pellets. One stock is operating in this part of the model that describes the amount of energetic wood or firewood (WS), which can be further used in various ways. The stock has one incoming flow and three outgoing flows.

The incoming flow regulates the incoming amount of energetic wood (TEWR), and it is made up by the amount of energetic wood (LR) used in the local market. At a beneficial purchase price, paper logs can be used for pellet production. Data shows that export part of paper logs decrease due to capacity increase for pellet production; however, this model does not look at paper logs as raw material for pellet production. Energetic wood resources from low quality wood (firewood), production and forestry residues are compared. The model takes into account the fact that part of the energetic wood provided for the local market goes to the production of chipboards.

One of the stock's outgoing flows is firewood production for end-consumption (WLR). The flow describes the total energetic wood amount that goes to the firewood end-consumption use. This amount is determined by comparing two values – firewood production potential (PWLP) is compared with the actual operating firewood processing capacity (CWL). Firewood production potential can be significantly larger than its processing capacity. If capacity is insufficient, the firewood is produced in the amount that is allowed by the existing capacity. Woodchip and pellet production amounts are determined by the same principle.

The potential production capacity is determined by studying the total amount of energetic wood and taking the part determined by comparing the profits of firewood, woodchips and pellets. The time is required to react to the changes in the profit between various product types; therefore, a third-degree material prevention function with time delay of two years is used in the model. In the result of profit comparisons given, energetic wood part for the production of a particular product is delayed and will start operating after a specific period of time.

Additional wood for power industry is obtained from wood processing residues. This wood can be used as woodchips or raw material for pellet production. The part of wood used as woodchips and the part of wood for pellet production are determined by comparing the profits of woodchips and pellets, excluding firewood. The model has an additional energetic wood source – forest residues that can be used for energy generation. They can only be used as woodchips because the high additions of sand make it impossible to use them for pellet production. Forest woodchips take part in pellet production as a fuel to generate thermal energy. As this resource can be used only for woodchips, it is divided separately.

The model has another additional energetic wood resource that comes from wood processing residues. The largest part of this resource comes from wood sawmills and plywood production. This part of the model is divided separately.

4.3.4. Sub-model of income and expenses

The profit of each product is calculated taking into account the income from firewood, woodchips or pellet sales, and from the expenses related to the production process: capital expenses of equipment, consumption and costs of electricity and thermal energy, workforce expenses, and additional costs for the production of the product.

The profit sub-model part has two basic stocks that describe the total saved up income and total saved up expenses (APPC). They are regulated by incoming flows, which are annual income (PRR) and annual expenses (PPCR). The expense flow consists of capital costs and also of variable costs. Only annual expenses of the basic equipment are under the capital costs (TCC). Variable costs (TVC) include both the raw material costs for pellet production and heat and the electricity costs, as well as also the workforce costs, and other costs that do not fit into any category. The chapters of expenses and the model structure are shown in further sub-chapters.

Raw material expenses consist of two parts – the woodchip and firewood expenses – depending on how much a certain raw material is purchased and used. The income flow is calculated taking into account the pellet sales rate (PSR) and the pellet price in the market (PP). It is assumed that the prices of all end-products could grow by 2.5 % per year.

Profit value is determined by comparing the income and expense flows. Profit value is calculated to the unit volume of wood used to make comparison of pellets, woodchips and firewood possible. The profit for woodchips and firewood is calculated using the model structure described in this chapter. Some expense positions were changed – for example, for firewood, there were added logging expenses and forest planting expenses, but for woodchips, part of the logging costs and chipping costs were added. Woodchips from forestry residues were divided separately; therefore, the profit was calculated separately as well.

4.3.5. Sub-model of installed processing capacity

Processing capacities are technological solutions that allow producing a certain amount of production. In the case of woodchips and firewood, the capacity is marked by a specific amount of cubic metres (for woodchips – bulk cubic meters; for firewood – close cubic meters) that can be produced in a year, but in the case of pellets, the particular installed processing capacity is producing in tons.

The sub-model of capacity is made up of two stocks that are mutually connected with the flow. One of the stocks describes the installed capacity (CIO), but the other stock describes capacities under construction (CUC) that have not been installed yet. The stock of the installed capacities is regulated by the incoming flow or the exploitation set for new capacities (CR), and the outgoing flow or the writing off of capacities that are obsolete (DCR).

The flow that describes the writing off of obsolete capacities is described by the material delay function. The initial wear is taken into account from the currently installed capacity, but, in continuation, the delay function also outputs the new installed capacities after the specified lifetime of technology (LT).

The incoming flow, which is also the outgoing flow of the capacity flow under construction, is determined by taking into account the value of capacity under construction and the necessary construction time (CT). The stock of the capacity under construction is regulated by the incoming flow or the orders of capacity (OR), and the outgoing flow or the exploitation set for newly built capacities. Ordered capacity cannot be a negative value, so the MAX function is used.

Ordered capacities for appointed parameter (EOR) have to ensure that additional capacities are added if the potential production rates (PPR) require them. This value must compensate the obsolete capacities and shortages in capacity under construction. The necessary capacity under construction is dependent on the necessary orders (DOR). Necessary orders consist of the capacity depreciation rate and, by comparing the installed capacity with the potentially possible capacity amount, that is allowed by the resource stock. This technology scheme works for all product types.

4.3.6. Sub-model of capital expenses

This part features the description of capital expenses that form from the capacity sub-model described in the sub-chapter 4.3.5. Investment rate (IR) is the flow that determines the amount of investments necessary to install the new capacities. Capital expenses are the stock regulated by the incoming flow or capital expense increase rate (CCIR), and the outgoing flow or the capital expense decrease rate (CCDR).

The new investments increase the total share of capital expenses, which means that the investment amount affects the capital expense increase. When determining the increase in capital expenses, the economic lifetime of technologies (ELT) and the discount rate (DR) of investments are taken into account.

For the calculation of capital expense decrease, the delay function DELAYPPL is used. It promotes the discharge of capital expenses from the stock after the end of their payback period.

Stock value for capital expenses is used for the capital expense calculation shown in the sub-chapter 4.3.4. The structure of this model works for all product types, changing only the numerical values.

4.3.7. Sub-model of electricity consumption

An essential part of production process expense is the consumption of electricity and thermal energy. Specific amount of electricity and thermal energy is necessary for use in all production steps to operate the equipment or provide the processes. The structure of the electricity sub-model is described in this chapter, but the structure of the thermal energy sub-model is created by a similar principle.

There are two stock values in the electricity sub-model: the current specific electricity consumption (EEC) and the electricity consumption (ER). The current specific electricity consumption describes the current level of energy efficiency or the energy efficiency. This stock and its formation are described in detail in the sub-chapter 4.3.8.

Electricity consumption is regulated by the incoming flow or the increase in electricity consumption (IER), and the outgoing flow or the decrease in electricity consumption (DER). Increase in electricity requirement (IER) is determined by the installation of new capacities and the current specific electricity consumption. It is assumed that for installation of new capacities, the best possible technologies will be chosen, thus increasing the energy efficiency.

Average specific electrical energy consumption, which is further used in the sub-chapter 2.2.4 to calculate the electrical energy costs, is acquired by dividing the electrical energy consumption with the installed capacity of equipment. It shows the electrical energy consumption while taking into account the efficiency level of both the old and the new capacity. Electricity consumption decrease depends on the write-off of depreciated capacities and on the average specific electricity consumption.

4.3.8. Sub-model of energy efficiency increase

Energy efficiency sub-model is built in a way that takes into account the predicted increase in electricity and thermal energy efficiency for the future technologies. The sub-model consists of three stocks: the current specific electricity consumption, the potential specific electricity consumption (PEE), and the electricity consumption potential (EEP). Stocks are mutually connected with two flows that indicate the electricity efficiency level increase (EEIR).

Energy efficiency level increase is determined by taking into account the potential specific electricity consumption and the time required to develop the efficiency level. The value of the potential specific electricity consumption stock is regulated by the outgoing flow or the efficiency level increase, and the incoming flow or the newly obtained electricity efficiency potential increase from the results of research activities (EERR).

The new potential flow is obtained from research results, and it is determined from the maximum electricity potential and the time necessary for research. The principle of this sub-model is used to make the efficiency part of thermal energy.

4.3.9. Workforce sub-model

Workforce is an essential part of each production process. The workforce sub-model is built by taking into account the increase or decrease in the workforce demand based on the increase or decrease in production capacities. The main flow for the stock is the number of employees regulated by the incoming flow or the increase in employees, and the outgoing flow or the number of people dismissed.

During the development stage of the model, the fact that the capacity increase is not proportional to the workforce increase is taken into account; therefore, the workforce increase will be slower in the case of capacity increase. Due to this intention, a new parameter – "effect of production capacity on workforce requirement" (EPLB) – was introduced, and it depends on the new planned capacity (NPC), the reference capacity that describes the capacity of a particular activity with a known number of employees, and on the step, stating after what increase in capacity, the required number of employees per additional new capacity unit will decrease. Next, the new labour requirement (NLBR) amount per capacity unit is determined. The initial workforce requirement (ILBR) is taken according to the reference capacity. The workforce requirement is determined by taking into account the predicted new capacity and the new necessary workforce amount. The new production capacity is determined by the existing capacity and the predicted exploitation and write-off capacities:

$$NLR = \mathrm{NPC} \cdot \mathrm{NLBR}\,, \tag{4.2}$$

where

NLR – necessary workforce, people;

NPC – predicted new capacity, t/year.

$NLBR$ – new labour requirement, amount per capacity unit.

Regulating flows of the workforce stock are calculated using the *if* function, when comparing the stock value with the required amount of workforce. More time is needed to react to the necessary workforce changes because of the capacity decrease; therefore, the delay time for detecting the changes is introduced in the formula. The workforce model works by this principle in the production of each product.

In the sub-chapters described previously, the main structure elements of the models are shown. They create the basis of the system dynamics model. There are more links and variable values to adjust the operation of the system functioning in the model, but the most important elements of the model are shown and their operating principles are explained.

4.4. Model validation

Model validation consists of two steps:

- the validation of model structure, where it is verified, if the model structure and the mutual links between elements in the model match up to the generally accepted assumptions on the real system;

- the validation of behaviour, where it is determined, if the behaviour generated by the structure of the model matches up to the behaviour of the real system.

The validation of the model structure in most of the cases is carried out by consulting the experts of the industry, with good knowledge of the industry nuances, and who help to develop a correct structure of the system. The testing of various extremes is carried out during the validation to verify whether the model works precisely in the case of extreme situations.

System behaviour validation is carried out by comparison of the behaviour generated by the system with the available historical data. If the model behaviour can closely represent the behaviour of the real system, then the model can be used to further research the system. If it is not possible to represent the behaviour of a real system, then it is necessary to go back to the structure of the model and make changes in it.

4.5. Results

A hypothetical energetic wood development scenario was determined based on historical data. Comparing the hypothetical scenario with the development scenario generated by the model, a conclusion can be drawn that the tendencies of firewood and woodchips are similar; whereas in the case of pellets, the hypothetical and model scenarios are noticeably different.

All values were recalculated to firewood close cubic meters to better compare the development tendencies of all products. The hypothetical scenario, based on historical data, predicted a similar development for woodchips and pellets, with a slower increase rate for woodchips. The result generated by the model (see Fig. 4.3.) shows that woodchip production amount could increase similarly to that predicted in the hypothetical scenario, whereas pellet production development will not be as rapid as that in the hypothetical scenario. It can be explained by the fact that pellet production in Latvia and in the whole world is at the beginning stage of its development, and the rapid development rate in the last years has allowed Latvia to become one of the leading pellet producers in the world; however, due to limited resources, rapid increase rate cannot last forever.

Fig. 4.3. shows that in recent years pellet production takes noticeable part of energetic wood resources and, in order to increase pellet production rates after the rate given by hypothetical scenario, it would be necessary to stop the firewood and woodchip production for end production and consumption, to use paper logs for pellet production, or to increase wood logging amount in the country.

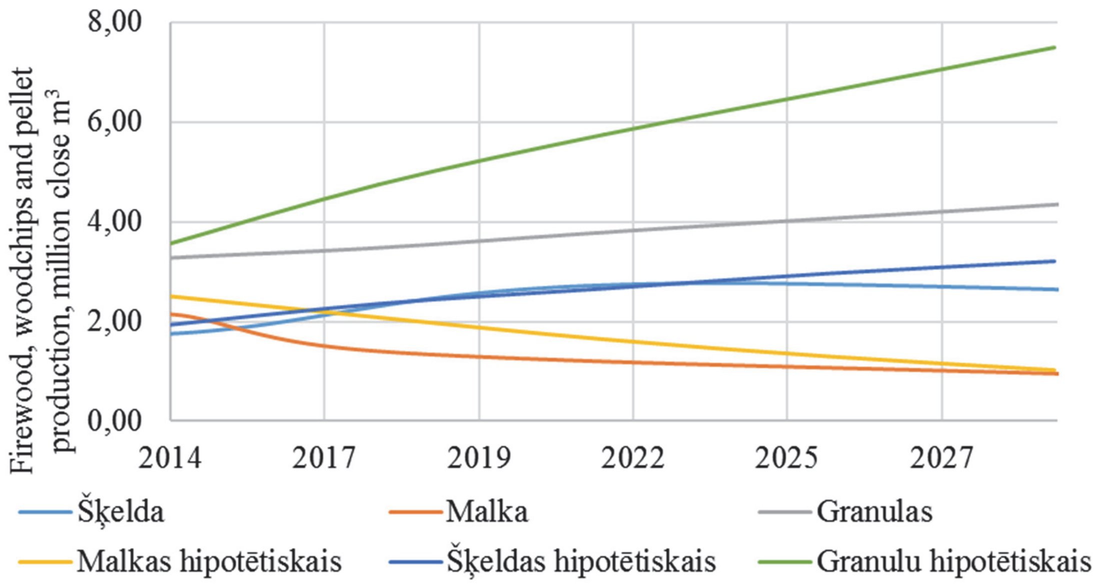


Fig. 4.3. Energetic wood development.

In order to better understand what makes the results generated by the model, the attention should be focused on the profit part. The resource choice for a certain product in the model is done basing on profit values. To compare profit values between the products, they were applied to wood amount for product production, obtaining specific profit indicators.

The profit from pellets noticeably exceeds the profit from firewood and woodchips, and this difference will grow even more as the pellet production develops. Explanation for this could be seen in the causal loop diagram (see Chapter 4.2.). Reinforcing loops in the case of larger profit promote the increase in specific profit, thus making a larger difference between the value of pellet specific profit and the value of firewood and woodchip specific profit. The difference in profit values indicate that the pellet manufacturing increase can potentially be even larger, but in this case one should take into account the circumstances that prevent this from happening.

As seen in the case of firewood (Fig. 4.3.), its production volume could decrease by approximately 50 %; however, it should be taken into account that this decrease is mostly happening because of the amount of wood acquired in licensed clearing sites. Part of the firewood resources are obtained in private forests without the licence and will most likely be used in local households as firewood. This means that this part of firewood does not compete with pellet production; therefore, a more rapid decrease in firewood production will not occur.

Woodchips development rate obtained from the model is close to that determined in the hypothetical scenario. Woodchip production increase is predicted. It has to be taken into account that there are two types of woodchips: industrial, made by chipping of firewood or wood processing residues, and forest woodchips, made from forestry residues – stumps, branches, and crests. Industrial woodchips can be used for pellet production and, therefore, are in competition with pellet producers, while forest woodchips can be used only for power industry's purposes. The results of the model show that the total amount of woodchips could increase; however, pellet production has a larger profit, therefore the production of industrial woodchips as end production will decrease on the basis of pellet production increase, but the total amount of woodchips could increase because of the forest woodchip production. In recent years, the use of forest woodchips is noticeably increasing.

Overall, the results indicate that the pellet production development is a very believable scenario, and, taking into account the rapidly rising demand for pellets in Europe, a very large export potential exists. However, to be able to increase the pellet export volumes, it is necessary to increase the acquisition volumes of energetic wood, because the results obtained in the model indicate the share structure of the energetic wood necessary in the local market. Besides, it is predicted that in Latvia, not only the amount of produced pellets will increase but also the consumption, substituting the firewood and woodchips. The specific profit from the pellet production (Fig. 4.4.) is higher than for firewood and pellets, a rapid development of pellet production follows, but, as a delaying loop in the model related with the resource availability is functioning, the growth speed is decreasing. This means that the pellet production volume at the current speed of energetic wood acquisition approaches the maximum, and the only possibility of increasing the pellet production amounts even more is by increasing the acquisition of energetic wood.

To understand how the production speed development course of pellets would impact the mutual distribution of expenses and profit, their comparison was carried out. Fig. 4.4. displays that initially, the largest part of money flows involved in pellet production consists of intermediate consumption, followed by profit and workforce expenses and capital costs. The profit from the total money flow accounts for less than 10 %.

Main expenses in intermediate consumption are made up by the wood purchase necessary for pellet production and preparation, which also are the essential expenses of the process. This part includes wood resources used directly for pellet production, and wood resources used for thermal energy generation. It can be seen that intermediate consumption has a tendency to decrease applied to other parameters, while profit has grown slowly and accounts for 15 %. It was assumed during the model development, that the price of products could increase for 2.5 % per year, and this increase would promote the increase in profit; whereas for raw materials, this specific profit indicator does not grow so rapidly, which means that the profit part has a possibility of growing applied to intermediate consumption expenses.

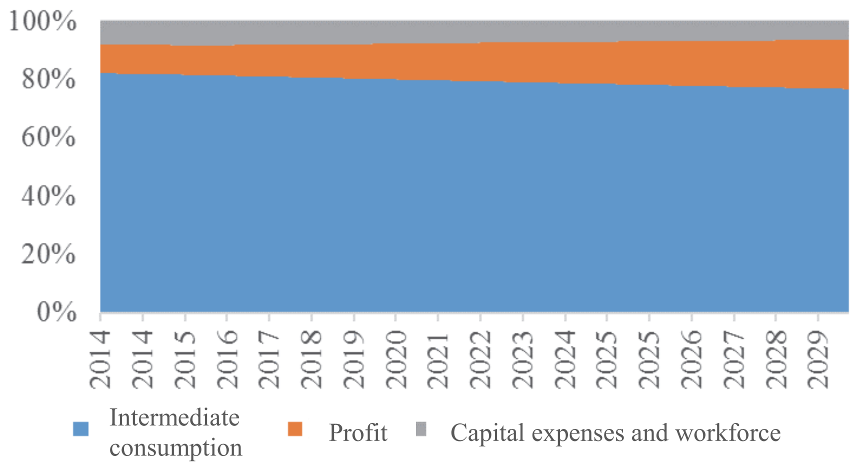


Fig. 4.4. Distribution of profit and expenses.

Workforce expenses and capital expenses have a tendency to decrease. Although the absolute values keep growing, their increase applied to profit is slower. At the end part of model simulation, the workforce and capital expenses account to less than 10 % from the total money flow. For the workforce, it can be explained with the decrease in relative workforce demand, because it is taken into account that necessary workforce amount does not grow proportionally to production capacities, which is true in the actual situation. If the capacities are increased in the existing company, then the capacity increase requires a smaller amount of additional labour force compared to that when establishing a new company with the same capacity, taking into account the high level of automation in manufacturing companies nowadays. The capital costs are considerably lower when larger capacities are installed; therefore, the decrease in the capital costs part is natural.

The cash flow distribution largely depends on the increase or decrease speed in the equipment costs, workforce salaries, rates, and products and raw materials; the graph (Fig.4.4.) shown in the Results part matches up to the made assumptions.

It is also important to take into account the fact that the system dynamics modelling method is not intended for achieving precise future outcomes but for predicting the dynamics of development; therefore, when looking at the results, it is not necessary to look at absolute values but on the dynamics of the development.

Conclusions

1. The pellet production operation scheme can be improved by implementing pre-milling. Pre-milling mills should be productive to provide material hammer mills as well. There is also a possibility of using the existing mills as pre-milling mills and of installing new ones for milling with a smaller capacity, because productiveness increases when the pre-milled material is used. Electricity efficiency per one ton of production is increased in both cases.
2. When implementing the pre-milling in pellet production, it should be taken into account that there is one more device that has a need for mandatory maintenance and unplanned stoppages may occur. After implementing the pre-milling mills, the air flows will change; therefore, the air suction system should be changed, creating additional investments and operational costs.
3. Optimisation principle is developed for controlling industrial CPs at open energy market conditions. A global optimal operation model for electricity export is developed for a production unit with CP. It can be used for production optimisation at industrial CPs, taking into account industrial load control options, power plant's load planning, and electricity market price.
4. Different electricity loads should be separated one from the other and compared with the electricity market price. The load model results help to precisely obtain elastic loads. Load elasticity allows maximizing the incomes, switching the load when necessary. Load switches are made taking into account electricity production and consumption together with the limits.
5. A traditional cogeneration station can be transformed into a tri-generation station if appropriate cooling demand is available. The method is developed in the present Doctoral Thesis, showing how to calculate and rate cogeneration plant's transformation into a tri-generation station. A case study was made for the existing wood industry that uses a local cogeneration plant. Actual data from the studied case were modelled for calculations.
6. The use of absorption coolers allows the cogeneration plant to become a tri-generation plant that produces a larger amount of electricity in summers because of the increased thermal energy load. Cooling energy generation from the remaining heat leads to savings from the decrease in primary fuel consumption. The payback period for investments in absorption coolers technology is less than six years.
7. The main goal of the research was to develop a structure with which it would be possible to analyse the pellet production development perspectives in Latvia. A system dynamics model was developed to reach this goal. The research suggests that by additionally investing in pellet production, specific profit indicators per one produced unit are increased, when compared to the firewood or woodchip production. This results in a slow use of free firewood and industrial woodchip resources for pellet production, thus decreasing the consumption of firewood and woodchips as end products.
8. The amount of pellet production will not be able to increase as rapidly because of the limited amounts of available raw materials. The government regulates the annual wood logging amount based on sustainable forestry principles; however, to keep pellet production development rate at the existing level, it is necessary to increase wood logging amounts and import firewood or pellet for pellet production in search for extra resources from useful wood. An increase in woodchip production from forestry residues – sumps, branches, and crests – is predicted; however, this resource can be used only in the production of pellets as a fuel.

Suggestions

1. For future research, it is necessary to study other markets that effect the operation of a pellet production unit and the energy producer in the same way to be able to optimise the production of all the equipment. The greatest effect on profit was made by the storage capacity and load management activities. Future research should be expanded taking into account market behaviour in connection with raw materials and industrial end production.
2. It is necessary to study similar industrial cogeneration plants that are in need of constant cooling, using the developed method, and compare them with the results of this research. It is necessary to make actual case study conversion in order to compare practical results with the theoretical results of this research. Practical conversion tests would be especially essential to compare thermal-energy-based cooling activity savings with traditional cooling.
3. Further studies should focus on high added value products, such as furfural, bioethanol, etc., that could develop in the future, as well as on how they could affect the search for low-quality wood resources.