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Industrial CHP Optimal Management Model in the Energy Market under Incomplete Information

PRIIT UUEMAA

TUT PRESS

TALLINN UNIVERSITY OF TECHNOLOGY
Faculty of Power Engineering
Department of Electrical Power Engineering

This dissertation was accepted for the defense of the degree of Doctor of Philosophy in Power Engineering and Geotechnology on May 5th, 2014.

Supervisors: Professor Heiki Tammoja, Department of Electrical Power Engineering, Tallinn University of Technology

Professor Juhan Valtin, Department of Electrical Power Engineering, Tallinn University of Technology

Opponents: Professor Gatis Bažbauers, PhD
Faculty of Power and Electrical Engineering, Institute of Energy Systems and Environment, Riga Technical University, Latvia

Professor Andres Annuk, PhD
Institute of Technology, Department of Energy Engineering, Estonian University of Life Sciences, Estonia

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

Priit Uuemaa

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LIST OF PUBLICATIONS

The present doctoral thesis is based on following publications, which are referred to in the text using Roman numbers I-VI:

[I] **Uuemaa, P**., Drovtar, I., Kilter, J., Vigants, H., Blumberga, D., Puusepp, A., "Industrial CHP Optimal Management in the Energy Market under Incomplete Information," *Innovative Smart Grid Technologies Conference (ISGT Asia)*, *2014 IEEE, Kuala-Lumpur, Malaysia,* pp.407-411, 20-23 May. 2014.

[II] **Uuemaa, P**., Vigants, H., Blumberga, D., Drovtar, I., "Industrial CHP Excess Heat Efficient Usage for Cooling," *Energetika,* 2014 [in press].

[III] Vigants, H., **Uuemaa, P**., Veidenbergs, I., Blumberga, D., " Cleaner pellet production – an energy consumption study using statistical analysis," *Agronomy Research*, pp.633-644, vol.12(2), 2014.

[IV] **Uuemaa, P**., Drovtar, I., Puusepp, A., Valtin, J., Rosin, A., Kilter, J., "Cost-Effective Optimization of Load Shifting in the Industry by Using Intermediate Storages," *4th IEEE/PES Innovative Smart Grid Technologies Europe (ISGT EUROPE), Copenhagen, Denmark*, pp.1-5, 6-9 Oct. 2013.

[V] Drovtar, I., **Uuemaa, P**., Valtin, J., Rosin, A., Kilter, J., "Using Demand Side Management in Energy-Intensive Industries for Providing Balancing Power – the Estonian Case Study," *IEEE Power and Energy Society General Meeting (PES), Vancouver, Canada*, pp.1-5, 21-25 July 2013.

[VI] **Uuemaa, P**., Puusepp, A., Drovtar, I., Valtin, J., Rosin, A., Kilter, J., "Load Control Implementation in the Energy Intensive Industry," *17th IEEE Mediterranean Electrotechnical Conference (MELECON), Beirut, Lebanon,* pp.213-218, 13-16 April 2014.

INTRODUCTION

The purpose of the thesis is to maximize the profit of the energy intensive industry which operates an on-site energy production unit. Energy production unit in this thesis is considered as the industrial combined heat and power plant (CHP) which supplies the nearby industry with necessary heat and electricity. This thesis proposes the open electricity market based *management model* for the entire facility. The main outline of this thesis is to introduce optimal management techniques driven by the electricity spot market opportunities. As the result of the research the combination of these techniques are formed into one management model. The model focuses on the profit maximization from the perspective of energy, fuel, raw material and end product markets point of view.

Industrial CHP is a type of the power plant which produces the heat and electricity to one single factory or the group of the factories. The distinguishing nature which separates this type of the CHP from any other CHP is the inexistence of the heat market. The heat price is determined by the alternative cost of the heat production. On the other hand the electricity market plays the key role of the industrial CHP economical performance. Considering that the energy intensive industrial production in the same factory is also highly dependent to the electricity market level and behaviour then maximizing the profit over the total production process becomes the desired target for this type of the industries.

In this thesis the possible areas where the electricity market can be used for the profit optimization have been determined and the optimization methods have been developed. The constant change and volatility of the electricity market price makes the research topic interesting and attractive for the energy intensive industry whether as a consumers or as a producers. Traditionally when the electricity price was fixed the electricity market participants have minimized their cost. During the electricity market liberalization the market has opened for much wider range of participants and the prices are formed in the daily auctions. This places the market participants into totally new situation where the electricity market prices are much more volatile and unpredictable than any other goods. Therefore the successful transformation of the electricity producer such as the CHP and the electricity consumer like factory plays the important role in nowadays profit maximization task.

In the open electricity market context the electricity producer is a negative consumer and the electricity consumer is a negative producer. In the facility where the electricity consumption is as high as the electricity production the influence of the electricity consumption management is as important as the electricity production management. Therefore in this study the focus is to find the existing flexibilities in the electricity production process and also in the electricity consumption process in order to turn this for the benefit of the participant. Maximizing the profit over the total produced electricity in CHP and consumed electricity in the factory is the target function of this research.

In the open electricity market conditions the factory electricity consumption becomes the integral part of the industrial CHP electricity trading. It is considered as the negative production. Therefore the industrial CHP optimal management is inseparable from the electricity consumption optimization in the same facility. As this research has revealed the optimization potential in the electricity consumption side can be far more effective than on the electricity production side. The natural existing consumption flexibility in the factory can be deployed for the consumption management and hence maximizing the profit of the entire facility electricity trading. The management model which is developed in this study can be deployed for the industrial CHP profit maximization taking into account the factory electricity consumption. The management model is the model to manage the entire facility on the open electricity market with the purpose to maximise the market participant profit.

Development of the study

Electricity spot market behaviour plays a key role in nowadays energy intensive industry. As of today in Nordic and Baltic countries 84% of the electricity is traded through Nord Pool Spot (NPS) market [1]. Therefore the power plant and energy intensive industry's economic performance is affected by the ability of the facility to adjust its technical performance according to the conditions on the spot market. Exploiting the flexibility of the CHP and the factory in the energy intensive industry significantly increases its profit.

The electricity market liberalization started in the early 1990-s and as of today all Nordic and Baltic countries have liberalized their electricity markets allowing the producers and consumers to compete on the open market. At the same time it has brought more challenges for the large-scale and industrial electricity consumers who have to adapt with new situation where prices variations are rapid and unexpected. The spot market price reflects the status of the electricity system's physical state, whereas the high market prices emerge in the condition of shortage of the generation and vice versa [2].

Producers and consumers which are able to adapt in these conditions can have the opportunity to turn the system state into their benefit and hence increase their profit. It can increase the electricity sales income by optimizing the electricity production and decrease the electricity costs through adapting the consumption according to the prices. On the other hand the changes in the electricity consumption can affect the industrial production; therefore this has to be taken into account. Since the electricity prices differ throughout the year the increase of the electricity production or decrease in the electricity consumption volume is not necessary to improve the economic performance of the facility. The electricity income can be increased by adjusting the timing of consumption and production even if the overall volume remains the same.

This is a new approach for the energy intensive industry to turn its flexibility for its benefit and hence maximize the profit. The key aspect in this approach is the existence of the on-site energy production unit which allows the industry to be highly competitive with its energy cost. It also allows the industry to be more competitive in the market compared to the other producers who do not optimize their production. This establishes a new mindset where the advantage on the market is given to the participant who can adjust its needs according to the market conditions.

The industry that also produces electricity can benefit from the electricity production and consumption at the same time by utilizing the optimization techniques in both areas introduced in this thesis. The purpose of this thesis is to optimize the entire industrial facility from the economic perspective and hence maximize the profit. The profit maximization is chosen for the objective of the research because this gives the real input for the industry and is likely to being commercially exploited in large scale. In this study the industry's operational profit is maximised over the desired timeframe which is one year and the time interval is one hour.

This research has developed and tested several different techniques that could increase the industry's profit. In this thesis these techniques are combined together to form a complete package of the profit maximization model for the industrial CHP and for the industrial factory. The developed technique includes several adjustments, services, investments, and etc. which combined together strengthen the industry's competitiveness and gives additional advantage amongst other competitors. The strength of this research is that it combines different previous researches and adjust those techniques to a country specific industrial facility throughout the Baltic countries and especially in Estonia. The developed combinations of these techniques presented in this thesis, are unique and have not been studied intensively before.

Importance of the study

This research topic is chosen in order to push the Baltic countries energy intensive industries to develop the on-site power production units and exploit their technological flexibilities in order to benefit from the economical results and therefore be more competitive with their products in the global market. The industries that operate the local CHP plant can reduce the power production in the times of surplus of power in the system and reduce the electricity consumption in factory in the shortage of power. This helps to smooth the electricity generation and demand profiles in the electricity system and in return lower the cost of the electricity system [3].

A relatively big wood processing industry which operates the on-site industrial CHP plant was taken under observation. The research practical data was collected from it and the results were modelled for this specific company. However, the development of the optimization was always done in a way which allows other type of industries to adapt these techniques with same success. The developed management techniques in this research can be deployed in any power production and energy intensive factory in the world as long as there is a free market for the goods and products used and produced in the facility. In this thesis the electricity is considered as a goods when consumed and product when produced because its trading nature is the same like with any other article which is consumed or produced in the industry. Most importance is the existence of the open electricity market without any access barriers. Finally, the bigger are the capacities of a single machine or aggregated loads and generations, the bigger is the effect that could be gained from this kind of management optimization model.

Subject of the research

The research was carried out during the period of 2010-2014 in a case study facility where the necessary input data was collected. The collected data was then used for the optimization and the results were modelled in different optimization programs. The long period of time for the data collection enabled the valuable information for more comprehensive optimization and conclusions.

The methods that were used in this research were developed from previous researches in the field of CHP electricity trading optimization [4]. The main concept was to keep different products and markets separated and make decisions based on the economic perspective. All decisions and actions which were made were put in the context of maximizing the profit.

The practical information and the constraints of the optimization came from the case studies. The case studies were carried out by the simulations which input was actual factory and power generation process data. The observations and data collection was carried out over several production lines and during several years. Since most of the data was electronically available the data collection was not complicated and allowed to process vast amount of data to get more accurate results.

Theoretical and practical originality of the work

The thesis originality is based on the investigation of the profit maximization by the means of exploiting the electricity market possibilities. The key aspect which distinguishes this research from any previous is the profit maximization throughout the entire facility taking also into account the fuel, raw material and industrial end product markets.

Originality of this research is that the entire industrial facility is managed and optimized together including the on-site CHP unit and utilizing the liberalized electricity market set-up.

The key factors that distinguish this research from any other previous researches are:

- The research has developed an optimization technique for the entire industrial facility in a one single geographical location taking into account the knowledge from previous research and combined it with the possibilities of the spot electricity market
- The optimization results can be used in any power production unit and energy intensive industry in the electricity spot market area for estimation of the possible effect on the profit.

- The industrial CHP and factory profit is maximized by exploiting the state of electricity market.
- Complete facility is analysed making sure the optimization does not cause any extra cost that could diminish the achieved benefits.
- Economic based approach. The traditional approach has been to minimize the fuel consumption, carbon emissions (CO_2) etc. [5]. This thesis is targeting to optimize the profit.
- Smart grid application solutions are used in the industry for the optimization practical exploitation. Initiative comes from the industry side.
- The entire model development is targeted for increasing the profit showing that the biggest effect comes from optimizing the consumption and not from the CHP optimization which already is working on full load.

The electricity market itself is an uncertain component in the study because the price in the electricity spot market is not known more than one day ahead. The incompleteness comes by the uncertainty about the price peaks and valleys. Furthermore there is not known even if the price has fluctuations at all and if these fluctuations form a predictable pattern. Another uncertainty depends on the regulation of the electricity system, and if there is a need for regulation services. As authors of [6] have shown the economically optimal operation does not necessarily match with the environmentally optimal operation like it traditionally has been so far.

The management model is dependent on the incomplete information because the market participant, especially the consumer can make investments into demand side management and demand response activities if there are regular fluctuations in the electricity spot prices and demand for the corrective services. This kind of uncertainty plays key role in the further development of the management model.

Presentation of the research results

Components of this study were presented and published in several scientific conferences and journal articles. This thesis has emerged as a combination of these articles where the research topic is outlined as a complete scientific research with conclusions.

During the presentations of the conference papers the guests have showed increased interest about the topic. Several researchers over the world were interested about the optimization principles and results. The papers have been attractive due to the reason that the modelling is done on the actual existing facility where the practical problems have been taken under study. Only the results of paper [II] are modelled by using the virtual auxiliary equipment.

The research results practical implementation in the industry has given preliminary good positive results which are in accordance with the theoretical modelling. Results of the research has strengthened the investigated company competitiveness on the market as well as increased its profit.

Paper [I] introduces the market based approach for the industrial CHP facility optimization task. In the study the entire industrial complex is studied in order to verify that the optimization in one place does not cause any extra cost in another place. Therefore it is an important constraint for the optimization. Paper [II] carries out the case study for adding the cooling production to the products of the CHP and paper [III] introduces the statistical research in the facility to determine the influence factors for the production efficiency and hence lowering the environmental impact of the facility. Paper [IV] analyses the possibilities to execute the optimization at once as soon as it indicates increased profit values compared to the non optimized reference scenario. Paper [V] studies the load response service provision by the large scale industrial factory. Paper [VI] summarizes the need of hardware and software installation in order to put the optimization process in action.

LIST OF SYMBOLS

K	entire facility profit	€
t	time interval of one hour	h
I	facility income	€
C	facility cost	€
I_E	electricity production income	€
I_I	industrial production income	€
I_R	residues production income	€
I_H	heat production income	€
C_E	electricity consumption cost	€
C_{OC}	CHP electricity own-consumption cost	€
C_F	fuel consumption cost	€
C_{RM}	raw material consumption cost	€
C_R	residues consumption cost	€
C_H	heat consumption cost	€
N	income or cost of an article	€
V	article volume	
P	price of that article	
V_{EP}	CHP electricity production	MWh_e
V_I	factory industrial end-product production	t
V_{RP}	factory residues production	t
V_{HP}	CHP heat production	MWh_{th}
V_{EC}	factory electricity consumption	MWh_e
V_{EOC}	CHP electricity own-consumption	MWh_e
V_F	CHP fuel consumption	MWh_f
V_R	factory raw material consumption	t
V_{RC}	CHP residues consumption	t
V_{HC}	factory heat consumption	MWh_{th}
P_E	electricity price	€/MWh_e
P_I	industrial product price	€/t
P_R	price of the residues	€/t
P_H	heat price	€/MWh_{th}
P_F	CHP fuel price	€/MWh_f
P_{RM}	factory raw material price	€/t

V'_{EN}	net exported electricity from the facility	MWh_e
V'_{EP}	CHP electricity production, including maintenance	MWh_e
V'_{EC}	factory electricity consumption, including maintenance	MWh_e
M	binary variable for the maintenance	
V^R_{EP}	CHP electricity production in ideal reference scenario without maintenances	MWh_e
D	maximum interval between two adjacent maintenances	
V^R_{EC}	factory reference electricity consumption	MWh_e
I^R_{exp}	electricity total income in the grid connection point on the reference scenario "operation as usual"	€
I^O_{exp}	optimized exported electricity total income	€
C_{EXT}	external cost of the load shifting e.g. start-up costs, labour costs, and etc	€
V^O_{EC}	optimized factory electricity consumption volume	MWh_e
$V^{R'}_{EC}$	factory electricity consumption volume on the reference scenario "operation as usual"	MWh_e
η_n	nominal total efficiency of the plant	
η_e	electrical efficiency of the plant	
η_h	heat efficiency of the plant	
V_{CC}	heat that is used for cooling	MWh_{th}
S_R	possible subsidy which is paid as a feed-in premium	€/MWh_e
P_{CC}	price of the heat which is supplied for the factory cooling	€/MWh_{th}
V_{AC}	cooling consumption of air conditioners	MWh_c
V_{PC}	cooling consumption of process cooling	MWh_c
η_{ABS}	efficiency of the absorption chillier	
V_{EP}^{extra}	additional electricity produced due to the increased heat load	Mwhe
V_{CD}	condensed heat load	MWh_{th}
P_{CD}	condensed heat load price	€/MWh_{th}
V_F^{extra}	required additional fuel	MWh_f
S_{AC}	operational cost savings with the absorption chillier compared to facility reference case electricity based air conditioning (AC)	€

S_{PC}	operational cost savings with the absorption chillier compared to facility reference case electricity based process cooling (PC)	€
V^{AC}_{EC}	reference case AC's electricity consumption	MWh_e
V^{ABS}_{EC}	absorption chiller based system electricity consumption	MWh_e
V^{PC}_{EC}	reference case process cooling electricity consumption	MWh_e
P_T	other saved electricity price component	€/MWh_e
V^{RE}_{EP}	additional electricity that can be produced on the condensation mode without losing the subsidy	MWh_e
η_R	minimum required total efficiency for receiving the subsidy	
E	expected value of the operator	
B^{CH}	output power of the chipper	MW_e
Q	required chipping volume	t
$Pr(s)$	probability of the scenario s	
W_t	actual storage volume in the given hour	t
W^{max}	maximum usable storage	t
W^{min}	minimum acceptable storage volume for the industry due to the production process' security of supply	t
F	volume of the pre-processed raw material which is purchased additionally	t
B_{ACL}	describes the service provider aggregated changeable load	MW_e
B_{TS}	TSO's minimum required regulation step	MW_e
Δt_r	service provider time for achieving the requested load change	min
Δt_{TR}	describes the TSO's maximum timeframe for achieving the requested up regulation	min
Δt_{SAL}	service provider's capability to change the load	h
Δt_{TS}	TSO's minimum regulation duration	h
P^C_{DR}	electricity consumer price of the DR service	€/MWh_e
I_{IP}	value of the lost industrial production income	€
C_V	cost of variable goods saved	€
Δt	duration of the ordered DR service from the TSO	h
P^G_{DR}	electricity producer price of the DR service	€/MWh_e

1. MATERIAL AND METHODS

1.1 Previous research in field of industrial CHP and factory optimization

As the electricity market develops the distributed energy production is coming more and more attractive due to improved feasibility [7-8]. The establishment of a local energy production has mainly two reasons, firstly economic and secondly security of supply. In some cases the combination of both.

Start of the thesis research was to have an overview of the different CHP optimization principles throughout the world. As the papers [9-13] reveal the main criterion for the CHP operational and design optimization has traditionally been related to the thermo dynamical optimization. In addition in these studies the information has been more or less determined and prices fixed and known several months ahead.

In other studies [14-18] the optimization method has been created especially for power units that participate on the electricity spot market. In these conditions the participant does not know the coming prices and therefore has to make its decision based on the historical data and future assumptions. The studies have revealed a significant cost effect for the participant who has been able to adapt with the spot market and react according to the prices. However there is no study where the power consumption would be observed in the same facility at the same time. Therefore the contribution of this thesis is to introduce the optimization technique which optimizes the production and consumption in a combination finding additional synergy.

Authors of [19-24] have specially optimized the industrial power production in the spot market conditions. However they optimize more in precisely the offers strategy by the producer but do not consider the electricity price as a known variable for one day ahead, like it is done by the market participants in the Nord Pool Spot area.

Authors of [25-29] have studied intensively the demand side management opportunities in order to optimize the energy cost. However their main focus has been on the peak shifting or emissions decrease rather than cost minimization. As in many countries the peak load of the consumer is heavily penalized due the congestions in the distribution grid then the peak load prediction and management becomes a key aspect of the cost reduction. This however is not the case in the Nord Pool Spot area.

The hardware technology for the demand response is similar which is used in the demand response however the nature of the demand response is much more demanding. Authors of [30-33] have proved that industry as a consumer can be effectively deployed for the demand respond actions. They have shown the additional income and benefit for the service provider.

Authors of [34-35] propose the specific optimization algorithm, such as multi-objective approach and MINLP in order to optimize the technical performance of the CHP plant. The approach however does not take into account the changing electricity market price.

Authors of [36-38] are proposing the optimal dispatch of the different generators in the market. The method however does not take into account the possible effect of the consumer dispatch on the same market place.

Intelligent smart grid type solutions have been developed by authors of [39-43]. Authors have developed and introduced a real hard- and software applications to commercially utilize the developed optimizations. These case studies show that there are numerous options to put the loads to operate on the optimized schedule. However in most of the researches the developed systems have been too much case specific and cannot be applied on a general level.

Similarly focused research to this thesis have been introduced by authors of Authors of [44-45] have created principles to develop a large scale optimized smart system which function for the benefit of the participant in the electricity market.

In a decision making process several strategies have to be considered which have been implemented by authors in [46-48]. These papers are rather focusing on the strategically decisions than on the daily base optimization and profit maximization.

Authors of [49-50] have brought out the uncertainty variables which make the optimization task a stochastic process. It is studied the fuel consumption in the uncertainty and the profit is maximized according to the uncertain information.

The novelty of this thesis is the new approach to the facility system based optimization by using the combination of the optimization measures developed before. It previous studies the combination of the optimization measures formed in a single management model has not yet emerged. Many studies address the optimal performance of an individual industrial CHP component, but do not resolve the facility-level dispatch problem of operating multiple components at the same time. Other research seeks the optimal system design, but does not consider the optimal dispatch of an existing system. This thesis focuses on the optimal dispatch of an industrial CHP which includes the industrial end-product production factory in the facility.

In general, studies that apply simulation cannot guarantee the global optimality of their solutions. The existing applications provide the guarantee of global optimality, but fail to consider many of the detailed performance characteristics of the technologies that are required to realistically model the system operation. Current thesis contributes to the literature by providing techniques for determining the provably globally maximum profit of an industrial CHP facility dispatch without sacrificing the realistic operation of the technologies.

The following literature overview shows that the specific components of current thesis have been studied before in very complex and high level manner. Therefore all these studies contribute to the overall management model which is the goal of this thesis. As the literature shows there is an active research ongoing in the aspects of the industrial CHP and factory load management actions. Until this date no specific study has been introduced which combines all these methods in one single management model. As a result of the previous researches this thesis has emerged.

1.2 Market driven approach for industrial CHP together with the factory

The research for the specific industrial CHP has been done according to the information from actual wood processing industry which operates in Estonia and Latvia. Other information about the market prices and market behaviour has been collected from open sources. Electricity prices are mainly accessed from NPS web page for price areas Estonia, Latvia, Lithuania and Finland [51].

Wood chips, as a primary fuel for the CHP prices are taken from the Estonian State Forest price statistics [52] and Estonian Statistical Database [53]. As for some articles there is only bilateral market then the prices were estimated or a small inquiry was carried out. The actual goods and products prices from the case study factory are not used.

The electricity market brings new opportunities for the large scale market participants whether consumers or producers. Even more advanced techniques can be used by the large scale consumer that operates an on-site electricity production unit. In that case the absolute power capacities can be added on top of each other for operating on the open electricity market. These capacities can be used for load management measures in the benefit of the participant.

This thesis observes the entire facility in one geographical location. The principle of the study is based on the market driven approach where everything is compared against the market conditions. The major cost and income articles have been separated. Until recently the electricity market was not liberalized. In Estonia it was opened for the consumers in first stage in year 2010 and in the remaining market share in 2013. Until that time the electricity market was opened only for the electricity producers. The electricity consumer price could only be lowered by the physical reduction of losses or consumption.

Case study factory share of the electricity cost in the end product price is around 5-10% therefore making it interesting study object. At the same time the industrial CHP in the same facility supplies 50 % of its electricity production to the factory. However the physical flows of the energy do not have to match with the financial electricity trading flows and thus the CHP cannot make any other price to the factory than the market price, as explained in paper [I].

Paper [I] describes the most conceptual approach of this study that aims to observe the markets of the CHP and factory to carry out actions according to the market states. In order to have a clear overview about the factors which influence the performance of the CHP and energy intensive industry, the major cost and income articles of the facility have to be separated and given the market prices like shown in Figure 1.

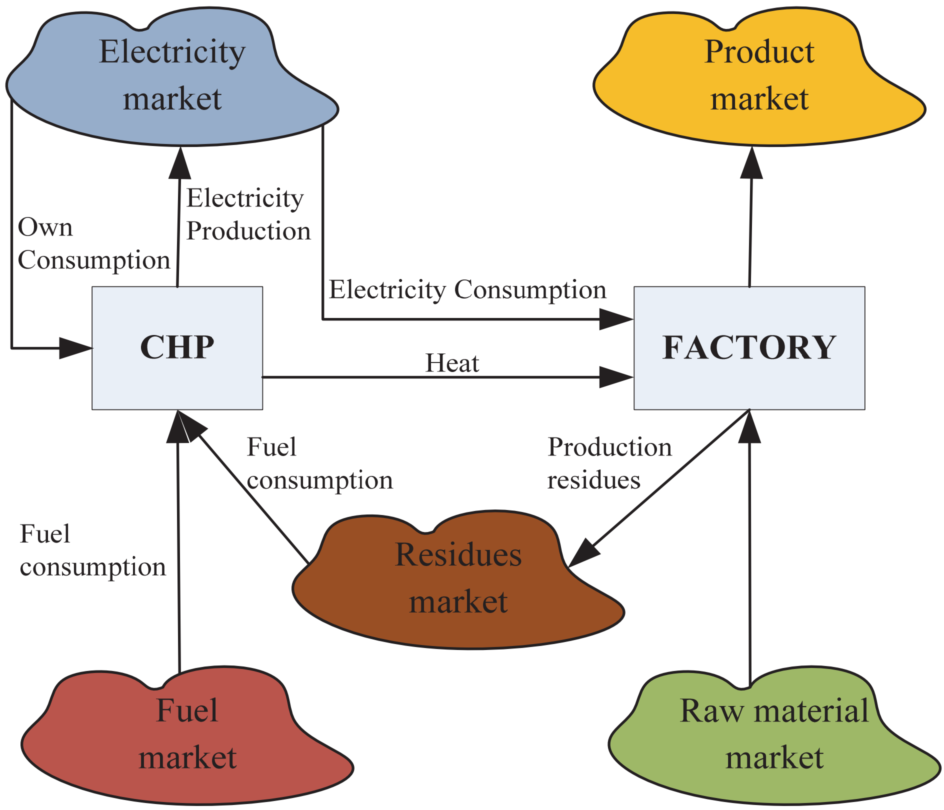

Figure 1. Industrial facility economical relations with the materials and products

As it can be seen from the Figure 1 the CHP and the factory are both participants of the electricity market. The CHP is an electricity producer as well as an electricity consumer and the factory is an electricity consumer. Remaining articles have been separated by the nature of their usage. Often the side products of the factory or the residues from the factory production can be the fuel for the CHP plant. These residues price can either be positive or negative depending if the residues can be sold on the market or it requires cost to deposit them.

In the current thesis the goods and materials are divided into five different markets. It is important to separate different articles from each other in order to clearly see the influence factors of the electricity and other goods to the economic performance of the facility. The dividing principle of the markets depends on the type of the industry and has to be considered case by case.

In general there are 5 types of markets in any industrial CHP facility regardless of the area of the industrial factory production and its characteristics like proven also by authors of [54]. These 5 markets are:

- factory raw material,
- factory end product,
- electricity,
- residues,

- fuel.

In case the CHP can sell the heat to the district heating network then there is also a heat market. However since in this study the CHP is solely an industrial CHP then the heat market is not observed. Depending of the nature of the industry these markets can have a different impact factor for the facility’s economic performance. The main goal of the research is to maximize the facility total profit *K* over the desired time interval *n* according to (1.1):

$$\max \sum_{t=1}^{n} K_t \,, \tag{1.1}$$

where
K is the entire facility profit in €
t is the time interval of one hour (h).

The target of the mathematical formulation is to find the load point of the entire facility in each hour *t* which gives the highest possible short-term marginal profit. Profit is always the sum of cost and income; therefore (1.1) can be expressed by (1.2):

$$\max \sum_{t=1}^{n} K_t = \max(\sum_{t=1}^{n} I_t - \sum_{t=1}^{n} C_t) \,, \tag{1.2}$$

where
I is the facility income in €
C is the facility cost in €.

As it can be seen from Figure 1 the income comes from the excess electricity sold on the market, sales of the factory end-product and sales of any side products. The cost articles are fuel for the CHP and raw material for the factory. In the case the heat market would be included then also the excess heat could be sold. Any materials and goods which are consumed in the facility have to take into account the market price as an alternative cost or income. This alternative cost and income forms the base of the optimization task in order to maximize the facility profit.

Regardless of the materials and goods physical flow the each cost and income articles pricing has to be taken into account in separately, therefore the income and costs in equation (1.2) can be explained by the equation (1.3) and (1.4):

$$\sum_{t=1}^{n} I_t = \sum_{t=1}^{n} (I_{E,t} + I_{I,t} + I_{R,t} + I_{H,t}) \,, \tag{1.3}$$

$$\sum_{t=1}^{n} C_t = \sum_{t=1}^{n} (C_{E,t} + C_{OC,t} + C_{F,t} + C_{RM,t} + C_{R,t} + C_{H,t}) \,, \tag{1.4}$$

where
I_E is the electricity production income in €
I_I is the industrial production income in €
I_R is the residues production income in €
I_H is the heat production income in €
C_E is the electricity consumption cost in €
C_{OC} is the CHP electricity own-consumption cost in €
C_F is the fuel consumption cost in €

C_{RM} is the raw material consumption cost in €
C_R is the residues consumption cost in €
C_H is the heat consumption cost in €.

The income and cost for each article is always a multiplication of volume and unit price, equation (1.5):

$$N_t = V_t \cdot P_t \, , \tag{1.5}$$

where
N is the income or cost of an article in €
V is the article volume
P is the price of that article.

In general equation (1.5) refers to the principle that income or cost always depends on the volume and the market price of that same article. This means that the market participant can influence the articles cost and income by the consumed or produced volumes and the timing of the consumption or production. The higher is the volume the bigger is the income or cost. Therefore industry can increase physically the production and decrease the consumption making the production process more efficient. The efficiency can only be increased by means of investments. *In this thesis it is studied how to optimize the production process without any significant investments and instead exploit the existing means for higher profit.*

The target function for the industrial facility which operates the CHP and a factory can be written as follows in (1.6):

$$\begin{aligned} \max \sum_{t=1}^{n} K_t = \max(&\sum_{t=1}^{n} (V_{EP,t} \cdot P_{E,t} + V_{I,t} \cdot P_{I,t} + V_{RP,t} \cdot P_{R,t} + V_{HP,t} \cdot P_{H,t}) - \\ &- \sum_{t=1}^{n} (V_{EC,t} \cdot P_{E,t} + V_{EOC,t} \cdot P_{E,t} + V_{F,t} \cdot P_{F,t} + V_{RM,t} \cdot P_{RM,t} + V_{RC,t} \cdot P_{R,t} + V_{HC,t} \cdot P_{H,t})) \end{aligned} \, , \tag{1.6}$$

where
V_{EP} is the CHP electricity production in MWh_e
V_I is the factory industrial end-product production in tons (t)
V_{RP} is the factory residues production in tons (t)
V_{HP} is the CHP heat production in MWh_{th}
V_{EC} is the factory electricity consumption in MWh_e
V_{EOC} is the CHP electricity own-consumption in MWh_e
V_F is the CHP fuel consumption in MWh_f
V_R is the factory raw material consumption in tons (t)
V_{RC} is the CHP residues consumption in tons (t)
V_{HC} is the factory heat consumption in MWh_{th}.
P_E is the electricity price in €/MWh_e
P_I is the industrial product price in €/t
P_R is the price of the residues in €/t
P_H is the heat price in €/MWh_{th}
P_F is the CHP fuel price in €/MWh_f
P_{RM} is the factory raw material price in €/t

In this thesis it is simplified and considered that the participant can never influence the market price due to the reason that the market is big and liquid enough. This is the key characteristic of a well-functioning electricity market as of any other open market. Therefore in this research market price P_t is considered as an independent stochastic value. This means that the market is big enough when one single participant cannot have an influence to the market price solely on his own will. However the participant may always use the favourable market conditions to purchase or sell goods with desired prices without its decisions having an influence on the same price. In this study the key role of the optimization is the electricity market where price changes are significant and hourly planning and execution of the production can have a positive economic effect.

Since the CHP electrical efficiency is usually 30% compared to the heat efficiency which is around 60% then that majority of the energy production is in the form of heat. In that aspect the heat price plays a key role in the economic performance of any CHP. However in the industry there is hardly ever any market for the heat. The only case is if the industrial CHP has an access to the district heating network and can sell all or some of its heat into the district heating network. However in most of the cases the industrial facility is always away from the district heating areas.

Therefore the heat market price can only be compared against the cost for alternative heat solutions. This cost is the justified price for the heat. The same applies for any other goods which is produced or consumed in the facility and has no market. If there is no clear and liquid market for some articles then the item price has to be determined by the alternative cost. This way it is guaranteed that the facility does not have any internal subsidization and the optimization base information is correct. However with the majority of the materials and goods it is clear how to determine the justified price. For most of the goods and materials there is a spot market or bilateral market which is a public trading place and where the prices can be found.

When observing the other markets of the case study facility it became obvious that the electricity market is like no other. In the electricity market there is a price pattern which is predictable and has significant difference within one single day whereas on the rest of the markets the price patterns are not seasonal and cannot be predicted either. *Therefore this thesis focuses on the management model on the perspective of the electricity market.*

1.3 Introduction of the electricity spot market behaviour

Electricity spot market is one of the most liquid and volatile market in the world. The price of the electricity is determined for each full hour throughout the year. Electricity market is more close to the financial commodities market rather than on the goods market. The night and peak hour price can be over 1.5 times different in the average. As illustrated on Figure 2 the electricity spot market weekday (WD) price has a somewhat predictable pattern whereas the price is higher during peak hours and lower during night hours.

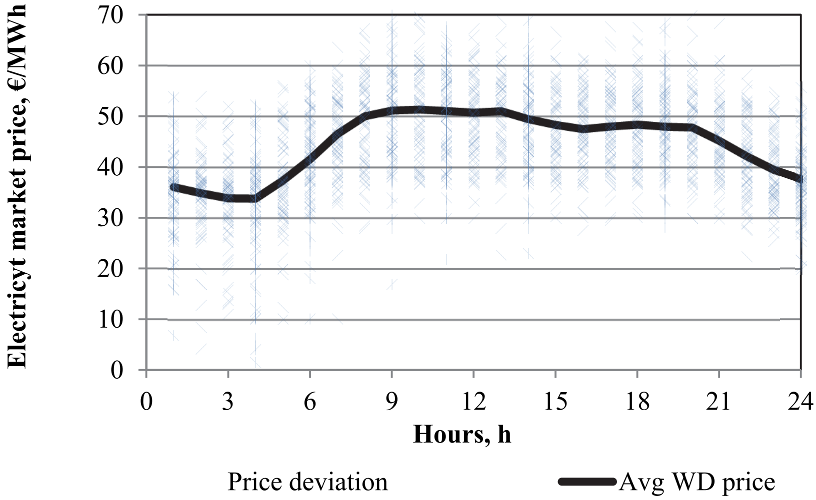

Figure 2. Typical Nord Pool Spot electricity market price pattern

Taken over a long period of time this pattern does not vanish and can be observed more over the weekdays rather than weekends. This creates good ground for the utilization of this difference for the benefit of the market participant. The CHP can utilize this difference by doing the daily maintenance on the night hours and the factory can carry out the daily maintenance on the peak hours.

For other goods in the industrial facility like fuel, raw material, residues and end product the price is normally given or determined on monthly basis whereas the electricity has 720-744 different prices within one single month. This makes the electricity market a whole new variable for the industry.

On the Table 1. can be seen the difference of the minimum and maximum prices of the market items which have a direct influence to the CHP.

Table 1. Case study facility monthly exported electricity optimization results

2013	€/MWh	
	min	max
Electricity (hourly)	5,1	210,0
Electricity (monthly)	36,8	53,4
CHP Fuel (monthly)	10,3	13,8

Even though the electricity monthly arithmetical average prices are relatively stable their monthly variation is still exceeding the other components monthly price variations. Figure 3 illustrates the typical fuel price pattern compared to the electricity monthly price in Estonia, 2013. As it can be seen then there is significantly higher amplitude in the electricity price than in the fuel price.

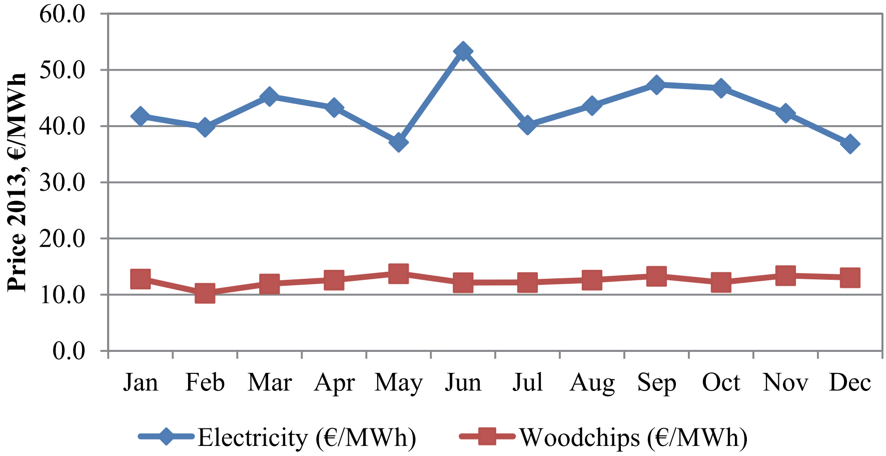

Figure 3. Typical fuel and electricity annual price levels and monthly variations

In the figure above the fuel price fluctuation over one calendar year are not as high as the fluctuation on the electricity monthly prices. As it can be seen the electricity price in one month can be below 40 €/MWh$_e$ and on the next month over 50 €/MWh$_e$. The market price of the electricity P_E is always a stochastic variable and cannot be predicted. The example electricity price P_E histogram is shown on Figure 4. The histogram is an actual year 2013 Estonia area annual prices.

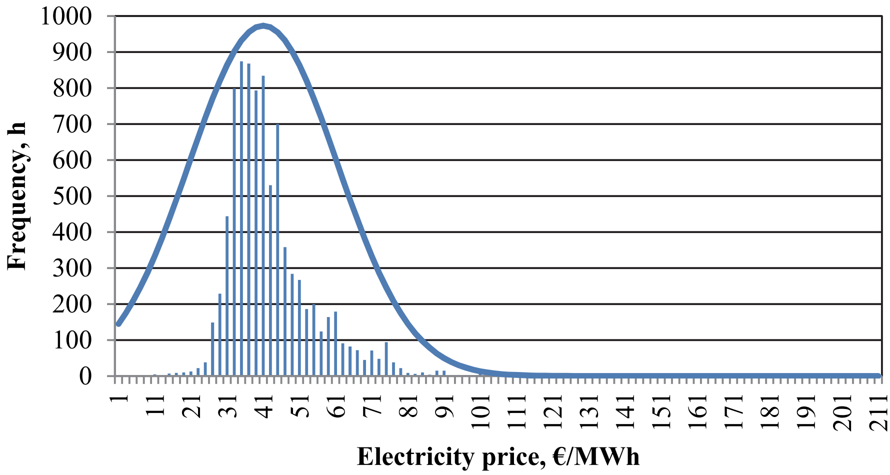

Figure 4. Electricity price P_E histogram for the Estonia in 2013

As the figure above demonstrates the electricity market price range varies mostly between 30-70 €/MWh$_e$. Sometimes lower and in extreme cases even much higher. The histogram shows clearly close match with normal distribution however it is rather a "normal distribution with a tale".

2. CHP ELECTRICITY INCOME MAXIMIZATION

2.1 Electricity export optimization

Industrial CHP and the factory have in most of the cases one single physical connection to the market place, through the grid operator's connection point. For the case study industry this is a system operator connection point. The concept for the exported electricity optimization is to separate the facility load components from the grid connection load profile as it was done in the paper [I]. In Figure 5 is shown one month load profiles for the facility where the CHP electricity generation is separated from the factory electricity consumption and from the CHP plant own consumption.

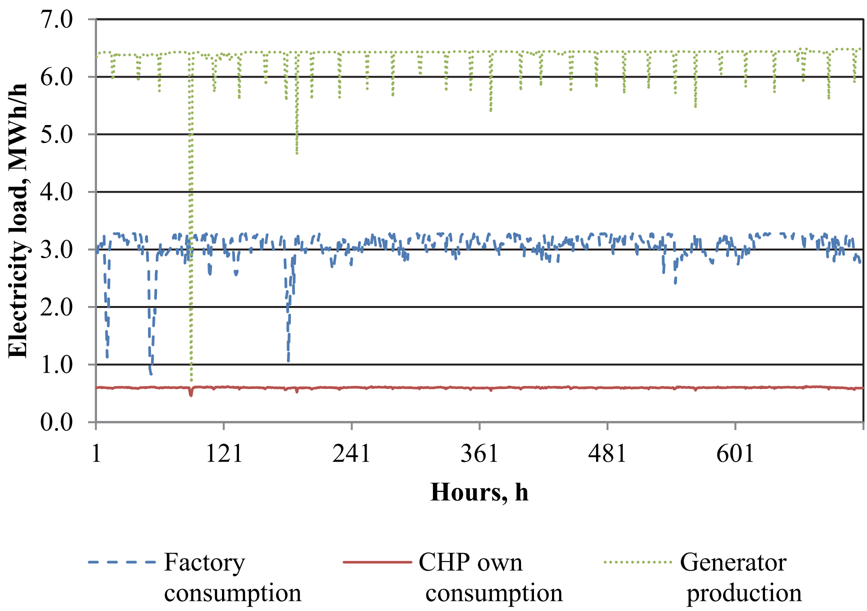

Figure 5. Separated load profile according to the different sources

As it can be seen from the figure above the nature of these components are different. The CHP electricity production is fairly stable and only a daily boiler surface cleaning which is called as a soot blowing requires the electricity production regular decrease. On the other hand the factory electricity consumption fluctuates in 10% range. Thirdly, there is a CHP own consumption which is a flat load and cannot be regulated or managed.

On Figure 5 can be observed that the optimization has to be carried out over the load profile of each component separately. For example it is clear that a CHP own consumption has to remain stable and untouched in order to maintain the energy production availability. On the other hand it can be clearly seen that the production of the electricity has a certain pattern which can be adjusted according to the market price and the benefit can be calculated. The figure also illustrates that the variation of the consumption load is not significant, but if that profile would be divided between different factory production line sub-cycles then flexible loads could be determined.

The goal of optimization in paper [I] was to maximize the profit of the electricity which is exported through the grid connection point over the total period of one month, (2.1) and (2.2).

$$\max_{V'_{EC,t}, M_t} \sum_{t=1}^{n} P_{E,t} \cdot V'_{EN,t}, \quad (2.1)$$

$$V'_{EN} = V'_{EP} - V'_{EC} - V_{EOC}, \quad (2.2)$$

where

V'_{EN} is the net exported electricity from the facility in MWh_e

V'_{EP} is the CHP electricity production, including maintenance in MWh_e

V'_{EC} is the factory electricity consumption, including maintenance in MWh_e

M is the binary variable for the maintenance.

The calculated optimum gives the load profile for the electricity production and consumption including the maintenances. In the case study facility the soot blowing which reduces the CHP electricity production can be defined as a scheduled mandatory maintenance. This maintenance can be formulated through a binary variable M_t (2.3), (2.4) and (2.5).

$$V'_{EP,t} = (1 - M_t) \cdot V^R_{EP,t}, \quad (2.3)$$

$$M_t \in \{0,1\}, \quad (2.4)$$

$$M_t = 1 \Rightarrow \text{Maitenance}$$

$$M_t = 0 \Rightarrow \text{Production}$$

$$\forall t' \sum_{t'}^{t'+D+2} M_t \geq 2 \ , \quad (2.5)$$

where

V^R_{EP} is the CHP electricity production in ideal reference scenario without maintenances in MWh_e

D is a maximum interval between two adjacent maintenances.

In the practical modelling the average time interval between the two maintenances was taken 24 hours which is also the case of the actual reference CHP operation.

For the second component in the load profile which is the factory electricity consumption the same type of optimization was modelled. As the consumption load profile shows in average the fluctuation of the consumption load remains within 10%. Mainly this fluctuation is caused by the factory regular daily maintenances. It can be expected that theoretically all of that 10% can be used to shift the load according to the electricity prices. More in detail a specific factory sub-cycle cost optimization is introduced in chapter 3.1 of this thesis.

Factory electricity consumption load can be shifted between the minimum and maximum output of the aggregated factory load. Whereas L is the relative amount of load shifting, (2.6), (2.7) and (2.8):

$$0 \le L \le 1, \quad (2.6)$$

$$\forall t \;\; V'_{EC,t} \le (1+L) \cdot V^{R}_{EC,t}, \quad (2.7)$$

$$\forall t \;\; V'_{EC,t} \ge (1-L) \cdot V^{R}_{EC,t}, \quad (2.8)$$

where

V^{R}_{EC} is the factory reference electricity consumption in MWh_e.

In this case study modelling the *L* has been given 10 different values from 0.01 until 0.1 with the step 0.01. This means that the optimization results have been modelled for the 10 different cases whereas in the worst case only 1% of the factory load can be shifted and in best scenario 10% of the factory load can be shifted.

Constraint of the electricity export optimization is that the optimized and shifted load profile can be accepted and put in operation if the profit increase exceeds the load shifting external costs C_{EXT} according to (2.9):

$$I^{O}_{\exp} - I^{R}_{\exp} > C_{EXT}, \quad (2.9)$$

where

I^{R}_{exp} is the electricity total income in the grid connection point on the reference scenario “operation as usual” in €

I^{O}_{exp} is the optimized exported electricity total income in €

C_{EXT} is the external cost of the load shifting e.g. start-up costs, labour costs, and etc.

Final constraint is that the electricity export volumes over the optimized period of one month need to remain the same, (2.10).

$$\sum_{t} V^{O}_{EC,t} = \sum_{t} V^{R'}_{EC,t}, \quad (2.10)$$

where

V^{O}_{EC} is the optimized factory electricity consumption volume in MWh_e

$V^{R'}_{EC}$ is the factory electricity consumption volume on the reference scenario “operation as usual” in MWh_e.

This kind of constraint equation means that the industrial end-product production also remains the same. Usually there is a linear correlation between the industrial production and the electricity consumption. Therefore if the absolute volume of the consumed electricity over the time period remains the same then also the industrial production volume does not decrease.

2.2 Electricity production maximization by increasing the heat load

Paper [II] brings out the interesting aspect of the profit maximization. The electricity production of the industrial CHP can be increased by condensing the excess heat in the periods of lower heat demand from the factory. However this can only be done if the electricity price and income are big enough to compensate the dramatic total efficiency decrease.

Profit is maximized using the dry coolers and absorption chillier. In article [55] the principal approach is effectively demonstrated how the absorption chillier can be optimally dispatched together with the CHP in order to optimize the profit and environmental impact. The technical figures in that paper are close to the figures which were gathered during research of this thesis. In order not to lose in the CHP total efficiency, some of the excess heat could be converted into useful cooling. This cooling can be used in the industrial process cooling (PC) as well as for air conditioning (AC) in the facility, as shown on Figure 6.

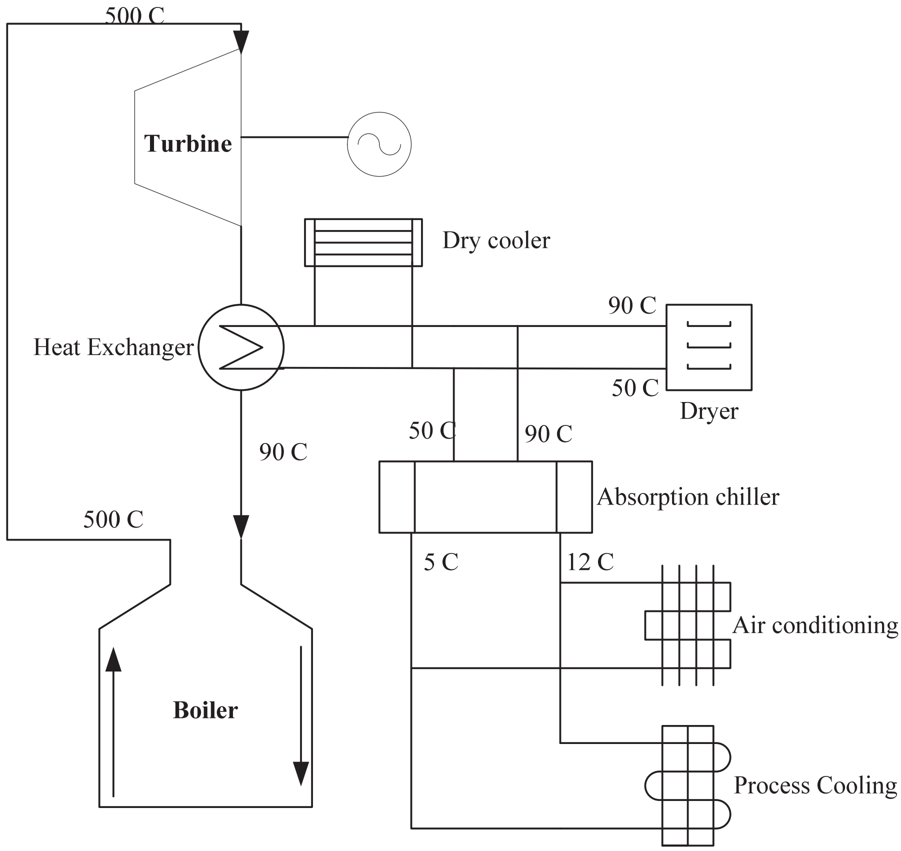

Figure 6. Industrial excess heat utilization for cooling

Majority of the CHP variable cost is usually the fuel cost. Therefore the CHP electricity output is operated based on the cost of the fuel and income from the electricity and heat sales. In normal operation the power plant is expected to run even in condensation mode if the electricity production income covers the variable cost of the plant [56]. Otherwise it is more profitable not to run the pant. The industrial CHP follows in the normal operation the factory heat load. Usually the CHP in the industry is using the back-pressure turbine which electrical output depends on the heat load. If the heat load decreases then also the electrical output decreases.

The marginal cost of the CHP is the cost to produce one extra MWh_e of electricity. In this thesis the marginal cost definition is rather equal to the short term marginal cost. When changing the power plant load from the partial load to the full load then there is no other significant marginal cost than the fuel cost. The CHP is expected to increase the electrical output as long as the plant marginal cost is covered. Therefore traditionally the criterion for operating the condensing power plant is written in the equation (2.11):

$$V_{EP} \cdot P_E > V_F \cdot P_F \, , \tag{2.11}$$

In any case where income exceeds the variable cost of the production, the plant is expected to produce electricity. There are no technical restrictions to run the CHP plant on condensing mode, but in that case the plant has to manage with market conditions. This however is not possible in the Estonia or other Baltic States where the fuel cost is higher than income from electricity [51-53]

Traditionally a CHP produces two forms of commercially usable energy – electricity and heat. In paper [II] also the third sales article for the industrial CHP is introduced – cold production. When converting some of the CHP heat production to commercially needed cold water the plant becomes a combined cooling, heat and power (CCHP) plant. In this research the technology for the required cooling energy production was chosen the absorption chiller. Absorption chiller was used due to the reason that it is commercially most available and commonly used technology for the cold production.

Usually the traditional biomass fired CHP plants have quite low electricity share in the total produced energy [57]. This however is compensated with the significantly high total efficiency on conversion the primary fuels to the useful energy [6]. Introducing the cold production enables the CHP to increase the heat production and therefore also produce additional electricity to the market. The CHP technical thermodynamic total efficiency can be described as follows in equation (2.12):

$$\eta_n = \frac{V_{EP} + V_{HP}}{V_F} = \eta_e + \eta_h \, , \tag{2.12}$$

where

η_n is the nominal total efficiency of the plant

η_e is the electrical efficiency of the plant

η_h is the heat efficiency of the plant.

Usually the biomass CHP-s total efficiency is in the range of 0.85-0.9. The CHP heat production V_{HP} can be divided between the factory heat consumer and the chiller production as follows in equation (2.13):

$$V_{HP} = V_{HC} + V_{CC} \, , \tag{2.13}$$

where

V_{CC} is the heat that is used for cooling in MWh_{th}.

Thereby the market based optimization algorithm for the total CCHP plant operational profit maximization can be written in equation (2.14) as follows:

$$max \sum_{t=1}^{n} (V_{EP,t} \cdot (P_{E,t} + S_{R,t}) + V_{HC,t} \cdot P_{H,t} + V_{CC,t} \cdot P_{CC,t} - V_{F,t} \cdot P_{F,t}) \, , \tag{2.14}$$

where

S_R is the possible subsidy which is paid as a feed-in premium in €/MWh_e

P_{CC} is the price of the heat which is supplied for the factory cooling in €/MWh_{th}

Cooling heat is the sum of the different types of cooling applications. In this thesis it is an air conditioners and process cooling as shown in equation (2.15):

$$V_{CC} = \frac{(V_{AC} + V_{PC})}{\eta_{ABS}}, \quad (2.15)$$

where
V_{AC} is the cooling consumption of air conditioners in MWh_c
V_{PC} is the cooling consumption of process cooling in MWh_c
η_{ABS} is the efficiency of the absorption chillier.

In order to run the CHP plant electrical output even more than the total available heat load would allow then criterion (2.16) below which is in accordance with equation (2.11), have to be full-filled:

$$V_{EP}^{extra} \cdot P_E + V_{CC} \cdot P_{CC} - V_{CD} \cdot P_{CD} > V_F^{extra} \cdot P_F, \quad (2.16)$$

where
V_{EP}^{extra} is the additional electricity produced due to the increased heat load in MWh_e
V_{CD} is the condensed heat load in MWh_{th}
P_{CD} is the condensed heat load price in €/MWh_{th}
V_F^{extra} is the required additional fuel in MWh_f for the increased load point.

The price of the additionally produced heat can be either negative or positive depending if the additional heat is commercially needed or it is just cooled down. If it is cooled down (condensed) then there is negative cost for the condensing operation itself, i.e. electricity cost of the fans, etc operational condensing costs. If it is commercially needed for the cooling then there is a positive price for that additional heat.

Heat, which is consumed for commercially needed cooling, price P_{CC} can only be determined by the alternative cost compared to costs occurring with traditional chillers or air conditioners (AC-s) which is used in the factory. Since cooling in the industry has no market like there is no market for the heat in the industry then the cooling income can only be determined by the alternative cost. The cooling energy direct income is calculated by the savings it gives to the facility when it switches over from the electricity driven local cooling to the central excess heat based cooling. Therefore the income of the excess heat which is converted into cooling energy can be written in equation (2.17) as follows:

$$V_{CC} \cdot P_{CC} = S_{AC} + S_{PC}, \quad (2.17)$$

where
S_{AC} is the operational cost savings with the absorption chillier compared to facility reference case electricity based air conditioning (AC) in €
S_{PC} is the operational cost savings with the absorption chillier compared to facility reference case electricity based process cooling (PC) in €.

The comparison of the two cases will give the volume of the electricity which is saved in the cooling operations. This volume is then multiplied with the total price of the electricity. The results will give the absolute figure about the savings as shown in the equations (2.18) and (2.19):

$$S_{AC} = (V_{EC}^{AC} - V_{EC}^{ABS}) \cdot (P_E + P_T), \qquad (2.18)$$

$$S_{PC} = (V_{EC}^{PC} - V_{EC}^{ABS}) \cdot (P_E + P_T), \qquad (2.19)$$

where

$V^{AC}{}_{EC}$ is the reference case AC's electricity consumption in MWh_e

$V^{ABS}{}_{EC}$ is the absorption chiller based system electricity consumption in MWh_e

$V^{PC}{}_{EC}$ is the reference case process cooling electricity consumption in MWh_e

P_T is the other saved electricity price component in €/MWh_e.

Since the factory electricity consumption includes the various price components on the purchased electricity then these components have to be taken into account. Regardless of the physical electricity delivery the consumer it is often eligible for the certain taxes on top of the electricity price like excise, subsidy tariff, VAT and other. These price components are separated from the electricity spot price due to the reason that the spot price is given for each hour separately throughout the year, but the remaining components are most likely fixed by the regulation. Therefore in order to determine the facility electrical energy savings the location specific marginal electricity cost P_T has to be taken into account case by case.

The industrial CHP plant will run on market conditions with the higher electrical load if the savings from the absorption chiller usage together with the additional electricity income are bigger than the cost of the extra fuel. In biomass based power plants there is usually in the European Union always some subsidies involved [58]. However it should be noted that the profitability of exploiting heat based cooling opportunities is strongly affected by the local energy policies and therefore is a subject to the energy policy changes. Absorption chiller based cooling enables the CHP plant to increase electricity production and hence receive the additional subsidy income on top of the electricity price as shown in equation (2.20):

$$E_{EP}^{extra} \cdot (P_E + S_R) + S_{AC} + S_{PC} - V_{CD} \cdot P_{CD} > W_F^{extra} \cdot P_F, \qquad (2.20)$$

Therefore the plant can operate in the partially condensing mode at certain higher range of efficiency as long as the minimum required total efficiency is maintained, constraint (2.21):

$$\frac{V_{EP} + V_{EP}^{RE} + V_{HP}}{V_F} \geq \eta_R, \qquad (2.21)$$

where

$V^{RE}{}_{EP}$ is the additional electricity that can be produced on the condensation mode without losing the subsidy in MWh_e

η_R is the minimum required total efficiency for receiving the subsidy.

2.3 Environmental aspect of the optimization

The use of the excess heat enables the industrial CHP to increase the heat load and therefore also increase the electricity production without decreasing the plant efficiency. This is also an important aspect from the environmental point of view where the heat based cooling allows remarkable savings for the energy sector in the primary energy consumption and emissions.

The efficiency and emissions are also an important aspect of the paper [III] where the facility's overall efficiency is observed and optimized using the statistical approach. The study shows that by gathering enough statistical data from the production process then the most important figures are determined which influence the entire facility economic and environmental performance. Since the industry normally works throughout the year and the production state is giving values for each hour then there is an enormous amount of load points to use in efficiency modelling and calculations. Therefore this establishes a solid ground for lowering the environmental impact in the facility.

In paper [III] the following facility operational data is collected and processed with Statgraphics Plus software using Pearson's correlation equation:

- CHP own electricity consumption
- Factory dryers electricity consumption
- Factory remaining electricity consumption
- Specific sub-cycle electricity consumption
- CHP electricity production
- Exported electricity to the grid
- Industrial end product production
- Sub-cycle intermediate product production
- Specific electricity consumption in the factory
- Specific electricity consumption in the CHP electricity production

The target of the statistical analyze is to find the correlation of different processes and therefore minimize the environmental impact of the facility. However the optimization of the environmental impact has to be done on economic basis. It is expected that in any country the environmental emissions, pollutions and consumables are put in the relevant impact to cost ratio. This means that the cost of any certain pollution is determined by the negative effect of that specific pollution. In any energy or industrial production the negative environmental aspect has the impact on the profit. Therefore minimizing the environmental impact will most likely increase also the production site economical profit due to the optimized consumption of goods and materials.

In this study the environmental aspect has been put in the calculation formulas like any other variable which has a volume dependent cost. In most of the cases the environmental pollution tax is defined per unit. This creates an extra opportunities for the industry where the environmental impact decrease can also give profit increase due to the increased efficiency or less pollution emissions.

3. CONSUMPTION MANAGEMENT

3.1 Demand side management in the factory

Demand side management (DSM) and demand response (DR) are efficient tools for the factory's electricity cost reduction. DSM in the factory can be done because there are production cycles which work on partial load and include intermediate production storages which allow producing end-product even when certain product preparation cycles have been turned off. The similar model has been developed by [59] but only in the closed electricity market conditions with the fixed tariffs. The principle of the intermediate production storages is shown in the Figure 7 and discussed more thoroughly in paper [IV].

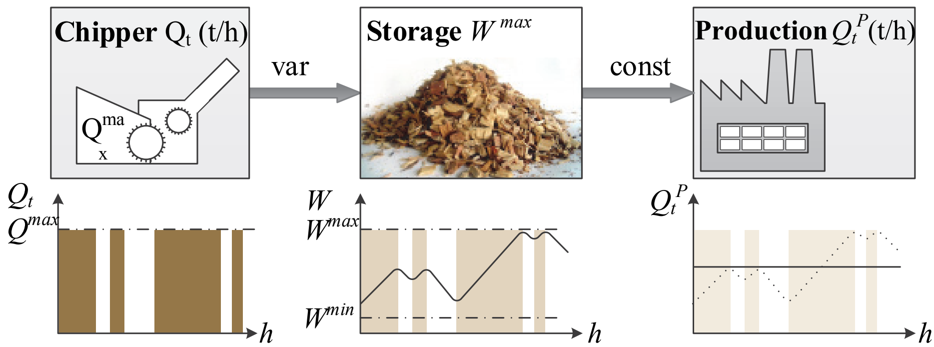

Figure 7. The principle solution of intermediate production storages which allow to switch off the sub-cycle in front of the intermediate storage without affecting the final end-product production

Figure 7 shows that the wood chipper production capacity Q^{max} exceeds the factory production load Q^P and therefore using the intermediate storage with the volume W^{max} allows the chipper to work on partial load throughout the production period. In paper [IV] it was determined that the electricity cost C_E for a single load under investigation, i.e. wood chipper can be minimized with equation (3.1):

$$\min_{Q_t} E\left[\sum_{t=1} P_{E,t} \cdot B^{CH}(Q_t) + C_{EXT}(Q_t)\right], \qquad (3.1)$$

where

E is the expected value of the operator

B^{CH} is the output power of the chipper in MW_e

Q is the required chipping volume in tons (t)

Since the electricity price is a stochastic parameter which can be different in each day of the year, then P_{Et} will be given for the scenarios s as follows (3.2):

$$\min_{Q_t} \sum_s \sum_t P_{E,t}^s \cdot B^{CH}(Q_t) \cdot \Pr(s) + C_{EXT}(Q_t), \qquad (3.2)$$

where

Pr(s) is a probability of the scenario *s*.

The restrictions and assumptions are that the profit cannot be hindered due to the load shifting, meaning that the system's global optimum needs to be found for the facility in order to minimize the electricity cost. The key factor that enables this optimization to take place is the wood chipper's production volume Q_t. In this case study the wood chipper can produce much more material than the factory requires therefore it is an ideal application for the load shifting operations. The chipper production volume can be controlled quite simply between zero and maximum output, (3.3):

$$0 \le Q_t \le Q^{\max} . \quad (3.3)$$

It can be assumed that the more the chipper's maximum capacity Q^{max} exceeds the industry's required material flow Q^P, the higher the production line's flexibility is, which in return gains in lower costs. Additional physical constraints arise from the fact that the storage cannot be overfilled or run below critical level (3.4):

$$W^{\min} \le W_t \le W^{\max}, \quad (3.4)$$

where
W_t is the actual storage volume in the given hour in tons (t)
W^{max} is the maximum usable storage in tons (t)
W^{min} is the minimum acceptable storage volume for the industry due to the production process' security of supply in tons (t).

In the long run the DSM planning can even be used for the long term production process planning. The annual maintenances could be decided by the Figure 8 which indicates the periods when the material is taken from the storage and therefore the production system is stopped. Annual facility maintenance for the factory production should be done during high electricity prices when the storages are running empty. On the other hand CHP maintenances should be planned over the low electricity price periods when the storages are being filled.

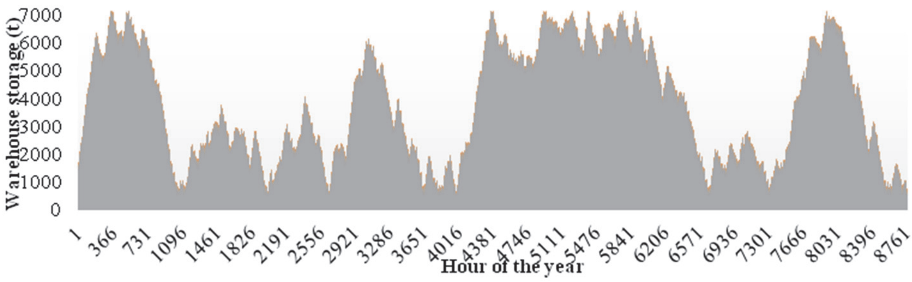

Figure 8. Warehouse storage dynamics when using DSM

In order to create the factory electricity cost optimization algorithm for the entire production process which includes several sub-cycles then the simplified principle is introduced. If there are several sub cycles in the production line then the equation (3.1) is redefined as (3.5):

$$\min_{Q_t^i} E\left[\sum_{i=1}^{m}\sum_{t=1}^{n} P_{E,t} \cdot B^i(Q_t^i) + C_{EXT}^i(Q_t^i)\right], \quad (3.5)$$

With the following constraints in (3.6) – (3.9):

$$\forall_i \forall_t \ 0 \le Q_i^t \le Q_i^{\max} \ \ i \in \{1 \ldots n\}, \tag{3.6}$$

$$\forall_i \forall_t \ W_i^{\min} \le W_i \le W_i^{\max} \ \ i \in \{1 \ldots n\}, \tag{3.7}$$

$$\forall_i \forall_t \ W_i^t = W_i^{t-1} + Q_i^t - Q_{i+1}^t + F_i^t \ \ i \in \{1 \ldots n-1\}, \tag{3.8}$$

$$W_n^t = W_n^{t-1} + Q_n^t + F_n^t, \tag{3.9}$$

where

F is the volume of the pre-processed raw material which is purchased additionally in tons (t).

In further studies of the DSM potential the research of authors [60] should be studied closely in order to develop more sophisticated load shifting model where the factory has to handle the large number of controllable loads of several types. Authors propose a heuristic optimization method to use in the smart grid for the load shifting. The approach is interesting and has great potential to be used also in the industrial load shifting. Even though the authors find the small potential in the industry due to the security of supply reasons then the optimization method can be adapt to the specific requirements.

3.2 CHP and factory load regulation services for the system operator

The demand response (DR) nature is somewhat different from the DSM activities because it requires a swift action in the case of a sudden notice by the system operator. The goal of the system operator is to guarantee the electricity system balance in each hour within a given range. For that purpose the system operator purchases regulating services from the market participants which are usually the power plants. The regulation can be either an up-regulation where there is a shortage of the power or down-regulation where there is a surplus of the power in the system.

In paper [V] the case study calculations were carried out in the same industrial facility in order to determine possible revenues from the DR services which the factory could provide for the system operator (TSO).

Criteria's for providing DR services are analysed more thoroughly in paper [V]. Based on the interviews with the studied wood industry representative and the Estonian TSO there are three main factors that need to be addressed to qualify as a DR service provider. The first criterion (3.10) describes the minimum regulating power that is acceptable by the TSO:

$$B_{ACL} \ge B_{TS}, \tag{3.10}$$

where

B_{ACL} describes the service provider aggregated changeable load in MW_e

B_{TS} is the TSO's minimum required regulation step in MW_e.

The second criterion (3.11) takes into account the response time of the service provider:

$$\Delta t_r \le \Delta t_{TR}, \tag{3.11}$$

where

Δt_r is the service provider time for achieving the requested load change in minutes

Δt_{TR} describes the TSO's maximum timeframe for achieving the requested up regulation in minutes.

The final criterion (3.12) takes into account the duration of the regulation:

$$\Delta t_{SAL} \geq \Delta t_{TS}, \tag{3.12}$$

where

Δt_{SAL} is the service provider's capability to change the load in hours

Δt_{TS} is the TSO's minimum regulation duration in hours.

The service provider pricing principle is rationally based on the lost profit (or on the risk of losing production). Lost profit is used to determine the price for load shedding and the risk of losing production is used to determine price for load shifting. Therefore, whenever the regulation price exceeds the industry's price cap for the service provision, the DR service could be provided. Large industrial consumers are expected to act in a rational way i.e. it can be expected that they will provide the DR service if they find it cost-effective [61].

The aggregated demand profile of the consumers who is providing the regulation service (with load shifting and load shedding) before, during, and after service provision to catch up on the production quota is illustrated on Figure 9.

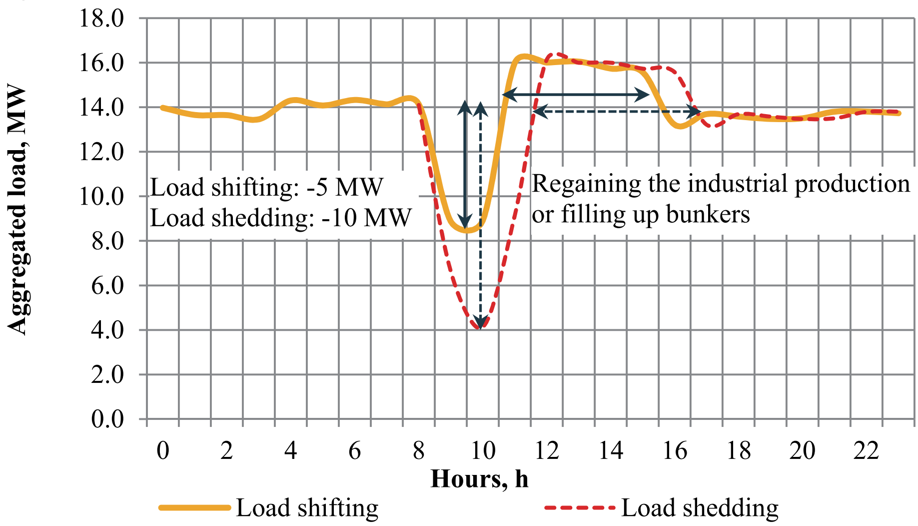

Figure 9. DR and DSM can be executed through aggregated load cut and regaining the industrial production thereafter with increased production intensity

It should be noted that while with load shifting it is possible to catch up the production quota by increasing the demand for a couple of hours, then with load shedding the increased consumption after regulation can only fill up the intermediate storages in the production line but the production quota will not be caught up. Also, the consumer can provide only the up-regulation for the system. As explained in the introduction part of this thesis for the system operator the consumer is like a negative producer. It means that if the consumer decreases the electricity load then this equals with the generator being increasing the generation.

The factory in the industrial facility can provide the up-regulation by decreasing the consumption load and CHP can provide down-regulation by decreasing the generation load. Also, the CHP down regulation cannot affect the heat production and therefore does not affect the industrial end-product production. When the CHP operates on the partial load then it can be also used for the up-regulation, but in normal cases the industrial CHP runs on the maximum load all year round therefore being unable to participate on the up-regulation service provision.

The consumer's pricing principle can be described as in equation (3.13):

$$P_{DR,t}^{C} = \frac{\sum_{t=1}^{n}(I_{IP,t} - C_{V,t}) + C_{EXT}}{B_{ACL} \cdot \Delta t}, \tag{3.13}$$

where

P^{C}_{DR} is the electricity consumer price of the DR service in €/MWh$_e$

I_{IP} is the value of the lost industrial production income in €

C_V is the cost of variable goods saved in €

Δt represents the duration of the ordered DR service from the TSO in hours (h).

The industrial CHP down-regulation service price principle can be described by the same principal according to the equation (3.14):

$$P_{DR,t}^{G} = \frac{\sum_{t=1}^{n}((P_{E,t} + S_{R,t}) \cdot V_{EP,t} - C_{F,t}) + C_{EXT}}{B_{ACL} \cdot \Delta t}, \tag{3.14}$$

where

P^{G}_{DR} is the electricity producer price of the DR service in €/MWh$_e$

Paper [V] summarized that the aggregated factory consumption load could practically participate in the DR service provision and its cost would be lower for the system operator than cost of the generators in some extreme cases as shown on Figure 10 [51].

Due to the reason that the system regulation prices were not publicly available for Estonia or Latvia then the Finnish TSO prices were used for the example. Figure 10 is an actual Finnish TSO up-regulation service prices distribution. As it can be seen from the figure then 50% of the Finnish TSO up-regulation cost came from the regulation purchase which prices were higher than 100 €/MWh$_e$. Majority of the regulations are normally still done with prices close to the electricity spot market prices and usually remain below 100 €/MWh$_e$. Only in few cases the regulation generators service fee rockets out of the normal price range. These peak prices however create the biggest cost for the TSO. That high level of the service price encourages the market participants to exploit further the existing opportunities for the service provision. On the other hand the different type of market participants providing the regulation service can cut the peak prices and bring down the TSO overall cost.

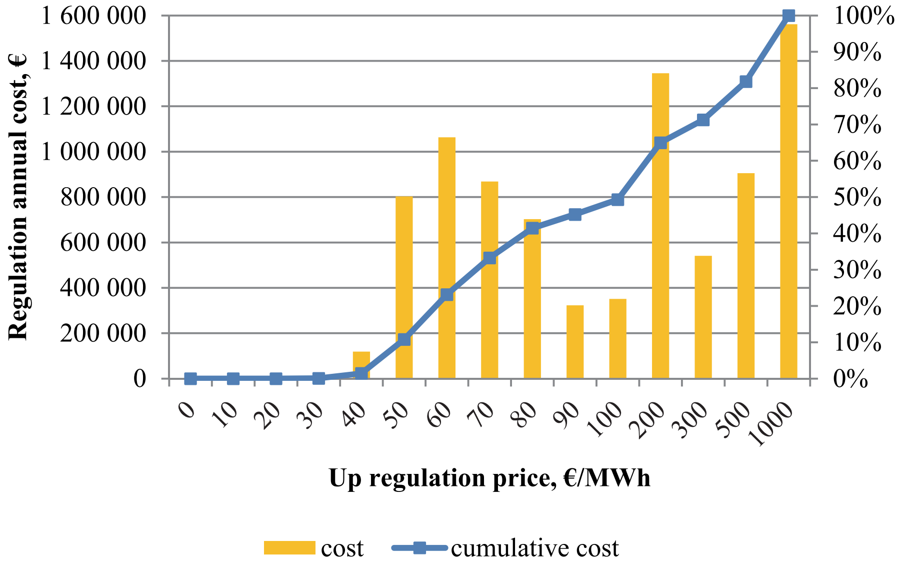

Figure 10. Finnish TSO's up-regulation costs in 2011

3.3 Implementation technology for the load management

In order to carry out the actions and services described in the previous chapters of this thesis the combination of the hardware and software has to be used. The machine either a generator or a motor has to run according to the optimized load curve. This means that there has to be a controlling unit which gives the operation command for the electrical machine. This physical control can be done using the programmable logic controller (PLC).

In the future it is expected that much more electrical machines and applications are connected to the server and the smart load controlling is more commonly used. The necessary technology for the smart load implementation already exists, but this have to be adapted conveniently to the existing machinery atomization. When the electricity consumption and production equipment is connected to the so called smart grid and are operating according to the optimized load profiles then this benefits the whole energy system.

This thesis proposes the technical layout of the load controlling equipment which is more in detail described in paper [VI]. The optimization which is developed in previous chapters of this thesis is carried out in the remote server. The optimization algorithm takes the publicly available data like the electricity market spot price from the public source. The location specific information like the machine load and storage level is taken directly from the facility. Once the next day prices are known the optimization is carried out and the optimized load profile is forwarded to the PLC. The proposed example smart load technical layout is shown in the Figure 11. This kind of easy and simple communication between the application and the server enables the load control to be used in larger scale than only in the specific industry.

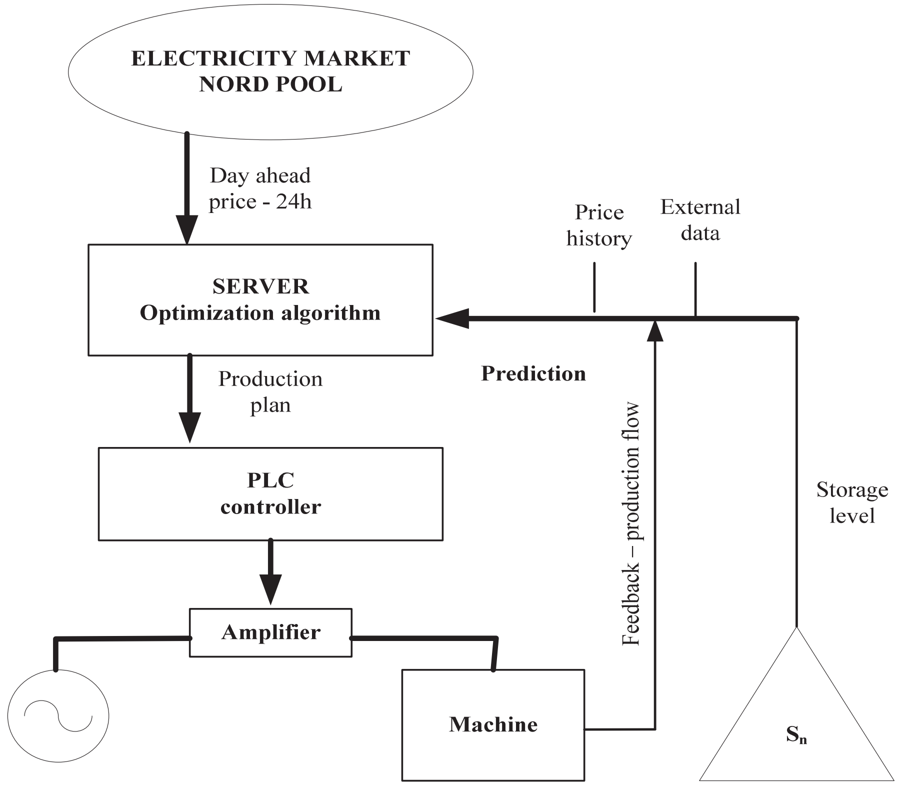

Figure 11. The control mechanism of the industrial electricity consumption applications to automatically work with optimized load profile

In more advanced controlling system the external data and the price history can be used to predict the electricity price and therefore make the optimization even more feasible. For example the optimization model can take into account the lower prices on the weekend and generate the load profile which utilizes the storage capacity for a longer period than one day. Even further study in this application is to develop the control mechanism which can adjust and adapt with the new situation independently on his own due to the changed characteristic of the machine, storage size etc. This would be then so called smart self studying load controller.

4. RESULTS

The results of this research papers have been very promising. On the absolute figures the increase of facility profit is remarkable. Percentages which are improved in the cost side can have a relatively high effect on the profit. Therefore the results are worth to examine by any industry which is operating an on-site CHP and is interested to gain additional revenues from its production.

Results of thesis define the principle difference of the non-optimized operation compared to the optimized operation. Results show that there is a significant potential to improve the facility economical performance and hence maximise the industry's profit. However this increase and potential is not yet fully exploited in the emerging industries in the Baltic countries where the main focus is on the organization and volume growth rather than on efficiency. On the other hand the industries who do not improve their efficiency are not competitive in the market and are expected to vanish in the future.

Figure 12 illustrates the sensitivity of the market price deviation to the economic performance of the industrial case study facility.

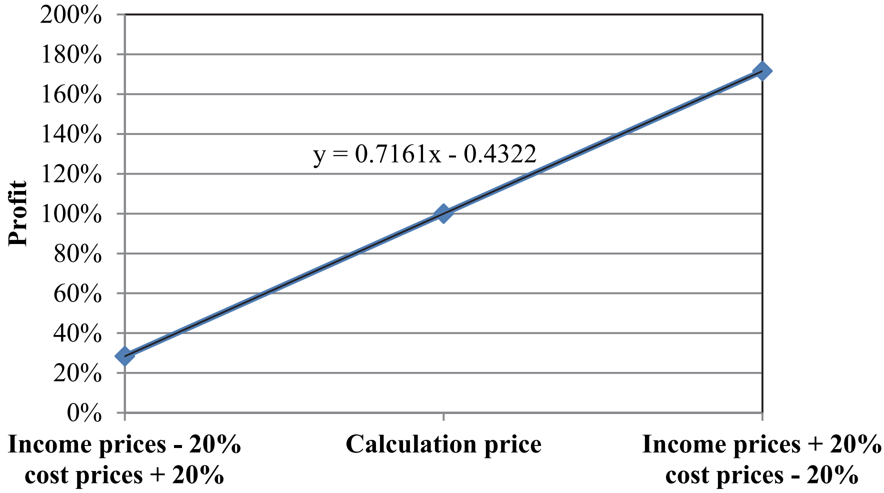

Figure 12. The case study industry profit sensitivity to the weighted market prices

In the Figure 12 it is shown how the market prices in the specific case study industry affect the economical performance of the market participant. As it can be seen when the cost articles prices increase 20% and at the same time the income articles decrease 20% then this facility profit decreases on the 28% from the original profit level. This means that the overall profit decreases more than 3 times. On the other hand if the conditions for the facility are favourable and the market prices of the income articles rise 20% and at the same time the cost articles decrease 20% then the overall profit increases 72%. This is more than 1.5 times higher than originally. As this example shows the industrial facility sensitivity is relatively high to the influence of the market prices. Therefore the industry has to focus on the different aspects of the markets and take advantage of the market variations when possible. As this thesis has introduced the goal of the research was to take advantage of the electricity market.

Results of paper [I] show that the industry which has one single connection point to the electricity market has to separate its load profiles in order to verify the optimization possibilities. The key aspect of the optimization approach was that the electricity price is the spot market price for all of the CHP and factory electricity loads. The case study showed that facility was able to increase its exported electricity income roughly 2.5% by utilizing its load management potential as shown in Table 2.

Table 2. Case study facility monthly exported electricity optimization results

Actual spot price	42.32 €/MWh$_e$	Initial difference	Optimized load price	Difference after optimization
Generator average income	42.30 €/MWh$_e$	-0.04%	42.37 €/MWh$_e$	0.13%
Consumption average cost	42.36 €/MWh$_e$	-0.10%	41.59 €/MWh$_e$	1.72%
Export average income	42.22 €/MWh$_e$	-0.23%	43.28 €/MWh$_e$	2.27%

Table 2 shows that in the reference actual example month the electricity production and consumption weighted average income and cost prices were poorer than the market arithmetical average. Using the optimization method developed in this thesis the weighted average cost and income improved in all aspects contributing to the profit increase. Figure 13 shows the optimized export results in the example day which were calculated in paper [I].

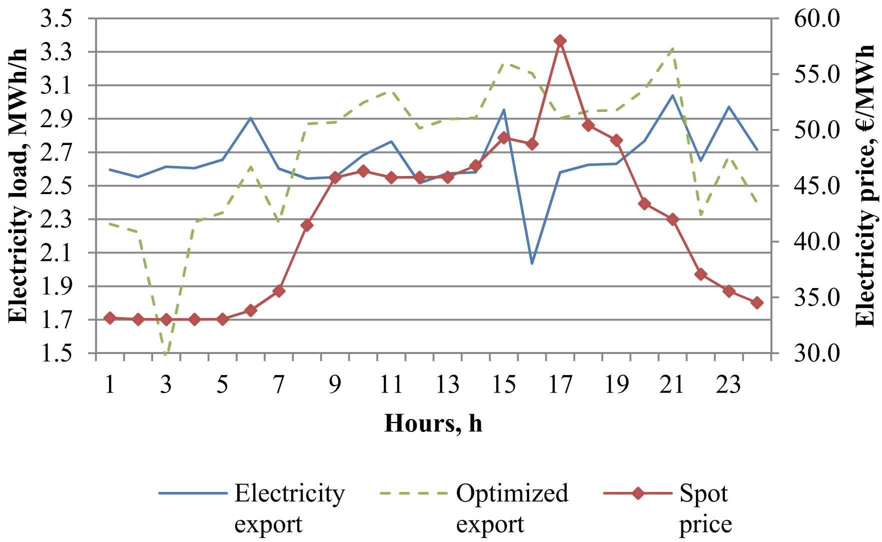

Figure 13. Example day of the facility exported electricity load profile

The estimated factory consumption load management potential in paper [I] was considered 10% from the nominal load. This means that factory is able to shift at any time 10% of its electricity consumption as long as the total consumed electricity volume within one day remains the same. The 10% figure was taken by the factory electricity consumption profile where it was seen that this is the amount of the load which is varying throughout each day due to the regular daily machinery maintenances. After observations carried out in the case study industry it was confirmed that this load can be adjusted deliberately if there is a need for that. Once all the production lines in the factory get fully automated then this type of load scheduling becomes technically more comprehensive.

In paper [II] a somewhat different approach was introduced. The increase of electricity production is compared against the variable cost of changed load point. The results show that it is worth to condensate the excess heat in order to gain additional income from the electricity production as long as the variable cost of fuel does not exceed the income from electricity sales.

The same paper also shows that if an industry wants to use the cooling load in order to increase the electricity production in summer period then the payback time for absorption chillier is 6.5 years as shown in Table 3.

Table 3. Case study industry calculation results

Output data	**Variable**	**Value**	**Unit**
Process cooling consumption	V_{PC}	1 583	MWh_c
Air conditioners cooling consumption	V_{AC}	2 491	MWh_c
Total cooling consumption		4 074	MWh_c
Total heat consumption for cooling	V_h^C	5 432	MWh_{th}
Heat consumption for drying	V_h^H	147 507	MWh_{th}
Excess heat		6 180	MWh_{th}
Excess heat peak		7.8	MW_{th}
Excess heat for cooling production		2 927	MWh_{th}
Cooling load peak		1.7	MW_{th}
Additional condensation need		3254	MWh_{th}
Condensation peak		6.8	MW_{th}
Additional electricity production		1 057	MWh_e
Additional electricity income		105 478	€
Additional fuel consumption		4 476	MWh_f
Additional fuel cost		53 708	€
Additional profit		51 770	€
Payback time		5.6	Years

The table above shows how much heat can be converted for cooling production. It has to be noted that the heat is supplied to the cooling production only when there is no demand from the drying unit. If there is a demand from the drying unit then firstly the heat will be supplied for the drying process and the remaining heat for the production of cooling.

The extremely high investment cost of the unit inhibits the usage of absorption chillers. The units are produced only by few companies worldwide and the average payback time is not less than 6 years. Depending of the size of the industry the payback time can also be much shorter if there is a commercial demand for the cooling and this cooling has also a price or gives remarkable savings in facility electricity consumption. In that case the payback time and hence the utilization of the heat based cooling is much more justified.

The paper [III] shows the results of the variables which have an effect on the electricity production. There is a strong correlation between the CHP own consumption electricity and the produced electricity. Also the results show the correlation of the factory electricity consumption with the CHP electricity production. According to the calculations the dryer production cycle has an effect to the CHP electricity production.

In paper [IV] the electricity consumption optimization according to the electricity market price is taken under investigation and the optimization principles have been introduced. Specific factory production sub-cycle was investigated and the optimized production profile was modelled. The results reveal that the single energy intensive machine savings were between 11-17%. It has to be noted that the optimization effect cannot be determined exactly due to the reason that the "operation as usual" can also give different economic results. In paper [IV] a long period of specific factory sub-cycle load history was used to compare the results. The analysis revealed a relatively predictable variable cost for the sub-cycle and this cost was compared against the optimization results. The machine consumption profile after applying the optimization application is shown on Figure 14, paper [VI].

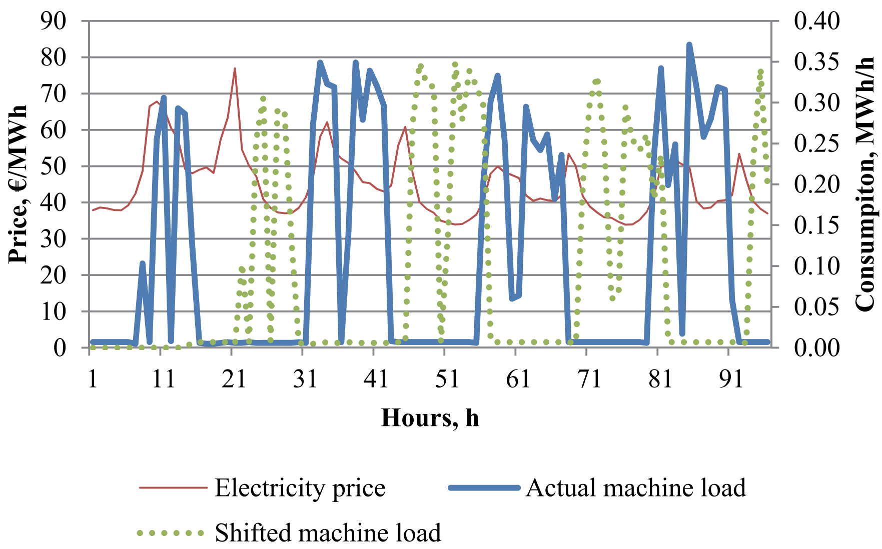

Figure 14. Case study sub-cycle modelling with optimized operation profile

On Figure 14 is shown the load profile of the specific machine under investigation before and after the optimization. It can be seen that by exploiting the intermediate storages the optimized load control has shifted the majority of the machine operation in the valley hours of the electricity price.

For an industrial CHP and the factory there is one more interesting service that could be provided. As paper [V] shows there is a potential for the facility to provide load response services for the TSO-s. The facility can aggregate the consumers for the up-regulation of the system or use a CHP for a down-regulation, with a minimum load step of 5 MW_e. This 5 MW_e step is the current minimum step which is required by the TSO to participate in the regulation market with balancing services.

The results in paper [V] show that the electricity consumer's price can be up to 100 €/MWh_e when shifting the load and up to 600 €/MWh_e when shedding the load. The preliminary results are promising for the TSO, because according to their information time to time there is a need for balancing services with extremely high prices, up to 2000 €/MWh_e.

Paper [VI] has developed a real world application which can be easily implemented in any industrial load or aggregated load management. The developed technical solution requires minimum investment cost. In fact the other researchers are already further developing paper [VI] approach and implementing the first actual commercial prototype application. The higher is the automation level of the industry the easier it is to put the load controller in operation. The estimated savings are shown in Figure 15.

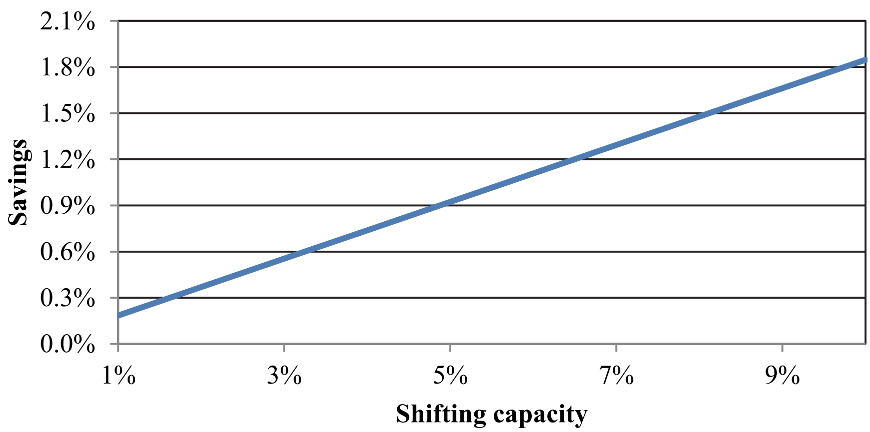

Figure 15. Relation between the consumption flexibility and savings

The Figure 15 shows that when the electricity consumer or producer has the flexibility to shift 10% of its daily load according to the optimized load profile then is gives additional revenues or saving around 1.8 %. As it can be seen from the graph the higher is the flexibility the more profit it gains for the market participant. In this study the results showed the linear relation between the flexibility and the savings.

CONCLUSION AND FUTURE WORK

In a conclusion the industrial CHP optimal management model contributes to the industry profit maximization. The industrial facility which includes the CHP and a factory can increase its profit by increasing the production volumes or scheduling the loads according to the market prices. In this thesis both of the options were studied. However if the production volumes are in the maximum limit and cannot be increased then the load scheduling becomes a key element of the optimization.

The industrial facility which also operates the CHP plant has to adapt with the market prices from where the raw material and fuel is purchased and where the products are sold. During the research it became apparent that none of the related markets are as rapid and as predictable as the electricity market. For that reason the electricity market was chosen as the variable in the profit maximization.

The industrial CHP profit together with the factory was maximized. The actual wood processing factory with an existing CHP unit was taken under investigation. The theoretical methods and approach was modelled by using the actual existing case study facility technical operations data. The modelling results showed improved profit in all aspects of the research.

Exploiting the market condition for the benefit of the market participant is the key factor in the future energy intensive and electricity production industries. Inability to adapt the production process to the conditions of the market may define the separator which determines the participants who will be more competitive and can continue operating in the market.

The thesis concludes the studies which were presented throughout published papers [I – VI]. The thesis concludes the different studies which were carried out over the years of observation, measurements and investigation. As a conclusion a management model has emerged. This model enables the industrial facility which operates the on-site CHP to maximize its production short-time marginal profit. Even more, the developed model enables any type of energy intensive industry to optimize its production and hence maximize the profit. The developed model is a general model and can be used in any type of industry where there is a free access to the electricity spot market.

This research gives sufficient ground for further studies in the field of market based optimization. Smart economic based approach to any electrical applications either a generator or motor which operates on partial load can be implemented. Furthermore in the future so called smart modules can be added into to the devices during the designing and installation of the technology. From the optimization point of view in the future research the mathematical *minimax* risk criterion should be used for scientific risk assessment in the conditions of uncertainty.

DISCUSSION

The developed industrial CHP management model can be used in any branch of industry, not just on the case study wood industry, making this research a high value material. In fact several researchers from other regions out of Nordic and Baltic countries have had an interest to exploit this model in their conditions. This interest shows that this topic has a high potential in much broader spectrum. The research has the high practical value which can be implemented already in the near future and therefore improving the competitiveness of the user. Even further the management model can be adjusted to different needs of the user besides the profit maximization like peak load control, risk management, technology designing and operation practices. Therefore this thesis has fully achieved the tasks which were set in the start of the research.

Optimization is the next big step in the industrial era. As the world is seeking more energy efficient solutions in order to save primary fuels and reduce the pressure on the environment then optimization has much more potential. When industry stops consuming electricity during the market price peak hours then it can be just the right amount of energy which is needed in the system to keep the system balanced and not to put inefficient peak production generators into operation. The same applies for the on-site power production, if it does not decrease the power output on the peak hour when there is a shortage in the system then it improves the system balance situation.

The industry which operates the local heat and electricity production unit also contributes to the savings of transfer losses in the electricity and heat networks. Decrease in the network losses in return mean less primary energy consumption and therefore less pollution. All this is considered as a reduction of the environmental impact which is nowadays a critical factor for a long time sustainable development.

CHP's are divided into two types. First type is the plants which sell the heat to the public district heating network. These plants traditionally optimize their performance according to the heat demand. The second types are the industrial CHP's which optimization task is much more sophisticated as this thesis has revealed. The optimization is done over many criterions and the variables are not always determined but rather have some uncertainties in them. In this study the electricity price was uncertain figure which minimum and maximum values were significantly different from each other and unknown more than one day ahead.

In the conditions of uncertainty with the market prices it is impossible to make determined decisions and not to correct them during the execution. Market participant has to have the constant overview of the market conditions and make its decisions according to the real time information. Therefore the constant feedback for the optimization algorithm is a core prerequisite for the developed management model. This creates a demand for the easy and reliable communication technology in order to put this management model into practice.

Therefore the key developments are needed in the other fields of research which would create the necessary informational and communication technology platforms. With the real time smart grid solutions it is easy to adjust industrial and other applications according to the electricity market prices.

In the future it is expected that the applications will be connected to the overall network so that their control system is constantly observing the situation on the electricity market and can make a calculated optimized decisions. This approach means more sophisticated network, so called *smart grid*. The development of the technology is moving towards the more communications between the different applications and this tendency will create a better ground for the market based optimization. It allows the electrical applications to determine automatically the optimal working load. In future this means more savings, higher profit and better position in the global competitive market.

As the research showed there is a huge difference in the electricity market prices throughout the each day and year. The price is determined by the market and the participant cannot change the market price solely on its own will. In this context it is important to exploit the market opportunities to the benefit of the market participant by changing the electrical loads. Load management principle in the market conditions can be the same for the generator and for the motors due to the reason that their nature is exactly the same only the flow of energy is opposite. It is expected the participants who can adjust their production process to the more demanding and changing environment will be more competitive than the ones who do not. Therefore the real time optimization employment will distinguish in future the success of the participant and possibly determine who can continue production in the long term.

With the electricity market price continuously changing the results will always stay in the certain range and the effect of the optimization can never be exactly forecasted. There cannot be a certainty how a market participant would have acted without optimization and therefore cannot be determined the exact cost effect of that optimization. In more specific the effect can be given as a certain range. However it is clear that by using the science based mathematical approach the economical performance is likely to be increased.

The developed optimization approach can have high value for the CHP and industry which energy consumption is intensive. In the conditions where the electricity market is closed and regulated the optimization becomes rather the task of higher physical efficiency. This however means usually significant investments for upgrading the technology and is a different task. By using the developed management model the higher economical efficiency can be achieved without any significant investments. When the electricity market is volatile and price differences are remarkable then capability to be flexible determines the success for the power and industrial companies in the long run. The electricity market price volatility is expected to increase in the future when more unpredictable renewable energy are connected to the grid like wind and solar energy. This means that the developed industrial CHP optimal management model has much wider potential to be exploited in the large scale.

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ABSTRACT

This thesis investigates the profit maximization of the industrial CHP together with the industrial factory which together form an inseparable production facility. The thesis focuses on the facility profit maximization by utilizing all existing means and flexibility. Majority of the additional profit is gained from flexibility in the electricity production and consumption.

The core concept of the research is to divide the markets which affect the facility economical performance. Out of all the other markets the electricity market is much different due to its fluctuating nature and predictable pattern. Therefore the optimization is chosen to be carried out over the electricity market.

Industrial factory has in many cases the internal flexibility where it can shift its electricity load without having any negative influence on the production volumes or cost. In return the factory can benefit from the lower electricity cost. In this study it was assumed that the market participant is small enough without having an influence on the market due to its own actions. At the same time the CHP can shift its regular maintenances according to the electricity market price therefore increasing the facility profit even higher.

The market participant profit depends on two components – price and volume. The facility can increase its volume and choose the timing of production or consumption. This is exactly the case of the electricity market where the price is much different throughout the single day. There are no other goods in the industry which price is different in day and night time. Therefore by changing the electricity volume and timing of the electricity consumption and production the market participant can significantly increase its profit.

This dissertation has developed a management model for the wood industry facility which operates the on-site CHP unit. However the model can be used in any energy intensive industry which has its own local electricity generation. Therefore the developed management model is a unique and general at the same time allowing the different type of market participants to increase their profit and therefore be more competitive in the global market.

The research shows different management and service provision which in all increase the company profit. In this dissertation these management techniques have been combined into one single management model. This model enables the industrial CHP and neighboring factory to significantly increase its profit.

KOKKUVÕTE

Käesolev doktoritöö uurib tööstusliku koostootmisjaama kasumi maksimeerimise võimalusi koos samas kompleksis asuva tööstustootmisega. Tööstustehas koos lokaalse koostootmisjaamaga moodustab lahutamatu tööstuskompleksi, mille kogukasumi suurendamine on käesoleva töö eesmärk. Kasumit maksimeeritakse kasutades olemasolevaid vahendeid ning tootmise paindlikkust. Enamus suurenevast kasumist tuleb tootmiskompleksi paindlikkuse arvel elektrienergia tootmises ja tarbimises.

Põhimine kontseptsioon, millele antud uurimistöö toetub, on erinevate turgude lahutamine tootmiskompleksi majandustulemuste hindamiseks. Sellest nähtub, et elektriturg on oluliselt erinev kõikidest teistest turgudest oma volatiilse kõikumise ja selle seaduspärasuse poolest. Seetõttu on lahendatud optimeerimisülesanne lähtuvalt elektrituru võimalustest.

Tööstusel on nii mõnigi kord olemasolevad sisemised paindlikkused, mis võimaldavad tootmisettevõttel elektritarbimist nihutada ilma negatiivse mõjuta tööstustootmisele või kuludele. Elektri koormust nihutades on võimalik tootmisettevõttel oma elektrikulusid vähendada. Käesolevas uurimistöös on eeldatud, et turuosaline on piisavalt väike ning ei mõjuta oma käitumisega turgu. Samuti saab tööstuslik koostootmisjaam oma regulaarseid hoolduseid ajastada vastavalt elektrituru hinnale ning sellega suurendada tootmiskompleksi kasumit veelgi.

Turuosalise kasum sõltub kahest komponendist – hinnast ja kogusest. Tootmiskompleks saab suurendada oma tootmismahtu ning ajastada oma tootmist või tarbimist. Täpselt selline on olukord elektriturul, kus turuhinnal on oluline erinevus öisel ja tipu ajal. Seega, turuosaline, kes suudab oma elektri kogust ja tarbimise või tootmise ajastamist muuta, saab oluliselt oma kasumit kasvatada.

Käesolev doktoritöö on välja arendanud juhtimismudeli puidutööstus-kompleksile, mis opereerib lokaalset tööstuslikku koostootmisjaama. Siiski saab antud mudelit kasutada ka mõne muu energia mahuka tööstuse ja elektritootmise tarbeks. Seega on loodud mudel üheaegselt nii uudne kui ka üldine võimaldades erinevatel turuosalistel suurendada oma kasumit ning seega olla konkurentsivõimelisemad globaalsel turul.

Uurimistöö annab erinevad juhtimis- ja teenuse osutamise võimalused, mis kokkuvõtvalt panustavad kasumi kasvu. Antud doktoritöös on publitseeritud artiklid formuleeritud ühtseks juhtimismudeli tervikuks. Loodud juhtimismudel võimaldab tööstuslikul koostootmisjaamal ja tööstustehasel oluliselt kasumit suurendada.

ELULOOKIRJELDUS

1. Isikuandmed

Ees- ja perekonnanimi: Priit Uuemaa
Sünniaeg ja -koht: 09.01.1984, Rae vald, Eesti
Kodakondsus: Eesti
E-posti aadress: priit.uuemaa@eesti.ee

2. Hariduskäik

Õppeasutus (nimetus lõpetamise ajal)	Lõpetamise aeg	Haridus (eriala/kraad)
Tallinna Reaalkool	2002	Keskharidus
Tallinna Tehnikaülikool	2007	Elektroenergeetika, Tehnikateaduste bakalaureuse kraad
Tallinna Tehnikaülikool	2010	Elektroenergeetika, Tehnikateaduste magistri kraad

3. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
Eesti	Emakeel
Inglise	Kõrgtase
Vene	Kesktase

4. Täiendusõpe

Õppimise aeg	Täiendusõppe korraldaja nimetus
2013-2014	Riia Tehnikaülikool, Läti

5. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2006 – 2007	Õismäe Humanitaargümnaasium	Füüsika õpetaja
2003 – 2010	Eesti Kaitsevägi	Allohvitser
2010 –	AS Graanul Invest	Elektroenergeetika spetsialist

6. Teadustegevus, sh tunnustused ja juhendatud lõputööd
- Parim üliõpilasartikkel IEEE ISGT 2014 Aasia konverentsil
- Parim üliõpilastöö 2010
- Jaan Poska stipendium 2007.

CURRICULUM VITAE

1. Personal data

Name: Priit Uuemaa
Date and place of birth: 09.01.1984, Rae parish, Estonia
Citizenship: Estonia
E-mail address: priit.uuemaa@eesti.ee

2. Education

Educational institution	Graduation year	Education (field of study/degree)
Tallinn Secondary Science School	2002	Secondary education
Tallinn University of Technology	2007	Electrical Power Engineering, Bachelor of Science in Engineering
Tallinn University of Technology	2010	Electrical Power Engineering, Master of Science in Engineering

3. Language competence/skills (fluent, average, basic skills)

Language	Level
Estonian	Native language
English	Fluent
Russian	Average

4. Special courses

Period	Educational or other organization
2013-2014	Riga Technical University, Latvia

5. Professional employment

Period	Organization	Position
2006 – 2007	Õismäe Humanitarian Secondary School	Teacher of Physics
2003 – 2010	Estonian Defence Forces	Non-Commissioned Officer
2010 –	AS Graanul Invest	Specialist of Power Engineering

6. Research activity, including honors and thesis supervised
- Best Student Paper Award 2014 IEEE ISGT ASIA Conference
- Best Master Thesis in 2010
- Jaan Poska Award 2007.

PAPER I

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Industrial CHP Optimal Management in the Energy Market Under Incomplete Information

Priit Uuemaa
Imre Drovtar
Jako Kilter
Dept. El. Power Engineering
Tallinn Univ. of Technology
Tallinn, Estonia
priit.uuemaa@student.ttu.ee

Haralds Vigants
Dagnija Blumberga
Dept. Electrical Engineering
Riga Technical University
Riga, Latvia
haralds.vigants@rtu.lv

Allan Puusepp
Dept. of Energy Trading
Eesti Energia
Tallinn, Estonia
allan.puusepp@energia.ee

***Abstract*—This paper investigates the possibilities how to optimize the industrial combined heat and power plant (CHP) daily operations and decision making process. The aim of the paper is to develop a method for an economic optimization of the industrial CHP. The method takes into account the industrial production together with an energy production in order to maximize the global profit for the entire facility. The method utilizes the electricity spot market price variation for the benefit of the market participant.**

***Index Terms*-- combined heat and power plant; demand side management; energy efficiency; industrial processes.**

I. Introduction

Industrial CHP optimal operation modeling has been widely studied. The traditional optimization method uses the available heat storages on site which allow shifting the load without affecting the factory industrial production in a negative way. The liberalization of the electricity markets are bringing in new dimensions for the optimization. Volatile price deviations on the electricity spot market allow industry to optimize the electricity cost by using its industrial production flexibility. This study is focusing to find the optimized operation and decision making model for the industry facility which owns and operates the on-site energy production unit.

From the opened energy market point of view the physical proximity does not necessarily give the economic advantage for the on-site electricity producer. The industrial electricity producer has to take into account the electricity market price and consider the market behavior. This in return gives the opportunity for the electricity consumer to exploit the market fluctuations to its benefit which is a key component to reduce the energy cost and hence maximize the profit.

The distinguishing nature of the CHP which separates this kind of electricity production from any other conventional power plants is the ability to use the produced heat in a profitable manner. Heat is either sold to the public heating network or utilized on-site for industrial purposes.

The main criterion between the industrial CHP plants and the public district heating (DH) plants is the size of the heat market. Commonly the industrial CHP-s are using the produced heat for them or selling it to one single customer, whereas the DH CHP plants are selling the heat to the public DH network, which is supplying the heat to numerous customers. In that sense the heat market is limited for the industrial CHP and it has no connection to the bigger market. This means the heat price has no variations and is fixed for a long period of time. Therefore the heat has a certain price for the facility and no profit can be earned from that. This makes the electricity load scheduling (LS) and demand side management (DSM) actions even more attractive for the industry.

In this study the industrial CHP is observed together with the industrial production in order to maximize the global profit for the whole facility. The model has to take into account the industrial production optimization as well in order to observe the influence of the decisions to each of the facility input and output variables. In order to avoid any conflicts of interest as well to make a clear separation of different products the key role of determining the optimal management point is to separate the different products by the existing markets. In this study it is expected that an industrial participant makes economically rational decisions. Like with any other item which has economic value if the market participant is able to produce and consume the same item, then the participant has to take into account the market price of that item. When the own cost of producing this item exceeds the market price then it is assumed this item is purchased from the market rather than produced on-site. Therefore any sub product which is produced inside the industrial facility has to be given a justified market price. In order to verify the profitability of producing sub products itself the production has to use a market price for the sub product price determination.

The paper has been divided into five sections. Section II gives an overview of the topic, section III outlines the possibilities in the wood industry and investigates the case study facility, section IV concludes the results and section V summarizes and gives guidelines for the future work.

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II. OVERVIEW OF THE TOPIC

A. Previous Research in the CHP Optimal Management

Several papers have shown that the optimized operation of the industrial CHP together with the demand side management (DSM) has a positive effect on the efficiency and profit [1] – [3]. Authors of [4], [5], [14] have developed methods to optimize the industrial CHP and the industry demand side management (DSM) in the incomplete information conditions.

Authors of [6] – [7] are showing the positive effect of the developed optimization technique under the open electricity market conditions. Papers [10] – [13] are proposing intelligent micro grids together with the optimization techniques in order to maximize the profit for the whole production facility. Articles [8] and [9] are proving that the consumer which is located at the same site with the electricity producer has the freedom to purchase the electricity from the market and therefore is free of its decision to choose the most feasible solution.

The key contributor which allows optimizing the production process through DSM actions is the electricity market where volatile price variations exist. The electricity spot market is like no other market where the price fluctuations can be considerable within one single day whereas the other goods have no spot market but only bilateral agreements which determine the price for a much longer period. The electricity market price for example in the North-European Nord Pool Spot area is varying frequently depending of the energy system state at each hour. It is a unique market place throughout the world where the price of the electricity is given only one day ahead and for each hour separately. Usually the price deviations are driven by consumption where the price is normally lowest during nights and highest during peak hours. This type of pattern can be easily expected from any usual trading day. The average example week day pattern is shown in the Fig. 1.

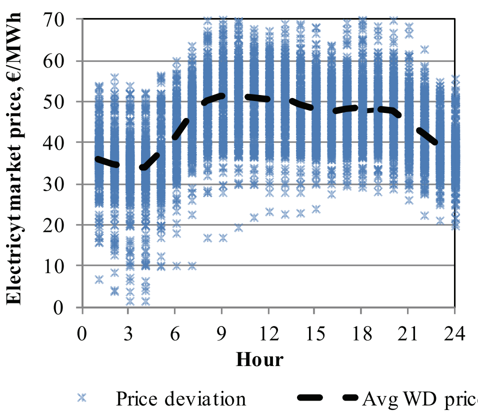

Figure 1. Typical Nord Pool Spot electricity market price pattern.

Changes in the market price should motivate the market participants to comprehend the market situation and exploit the process storages in order to make savings from the market price fluctuations. Industrial production process can only participate in the DSM actions if there are some storage possibilities. Utilizing the intermediate production storages allows the consumer to fill the process storages during the low price hours and consume the medium from the storage during the peak hours.

B. Market based approach of an industrial on-site energy Producer

The liberalized electricity market makes it possible to make the electricity transactions similar to other transactions. As in Nord Pool Spot trading areas the electricity is traded like any other commodity where the MWh can be purchased from the market based on the demand of the consumer or sold based on the supply of the producer, Fig.2.

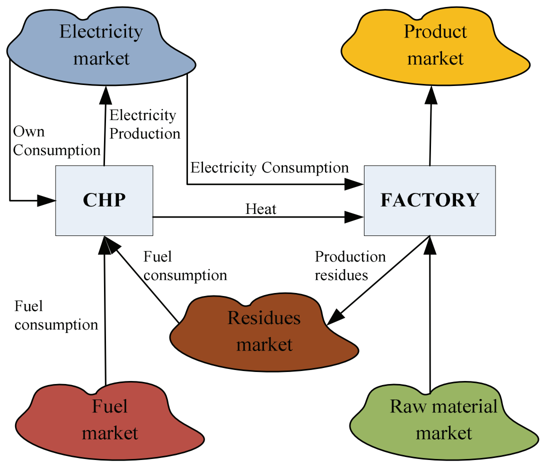

Figure 2. Industrial facility relations with the input and output markets.

The flows in Fig. 2 are representing the financial flows of the medium, not the physical flows. The principal approach of the current study is to optimize the production process based on the economic performance of the facility. In order to do that the precondition is the existence of a market. It means each of the given articles (except for the heat) should be easily sold on the market or purchased from the market without having any barriers. If the market prices are fluctuating and the facility has efficiently usable storages, then the optimization modeling needs to be executed in order to maximize the profit.

III. POSSIBILITIES IN THE WOOD INDUSTRY

A. Key figures describing the industrial CHP under investigation

The wood industry under investigation operates an on-site biomass fired CHP plant with an electrical output of 6.5 MW_e and heat output of 15 MW_{th}. At the same site the industrial factory's average consumption is 3.2 MW_e of electricity. As shown in the previous study [15] the consumption load is flexible in certain conditions. The facility ownership is the same for both the industry and energy production, making the global profit optimization as the ultimate goal.

In this study it is considered that the remaining markets other than electricity market volatility is extremely low and has only long term fluctuations therefore making it impossible to optimize the production according to the other markets behavior.

The electricity market however is extremely volatile and the pattern is somewhat predictable. For each coming day the prices are known one day ahead. Also the electricity production and consumption is controllable and adjustable within certain limits. Ability to control the load in the predicted variable market allows remarkable savings in the cost and maximizes the sales income.

B. *Wood Industry – Case Study*

The investigated facility has one single connection point with the electricity grid. It is equipped with smart metering allowing recording imported and exported electricity in each hour. Since the electricity production capacity is bigger than the consumption then most of the electricity is exported. The example monthly electricity export profile is shown on Fig. 3.

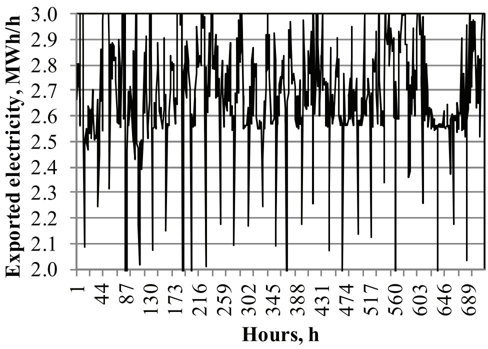

Figure 3. Facility exported electricity profile in the example month.

The optimization task is to maximize the income revenues. Using the market price forecasts these optimization tasks can be solved even more efficiently. Analysis of the sites electricity profile indicated that it is dependent on 3 different components. As shown in the Fig. 4 the profile dips are caused by the electricity production periodical decrease and the rest of the profile fluctuations are caused by the factory's consumption load variations.

According to the observations which were carried out in the investigated facility, the CHP production dips are caused by the regular soot blowing in order to keep the boiler surfaces clean and maintain the plant thermal efficiency. Based on interviews with the plant staff the soot blowing interval is chosen by the empirical experience but the time of the activity can be adjusted within any time during a 24 hour period. The irregular factory consumption dips are caused by non-planned shutdowns of some equipment. The CHP own consumption is fairly even and is considered as non-flexible load. Therefore the optimization task can be focused only on two profile optimizations – electricity production and factory electricity consumption.

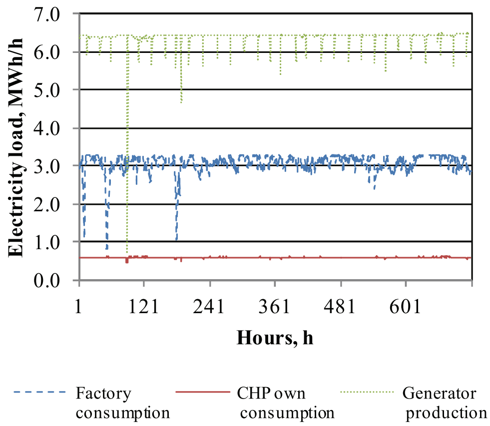

Figure 4. Separated load profile according to the different sources.

According to the staff there is some flexibility in the industrial production process where some of the consumption load can be stopped without affecting the final production output. Factory has the intermediate material storages which allow stopping time to time some production processes because the storages are full. The principal of the load shifting is shown on Fig. 5.

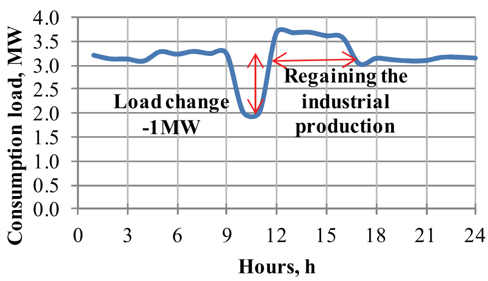

Figure 5. Wood industry electricity consumption flexibility.

The factory has medium material storages on the site which enable to produce the medium during the valley hours of electricity price and consume the medium on the peak hours. Factory has estimated that it can shift 10% of its consumption load and the rest of the 90% is the base load which cannot be shifted. The main criterion which allows this kind of flexibility is the nominal capacity of the motors which is higher than the average working capacity. The restrictions and assumptions are that the profit cannot be hindered due to the load shifting. By the facility internal calculations the income from the industrial product exceeds significantly any income from electricity production or load shifting. This means that any production loss due to the DSM actions is not accepted.

C. Optimization calculations.

The goal of optimization is to maximize the profit of the exported electricity over the total period throughout each given hour t.

$$\max_{C_t^O, M_t} \sum_t W_t^O \cdot P_t - \sum_t C_t^O \cdot P_t , \quad (1)$$

where W_t^O is the optimized electricity production at time t with maintenance included (MWh), C_t^O is the optimized electricity consumption at time t (MWh) and P_t is the electricity market spot price at time t (€/MWh).

In this kind of approach the optimum is calculated for each hour separately due to the different electricity price in every hour studied. In the case study facility the soot blowing can be defined as a scheduled mandatory maintenance which can be formulated through a binary variable M_t.

$$W_t^O = (1 - M_t) \cdot W_t , \quad (2)$$

$$M_t \in \{0,1\}, \quad (3)$$

$$M_t = 1 \Rightarrow \text{Maitenance}$$
$$M_t = 0 \Rightarrow \text{Production}$$

$$\forall t' \sum_{t'}^{t'+D+2} M_t \geq 2 , \quad (4)$$

where Mt is the binary variable for maintenance of electricity production at time t, W_t is the electricity production in ideal reference scenario without maintenances (MWh) and D is a maximum interval between two adjacent maintenances.

For the electricity consumption load shifting the load can be shifted between the minimum and maximum output. Whereas L is the relative amount of load shifting.

$$0 \leq L \leq 1 , \quad (5)$$

$$\forall t \;\; C_t^O \leq (1 + L) \cdot C_t^R , \quad (6)$$

$$\forall t \;\; C_t^O \geq (1 - L) \cdot C_t^R , \quad (7)$$

where C_t^R is the reference electricity consumption at time t (MWh). In this case study modelling the L has been given 10 different values from 0.01 until 0.1 with the step 0.01.

Optimized load profile can be accepted if the profit increase exceeds the LS external costs C_{LS}

$$E_{\exp}^O - E_{\exp}^R > C_{LS} , \quad (9)$$

where E_{exp}^R is the exported electricity total income on the reference scenario "operation as usual" , E_{exp}^O is the optimized exported electricity total income. Another constraint is that the electricity consumption volumes need to remain the same.

$$\sum_t C_t^O = \sum_t C_t^R . \quad (10)$$

This kind of constraint equitation means that the industrial product production also remains the same.

IV. RESULTS

The developed optimization model as per (1) is solved using Microsoft Solver Foundation using the Mixed Integer Linear Programming method. The spot prices are based on the historical Elspot Estonia price area prices in November 2013. The modeling was carried out by the flexible consumption of up to 10% from the average consumption load.

The consumption was modeled with 10 different scenarios based on the ability of load shifting capacity, from 1-10% (0.01 ≤ L ≤ 0.1). It can be seen from the Fig. 6 that the more the factory has shifting flexibility the more savings it brings. The pattern of the savings appeared to be linear between the flexibility and savings. As it can be seen with more than 10% flexibility the savings increase even more.

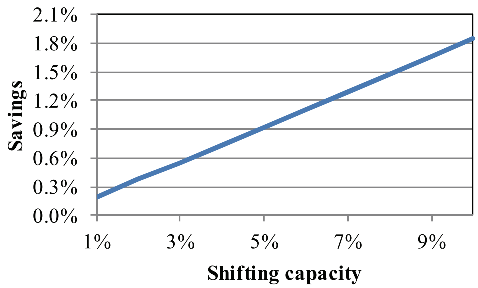

Figure 6. Consumption savings load shifting effect.

Load shifting capacity is the share of the consumption load from the average full load which can be shifted. In this study it is assumed to be up to 10% (L=0.1) from the average full load. The industry representative has confirmed that with some modifications in the production process this kind of flexibility can be achieved without any major reconstructions or investments. The results are shown in the Table 1.

TABLE I. THE OPTIMIZATION RESULTS

Actual spot price	42.32 €/MWh	Initial difference	Optimized load price	Difference after optimization
Generator average income	42.30 €/MWh	-0.04%	42.37 €/MWh	0.13%
Consumption average cost	42.36 €/MWh	-0.10%	41.59 €/MWh	1.72%
Export average income	42.22 €/MWh	-0.23%	43.28 €/MWh	2.27%

As it can be seen from the table the increase of the profit is significantly higher than the individual results from each action separately. This shows that there is a cumulating effect on the profit. Modeling results show that the increase in the profit would be 2.5 % from the initial "operation as usual" case when using the optimization method. The industry's representative has confirmed that the used method's error is acceptable and it represents the actual situation as good as the data provided allows to assume.

Fig. 7 shows the example day of the load shifting where the exported electricity profile is shifted according to the electricity price and given constraints.

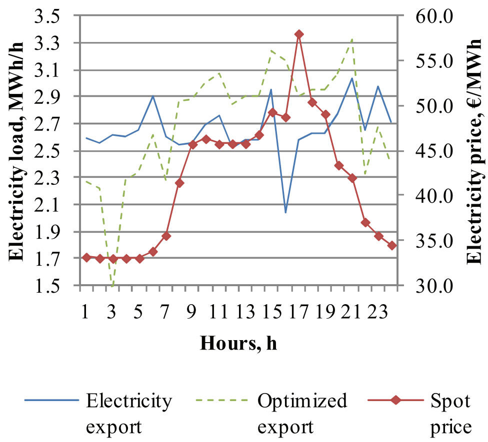

Figure 7. Load shifting profile with the ability of 10% consumption flexibility.

The optimization model shows the efficient use of the market situation where the market opportunities are fully exploited in order to maximize the profit.

V. CONCLUSIONS AND FUTURE WORK

An optimization principle has been created for the industrial CHP management under the open energy market conditions. The global optimum operation model for the electricity export has been created for the whole facility together with the on-site CHP plant. This model can be used to optimize the industrial CHP production taking into account the industrial load management opportunities, power plant load scheduling and the electricity market price.

The key decision making concept was to separate the different products by the markets which these products can be traded. The separated approach allows giving the better overview about the profitability of certain actions.

In addition it was showed that the different type of electricity loads have to be separated from each other and then compared against the electricity market price. The results of load patterns help to determine exactly the flexible loads. The flexibility of the loads allows maximizing the profit by shifting the load at the necessary time. Load shifting is done taking into account the electricity production and consumption together with its constraints.

Future studies should investigate the other markets influencing the operation of the plant and energy producer on the same way in order to optimize the production of the total facility. As it was shown, the highest impact to the profit was the change of the storage capacity and the load management actions. In the future the study should be also extended taking into account the market behavior for raw material and industrial end product.

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PAPER II

Uuemaa, P., Vigants, H., Blumberga, D., Drovtar, I., "Industrial CHP Excess Heat Efficient Usage for Cooling," *Energetika* [in press].

Industrial CHP Excess Heat Efficient Usage for Cooling

*Priit Uuemaa[a], Haralds Vigants[b], Dagnija Blumberga[b], Imre Drovtar[c]

[a]*Deptartment of Electrical Power Engineering, Tallinn University of Technology, Tallinn 19086, Estonia*
[b]*Deptartment of Electrical Power Engineering, Riga Technical University, Riga LV-1658, Lavtia*
[c]*Deptartment of Electrical Engineering, Tallinn University of Technology, Tallinn 19086, Estonia*

Abstract

This study investigates the possibilities how to utilize the combined heat and power plant (CHP) excess heat in the industry during the hot periods of time when the heat demand is limited. In order to maximize the CHP electricity production the efficient heat load has to be increased. The goal of this article is to present the solution for the industrial CHP excess heat utilization for the local cooling. The study introduces the method and model of how to evaluate the industrial CHP plant potential and economical benefit for the production of local cooling from the excess heat.

Keywords: combined cooling, heat and power plant; energy efficiency; HVAC systems; industrial processes.

1. Introduction

CHP plants are widely used in the areas where there is a heat demand. They can be categorized into two categories depending of the nature of the heat consumer. Firstly, the district heating (DH) CHP plants which use the DH network to transfer the heat to the residential area which is either a city or a local settlement. Secondly, the industrial CHP, which produces the heat to the on-site industry or for the group of industries nearby. Depending of the industry production profile, the heat consumption is usually lower on summer time whereas the cooling demand is the biggest. Therefore this makes the production of local cooling from the excess heat an efficient solution to improve the economical performance of the entire facility.

The maximum heat production is limited in the summer time due to the decreased heat demand. Since the industrial CHP plants are mainly working with back pressure turbines, in order to maximize the thermo dynamical efficiency, the electricity production will decrease accordingly during the periods of lower heat demand. Therefore, finding solutions to increase the heat load is a key factor for maximizing the CHP electricity production and hence the economical performance of the plant.

Technically a CHP plant can also operate in condensing mode during the summer period if the plant has sufficient auxiliary cooling devices. However the relatively low electrical efficiency and low electricity market price do not cover the variable cost of the fuel. Utilizing the excess heat for producing local cooling enables the CHP to increase its electrical output. In an ideal case it could run as a base load plant which produces electricity on full load all year round maximizing the operational profit. Primarily the additional income comes from increased electricity production. Some income would also come from savings on cooling costs that otherwise would be done with solely electricity driven chillers.

Contribution of this study is to investigate the local absorption chiller profitability in wood industry under open electricity market conditions. In the 2nd section the previous research is introduced, in the 3rd section the CCHP operation in the open electricity market conditions is introduced, 4th section outlines the possibilities in the wood industry and a specific example case study is performed. In the 5th section the study is concluded.

* Corresponding author.
E-mail address: priit.uuemaa@student.ttu.ee

2. Previous research on heat based cooling

Industrial three generation means production of electricity, heat and cooling in a combined cooling, heating and power (CCHP) plant. The authors of [1-3] have optimized the CCHP operation in order to minimize the operational cost and have concluded that the optimized CCHP operation have better economical results than non-optimized system. They have simulated a consumer with the cooling demand and shown that the cooling system which is driven by the recovered heat has operational savings and allows the CHP to increase its electrical output.

Heat based cooling is often not used due to the insufficient knowledge about its possibilities and also the high investment cost of the technology. Normally the industrial cooling demand is covered with electricity driven chillers [4]. Authors of [5] have studied the adsorption systems in different applications. They have introduced the development of relevant materials, technologies and projects. As they have concluded the adsorption chiller technology has a great potential for converting the waste heat to the useful cooling. However the most commonly available technology for the heat driven cooling is absorption chiller [5]. Absorption chiller enables to recover the heat and produce cold water. Authors of [7] propose to use the absorption cooling in summer time from waste heat in order to save costs. Authors of [8] have developed a new optimization method which optimizes the cost, emissions and social impact through using the absorption systems.

Cooling possibilities in the industry by using locally produced heat has been investigated intensively by authors of [9-11]. They all line out that the industrial absorption chiller has to be studied case by case, because it does not necessarily mean lower overall cost compared to the stand alone cold water production. They have shown it is worth to exploit the saving opportunities through heat based cooling. However their studies are mainly focused of lowering the cost and primary energy consumption rather than maximizing the profit. Authors of [12-14] have illustrated that it is profitable in commercial buildings large enough to use heat based central cooling unit. They prove that the waste heat based cooling is allowing the system to be operating in a more profitable manner than the system with the electricity based cooling. They also point out the importance of the size effect of the cooling system. This means that there has to be a minimum critical cooling load which makes it worth to use the central cooling rather than local chillers. In another studies the authors of [15-17] have introduced different optimization strategies based on the load distribution between heat and cooling energy production. The main idea of the authors [18-19] has been to investigate the environmental impacts and cost effectiveness of CCHP systems.

Previous research as described above has introduced different cooling technologies and proves the absorption based cooling is the most suitable waste heat based cooling technology. Therefore the absorption chiller is chosen for the production of industrial cooling in this study. The previous research has also shown the positive effect on the cost, emissions and fuel savings of the excess heat utilization in the CCHP systems. The focus of this study is to exploit even further and maximize the electricity production by converting the existing CHP into the CCHP plant. This conversion helps to improve the economical performance of the entire industrial facility and hence maximize the profit.

3. CCHP operation in the open electricity market conditions

Majority of the CHP variable cost is usually the fuel cost. Therefore the CHP is operated based on the cost of the fuel. In normal operation the power plant is expected to run even in condensation mode if the electricity production income covers the variable cost of the plant [20]. Otherwise it is more profitable not to run the pant.

The marginal cost of the CHP is the cost to produce one extra MWh of electricity. In this study the marginal cost definition is rather equal to the short term marginal cost. When changing the power plant load from the partial load to the full load then there is no other significant marginal cost than the fuel cost. The CHP is expected to increase the electrical output as long as the plant marginal cost is covered. Therefore traditionally the criterion for operating the power plant is written in the equation 1:

$$W_e \cdot P_e > W_f \cdot P_f , \qquad \text{Eqn. (1)}$$

where W_e is the production of electricity in MWh, P_e is the electricity spot market hourly price in €/MWh, W_f is the consumption of fuel in MWh and P_f is the price of the fuel in €/MWh. Therefore in any case where income exceeds the variable cost of the production, the plant is expected to produce electricity.

CHP produces two forms of commercially usable energy – electricity and heat. In this study also the third sales article is introduced – cold production. Usually the traditional biomass fired power plants have quite low electricity share in the total produced energy [21]. This however is compensated with the significantly high total efficiency on conversion the primary fuels to the useful energy [22]. Therefore utilizing the heat in a commercially rational way distinguishes the CHP from a conventional heat condensing power plant. It allows the producer to be more competitive on the electricity market as well as save the primary fuels in the energy sector. In this aspect the existence of the heat load has the critical influence on the CHP operation. Introducing the cold production enables the CHP to increase the heat production and therefore also produce additional electricity to the market. The CHP technical thermo dynamical efficiency can be described as follows in equation 2:

$$\eta_n = \frac{W_e + W_h}{W_f} = \eta_e + \eta_h, \qquad \text{Eqn. (2)}$$

where W_e is the production of electricity in MWh, W_h is the production of heat in MWh, η_n is the nominal total efficiency of the plant, η_e is the electrical efficiency of the plant and η_h is the heat efficiency of the plant. Usually the biomass CHP-s total efficiency is in the range of 0.85-0.9.

The heat production W_h can be divided between the heat consumer and the cooling consumer as follows in equation 3:

$$W_h = W_h^H + W_h^C, \qquad \text{Eqn. (3)}$$

where W_h^H is the heat that is used for heating and W_h^C is the heat that is used for cooling. Cooling heat is the sum of the different types of cooling applications, in this study it is an air conditioners and process cooling as shown in equation 4:

$$W_h^C = \frac{(W_{AC} + W_{PC})}{\eta_{ABS}}, \qquad \text{Eqn. (4)}$$

where W_{AC} is the cooling load of air conditioners in MWh, W_{PC} is the cooling load of process cooling in MWh and η_{ABS} is the efficiency of the absorption chillier.

The main principal of the CHP plant is that usually it runs according to the heat load due to the reason that in the condensation mode it is not competitive enough on the electricity market. Ability to sell the produced heat to the DH network or to the industrial customer makes the CHP plant electricity price much more competitive. When the CHP plant can sell the produced heat then this income will be added on top of the electricity income. This in return allows the CHP plant electricity price to be lower than the average market price.

Heat market enables the CHP plant to exploit the total efficiency for its benefit. However maximizing the total efficiency decreases the electricity share in the total energy production mix and this share is lower than in conventional condensing power plants. Therefore with the same primary fuel the condensing power plant electricity price is lower and it can sell its electricity on the spot market whereas the CHP electricity offer is not accepted due to too high price. The price formation in the electricity spot market depends on numerous aspects, but as explained above the average electricity spot price level is too low for the biomass CHP. In the traditional condensing power plant the electricity output is maximized sacrificing the efficiency of total primary energy usage. In order to run the CHP plant electrical output even more than the available heat load would allow then a criterion 5 below which is in accordance with equation 1, have to be full-filled:

$$W_e^{extra} \cdot P_e + W_h^{extra} \cdot P_h > W_f^{extra} \cdot P_f, \qquad \text{Eqn. (5)}$$

where W_e^{extra} is the additional electricity produced due to the increased heat load in MWh_e, W_h^{extra} is the additional artificial heat load in MWh_{th}, P_h is the price of the heat in €/MWh, W_f^{extra} is the required additional fuel for the bigger load point in MWh. The price of the additionally produced heat can be either negative or positive depending if the additional heat is commercially needed or it is just cooled down. If it is cooled down (condensed) then there is negative cost for the condensing operation itself, i.e. electricity cost of the fans, etc operational condensing costs. If it is commercially needed for the cooling then there is a positive price for that additional heat. In this study the available cooling demand is covered by the additional heat which is produced in the CHP. When converting some of the CHP heat production to commercially needed cold water the plant becomes a CCHP.

Heat, which is consumed for commercially needed cooling, price can only be determined by the alternative cost compared to costs occurring with traditional chillers or air conditioners (AC-s). Usually there is no market for cooling and hence no market price for cooling because there is no district cooling networks. The cooling energy price can only be calculated by the savings it gives to the facility when it switches over from the electricity driven local cooling to the central excess heat based cooling. Therefore the excess heat income can be written in equation 6 as follows:

$$W_h^C \cdot P_h^C = S_{AC} + S_{PC}, \qquad \text{Eqn. (6)}$$

where P_h^C is the price of the heat which is used for the absorption chiller in €/MWh, S_{AC} is the operational cost savings with the absorption chillier compared to reference case electricity based air conditioning in €, S_{PC} is the operational cost savings with the absorption chillier compared to reference case electricity based process cooling (PC) in €.

In order to define the savings then two different scenarios have to be compared. What are the operational cost of the reference case AC and PC when this cooling is produced separately by the electricity driven applications and what is the operational cost of the absorption chillier based cooling. The savings can be calculated according to the equations 7 and 8:

$$S_{AC} = (C_e^{AC} - C_e^{ABS}) \cdot (P_e + P_T), \qquad \text{Eqn. (7)}$$

$$S_{PC} = (C_e^{PC} - C_e^{ABS}) \cdot (P_e + P_T), \qquad \text{Eqn. (8)}$$

where C_e^{AC} is the reference case AC's electricity consumption in MWh, C_e^{ABS} is the absorption chiller based system electricity consumption in MWh, C_e^{PC} is the reference case PC electricity consumption in MWh, P_T is the remaining marginal electricity consumption cost in €/MWh.

Since the consumer has various price components on the purchased electricity then these components have to be taken into account. They are separated from the electricity spot price due to the reason that the spot price is given for each hour separately throughout the year, but the remaining components are most likely fixed by the regulation. However these components vary significantly through different countries and locations therefore they cannot be clearly written in the equations. It rather depends on the location specific regulation. For example the MWh which is purchased through the public network includes the retail cost, balancing cost, system operator transfer cost, distribution operator tariff, mandatory government taxes, etc direct costs. In most of the places these costs can be even higher than the electrical energy itself. However if the facility consumes the electrical energy which is produced on the site directly then only some of these components can be added, like taxes because the electricity is not purchased through the public network. Therefore in order to determine the facility electrical energy savings the location specific marginal electricity cost P_T has to be taken into account case by case.

It has to be outlined that heat based cooling which is based on the absorption chillier has a size based cost-effect. It can be assumed that a small cooling capacity can be full-filled much more efficiently locally with the electrical AC, rather than provide cold water from distance which requires additional water pumps and etc. operational energy and hence higher cost. If all the extra heat W_h^{extra} is consumed by the absorption chiller then equation 3 could be rather written as follows in equation 9:

$$W_e^{extra} \cdot P_e + S_{AC} + S_{PC} > W_f^{extra} \cdot P_f, \qquad \text{Eqn. (9)}$$

This means that the CHP plant will run on market conditions with the higher electrical load if the savings from the absorption chiller usage together with the additional electricity income are bigger than the cost of the extra fuel. In biomass based power plants there is usually in the European Union always some subsidies involved [23]. Absorption chiller based cooling enables the CHP plant to increase electricity production and hence receive the additional subsidy income on top of the electricity price as shown in equation 10:

$$W_e^{extra} \cdot (P_e + S_R) + S_{AC} + S_{PC} > W_f^{extra} \cdot P_f, \qquad \text{Eqn. (10)}$$

where S_R is the case by case specific subsidy in €/MWh$_e$ received by the producer according to the regulation. Since the feed-in tariff based subsidy do not require the producer to participate on the electricity market then this type of subsidy is not taken into account in this research. In equation 10 the so called feed-in premium is considered.

There are no restrictions to run the CHP plant on condensing mode, but in that case the plant has to manage with market conditions. This however is not possible in the Estonia or other Baltic States where the fuel cost is higher than income from electricity [24-26] as per equation 1. It should be noted that the profitability of exploiting heat based cooling opportunities is strongly affected by the local energy policies and therefore is a subject to the energy policy changes.

Usually the standard biomass fired CHP plant total efficiency η_n is higher [22] than normally required η_R [23] by the regulation in order to receive the subsidy. Therefore the plant can operate in the partially condensing mode at certain higher range of efficiency as long as the minimum required total efficiency is maintained, criterion 11:

$$\frac{W_e + W_e^R + W_h}{W_f} \geq \eta_R, \qquad \text{Eqn. (11)}$$

where W_e^R is the additional electricity that can be produced without losing the subsidy and η_R is the minimum required total efficiency for receiving the subsidy. In that case where the $\eta_n > \eta_R$ additional regulatory dependent electricity production can be written as follows in equation 12:

$$(W_e^{extra} + W_e^R) \cdot (P_e + S_R) + S_{AC} + S_{PC} > W_f^{extra} \cdot P_f. \qquad \text{Eqn. (12)}$$

The optimization algorithm for the total CCHP plant operational profit maximization can be written in equation 13 as follows:

$$max \sum_{t=1}^{n}(W_{et} \cdot (P_{et} + S_{Rt}) + W_{ht}^{H} \cdot P_{ht} + W_{ht}^{C} \cdot P_{ht}^{C} - W_{ft} \cdot P_{ft}), \quad \text{Eqn. (13)}$$

where t is the time period of one hour.

4. Possibilities in the wood industry CHP-s

4.1. Key figures describing the facility under investigation

This section uses the method developed in previous section to investigate excess heat utilization for cooling purposes and find the economical feasibility of the cooling process. The wood industry located in Estonia is under investigation. The industry main production activity is wood processing. Therefore the facility needs the heat for the drying process and cooling air to cool down the final product. Additionally cooling is also needed for the utility and office rooms which is at the moment done by local air conditioners. The industry also operates the on-site CHP plant which produces the required heat for the drying process. The key parameters of the industry under investigation are summarized in the Table 1.

However since the drying process requires less heat in the summer time due to the higher ambient air temperature the excess heat is left over. Figure 1. illustrates the actual heat production profile for the industrial CHP under investigation. The studied CHP plant is built with a backpressure turbine making it impossible to adjust the heat production without losing the electrical output. Therefore the decrease in the heat output also decreases the electricity output. At the same time in Figure 1. is also included the modeling results of the possible cooling capacity that could be added on top of the overall heat load. The remaining peaks which still have excess heat available can be simply cooled down with the dry coolers which are installed in the CHP plant while still maintaining the required minimum 75% total technical efficiency.

During the times of higher ambient temperature the drying process uses less heat. On the other hand the higher ambient air temperature requires more cooling energy to cool down the industrial product which is more energy intensive when the temperature rises. Therefore this makes the cooling demand ideal substitute for the heat consumption decrease. In the Figure 1. there is also some normal operation dips which are either caused by planned or unexpected maintenances. Due to the reason the modeling uses the case study facility actual historical data these dips are not taken out from the profile and are not meant to be filled with cooling load either. These dips are rather shown as a part of the modeling results.

Table 1. Key figures of the industrial facility under investigation

Input data	Variable	Value	Unit	Source
CHP electrical output capacity	W_e	6.50	MW_e	Case study industry
CHP heat output capacity	W_h	18.00	MW_{th}	Case study industry
CHP total efficiency	η_n	0.89		Case study industry
Fuel price	P_f	12	€/MWh	[24-25]
Subsidy, feed in premium		53.7	€/MWh_e	[27]
Price (savings) for cooling	S_C	0.00	€/MWh	Case study industry
Process cooling airflow		90 000	m^3/h	Case study industry
Process cooling temperature		5	^0C	Case study industry
Heat exchanger efficiency		0.85		Case study industry
Air conditioners (AC) capacity		0.334	MW_{th}	Case study industry
AC Load factor, $t>10^0C$		1		Case study industry
AC Load factor, $-10^0C < t < 10^0C$		0.75		Case study industry
AC Load factor, $t < -10^0C$		0		Case study industry
Absorption chiller efficiency	η_{ABS}	0.75		Case study industry
t^0 below full heat load required	t_{max}	10.00	^0C	Case study industry
Investment cost of the absorption chiller		170 000	€/MW_{th}	Case study industry

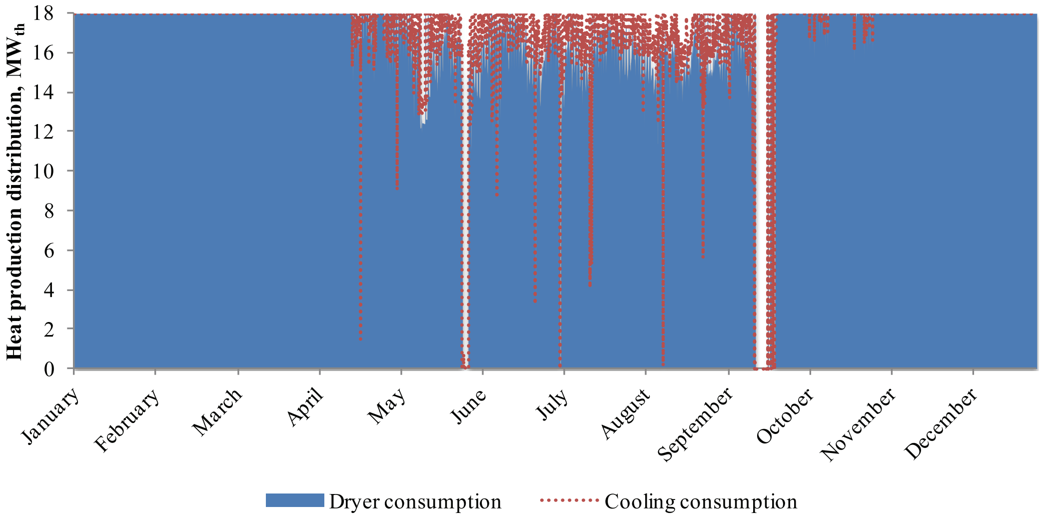

Fig. 1. Case study facility actual heat consumption profile where the added cooling load can help to even out the heat consumption in summer period.

From Figure 1. can be seen that the majority of the heat is used by the heat consumer which is the dryer unit and the heat valleys are covered by the cooling demand in the summer period. The combined heat load makes the production profile much more close to the base load plant profile. This in return allows more stable operation. The actual case study facility excess heat volume relation to the ambient air temperature is shown on the Figure 2. As explained above in order to maximize the electricity production the dry coolers are necessary to cover the reaming excess heat peaks which cannot be covered by cooling load.

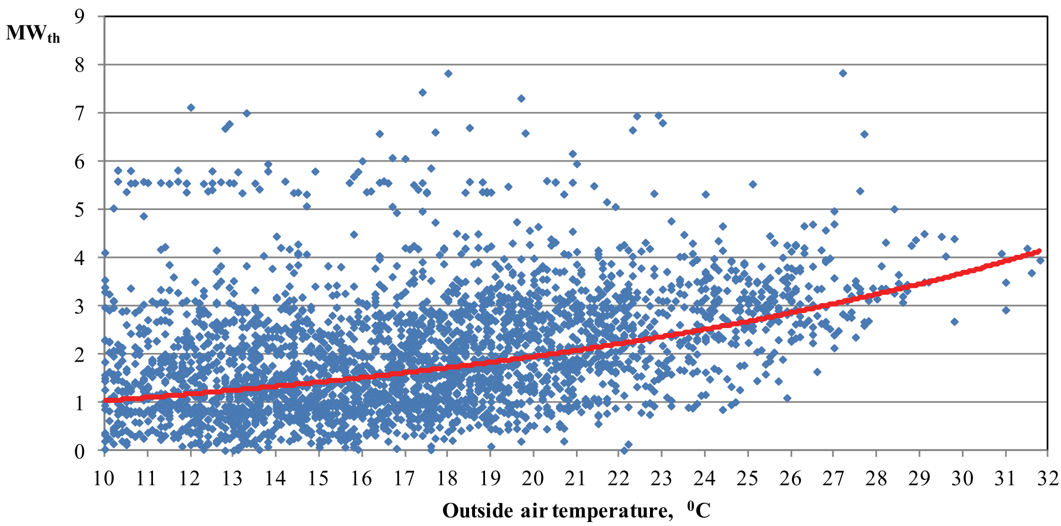

Fig. 2. Case study facility existing excess heat production relation to the ambient air temperature.

The excess heat deviation in the same ambient air temperature range is caused by the different operational influences. For example if the heat consumer has more pollution like dust in the system the heat transfer is poorer and hence the more excess heat is left over. Therefore the auxiliary cooling devices would also improve the reliability of the system.

4.2. Wood industry case study

In Nord Pool Spot market Estonia area small scale CHP plants cannot run on condensing mode in the market conditions because the fuel cost exceeds the electricity market price. According to the Estonian statistical database and state forest sales prices the average biomass fuel price was 12 €/MWh [24-25] in 2012. At the same year the average electricity market price was 39.2 €/MWh [26]. If the CHP total technical efficiency η_n is 89% then the fuel consumption on full load is 27,5 MW. According to the equation 2 this makes the electrical efficiency η_e 24%. This means that the 24% of the primary energy is converted to the secondary energy, in this case electricity. With this electrical efficiency the power plant short term marginal cost would have been 50.0 €/MWh$_e$ which significantly exceeds the electricity price. Traditional biomass fired small CHP plant would not be operating in these conditions.

Currently the industry has 0.3 MW$_{th}$ of cooling load for utility rooms and office which is at the moment cooled with electrical air conditioners. The wood processing requires also 0.8 MW$_{th}$ of cooling load to cool down the product. At the moment it is cooled down with outside air and not using the chillers. However if a heat exchanger would be used the electricity consumption of the fan would be lower. The company also loses some of the quality of the product due to the lack of cooling capacity during summer period. In total the existing cooling demand is 1.1 MW$_{th}$. However in order to convert this cooling capacity from the heat network and taking into account the conversion factors, the total cooling load in heat network would be 1.7 MW$_{th}$ as shown in the Table 2. As it can be seen from the Figure 2. the excess heat production can be up to 7.8 MW$_{th}$ which exceeds the cooling demand. Therefore the remaining 6.1 MW$_{th}$ excess heat has to be cooled down by the dry coolers shown in Figure 3. in order to maximize the electricity production.

The industry under investigation operates the CHP plant with the output power of 6.5 MW$_e$ and 18 MW$_{th}$ throughout the whole year, stopping only for annual maintenance. The heat is used currently 100% in the drying process of the same company. However in the summer time the heat demand for the drying process decreases due to the higher ambient air temperature. At the same time the cooling capacity rises for the electricity rooms cooling and for the process cooling. The proposed system for the developed industrial three generation is shown in the Figure 3.

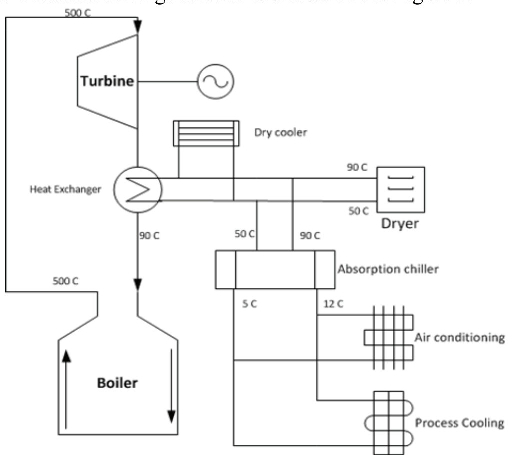

Fig. 3. Proposed technical solution for the Industrial CHP cooling system.

In Figure 3. the proposed process diagram is shown for the case study facility. Instead of using all the heat in the dryer and being dependent of the dryer heat consumption, the CHP can be run also using the excess heat in the cooling demand. For the cooling demand the absorption chiller is needed in the conversion of the heat to the cold water. In case the cooling load is not sufficient enough to maximize the electricity production the dry coolers will start to work to cool down the remaining portion of the heat and maximize the electricity production and hence the profit.

4.3. Results

Case study industry calculation results for the cooling energy production are given in the Table 2. As it is shown the payback time for the absorption chiller is less than 6 years. In addition to that there is an environmental saving through less used primary fuels.

Table 2. Case study industry calculation results

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	MW_{th}
Heat for cooling		2 927	MWh
Cooling load peak		1.7	MW_{th}
Additional condensation need		3254	MWh
Condensation peak		6.8	MW_{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 time		5.6	Years

The above case study calculations are done with the assumption that no heat is wasted or condensed. The payback time for the absorption chiller is calculated on the additional useful heat load that it provides. The savings are counted as 0, because due to the small scale cooling demand there is no size effect and the operation cost of the absorption chiller are as bg as the existing cooling equipment operation cost. If the existing cooling devices are replaced by the absorption chiller then there will be also some electricity consumption involved – cold water pump, absorption chiller own consumption etc. Therefore in this study the electricity consumption is neutral when making the transfer from existing electricity driven cooling system to the absorption chiller based cooling. The main income in this study comes from the CHP increased electricity production.

For the purpose of the simplification of the calculations in this study the capital cost and the interest rates were not taken into account. If some additional field tests are done then these can be taken into account in future studies. In case there will be some operational savings involved then this makes the feasibility even better.

It should be noted that this study was performed by taking into account the existing subsidy mechanisms and therefore the results are dependent of the energy policy. In case the energy policy should change the results can differ as well. However the developed method is still valid in any case even when there is no subsidy mechanism involved, because the equations can still be used for the feasibility study. The developed method is not dependent of the subsidy mechanism, but rather takes this into account, because it plays a key role in the case study calculations. However the developed method can be used in any CHP system conversion calculations. This study focused only on the producer aspect and did not take into account the indirect influence for the other market participants or wider aspects to the national energy mix.

5. Conclusion and future work

The traditional CHP plant can be converted into a CCHP plant if sufficient cooling demand is available. This study developed a method to calculate and assess the effectiveness of the CHP conversion to a CCHP plant. Actual case study was performed on the existing wood industry facility which operates the on-site CHP plant. Case study facility actual data was modeled for the calculation purposes. The investment payback time for the absorption chiller based cooling technology was found to be less than 6 years. Using the absorption chiller enables a CHP plant to become a CCHP plant which also produces more electricity in summer period due to the increased overall heat load. Additionally producing the cooling energy from excess heat means also savings in the environmental aspect through savings in primary fuels.

In future the developed approach should be studied on the similar industrial CHP-s which have a constant cooling need and compare it to the results found in this study. Furthermore an actual practical case study conversion should be made in order to compare the practical results with the theoretical results found in this paper. The practical conversion tests would be especially necessary to compare the heat based cooling operational savings with the traditional cooling.

Acknowledgements

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PAPER III

Vigants, H., **Uuemaa, P**., Veidenbergs, I., Blumberga, D., ”Cleaner pellet production – an energy consumption study using statistical analysis,” *Agronomy Research*, pp.633-644, vol.12(2), 2014.

Agronomy Research **12**(2), 633–644, 2014

Cleaner pellet production – an energy consumption study using statistical analysis

H. Vigants[1,*], P. Uuemaa[2], I. Veidenbergs[1] and D. Blumberga[1]

[1]Department of Electrical Power Engineering, Riga Technical University, Kronvalda bulv.1, LV-1010 Riga, Latvia; [*]Correspondence: haralds.vigants@rtu.lv
[2]Department of Electrical Power Engineering, Tallinn University of Technology, Ehitajate tee 5, EE19086 Tallinn, Estonia

Abstract. This study investigates and analyses the methodology for introducing cleaner wood pellet production. A statistical model is developed for the energy consumption analysis. Efficiency indicators have been chosen which allow determining the impact on the production process. The developed model can be used in other similar type of industries. This study has processed large empirical data with statistical methods in order to establish the efficiency indicators. The modelled results enable to define the indicators which lead to higher efficiency and hence to the cleaner production.

Key words: Energy efficiency, energy optimization, improvement of the production process, industrial process.

INTRODUCTION

Production of wood pellets in the Baltic countries has been growing (Mola-Yudego et al., 2013) as new large and small scale facilities emerge. Cogeneration plants are added next to the most advanced production sites of wood pellets in order to improve the production efficiency and secure cleaner production (Anderson & Toffolo, 2013; Kohl et al., 2013). The concept of cleaner production comprises the aspects of resources consumption. Reducing the resources consumption is an essential tool for industrial production. Efficiency is the basis for analysing and developing guidelines for continuous improvement in the production process (Song et al., 2011). At pellet production facilities, these resources are biomass, which is the raw material for pellets, and fuel for energy production, electricity, heat, and water. The contribution of this study is to develop a model for efficient use of these resources.

The second section introduces the materials and methods; the 3rd section outlines the modelling study results and includes the discussion. The 4th section concludes the study and makes recommendations for future work.

MATERIALS AND METHODS

Production description

When wood pellets are produced, they have to comply with generally accepted quality standards. Only clean sawdust can be used for production. The sawdust may not contain any impurities, it has to be dry, free of any sand, abrasive particles and chemistry. The produced pellets must be mechanically robust, should not contain any small sawdust particles, and have to be free of any foreign objects.

Damp sawdust is the basic material for the production of wood pellets. After additional processing, cellulose fibre and technological wood chips can also be used for the production. Processing of wood chips takes place at a special cutting device. The system of the cutter consists of a range of electrical machines like chippers, peelers, conveyors, ventilators, hydro devices, etc.

The wood chips that are made of branches and bark can be used as fuel and are combusted for production of flue gases and for energy production in the cogeneration plant. The furnace system in the flue gas production consists of several electrical motors that power the equipment for ensuring operation of the furnace, i.e. heating, cooling, feeding of fuel, ventilators, valves, and hydro machinery. The heat from the cogeneration plant on the other hand is transferred to belt-type dryers. The biggest electricity consumers of belt dryers are ventilators, which suck heated air through sawdust.

Sawdust needs to be dried to obtain the required humidity level for the production of wood pellets. Dried sawdust material is dosed to a hammer mill where the sawdust is crushed. During the milling process, dried sawdust is turned into small particles and dust, a uniform substance is obtained. The milling system consists of several electrical motors that power the equipment to ensure milling of sawdust, i.e. heating, cooling, a dosing device, a ventilator, a worm-type transporter, a mill, and hydro machinery.

In the granulating device, there is a process during which the mix of sawdust is delivered into two pressing rolls and a rotating matrix. The process results in production of hot pellets with a diameter of 8 mm. The following process is cooling and screening, where the pellets become hard and are cleaned of any dust. After this process, the pellets are ready for storage and transportation. The granulating system consists of several electrical motors that power the equipment, i.e. conveyors, suction devices, coolers, worm-type transporters, a vibrant-sieve, dosing devices, a mixer, a central lubricating system, and presses. On Fig. 1 the operational scheme of the pellet production facility with indications to analysed data is shown.

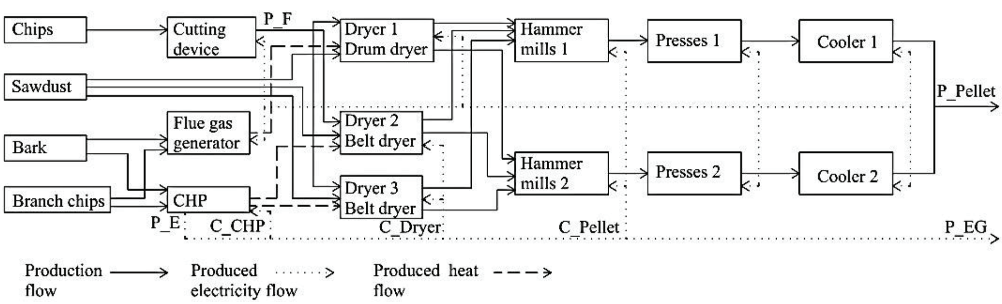

Figure 1. The operational scheme of the pellet production facility with the analysed indicators.

If power consumption at an industrial production facility is reduced, the share of generated electricity available for sale on the electricity market increases. Optimization of the production of the entire facility reduces the electricity bill of the pellet plant and increases the revenues from electricity sales.

This study will provide an analysis of power generation at a cogeneration plant, *P*_E. The target is to find the factors which have an impact on the power generation and therefore, once these factors have been defined, the next step is to optimize the production accordingly. Table 1 shows the list and explanations of the analysed data.

Table 1. Analysed data

Abbreviations	Explanation	Unit
*C*_CHP	Cogeneration plant power consumption	kWh
*C*_Dryer	Power consumption of the belt dryers	kWh
*C*_Pellet	Power consumption of the pellet production facility, excluding the belt-type dryers	kWh
*E*1 = *C*_DP	Power consumption of granulation	kWh
*C*_Total	Total power consumption	kWh
*P*_E	Produced electricity	kWh
*P*_EG	Produced electricity to grid	kWh
*P*_Pellet	Produced pellets	t
*P*_F	Sawdust crushed in the cutting device	m^3
*C*_DP/*P*_Pellet	Power consumption per produced ton of pellets	kWh t^{-1}
*C*_CHP/*P*_E	Power consumption per generated kWh	kWh kWh^{-1}

Analysis and data processing

Authors (Savola et al., 2007; Söderman & Ahtila, 2010) have used the modelling programme MINLP, MILP or simulation software (Mikita et al., 2012; Mobini et al., 2013). In this study, the empiric data was processed by applying statistical methods for data processing, correlation, and regression analysis. By means of a correlation analysis, the mutual link between two values and its strength are determined. The regression analysis is used for identifying the statistical importance of the multi-factor regression model and its coefficients (Blasnik, 1995).

The computer software STATGRAPHICSPlus was used for statistical processing of the data and development of the multi-factor empiric model. A similar model has been developed by other authors (Revina, 2002; Beloborodko et al., 2012).

In order to select the type of the regression equation, the linkage of the parameters by means of performing the correlation analysis is established by a single-factor linear model. The strength of the mutual link between independent and dependent random variables (correlation) can be assessed by means of a correlation coefficient. In case of a single-factor mathematic model, the Pearson's equation (1) is used for its estimation:

$$r = \frac{\sum_{i=1}^{m}(x_1 - x)\cdot(y_1 - y)}{(m-1)\cdot S_x \cdot S_y}, \tag{1}$$

where: x_i and y_i are the independent variables and pairs of their corresponding dependent variables; x and $y$are the arithmetic values of independent and dependent variables; S_x and S_y are the variables of the selection dispersion.

Correlation coefficients were used for evaluating the accuracy of the mathematic models describing the strength of the correlation. It is assumed that a correlation is good if the correlation coefficient is above 0.8. It should be noted that in software for statistic processing of data, the squared correlation coefficient is usually calculated. When the value R^2 is multiplied by 100, the value that characterises the changes of dependent variables is described by the resulting empiric equation. For example, $R^2 = 0.9$ indicates that the relevant regression equation characterises 90% of the changes of the dependent random variables.

Correlation analysis of produced electricity

In this study, the purpose is to analyse the operation of the production facility and find the correlation between produced electricity *P*_E and the following parameters:

- Cogeneration plant power consumption *C*_CHP, kWh;
- Power consumption of the belt dryers *C*_Dryer, kWh;
- Power consumption of the pellet production facility *C*_Pellet, kWh;
- Produced pellets *P*_Pellet, t;
- Crushed sawdust *P*_F, m^3.

RESULTS

Only the graphs where correlation between the values of dependent variables and independent variables can be seen are presented below. The dependence of electricity generation on the auxiliary power consumption of the cogeneration plant *C*_CHP is presented in Fig. 2.

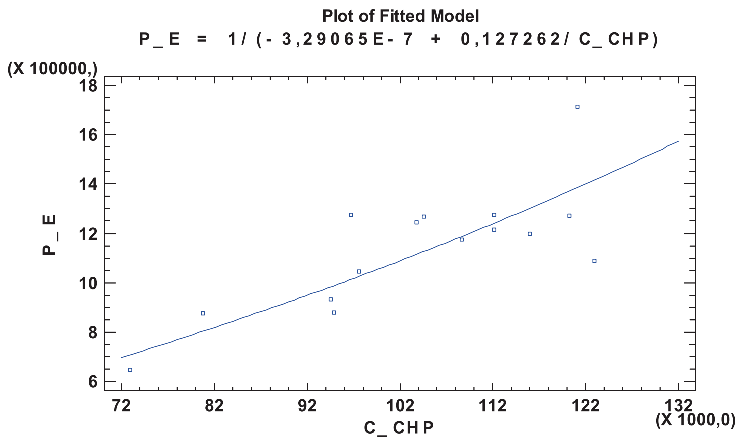

Figure 2. Produced electricity *P*_E depending of the CHP power consumption *C*_CHP.

In Fig. 2, it can be seen that there is a good mutual correlation between both variables. The value of the squared correlation coefficient as determined by the analysis is $R^2 = 0.75$ and the correlation coefficient $R = 0.87$. The relationship between the variables is non-linear and it is defined as follows, (2):

$$P\_E = 1/(-3.29065E\text{-}7 + 0.127262/C\_CHP), \quad (2)$$

The Eqn (2) explains 75% of the analysed changes in the data and it can be used for approximate calculations. 25% of generated electricity should be explained by the impact of other parameters.

The analysis of the data correlation shows that there is a certain correlation between the produced electricity P_E and the power consumption of the pellet production facility C_Pellet. The changes of the values are presented in Fig. 3.

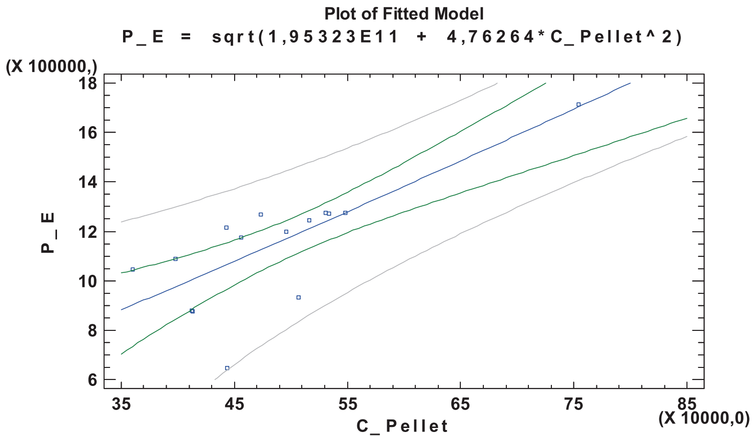

Figure 3. Produced electricity P_E depending on the power consumption of the pellet production facility C_Pellet.

The mutual correlation of the analysed variables is described by the value of the squared correlation coefficient $R^2 = 0.71$ and the correlation coefficient $R = 0.84$. The relationship between the variables is non-linear and it is defined as follows, (3):

$$P\_E = sqrt(1.95323E11 + 4.76264 \cdot C\_Pellet^2), \quad (3)$$

The mutual correlation of the variables is slightly lower than the correlation to the CHP electricity consumption. Eqn (3) explains 71% of the changes in the studied data. The impact of other parameters is higher, e.g. 29% of the electricity generation. The review of the correlation of other parameters demonstrates that there is no considerable correlation. Therefore, in further multi-factor regression analysis, the changes in the dependent variable of the produced electricity depend on two factors, i.e. the cogeneration plant power consumption C_CHP and the power consumption of the pellet production facility C_Pellet, Eqn (4):

$$P\_E = f(C\_CHP; C\_Pellet), \quad (4)$$

The performed correlation analysis of the data makes further regression analysis easier, as the set of factors that needs to be included in the multi-factor regression equation has been established.

Regression analysis of the data of power generation

The regression analysis is aimed at obtaining an empirical equation that would provide a quantitative description of the power generation depending on the indices that characterise the operation of the pellet production facility. These characteristics are statistically important and would serve as the basis for improving and evaluating the energy efficiency of the production facility. The regression analysis defines the accurate quantitative parameters of the change in random variables, i.e. explains the importance of the stochastic link by functional relationships.

The sequence of the regression analysis was as follows:

- the rule of the distribution of the dependent variable, i.e. the produced electricity *P*_E, was verified;
- the regression equation was established by applying the smallest square method;
- statistical analysis of the obtained results was performed.

The results of a regression analysis are correct if the rules for its application are complied with (Beloborodko et al., 2012). The number of rules is high and they cannot always be fully followed in practice. There are several main preconditions behind the application of the regression analysis. The use of the regression analysis of the data is correct if the normal distribution law is applicable to the dependent variable (produced electricity *P*_E). This requirement is not applicable to independent variables. The above means that the analysis starts with establishment of the distribution of dependent variables and the analysis may be continued if this distribution complies with the rule of the normal distribution. The results of verification of the rule of distribution are presented in Fig. 4. Normal distribution within logarithmic coordinates is graphically presented by a line. As can be seen in Fig. 4, the analysed data are placed close to the line in the graph. It means that the distribution is close to the rule of normal distribution and the application of the regression analysis is justified.

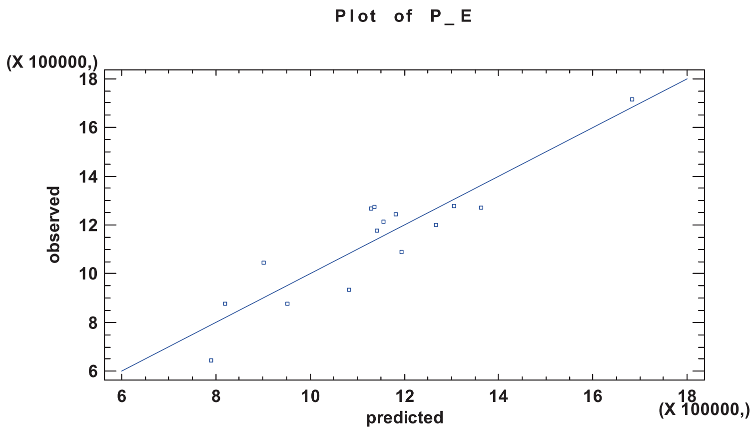

Figure 4. Distribution of the produced electricity *P*_E values.

When empirical models are developed in the form of the regression equation, several issues have to be solved. Whether the model comprises all the independent variables describing the analysed phenomenon and whether the model does not comprise unnecessary and non-essential variables, thus making the model too complicated. The answer to the above questions is provided by evaluation of the statistical importance of the variables contained in the model and the dispersion analysis of the model (Beloborodko et al., 2012).

The regression equation that is used by the author does not contain the effects of double and triple interaction of independent variables and is as follows in Eqn (5) (Beloborodko et al., 2012):

$$y = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + \ldots + b \cdot x = b_0 + \sum_{i-1}^{n} b_1 \cdot x_1, \qquad (5)$$

where: y is the dependent variable; b_o is the free member of the regression; b_i... b_n are the regression coefficients and x_1...x_n are the independent variables.

The regression equation that corresponds to the Eqn (5) and was obtained as the result of statistical processing of the data and contains statistically important independent variables, as in Eqn (6):

$$P\_\mathrm{E} = b_0 + b_1 \cdot C\_\mathrm{CHP} + b_2 \cdot C\_\mathrm{Pellet} \qquad (6)$$

The values of the coefficients of the regression equation and their statistical values are presented in Table 2.

Table 2. Coefficients of the regression equation and their values

Coefficients b_i	Values	t statistics	P value
Constant b_0	-5.27157	-2.36019	0.0360
Coefficient b_1	9.39524	4.27046	0.0011
Coefficient b_2	1.42205	4.10665	0.0015

In the data processing, the level of importance P = 0.1 was selected and it corresponds to the probability of credibility 0.90. For the purpose of evaluation of the importance of the coefficients b_0.....b_n of the regression Eqn (6), the t criterion with the Student's distribution with f freedom levels is applied in Eqn (7).

$$f = m - (n + 1), \qquad (7)$$

where m is the volume of the data which is the subject of the analysis, n is the number of independent variables in the regression equation.

The level of freedom is defined in Eqn (8):

$$f = m - (n + 1) = 12 - (2 + 1) = 9, \qquad (8)$$

The value of the t criterion corresponding to these values as taken from the tables of the Student's distribution is $t_{tab} = 1.9$. As can be seen from Table 2, the relationship (Blasnik, 1995) > t_{tab} is valid in all cases. It means that all the parameters are important and should be maintained in the equation.

The study has resulted in obtaining a regression equation that defines produced electricity depending on the data of the production facility, i.e. the cogeneration plant power consumption C_CHP and the power consumption of the pellet production facility C_Pellet in Eqn (9):

$$P\_E = -5.27157 + 9.39524 \cdot C\_CHP + 1.42205 \cdot C\_Pellet, \qquad (9)$$

The value of R^2 as determined as the result of statistical processing of the data which was established in the empirical model equals 0.83. It means that the established model (8) explains 83% of the change in the analysed data. The remaining 17% refer to independent variables that have not been included in the equation or defined in the study or the effect of their mutual interaction.

Evaluation of adequacy of the regression equation

Evaluation of the adequacy of the equation (9) is performed by means of the dispersion analysis by applying the Fisher's criterion F. For this purpose, the relationship between the dispersion of the dependent variable and the balance dispersion is analysed, Eqn (10):

$$F(f_1 f_2) = \frac{S_y^2(f_1)}{S_{atl}^2(f_2)} \qquad (10)$$

where: $S^2_y(f_1)$ is y dispersion of the dependent variable and $S^2_{atl}(f_2)$ is the balance dispersion.

The balance is defined as the difference between the dependent variable and the value calculated by means of the regression equation $y_i - y_{iapr}$.

The value as determined by means of the dispersion analysis performed by the software is F = 19.16. The obtained value is compared to the table value of the criterion, which is determined by applying the values of the freedom levels, Eqn (11):

$$f_1 = m - 1 = 12 - 1 = 11 \text{ and } f_2 = m - n = 12 - 2 = 10 \qquad (11)$$

The table value of the Fisher's criterion is $F_{tab.} = 2.9$. As can be seen, the relationship $F > F_{tab}$ is valid and it means that the Eqn (9) is adequate and can be used for describing the analysed data within the framework of their change:

- For produced electricity from 0.65 to 1.72 GWh per month;
- For the CHP power consumption C_CHP from 0.07 to 0.12 GWh per month;
- For the power consumption of the pellet production facility C_Pellet from 0.36 to 0.75 GWh per month.

Verification of the rules of correct application of the correlation analysis

When following establishment of the regression equation, it is possible to perform verification of the rules of correct application of the regression analysis based upon a range of other indices. These are autocorrelation, multicollinearity and heteroscedasticity.

By means of application of the Durbin-Watson's (DW) test, in the course of statistical treatment of the data and the data analysis, the DW criterion has been established. Its value equals 2.3 and exceeds the marginal value of 1.4. This means that there is no considerable autocorrelation of the balance and assessments of the values by means of the smallest squared values method in the course of the analysis are not performed.

The verification has been performed by analysing the correlation matrix of the coefficients calculated by means of the regression equation, presented in Table 3.

Table 3. Correlation matrix of the coefficients of the regression equation

Coeff.	Const.	*C*_CHP	*C*_Pellet
Const.	1.0000	-0.7155	-0.3338
*C*_CHP	-0.7155	1.000	-0.4095
*C*_Pellet	-0.3338	-0.4095	1.000

The analysis of the correlation matrix of the coefficients of the regression equation demonstrates that there is no considerable correlation between the coefficients and independent variables. This is attested by the low values of the correlation coefficient in Table 2. The values presented in the Table are below 0.5 or close to this level, and this means that the evaluation of the coefficients of the regression equation is correct.

The verification of the heteroscedasticity has been performed by means of graphic analysis of the distribution of balances depending on the cogeneration plant power consumption *C*_CHP. If an increase of variations can be seen in graphs (the points form a triangle or a wedge), it means that there is heteroscedasticity. The distribution of the balances is presented in Fig. 5.

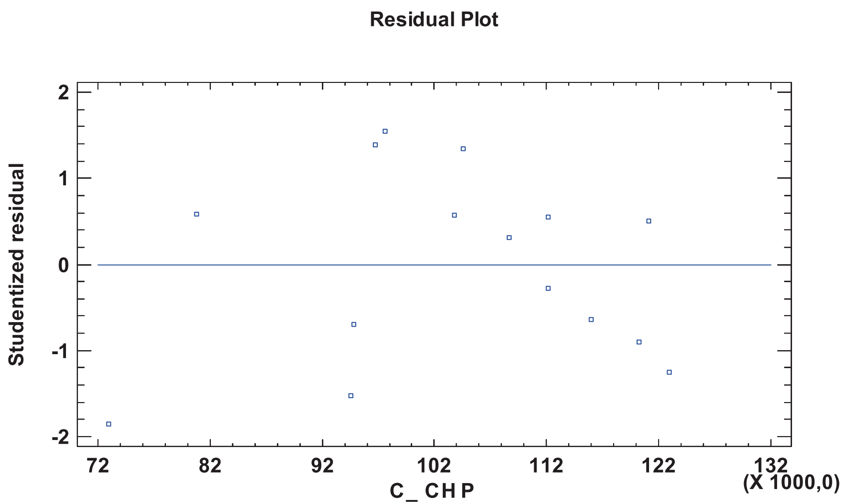

Figure 5. Distribution of balances depending on the cogeneration plant power consumption *C*_CHP.

In Fig. 5, it can be seen that there are no considerable changes in the distribution of balances depending on the cogeneration plant power consumption *C*_CHP. The values of the balances are similar along the whole range of changes in *C*_CHP. The distribution of the balances has been analysed based on other factors. In all cases, the conclusion has been that there is no heteroscedasticity and the standard error has been identified correctly.

One of the types of verification of the regression equation is related to the verification of the signs of its constituents and the fact that there is a logical explanation behind them. The identified changes in the equation from the physical essence perspective are described in the processes. In the regression equation for determining the produced electricity *P*_E (9), the signs of all the parameters are positive and an increase in their values causes an increase in produced electricity *P*_E. When the CHP power consumption *C*_CHP is increased, the produced electricity increases because, for a power plant to be able to generate more electricity, it has to consume more resources. The visible trends comply with the essence of the processes and there is a logical explanation behind them.

The question as to how complete is the correlation between the results calculated by means of the regression equation and the analysed data is among the basic questions regarding the use of empirical equations. It can only be stated in the case of satisfactory correlation that the model adequately describes the situation in practice and its use for simulating the situation is correct. For the purpose of verification of the adequacy of the empirical equation, the empirical and calculated data have been compared. The graphic presentation of the data comparison is in Fig. 6.

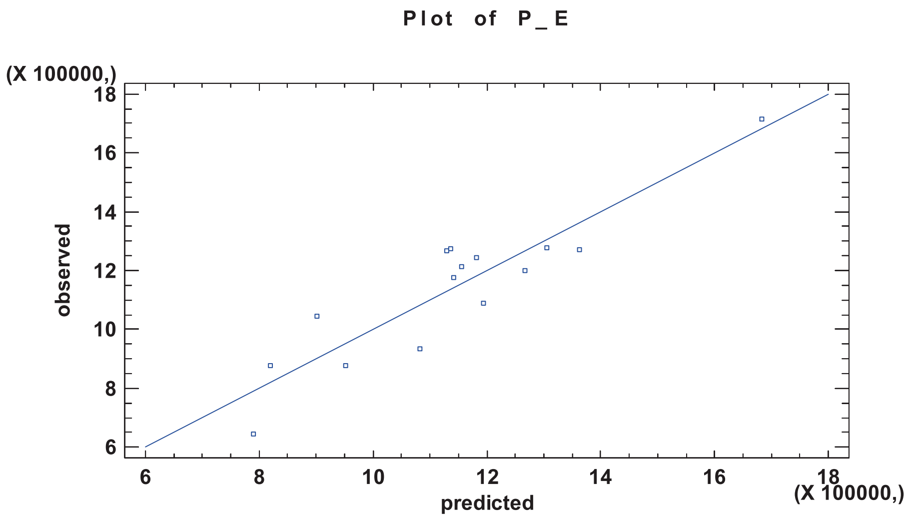

Figure 6. Comparison of the analysed and calculated data of produced electricity.

As can be seen from Fig. 6, there is a good correlation between both data sets. If the calculated value corresponded accurately to the surveyed data, the points would be located on the line in the figure. There is an increased dispersion of points at low values of the reduction of power generation.

CONCLUSION AND FUTURE WORK

Using the statistical processing and applying the methods of regression analysis, the most important factors describing the operation of the production equipment were identified. The relationship between the produced electricity and the parameters impacting this is defined by the regression equation which was obtained during the data processing. During the regression analysis, tests were performed at every stage regarding the correctness of the implemented steps.

According to the performed analysis, the electricity produced is determined by two statistically important parameters, cogeneration plant power consumption and power consumption of the pellet production facility. The adequacy of the equation was verified by applying the Fisher's criterion. The equation describes 83% of the changes in produced electricity.

This study has shown that there is a possibility to find a good equation which describes some independent values using variable values. This study shows that there is a possibility to make a model which describes all factory processes. This additionally enables to use this model for demand side management and hence improve the economic feasibility of the facility.

In future, this task should be studied further. More data must be gathered about another values, analysed and put in a model which can describe factory work.

ACKNOWLEDGEMENTS. This study is supported by the European Social Fund's Doctoral Studies and Internationalization Program DoRa, Estonian Archimedes Foundation program.

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PAPER IV

Uuemaa, P., Drovtar, I., Puusepp, A., Valtin, J., Rosin, A., Kilter, J., "Cost-Effective Optimization of Load Shifting in the Industry by Using Intermediate Storages," *4th IEEE/PES Innovative Smart Grid Technologies Europe (ISGT EUROPE), Copenhagen, Denmark*, pp.1-5, 6-9 Oct. 2013.

Cost-Effective Optimization of Load Shifting in the Industry by Using Intermediate Storages

Priit Uuemaa
Jako Kilter
Juhan Valtin
Dept. Electrical Power Engineering
Tallinn University of Technology
Tallinn, Estonia
priit.uuemaa@student.ttu.ee

Imre Drovtar
Argo Rosin
Dept. Electrical Engineering
Tallinn University of Technology
Tallinn, Estonia
imre.drovtar@ttu.ee

Allan Puusepp
Department of Energy Trading
Eesti Energia
Tallinn, Estonia
allan.puusepp@energia.ee

***Abstract*--This paper presents the results of a study carried out with the help of industrial consumer who is willing to shift their electricity consumption in time. The aim of the study was to develop an optimization model for a specific load cycle in an industrial process e.g. a wood chipper. The paper covers the main aspects and assumptions used to assess the possible demand side management revenues for the industry. The model is used to optimize the wood chipper's operation schedule according to the day-ahead spot market price information. The developed model and its results could be used by the industry as an input for optimizing its production cost for any industrial (sub) process under the open electricity market conditions.**

***Index Terms*--Demand side management, price based control of industrial processes, load shifting, peak demand.**

I. Introduction

The European Union's (EU) climate policy together with the liberalization of the electricity and energy markets are creating numerous challenges and opportunities for the market participants. On the electricity market the price of electrical energy is determined for each hour separately. As in most of spot markets, the electricity price can vary significantly within a single day. Peak consumption hours are generally more expensive than off-peak hours during night, therefore creating an opportunity for the consumer to gain benefit from shifting the load.

Optimizing the electrical load according to the electricity price is one of the key measures to lower the production cost in the industry. Fig. 1 illustrates the control principle of an industrial process according to market prices. Due to the dispersion and variability of the market price two scenarios are studied according to the data available – control according to the average historical price (s1) and in addition the possibility for load shifting according to the day-ahead market prices (s2) in order to gain additional benefit from actual price peaks and dips. The actual control range will be limited by the physical parameters of the production line i.e. power and output of the machinery and capacity of the intermediate storage.

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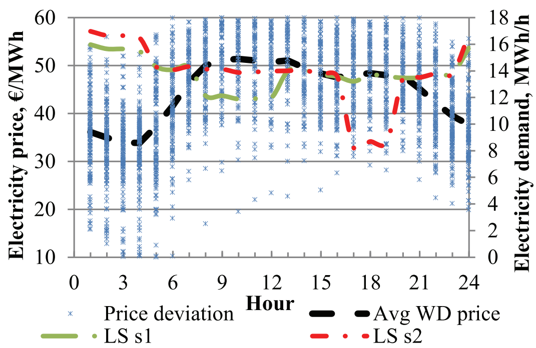

Figure 1. Dispersion of the stochastic market price allows two different load control methods; WD – work day, LS – load shift, s1 – scenario 1 and s2 – scenario 2.

Within this context, the authors are investigating a large electricity consumer's production line optimization possibilities which in future could also be adapted to domestic consumers. An optimization method has been developed and studied that allows the consumer, whether industrial or domestic, to lower their electricity cost. The results of this paper will cover two scenario analysis based on historical market data. The paper has been divided into five sections, with section II giving an overview of the topic under discussion and describing the optimization principles. Section III describes the possibilities in the studied wood industry. Section IV will summarize the modelling results. Finally, section V concludes the main results of the paper and discusses over research possibilities in the future.

II. Overview of the Topic

A. Previous Research in the Field of Load Shifting

Availability of energy storages allows the consumers to shift their load. Energy storage possibilities have been studied extensively by Furusawa et al in [1]. The authors of [1]-[3]

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have shown that by using any kind of energy storage, it has always a positive effect on the cost and profit. In addition, the market participant who can utilize any available storage will always have an advantage compared to other competitors who do not have such an opportunity. Torriti in [4] demonstrates that the consumers are willing to shift their load if there is an economic benefit in for them.

Several papers [5]-[7] have indicated that the future energy network will be based on smart grid applications, which will include vast sources of renewable energy. In such systems the consumer is expected to control its load and make decisions according to the situation in the system. From the one hand this will optimize the infrastructure and control of the energy system and on the other hand it will enable the consumer to reduce its energy bills.

Auväärt et al. in [8] have analysed the influence of the demand side management under the open electricity market conditions in the Nord Pool Spot market area. The study indicated that there is a significant difference between the peak hour electricity price and the off-peak electricity price, thus making it profitable for the consumer to participate in load following. The study revealed that it is worth to investigate consumer storage opportunities because there will always be a price difference in the peak and off-peak hours.

Papers [4], [9] analyse the time-of-use (TOU) tariff influence on the peak load shifting. The authors have demonstrated that the differentiated tariffs trigger a significant load shed and peak load shifting. The authors of papers [4], [10], [11] also conclude that the residential load shifting is mainly inhibited due to human behaviour and their comfort zones, however this is not the case with industrial consumers as long as they retain their production norm. Authors in [12], [13], [14] have developed a mathematical model for a mechanical process with the aim to maximize the industry's profit by taking into account the hourly variations of the electricity price.

The current study is focused on optimizing the timing of a production process according to the market price. The process under investigation is the industry's wood chipping line which consists of several machines like chippers, peelers, conveyors, and etc. All these sub processes are considered as a single load that is controlled separately with load management actions.

B. *Key figures of the industry's load under investigation*

The industry under investigation has a wood chipper line that is semi-automatic and works continuously (for 24/7). The industry's process line with the corresponding consumption loads are illustrated in Fig. 2 The production process is constrained by the Q_t^P (the final product output of the plant), which is determined to be constant by the industry. Therefore the production has to have constant flow of intermediate product that is constrained by the storage capacity W^{max} and by the required chipping volume Q_t. The flexibility of the control is determined by the maximum output of the chipper Q^{max} and storage capacity W. Higher chipper productivity and storage capacity gives bigger control flexibility for the industry.

Stops in the production process, as illustrated in Fig. 2, are mainly caused by the individual needs of the certain customers that require e.g. other type of wood for their product. In the case where electricity is purchased with a fixed price from the electricity trader, there is no need or economic motivation to consider load shifting. However, under open electricity market conditions and taking into account the TOU grid tariffs, it should be economically feasible to optimize the consumption profile in the industry according to the varying price. Additional costs arising from the load shift should be taken into consideration.

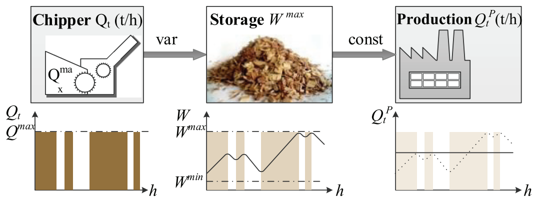


Figure 2. A wood industry's production process and the corresponding indicators (work cycle, storage capacity, final product output) and their correlation.

The authors of [15] have proved that their investigated load is very flexible and can be deployed or stopped within very short notice. The main limits arise from the production volumes that have to be met by the end of the day and the maximum production capacities of the intermediate processes.

The authors of this paper have determined that the electricity cost (E) for a single load under investigation can be minimized with (1).

$$\min_{Q_t} E\left[\sum_t P_t \cdot C^{CH}(Q_t) + C^E(Q_t)\right], \quad (1)$$

where P_t is the electricity price for time period t, C^{CH} is the output power of the chipper and C^E is the external cost of the load shifting e.g. start-up costs, labour costs and etc.

Since the electricity price is a stochastic parameter which can be different in each day of the year, then P_t will be given for the scenarios s with (2).

$$\min_{Q_t} \sum_s \sum_t P_t^s \cdot C^{CH}(Q_t) \cdot P(s) + C^E(Q_t), \quad (2)$$

where $P(s)$ is a probability of the scenario s.

The restrictions and assumptions are that the profit cannot be hindered due to the load shifting, meaning that the system's global optimum needs to be found for the industry in order to minimize the electricity cost. The key factor that enables this optimization to take place is the wood chipper's production volume Q_t. The production volume can be controlled quite simply between zero and maximum output (3).

$$0 \le Q_t \le Q^{\max}. \quad (3)$$

It can be assumed that the more the chipper's maximum capacity Q^{max} exceeds the industry's required material flow Q^P, the higher is the production line flexibility, which in return gains lower costs. Additional physical constraints arise from the fact that the storage cannot be overfilled and cannot run below critical level (4).

$$W_{\min} \leq W_t \leq W^{\max}, \quad (4)$$

where W_t is the actual storage volume in the given hour and W_{min} is the minimum acceptable storage volume for the industry due to the production process' security of supply.

III. Possibilities in the Wood Industry

Wood industry is an energy intensive industry which requires heat and electricity to produce goods. Depending on the goods, electricity can make up to 4-12% of the manufacturing costs of the final product [16], [17]. The increasing energy prices are making the industry to seek opportunities for lowering that cost. Although there are indications that industries are starting to manage their production according to the market conditions, it is not yet fully deployed technique.

A. Optimization Model Principles

The goal of this paper is to find and demonstrate the optimization cost effect using intermediate storages on the specific sub-system in the wood industry. For the purpose of this study wood chipper line process as a single load control is investigated. The chipping electricity cost is minimized depending of the electricity cost on the spot market for each given hour.

Two scenarios are studied. In the first scenario the production plan has been set for the wood chipper according to the historical spot market average prices. In that case the production plan is fixed and is exactly the same in each day throughout the year. The advantage of this approach is that the industry can easily adjust the rest of the production's behaviour according to the fixed plan of the wood chipper. It allows even in the low tech industry to optimize machine's production costs.

On the other hand the actual spot price dips and peaks might not be in the predicted range and time. Therefore there might be a more optimal schedule for production line that could be utilized instead. If the machinery and the process behaviour allows, then it could be more efficient to create the wood chipper's following day plans according to the day-ahead electricity market prices.

The second approach gives the industry even a higher cost optimization possibility because it makes possible to use the most optimal production plan for the specific day, which is not ensured with the fixed production plan. The precondition of that approach is installing information and communication technology platform that calculates, executes and analyses the optimized production plan. The simplified production control is illustrated on the Fig. 3.

To push the optimization even further with the aim to maximize the utilization of the available storage space, an electricity market price forecasting model could be used. For example, by knowing the weekend prices, it could be useful to take that into account in the workday production plans. In this case the storages could be used even more efficiently and the variation of the storage volumes would be more significant. The developed optimization approach within this study allows the industry to calculate the exact cost effect of the load shifting by using their intermediate storages.

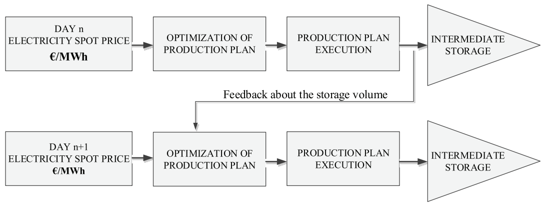


Figure 3. The simplified production control with day-ahead optimization of the wood chipper's operation schedule.

B. Wood Industry - Case Study

The industry under investigation operates a wood chipper with an electrical power of 0.5 MW (C^{CH}). The chipper's production capacity is 72 t/h (Q^{max}). The factory itself requires only 42 t/h (Q_t^P) chipped material in order to produce continuously the end product. The intermediate storage's total volume is 7096 t (W^{max}) and the factory's management has determined the minimum required storage volume at 500 t (W^{min}).

The wood chipper's production characteristic is linear, i.e. the correlation between electrical power and output capacity is linear. As a simplification the production characteristic the wood chipper used in the following calculations is its average output, which does not take into account differences between wood types, e.g. softwood and hard wood. The production characteristic is an actual long time average in the wood industry under investigation.

The reference scenario for this study is the assumption that without using any optimization the industry's wood chipper working hours are random and/or it works constantly at lower output. In this case the wood chipper's electricity cost would equal to the annual average spot price. However, with the optimization model the optimal production plan is found for each day separately and the total annual cost effect is compared to the reference scenario. Within this study historical market data was used for this comparison and analysis.

IV. Results

The developed optimization model as per (2) is solved using Microsoft Solver Foundation which uses the Simplex method. The spot prices are based on the historical Elspot Estonia price area prices in year 2012[1]. In the reference case, where it works at lower output constantly or randomly selected hours, the unit's electricity cost is found with (5). Note that as a simplification external costs described in (1) and (2) have been disregarded.

$$c_e = \frac{\sum_t P_t \cdot C^{CH}(Q_t^P)}{Q_T}, \quad (5)$$

where c_e is the specific cost of electricity and Q_T is the total annual production in time period t.

[1] www.nordpoolspot.com.

The chipper's specific energy cost is calculated because its actual electricity consumption measurements, on what the actual costs could be determined, are not available. The industry's representative has confirmed that the used method's error is acceptable and it represents the actual situation as good as the data provided allows to assume.

The calculated specific energy cost for the chipper which production curve is not optimized is 0.27 €/t (reference scenario). For the first scenario where the production process is controlled by the average historical price optimization algorithm, the unit's specific cost would be 0.24 €/t (scenario s1). The results show that when using the above mentioned optimization model the cost of the electricity could be remarkably decreased. The annual electricity cost reduction for the studied wood chipper would be 11% lower compared to an existing, not optimized, production schedule. Fig. 4 illustrates the daily optimal working schedule for the wood chipper and changes in the storage volume depending on the average historical electricity spot price.

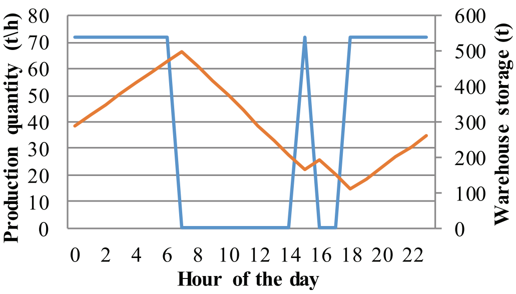
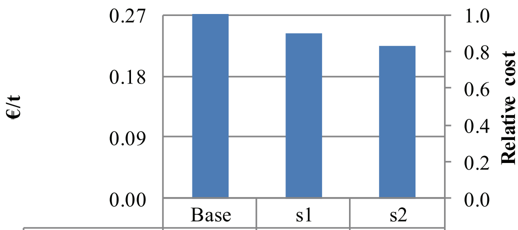


Figure 4. The optimized production characteristics with the changing storage volumes according to the sport market's average price (s1).

Fig. 4 clearly illustrates that the optimization algorithm finds the economically most reasonable production graphic for the average day, meaning that the algorithm has found the global optimum for the studied chipper in order to reduce the electricity cost.

In the theoretical scenario (s2) where the cost for each hour of the next day is known the chipper's specific cost could be lowered to 0.23 €/t as illustrated on Fig 5. Therefore this last scenario presents the theoretical minimum, which is 6% lower than the case study for the average price scenario (s1). As a result the electricity cost could be lowered as much as 17% compared to the base scenario. Since the Elspot market in Nord Pool Spot area provides prices only for the day-ahead, the model cannot take into account the possible changes that might occur in the longer future. For example, the model cannot know whether the prices will be lower on the weekends, thus limiting further optimization without additional forecasting models.



	Base	s1	s2
Specific Cost	0.27	0.24	0.23
Relative cost	1.00	0.89	0.83

Figure 5. Comparison between different study cases; s1 – optimization based on historical market data, s2 – optimization based on day-ahead market data.

The working schedule that is optimized according to the day-ahead market price is ideal for additional minimization of the electricity cost. Capacity for the chipper is determined for each hour independently throughout the whole year. Ideally this would be a good example of a well-functioning spot market where the consumer could benefit from the system and system could have a positive influence from the consumer. When consumer shifts the load into the off-peak hours of the day, then the electricity system would become more stable and less peak capacity would be needed. This in return would lower the cost of the electricity system for the society.

Fig. 6 illustrates that if the electricity price would be known more than one day-ahead then the usage of the storages could become even more cost effective. Analysing the historical long period price fluctuations on the electricity market, the most profitable shifting periods could be determined. During load shifts on peak hours and days, the required wood would be taken from the storage. Additional benefit could be gained by planning the annual or regular maintenance stops to the peak periods. This way the storage of physical medium i.e. wood chips would serve as energy storage during load shifts.

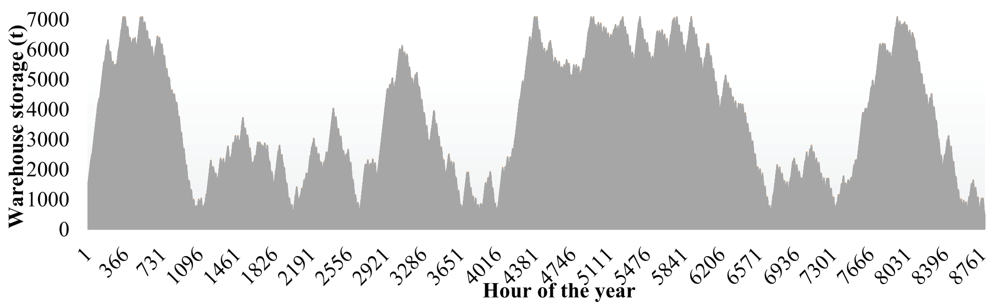


Figure 6. Warehouse storage dynamics according to s2 over on calendric year with preset storage limits and according to historical market data.

V. CONCLUSIONS AND FUTURE WORK

An optimization algorithm was created for an energy intensive industry in order to manage load shifting under open electricity market conditions. By implementing the developed optimization algorithm for a studied industry, the wood chipper's production line energy costs could be decreased based on historical market data up to 11% and with using day-ahead market prices and optimization up to 17% compared to the base case where the chipper is operated randomly or according to the needs. In addition to the cost benefit from optimization the industry could use the information and storage dynamics to determine the best periods to do the monthly and annual maintenance.

The key for a successful and cost effective optimization is to utilize the existing physical medium storages that are a part of the production line. These intermediate storages in the energy intensive industry's production line serve as simple energy storage – during peak hours medium is taken out and extra energy is not used and during off-peak hours energy is consumed to produce medium or to fill up the storage. The utilization of these existing storages provides the opportunity to optimize the industry's energy and hence the production costs without any significant additional investments.

The developed optimization technique should be possible to be extended to any type of loads, whether industrial or domestic, with continuous processes and controllable loads that have any kind of intermediate storages that could act as indirect energy storages. As a conclusion the electricity cost of the industry can be remarkably lowered through load shifting. Future studies will focus on analysing whether it is optimal to over dimension certain parts of the production line in the energy intensive industry in order to increase the manoeuvrability. Higher capacities in certain parts of the production line give bigger flexibility to implement load shifting in the open electricity market conditions.

In addition the studied industry's whole production facility (including also the local power plant) should be analysed in a similar way in order to find the global optimum for the entire production facility. The final aim is to maximize the profit and use the developed optimization mechanism for optimizing other production sites. It should be stressed that main task would be always to find the profit's global optimum because the cost minimization does not always guarantee the highest profit. Therefore similar studies with energy cost optimum calculations will be carried out at the industry's other process lines using the methods described in this paper. The article has also shown that the same principle could be launched among the domestic consumers on much lower scale. However, the sum of such consumers could contribute to remarkable total savings in the power system.

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PAPER V

Drovtar, I., **Uuemaa, P**., Valtin, J., Rosin, A., Kilter, J., "Using Demand Side Management in Energy-Intensive Industries for Providing Balancing Power – the Estonian Case Study," *IEEE Power and Energy Society General Meeting (PES), Vancouver, Canada*, pp.1-5, 21-25 July 2013.

Using Demand Side Management in Energy-Intensive Industries for Providing Balancing Power – the Estonian Case Study

I. Drovtar, *Student Member, IEEE*, P. Uuemaa, A. Rosin, J. Kilter, *Member, IEEE*, J. Valtin

***Abstract*--This paper represents the preliminary study results of industrial consumers who would be willing to provide demand response services for system balancing. Using aggregated load shifting in a wood industry over the whole Baltic power system for regulation is discussed. The paper covers the main aspects and assumptions used to assess the possible demand response outcomes for the transmission system operator in terms of regulation costs. The aim of the paper is to show that demand response can be deployed and consumers are willing to participate in providing demand response services for the transmission system operator, who should use this information as an input for developing the necessary market entity for balancing services.**

***Index Terms*--Demand side management, demand response, industrial processes, load following, balancing power, and balancing markets.**

I. Introduction

THE European Union's (EU) climate policy together with the liberalization of the electricity and energy markets are creating numerous challenges for the current power system. With the large scale development of distributed and renewable power plants, the once emerged hierarchical unidirectional topology of the grid has become outdated. The bidirectional, variable and unpredictable energy flows in the power system are making it harder to control and maintain stability in the grid.

The increasing share of stochastic and unpredictable generation in the system inevitably increases the need for additional balancing services to cover the possible mismatches between demand and supply. In addition, the liberalization of the electricity market has led to a situation where the migration of customers from a previously monopoly service provider to other market participants (so called balance providers) has occurred. This in return might increase and aggregate their load and generation forecast errors, thus also requiring additional balancing service.

Conventionally, this balancing is done using traditional power plants. However, with the continuous demand growth and increasing number of variable generation in the system, it is questionable how long this approach is economically feasible. The increasing need for short-term balancing power on the electricity market provides a new opportunity for consumers. Energy-intensive industrial consumers could participate more actively on the ancillary service markets e.g., with load following or providing balancing power[1] for the transmission system operator (TSO).

This paper analyses the possibilities in the Estonian power system to effectively deploy demand side management (DSM) amongst energy intensive industries to provide short term regulating service for the TSO. The study concentrates mainly on the willingness and possibilities of consumers to provide DR service and thus the issues with technical platforms will be addressed separately in future papers.

II. Overview of the Topic

DSM describes various measures that can be taken on the customer side for energy efficiency or conservation purposes and is thus rather vague term. Instead, the authors of this paper will use a more specific and widely used term, demand response (DR), to analyse the DSM possibilities in the grid. DR describes more accurately the customer's actions in response to particular conditions in the power system (outages, congestions, ancillary services, price, and etc.).

A. Previous Research and Experiences in Europe

Several papers [1-5] have brought out the coherence between the increasing need for additional regulating services and large scale variable generation integration into the power system. Similar tendency has also been observed in the Estonian power system [6].

Authors of [2-5, 7] bring out the importance of energy consumers providing additional balancing services to the system operator through DR. It is discussed that DR could reduce the need for balancing and peaking generators with higher marginal costs, supply balancing service at lower costs and even decrease the grid investments, leading to reduction of electricity prices. Although there are mechanisms designed that would enable demand side actions (such as load shedding) to be

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I. Drovtar and A. Rosin are with the Department of Electrical Drives and Power Electronics, Tallinn University of Technology, 19086 Tallinn, Estonia (e-mails: imre.drovtar@ttu.ee; argo.rosin@ttu.ee).

P. Uuemaa, J. Kilter, and J. Valtin are with the Department of Electrical Power Engineering, Tallinn University of Technology, 19086 Tallinn, Estonia (e-mails: priit.uuemaa@ttu.ee; jako.kilter@ttu.ee; juhan.valtin@ttu.ee).

[1] In the literature sometimes also referred to as tertiary reserve.

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competitive for providing regulation service, traditional supply side balancing is still favoured.

Torriti *et al.* in [5] give an overview of the DR experience in different European countries. Although there are numerous DR programmes and initiatives within EU Member States, the EU-wide DR initiative is missing mainly due to the inexistence of a single European energy market. Most of the DR programmes in place in EU Member States are focused mainly on large industrial users and miss the benefits possible from a more comprehensive approach to DR including commercial and household consumers. It was observed that customers are lack of means and adequate incentives to respond to DR requirements. Nevertheless, recent developments have reshaped the DR programmes, which are starting to focus on commercial and residential customers rather than industries.

Palensky and Dietrich in [7] point out that DSM's main advantage is that it is financially and economically more promising to intelligently control consumers for providing balancing services, than to build new power plants or install energy storage units. DR and demand shifting could be used more effectively for system-wide services through a platform, which would give the consumers the necessary information, such as actual need for regulating power in addition to simple price incentives, for scheduling its processes.

Bradley *et al.* in [8] bring out that deploying DR in the market can bring positive economic effect and increase the economic welfare for the society. The authors have brought out eight core benefits that DR can have on the power system e.g., absolute and relative reductions in electricity demand (up to 2.8% reduction in overall consumption and 1.3% shift of peak demand in the United Kingdom). In addition, by providing ancillary system services some investments into grid and plants can be displaced. Several studies analysed in the paper also indicated vast interest (participation over 75%) on the customer side to participate in those programs. Large scale participation in DR may be low without the appropriate sharing of benefits among the parties. In addition, incentives are needed that lower the participation costs in such programmes.

B. Key Indicators of the Estonian Power System

The Estonian power system is operating in parallel with power system of IPS/UPS of Russia. In 2012, the total capacity of installed power plants was 2647 MW, the peak demand has stayed so far around 1600 MW and is expected to increase annually approximately 1.8% for the following decade [9]. Together with the other two Baltic States, Latvia and Lithuania, the total system capacity is around 6 GW and total peak load around 5 GW.

All TSOs in the power system IPS/UPS of Russia have agreed to keep their national system balance by the end of each hour within a certain range (e.g., for the Estonian TSO this is ±30 MWh). All deviations have to be dealt with, in order to maintain the overall security and integrity of the IPS/UPS power system. In order to deal with the unexpected unbalances all TSOs have to maintain certain system services or power reserves.

Generally, the emergency reserves have to be maintained by the national TSO and all the costs are paid solidarily by the consumers through grid tariffs [10]. To balance the large mismatches between demand and supply, the TSO can order regulation services, which has been used so far to either increase or decrease the electricity production to balance the system. This service is realised through bilateral agreements between the TSOs and power plants in the Baltic region. The costs are reflected in the balancing electricity sales/purchase price and covered by the balance providers and their customers (consumers and producers).

The TSO has to purchase or sell the necessary balancing electricity to the service provider who offers the most techno-economically optimal price, assuring equal terms to all service providers [10, 11]. All balancing actions last until the end of the hour, when everything is reset and if balancing is still needed, it is reordered from the service provider. The balancing requirements of the Estonian power system in 2011 are presented in Fig. 1. The up regulation was ordered during 595 hours and down regulation during 779 hours of the year. [6] Although in 2012 the down regulation occurrences have decreased, there is an increasing need for additional up regulation services [12].

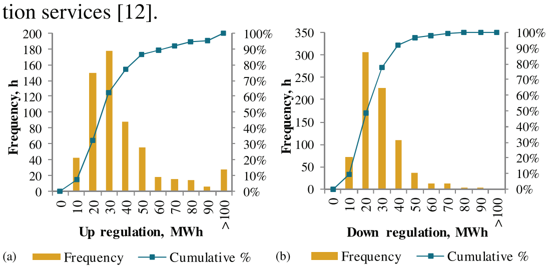

Fig. 1. Required balancing energy in the Estonian power system in 2011, (a) up regulation or positive tertiary regulation and (b) down regulation or negative tertiary regulation [6].

The TSO's costs for up regulation services in 2011 and their distribution are presented in Fig. 2. The following analysis is focusing mainly on the up regulation because due to safety and technical reasons consumers cannot ramp their consumption up as fast as they can switch it off. Therefore, from the consumer point of view, down regulation has little perspective.

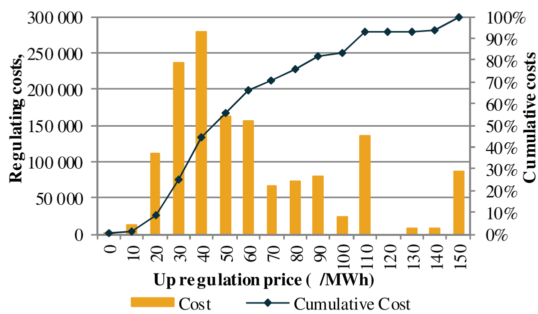

Fig. 2. Estonian TSO's up regulation costs in 2011.

The Estonian TSO's regulation cost allocation is subject to left-truncated distribution, meaning that most of the regulation costs are caused by low price occasions. It can be assumed that after creating a market mechanism for balancing services, the cost distribution may become more similar to the Finnish regulating market. The cost allocation on the Finnish regulating market is subject to right-truncated distribution, meaning that most of the costs are caused by high price occurrences. The up regulation cost histogram in year 2011 in the Finnish regulating market is illustrated in Fig. 3.

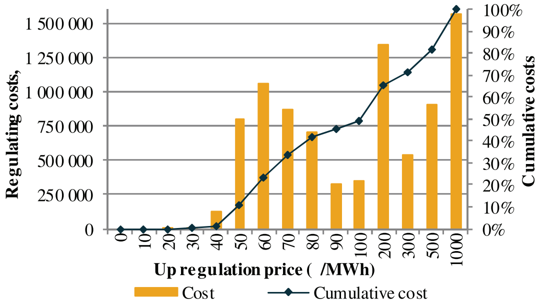

Fig. 3. Finnish TSO's up regulation costs in 2011 [13].

As it turns out, 50% of the cumulative regulation costs are caused by regulations with prices above 100 €/MWh. At the same time regulations with prices above 100 €/MWh constitutes only 10% of the total regulation occurrences. Even more, regulating with 1 000 €/MWh is only 0.2% of regulation occurrences but it makes up 18% of the costs. The authors are using the Finnish regulating market price information to analyse financial motivation of electricity consumers to provide system services for the TSO. After the regulating market is created, then due to the interconnections between Estonia and Finland, it can be assumed that the Finnish market will have some impact also on the Estonian market prices.

C. *Issues*

In theory it would be already today possible for large industrial consumers to provide regulating power for the TSO through bilateral agreements. The authors have interviewed the Estonian TSO and two industrial consumers in order to map the current situation and issues. As it turned out, large electricity consumers have started to monitor the situation on the electricity market and plan their production according to the market situation.

According to the Estonian TSO, it is already today possible to accept balancing services from electricity consumers because from the power system point of view, it does not matter whether the regulation is performed by increasing the production or lowering the consumption and vice versa. Nevertheless, the minimum capacity that consumer can offer for regulation is 5 MW. In addition, all the offers have to be submitted two hours prior to the possible request for service.

The main issue with the existing balancing service is that it is not based on a market mechanism and it lacks of transparency how the prices are formed. Estonia alone is too small to deploy a balancing service market, and taking into account that currently most of the service providers are from outside of Estonia, it would not be also reasonable. In order to establish a balancing market, all three Baltic States have to fully liberalize their electricity markets. After that it would be possible to start developing the regulating market, which could make it more attractive for a wider range of customers to provide regulating and/or emergency reserves.

From the consumer side two different views exist:

1. The consumer has totally misunderstood the concept of DR or assumes to have such a complex production technology that it is not feasible to adjust it for DR; nevertheless the consumer is monitoring the market situation and can make the necessary adjustments for load shifting.
2. The consumer has acknowledged the possibilities of DR, has implemented load shifting according to market price fluctuations and is seeking for opportunities to optimize and control its production so that it could provide additional services for the TSO.

Although the views are different, the common denominator between both views is the lack of information. There is no information about the procedures, requirements, obligations or price levels at which short term regulating service could be provided for the TSO.

III. Possibilities in the Wood Industry

Wood industry is an energy intensive industry which requires heat and electricity to produce goods. Depending on the goods, electricity can make up to 4-12% of the manufacturing costs of the final product [14, 15]. The increasing energy prices are making the industry to seek opportunities for lowering that cost. Although there are indications that industries are starting to manage their production according to the market conditions in Estonia, they could also utilize other unique opportunities to provide services and receive additional incentives to increase their production flexibility.

A. *Wood Industry – Case Study*

The wood industry is mainly a mechanical industry which uses large motors for chippers, conveyers, fans, pumps, and other applications. The production process is usually a straight forward end product manufacturing from the raw material. If the production chain is interrupted somewhere it can stop the whole process line. Without enough flexibility in the production line, it cannot stop the industrial process without economic consequences [2, 3].

However, interruptions in the production line tend to happen time to time anyway, and most of the industries have secured themselves against such sudden outages. Since not all of the processes in the production line are dimensioned to the same output power, the output of different intermediate processes varies. The variable output of indirect products in different parts of manufacturing process serve as natural storage buffers. The existing buffering systems could be used to stop some parts of the production line, without affecting the final output. This enables the consumer to shift some of the loads in time, offering additional flexibility. Deliberate shifting of electricity consumption on certain parts of the production line could be used to provide DR service for the TSO, without affecting the final production.

The studied wood industry has production units (companies) all over the Baltic countries, making their aggregated electrical load (15 MW) attractive for the balancing service. The wood industry has defined two different levels of balancing service that it could provide. With the first level of regulation (load shifting) the industry could provide 5 MW of regulating power to the TSO, without affecting its final production. This would require the company to make some adjustment in the production process but the regulation could be achieved within 15 minutes. The second level of regulation could provide additional 5 MW of regulation through load shedding. However, this would affect its final output and the later start-up of the manufacturing process could take up to 2 hours.

From the economical perspective the consumer would be willing to stop the production, if it is more profitable than producing its final product. The cost of the load shift for the TSO would be equal to the price of the final product not produced. Even though the shifting might not affect the final volumes of the product, it poses an additional risk for the company.

The most promising DR service provider(s) would be consumer(s) with total electrical loads over 10 MW from what at least 5 MW should be shiftable. From the power system balancing point of view it does not matter whether the consumer has a single unit with a load of 10 MW or aggregated number units with a total load of 10 MW dispersed over a geographical region.

B. Criteria for Providing DR Services

Based on the interviews with the studied wood industry representative and the Estonian TSO there are three main factors that need to be addressed to qualify as a DR service provider. The first criterion (1) describes the minimum regulating power that is acceptable by the TSO.

$$P_{ACL} \geq P_{TS}\,, \tag{1}$$

where P_{ACL} describes the consumer aggregated changeable load in MW and P_{TS} is the TSO's minimum required regulation step in MW.

The second criterion (2) takes into account the response time of the consumer:

$$\Delta t_r \leq \Delta t_{TR}\,, \tag{2}$$

where Δt_r is the consumers time for achieving the requested load change in minutes and Δt_{TR} describes the TSO's maximum timeframe for achieving the requested up regulation in minutes.

The final criterion (3) takes into account the duration of the regulation:

$$\Delta t_{SAL} \geq \Delta t_{TS}\,, \tag{3}$$

where Δt_{SAL} is the consumer's willingness to change the load in hours and Δt_{TS} is the TSO's minimum regulation duration in hours.

The consumer's DR pricing principle is rationally based on the lost profit (or on the risk of losing production). Lost profit is used to determine the price for load shedding and the risk of losing production is used to determine price for load shifting. Therefore, whenever the regulation price exceeds the industry's price cap for the service provision, the DR service could be provided. Large industrial consumers are expected to act in a rational way i.e., it can be expected that they will provide the DR service if they find it cost-effective [4].

The aggregated demand profile of the consumers who is providing the regulation service (with load shifting and load shedding) before, during, and after service provision to catch up on the production quota is illustrated in Fig. 4. It should be noted that while with load shifting it is possible to catch up the production quota by increasing the demand for a couple of hours, then with load shedding the increased consumption after regulation can only fill up the buffers in the production line but the production quota will not be caught up.

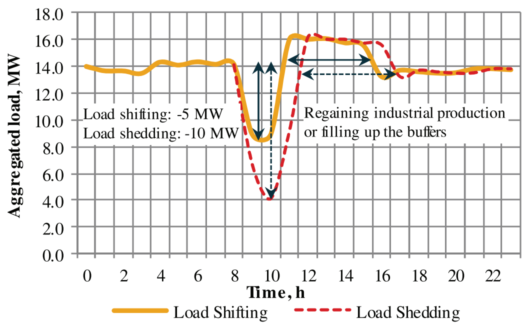

Fig. 4. Aggregated demand profile of the consumer providing regulating service for the TSO (before, during and after service provision).

Consumer's pricing principle can be described as in (4).

$$P_{DR_t} = \frac{\sum_{i=1}^{t}(C_{P_i} - C_{V_i}) + C_{SU}}{P_{ACL} \cdot \Delta t}\,, \tag{4}$$

where P_{DR_t} is the price of the DR service (€/MWh), C_{P_i} is the value of the lost industrial production (€), C_{V_i} is the cost of variable goods saved (€), C_{SU} is the cost of start-up (€), P_{ACL} is the consumers aggregated load shift/shed (MW) and Δt represents the duration of the ordered DR service from the TSO.

Most of the consumers do not have today the necessary technical platform for providing this service. The technical platform should consist of an information and communication technology solution which would enable to receive the necessary information in a central way so that the aggregated consumers would receive the order simultaneously.

IV. Results

The authors have made the preliminary estimation of the price, that the wood industry under investigation would be able to provide regulating services. The price level for these services should be competitive with the prices on a regulating market (100 €/MWh for load shifting and 600 €/MWh for load shedding, respectively). It can be assumed that on the rare occasions when the system runs out of other options, consumers could offer these services at lower and more competitive prices than expensive power plants. In the long term this should lower the regulation costs for the TSO and further optimize power system infrastructure.

Taking into account the demand levels in the Baltic countries the aggregated DR service possibilities should be further investigated even at smaller scales than industrial consumers.

V. Conclusions and Future Work

Using DR in the Estonian power system has so far not been researched thoroughly. Nevertheless, the preliminary interviews and studies with consumers have indicated their interest in more active participation on the market and even providing system services for the TSO. Since the liberalization of the electricity market in Estonia large consumers have started scheduling their larger loads according to the market situations. Several industries have already installed or are planning to install a local generating units utilizing manufacturing waste (bark, saw dust, etc.) as fuel, increasing furthermore their production flexibility. Taking these flexibilities to the ancillary service markets could optimize the power system even more and lower the costs for the society.

Future studies in this field will include a detailed market study and modelling of the socio-economic impact of consumers participating in the power system balancing. The industry under investigation is developing the necessary technical platform for its companies to actually participate in the Estonian power system regulation. Within those studies field tests are planned, which should demonstrate the feasibility and possibility to use aggregated DR for system regulations. This should also provide the necessary input information to further study the possibilities including residential and commercial sectors in the regulating markets in the Baltic region.

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VII. Biographies

Imre Drovtar received B.Sc. in electrical engineering and M.Sc. in sustainable energy engineering from Tallinn University of Technology, Tallinn, Estonia, in 2009 and 2011, respectively. He has started his PhD studies in Tallinn University of Technology. He is a board member of the Estonian Society for Electrical Power Engineering and student member of IEEE. His research interests are mainly in the field of power system and electricity demand optimization under open electricity market conditions.

Priit Uuemaa received the B.Sc. and M.Sc. degrees in electrical power engineering in 2007 and 2010, respectively, from Tallinn University of Technology, Tallinn, Estonia. He is currently working towards the Ph.D. degree and working as specialist of power engineering in the wood industry company. His research interests include essentially the industrial energy system optimization including the energy production under open electricity market conditions.

Argo Rosin received the Dipl. Eng., M.Sc. and Dr.Sc.techn. degrees in electrical engineering from Tallinn University of Technology, Tallinn, Estonia, in 1996, 1998 and 2005, respectively. He is presently a Senior Researcher in the Department of Electrical Drives and Power Electronics, Tallinn University of Technology. He has published more than 60 papers on energy management, control and diagnostic systems development and is the holder of a Patent in this application field. His research interests include modelling and simulation of power management and industrial control systems. He is member of Estonian Association of Engineers, Estonian Association of Transport and Roads.

Jako Kilter received the B.Sc., M.Sc., and PhD degrees in electrical engineering from Tallinn University of Technology, Tallinn, Estonia, in 2003, 2005 and 2009, respectively. Currently he is working at the Department of Electrical Power Engineering of TUT as an associate professor and at the Estonian TSO as a power system expert. He has published more than 30 papers on load modelling, system control and power quality and is the author of three textbooks. His special field of interest include electrical network state estimation and analysis, power system monitoring and control, modelling of loads, power system stability, power quality, HVDC and FACTS. He is a Chartered Engineer, Chairman of Estonian Centre for Standardisation Committee of High Voltage Engineering, member of Estonian Society for Electrical Power Engineering, and actively participating in the work of various ENTSO-E and CIGRE working groups.

Juhan Valtin received the Ph.D. degree in electrical power engineering in 1979 from Leningrad Technical University, Leningrad, Russia.. He is currently working as professor at the Department of Electrical Power Engineering in the Tallinn University of Technology. His research interest includes electrical network analysis, modelling of loads, electrical market analysis. He is a member of Estonian Society for Electrical Power Engineering.

PAPER VI

Uuemaa, P., Puusepp, A., Drovtar, I., Valtin, J., Rosin, A., Kilter, J., "Load Control Implementation in the Energy Intensive Industry," *17th IEEE Mediterranean Electrotechnical Conference (MELECON), Beirut, Lebanon,* pp.213-218, 13-16 April 2014.

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Load Control Implementation in the Energy Intensive Industry

Priit Uuemaa Juhan Valtin Jako Kilter Dept. El. Power Engineering Tallinn Univ. of Technology Tallinn, Estonia priit.uuemaa@student.ttu.ee	Allan Puusepp Dept. Energy Trading Eesti Energia Tallinn, Estonia allan.puusepp@energia.ee	Imre Drovtar Argo Rosin Dept. Electrical Engineering Tallinn Univ. of Technology Tallinn, Estonia imre.drovtar@ttu.ee

***Abstract*--This paper presents the principal solution for a real time load control application in the industry under the conditions of open electricity market. The aim of the study is to create the basic concept of a PLC controlled load optimization system for the group of energy intensive machines. The optimized load curve calculations for the specific machine or for the aggregated group of machines in the industry production process have been proposed using the optimization algorithm. The paper covers the main aspects and assumptions used to assess the possible demand side management revenues for the industry. The application is used to optimize the industry production cycles operation according to the day-ahead spot market price information. The developed application and its results could be used by the industry to optimize the whole production line electricity cost.**

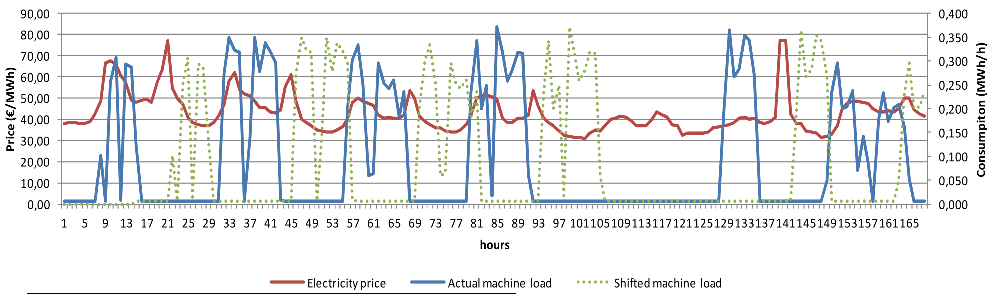
***Keywords* --Demand side management; load control; price based control of industrial processes; load shifting; peak demand.**

I. Introduction

The European Union's (EU) climate policy together with the liberalization of the electricity and energy markets are creating numerous challenges and opportunities for the market participants. The consumers are forced to move on to the smart solutions in order to cut back their rising cost of energy. The optimization effect what the smart solutions offer is so far not widely used among the consumers and especially in the industry. However the significant variations in the electricity prices on the spot market are creating an opportunity for the consumer to gain benefit from shifting the load.

Optimizing the electrical load according to the electricity price is one of the key measures to lower the production cost in the industry. The market place for the electricity in the Nordic and Baltic countries is the Nord Pool Spot market. In this market system the prices are given for one day ahead and for each 24 hours (h) separately. Fig. 1, illustrates the market price fluctuations and the industry aggregated single load actual and shifted consumption. The control principle for the industry is to shift the consumption to the time of the lowest prices. Due to the dispersion and variability of the market price the scenario of the real time load control is studied in order to gain additional cost savings from actual price peaks and dips. The control and hence the shifting is limited by the capacity of the machine and the required material flow over the specified time period.

Fig. 1. Effect on the daily load curve. Market price fluctuations create an opportunity for consumer to lower its weighted cost of electricity by implementing load shifting.



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Within this context, the authors are investigating a large electricity consumer's production line optimization possibilities. An optimization method has been developed in previous study for a single unit in the industrial process [1] and the optimization of the whole process is studied in this paper. The studied subject allows the consumer, to lower their electricity cost. The results of this paper will cover the fundamental principles how the production process electricity cost can be optimized and how to compare this with the non-optimized regular operation costs. The paper has been divided into five sections, with section II giving an overview of the topic under discussion and describing the optimization principles. Section III describes the possibilities in the studied wood industry. Section IV will summarize the results. Finally, section V concludes the main results of the paper and discusses over research possibilities in the future.

II. Overview of the Topic

A. Previous Research in the Field of Consumption Load Scheduling

The consumption load scheduling has been studied due to several reasons - lowering the cost, cutting the demand peaks etc. In order to cut the consumption peaks authors of [2], [3] have studied the results of the load response. They have shown the positive effect for the consumer to control its load. The key factor which allows load scheduling is the existence of some sort of energy storage. It can be a water reservoir for the pumps or a raw material warehouse for the wood industry. Availability of energy storages allows the consumers to shift their load. Energy storage possibilities have been studied extensively by Furusawa et al in [4]. It is assumed that the industrial consumers are willing to shift their load if there is an economic benefit in for them.

Several papers [5]-[9] have brought up the technical solution for the control principal itself. They have created pilot solutions and got a positive effect on the field tests. It is indicated that the smart load response requires the combination of the well programmed software together with the reliable hardware solutions.

The authors of [10]-[12] have extensively studied and outlined the potential savings and benefits for the industrial company that implements load shifting activities. The results indicate at least a 5% savings when following the electricity price and scheduling the consumption profile accordingly [11]. Previous studies include also the algorithm for maximising the profit or minimising the cost [12], [13].

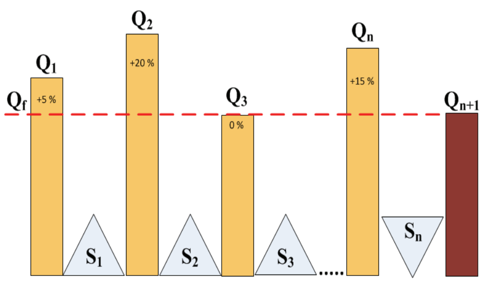
The current study is focused on optimizing the timing of a production process according to the market price. The process under investigation is the industry's production line which consists of several machine groups like chipping, drying milling, and etc. All these sub processes are considered as a single load that is controlled separately with load management application/controller.

B. Key figures of the industry's load under investigation

The industry under investigation has a 5 sub cycles in the factory process line that is semi-automatic and works continuously (for 24/7). The industry's process line with the corresponding production flows are illustrated on Fig. 2, and Fig. 4, The production process is constrained by the Q_t^P (the final product output of the plant), which is determined to be constant by the industry and depends on the sales and technical limit of the factory. Therefore the production must have a constant output of the final product. The flexibility of the control is determined by the maximum output of every capacity sub cycle P_i and intermediate storages capacity S_i. Higher sub-cycle productivity and storage capacity gives bigger control flexibility for the industry.

Stops in the sub cycle production process and therefore in the electricity consumption, as illustrated in Fig. 1, are mainly caused by the overproduction of a specific sub cycle. In the case where electricity is purchased with a fixed price from the electricity trader, there is no need or economic motivation to consider load shifting. However, under the open electricity market conditions and taking into account the time of use grid tariffs, it should be economically feasible to optimize the consumption profile in the industry according to the varying price. Additional costs arising from the load shift should be taken into consideration.

Fig. 2. A typical industry's production process structure, the corresponding production cycles and their respective production capacities including the sales capacity.



The load scheduling is only available with the flexible loads. As pointed out by Hazi *et al* in [10] the cost of outage is very high for the industry and therefore the optimization costs cannot exceed the savings from the load scheduling or its errors. The load scheduling application installation cost on the other hand has to be very cheap in order to implement it; this requires mainly cheap and reliable means of communications [8].

The authors of this paper have determined that the electricity cost (E) for a single load under investigation can be minimized with (1) [1].

$$\min_{Q_i} E\left[\sum_t P_t \cdot C\ (Q_t) + C^E(Q_t)\right], \qquad (1)$$

where P_t is the electricity price for time period t, C is the output power of the sub cycle and C^E is the external cost of the load shifting e.g. start-up costs, labour costs and etc.

Since the electricity price is a stochastic parameter which can be different in each day of the year, then P_t is given for the scenarios s with (2) [1].

$$\min_{Q_i} \sum_s \sum_t P_t^s \cdot C\ (Q_t) \cdot P(s) + C^E(Q_t), \qquad (2)$$

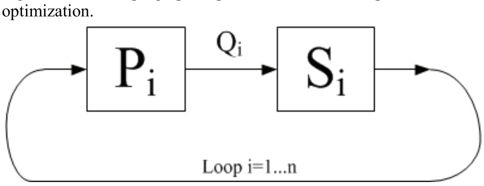
where *P(s)* is a probability of the scenario *s*.

The restrictions and assumptions are that the profit cannot be hindered due to the load shifting, meaning that the system's global optimum needs to be found for the industry in order to minimize the electricity cost. The key factor that enables this optimization to take place is the sub cycle's production volume Q. The production volume correlation with the consumed electricity is linear and can be controlled quite simply between zero and maximum output.

It can be assumed that the more some sub cycle maximum capacity Q_i^{max} exceeds the industry's required material flow Q_f, the higher is the sub cycle flexibility, which in return gains lower costs.

In order to create the algorithm for the entire production process the simplified principle is shown on Fig. 3.

Fig. 3. The looping principle for the whole production line optimization.



If there are several sub cycles in the production line then the equation (1) is redefined as (3):

$$\min_{Q_i^i} E\left[\sum_{i=1}^{n} \sum_t P_t^e \cdot C^i(Q_t^i) + C^{E,i}(Q_t^i)\right], \qquad (3)$$

Also the following conditions need to be fulfilled.

$$\forall_i \forall_t\ 0 \le Q_i^t \le Q_i^{\max}\quad i \in \{1 \ldots n\}, \qquad (4)$$

$$\forall_i \forall_t\ S_i^{\min} \le S_i \le S_i^{\max}\quad i \in \{1 \ldots n\}, \qquad (5)$$

$$\forall_i \forall_t\ S_i^t = S_i^{t-1} + Q_i^t - Q_{i+1}^t + B_i^t\quad i \in \{1 \ldots n-1\}, \qquad (6)$$

$$S_n^t = S_n^{t-1} + Q_n^t + B_n^t, \qquad (7)$$

where S is storage (t) and Q production flow (t/h).

III. Possibilities in the Wood Industry

Wood industry is an energy intensive industry which requires heat and electricity to produce goods. Depending on the goods, electricity can make up to 4-12% of the manufacturing costs of the final product [14], [15]. The increasing energy prices are making the industry to seek opportunities for lowering that cost. Although there are indications that industries are starting to manage their production according to the market conditions, it is not yet fully deployed technique. The problem so far has been the different constraints which do not allow rescheduling the load according to the electricity price but rather depend on outside influence e.g labour work organization, reliability reasons, etc. Therefore it is important to define the loads which are not influenced by other factors or do not cause some cost increase in the other sub cycles of the production. If it causes some other costs outside of the observed sub cycle then these costs have to be considered in the optimization calculations. The target is always to minimize the overall cost of the factory considering all the influences among the different sub cycles.

It is evident that the more energy intensive is the industry and the more flexible load it has available the easier it will be to control it and the more savings it produces.

A. Load Controlling Principles

The goal of this paper is to find and demonstrate the optimization using a PLC controlled optimal load curve for the machines throughout the entire factory process. The factory electricity cost is minimized depending on the electricity price on the spot market for each given hour.

The main objective of the industry is to produce goods according to the market situation or the production capacity. It means that the industry's production capacity is fully exploited unless unfavourable market conditions do not allow realizing the full volumes of the end products. Therefore industry mainly runs with 2 constraints. The product flow is constrained by the need of the market, i.e. by the sale volume which is the commercial limit of the production, as described in (8).

$$\sum_t Q_t^n \ge Q_{sales}^{\max}, \qquad (8)$$

where $Q_{sales}^{\max}$ – maximum average sale volume (t).

In energy intensive industries aggregated loads in different subsystems form a single load. This single load can be controlled independently from rest of the process without hindering the overall productivity of the system.

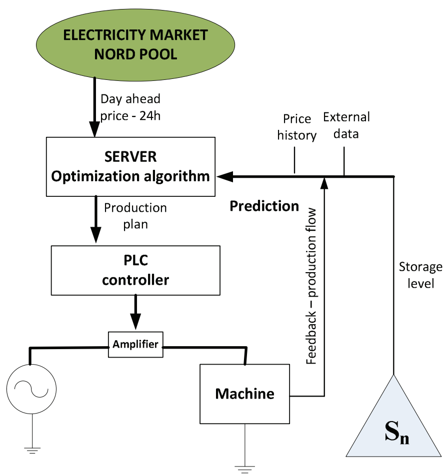
The subsystems of the process can be divided by the type of the consumers. The loads that act as a single cycle, which cannot be separated, form a controllable load. The single loads which have the medium storage between them do not depend from each other and therefore can be considered as a single aggregated load. These loads can be controlled independently in order to minimize their electricity cost under the open electricity market conditions.

The commercial limits are given by the market conditions and the technical limit is given by the lowest production cycle capacity in the factory. If the production capacity is even throughout the total process then there is now possibility to optimize the production because the system needs to run flat out in order to produce the required industrial product. Therefore the cost-effect optimization can be implemented in the factories where there is available overcapacity of the machines

However, in most of the energy intensive industries there is some overcapacity available for reliability reasons. The industry under investigation for example has a several single load sub cycles in order to gain in the production reliability. It means that if some equipment fails in the process it does not stop the end product production. The final product production can continue as long as there is a medium available in the intermediate storages. These kind of intermediate storages allow repairing the broken equipment during mid-production. They also provide the flexibility to make the necessary maintenance in the subsystem without losing the end production capacity. On the third aspect these storages can serve also as a simple energy storage allowing the industry to deliberately start and stop the subsystems for minimizing the cost of electricity.

Load control of the sub system has to be done automatically in order to implement it at a larger scale. The principal of the automated PLC based control system is described on the Fig. 4.

Fig. 4. The simplified production control with day-ahead optimization of the machines's operation schedule.



As studied previously in [1] these savings can be up to 17% from the electricity cost of a single optimized cycle. Depending on the energy intensity of the specific industry the absolute commercial savings could be remarkably high. It is evident that the more energy intensive is the industry and the more flexibility it has, the higher is the load control revenues for the consumer.

The automatic control systems excludes the human error factor for running the loads according to the given load profile. For automated systems it is easy to control the machine load according to the calculated optimization curve. Technically the machine or the industry needs the controllable load preferably together with frequency converters or other systems which allow to start and stop machines frequently with short start up times. Once the optimization system and algorithm is created the technical control and communication solutions are required. The machine needs a PLC controller for starting and stopping operations. The optimization program needs the information input about the market price and the feedback from the machines and storages about the volume available in the storages. In case of the commercial limits it also needs to know the required maximum production and sales volume.

The inputs of the required data together with the feedback from the system create a database for the optimization algorithm. This algorithm is used to create a load profile for each subsystem (single load) separately. Once the load curve has been formed the curve is transferred into the PLC and the PLC gives a command to the machine according to the calculated load profile.

In this kind of automated system every single load unit can be optimized no matter how big or small the unit is. However the bigger is the load the more revenues its controlling gives to the industry. Since the technical hardware which is required has a low cost then it is worth to use the system on any bigger load e.g. pumps, chippers etc which have a storage for the intermediate product.

To push the optimization even further with the aim to maximize the utilization of the available storage space, an electricity market price forecasting model could be used. For example, by knowing the weekend prices, it could be useful to take that into account in the workday production plans. In this case the storages could be used even more efficiently and the variation of the storage volumes would be more significant. Longer period prediction model even allows making decisions for scheduling a long term maintenance break.

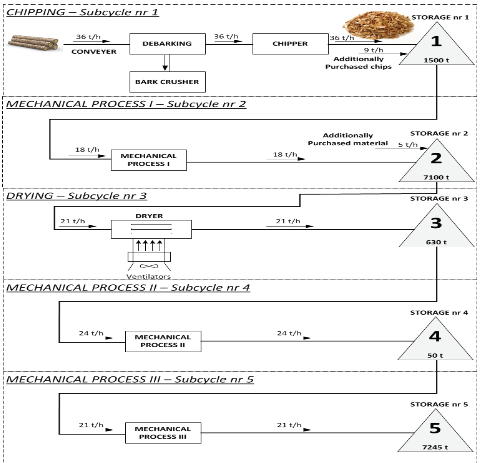
B. *Wood Industry - Case Study*

The aim of this study is to determine the flexible loads and the storage capacities for the industry under investigation. The factory full process line is tracked and the installed machines and their nominal output is described in the Table 1. The principal of the factory and its sub cycles are described in the Fig. 5. The over capacity sub cycles have been defined and their respective flexibility is found.

The industry under investigation operates a wood processing factory with an average electrical power of 3.2 MW (C^i). The factory production capacity is 21 t/h (Q^{max}). The factory production structure is illustrated on Fig. 5, and the technical parameters are given in the Table 1. The factory's management has determined the over dimensioned machines capacities are fully controllable and flexible for load response activities. The possible fixed additional costs might need to be taken into account for implementing such a concept.

As it can be seen from the table, the factory has some overcapacity in 3 of its sub cycles out of 5 which could be successfully used for the load response.

Fig. 5. Factory under investigation production structure.



The reference scenario for this study is the assumption that without using any optimization the industry's machines working hours are random and/or it works constantly at lower output. In this case the factory's electricity cost would equal to the annual average spot price which is also confirmed by the factory overall consumption measurement. However, with the optimization model the optimal production plan is found for each day separately for each sub cycle and the total annual cost effect is compared to the reference scenario. Within this study historical market data can be used for this comparison and analysis.

The factory machines' and subsystems' production characteristics are linear, i.e. the correlation between electrical power and output capacity is linear. As a simplification, the production characteristic of the sub cycle used in the later calculations is its average output, which does not take into account differences between wood types, e.g. softwood and hard wood. The production characteristic is an actual long time average in the wood industry under investigation.

IV. Results

The developed optimization model as per (3) can be solved using Microsoft Solver Foundation which uses the Simplex method. The base case scenario is known from the factory electricity cost history and this can be used to compare the cost of the optimized consumption profile. The results can first be simulated on the Microsoft Solver Foundation to find the cost effect in relative and absolute figures. After the successful simulation the factory can make a decision to install the necessary communication infrastructure and execute the load scheduling program. Since the Elspot market in Nord Pool Spot area provides prices only for the day-ahead, the model cannot take into account the possible changes that might occur in the longer future. For example, the model cannot know whether the prices will be lower on the weekends, thus limiting further optimization without additional forecasting models.

The working schedule that is optimized according to the day-ahead market price is ideal for additional minimization of the electricity cost in the industry who has already exploited all the other options like efficiency increase, power factor compensations, and etc. Ideally this demand response is a good example of a well-functioning spot market where the consumer could benefit from the system and system could have a positive influence from the consumer. When consumer shifts the load into the off-peak hours of the day, then the electricity system would become more stable and less peak capacity would be needed.

TABLE I. FACTORY PRODUCTION SUB CYCLE PARAMETERS

Subcycle number and description		Load (MW)	Control-lable	Production capacity (t/h)	Additional purchase (t/h)	Storage (t)	Storage (h)	Energy consum-ption (MWh/t)	Over capacity
	Chipping	0,4	YES	36	9	1 500	33	0,01	114%
2	Mechanical process I	0,3	YES	18	5,4	7 100	303	0,02	11%
3	Drying	0,7	NO	21	-	630	30	0,03	0%
4	Mechanical process II	0,5	YES	24	-	50	2	0,02	14%
5	Mechanical process III	1,3	NO	21	-	7 245	345	0,06	0%
	Total	**3,2**		**21**					

V. CONCLUSIONS AND FUTURE WORK

An optimization algorithm has been created to the online load controller for the overcapacity machines in the energy intensive industry. The application manages the load shifting under open electricity market conditions. By implementing the developed optimization algorithm together with the load profile controller for a studied industry, the factory's production line energy costs are estimated to decrease compared to the base case where the factory is operated normally according to the needs.

The developed algorithm and technique enables the energy intensive consumer as a factory to oversee its flexibility and determine the available resources for the demand response activities. The skill to execute the demand response optimization can decrease the industry's energy cost and therefore make the production more competitive than the industry who does not use this opportunity. Once the optimization technique has proved its success the consumers of other type can be expected to have more interest about the demand response as well.

It is important to investigate the studied industry in more depth to determine the details for the data necessary to make the simulation. The simulations should be tested under various conditions in order to see the total cost effect of the optimization. Once the simulations have been done the research should focus on the actual application implementation in the given industry. During the field test all the relevant costs can be recorded and taken into account. Also the non-technical aspects can be studied like the willingness of the factory personnel to adapt with the new principles of the work organization.

This approach gives the industry a high value cost optimization possibility because it makes possible to use the most optimal production plan for the specific day.

In the future there should be done some field tests with this equipment and the results should be compared to the previous simulation results. In case the field test comes out to be successful, the technology should be turned into a real product that should be released as a wide scale commercial application.

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