THESIS ON POWER ENGINEERING,
ELECTRICAL ENGINEERING, MINING ENGINEERING D78

Demand Side Management Possibilities and Viability for Voltage Support Services in Estonia

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TUT PRESS

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This dissertation was accepted for the defence of the degree of Doctor of Philosophy in Energy and Geotechnology on June 28, 2016.

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Defence of the thesis: August 30, 2016

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.

Imre Drovtar

ISSN 1406-474X
ISBN 978-9949-23-993-1 (publication)
ISBN 978-9949-23-994-8 (PDF)

ENERGEETIKA. ELEKTROTEHNIKA. MÄENDUS D78

Tarbimise juhtimise võimaluste uurimine ning rakendatavus pinge reguleerimise teenusteks Eestis

IMRE DROVTAR

TTÜ KIRJASTUS

Table of contents

Acknowledgements

Firstly, my deepest gratitude is due to my supervisors Dr. Argo Rosin and Dr. Jako Kilter who have guided me during my studies but also over my professional career. Furthermore, I would like to express my gratitude to my former colleagues at Elering AS: Dr. Mart Landsberg, Andrus Reinson, Mari Löper, Marko Tealane and Kalle Kukk for their contribution at the beginning and completion of this work.

Special thanks go to Dr. Priit Uuemaa whose role in providing crucial information about industrial consumers is invaluable and who has contributed to our common research papers and supported morally the finalization of this thesis. I would also like to thank Dr. Siim Link and Kaur Tuttelberg for giving valuable insight to some of topics and problems described in this work.

Tallinn University of Technology and Doctoral School of Energy and Geotechnology II are gratefully acknowledged for the financial support.

My sincere gratitude goes to Dr. Pavel Etingov from the Pacific Northwest National Laboratory for his kind permission to access and use the Load Model Data Tool (LMDT) in the final part of this research work.

Thank you!
Imre Drovtar

List of author’s publications

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

[I] **DROVTAR, I.**; Landsberg, M; Kilter, J.; Rosin, A., "Impacts of large scale wind integration on the Baltic region's thermal power plant economics and electricity market in 2025," *Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2012 International Symposium on*, Sorrento, 2012, pp. 684-689.
doi: 10.1109/SPEEDAM.2012.6264591

[II] **DROVTAR, I.**; Uuemaa, P.; Rosin, A.; Kilter, J.; Valtin, J., "Using demand side management in energy-intensive industries for providing balancing power - The Estonian case study," *Power and Energy Society General Meeting (PES), 2013 IEEE* , pp.1,5, 21-25 July 2013.
doi: 10.1109/PESMG.2013.6672418

[III] **DROVTAR, I.**; Rosin, A.; Landsberg, M; Kilter, J., "Large scale electric vehicle integration and its impact on the Estonian power system," *PowerTech (POWERTECH), 2013 IEEE Grenoble*, Grenoble, 2013, pp. 1-6. doi: 10.1109/PTC.2013.6652181

[IV] Uuemaa, P.; **DROVTAR, I.**; Puusepp, A.; Rosin, A.; Kilter, J.; Valtin, J., "Cost-effective optimization of load shifting in the industry by using intermediate storages," *Innovative Smart Grid Technologies Europe (ISGT EUROPE), 2013 4th IEEE/PES*, pp.1,5, 6-9 Oct. 2013.
doi: 10.1109/ISGTEurope.2013.6695404

[V] **DROVTAR, I.**; Rosin, A.; Kilter, J., “Demand Side Management in Small Power Systems – The Estonian Case Study,” in *ELEKTRONIKA IR ELEKTROTECHNIKA,* ISSN 1392-1215, pp. 13-19, vol. 22, no. 3, 2016. doi: 10.5755/j01.eie.22.3.15308

[VI] Uuemaa, P.; Puusepp, A.; **DROVTAR, I.**; Valtin, J.; Kilter, J.; Rosin, A., "Load control implementation in the energy intensive industry," *Mediterranean Electrotechnical Conference (MELECON), 2014 17th IEEE*, pp.213,218, 13-16 April 2014
doi: 10.1109/MELCON.2014.6820534

APPENDIX B includes copies of publications I-VI.

Author's own contribution

[I] Imre Drovtar was the corresponding author. He was responsible for the data collection, model development, modelling, and analysis of the results.

[II] Imre Drovtar was the corresponding author. He was responsible for the data collection and analysis of the proposed principle.

[III] Imre Drovtar was the corresponding author. He was responsible for the data collection, model development, and analysis of the results.

[IV] Imre Drovtar was one of the main author of the paper. He was responsible for data collection, analysis, and description of the proposed energy storage principle.

[V] Imre Drovtar was the corresponding author. He was responsible for the data analysis and collection.

[VI] Imre Drovtar had a minor role in the writing of the paper.

List of symbols

Abbreviations

AC	alternating current
CCL	conditionally controllable load
CHP	Combined heat and power plant
CLODxx	complex load model
CMLDxxU	PSS/E user written composite load model
CMPLDW	composite dynamic load model
DC	direct current
DG	distributed generation
DSM	demand side management
DSO	distribution system operator
DSR	demand side response
ECL	exceptionally controllable load
EV	electric vehicle
FCL	freely controllable load
GENSAL	salient pole generator model (quadratic saturation on d-axis)
HVAC	heating, ventilation, and air conditioning
ICT	information and communication technology
IND_PMT	industrial consumer model representing a paper mill with thermo-mechanical processes
LMDT	load model data tool, created specifically for WECC to help to write the custom load models for PSS
OB	office building
OLTC	on-load tap changer
P	active power
PCC	point of common coupling
PFC	power factor correction
PLC	programmable logic controller
PSS/E	Power System Simulator for Engineering
PSS2A	IEEE Dual-Input Stabilizer Model
Q	reactive power
QV	reactive power-voltage plane
RTU	remote terminal unit
SCADA	supervisory control and data acquisition
SPS	special protection scheme
TOU	time-of-use tariff
TSO	transmission system operator
U	voltage
UVLS	under voltage load shedding
VQ	voltage-reactive power plane

Institutions and organisations

CIGRE	International Council on Large Electric Systems (in French: *Conseil International des Grands Réseaux Électriques*, abbreviated *CIGRÉ*)
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
IEEE	Institute of Electrical and Electronics Engineers
WECC	Western Electricity Coordinating Council

Indexes

C^{CH}	output power of chipper
C_d	marginal cost of drying (euros per ton)
C_e	marginal cost of electricity excluding energy (euros per ton)
C^E	external cost of the load shifting
C_{iV}	inelastic variable cost for the production (euros per ton)
C_l	marginal cost of labour (euros per ton)
C_o	marginal cost of other concurring costs (euros per ton)
C_{rm}	marginal cost of raw material (euros per ton)
C_t	marginal cost of transport (euros per ton)
C_v	variable cost for the production (euros per ton)
$\Delta\tau_{A\Sigma}$	TSO's maximum response time allowed for ancillary service
$\Delta\tau_{\Delta\Sigma M}$	service provider's response time (minutes) for providing DSR
e_d	induction motor voltage on the direct axis for transient impedance
e_q	induction motor voltage on the quadrature axis for transient impedance
E_t	total electricity consumption over a calendric year (MWh)
H	combined inertia time constant for the induction motor (+ load)
i_d	induction motor stator current for the direct axis
$I_{P/S}$	value of lost income due to production or service interruption (euros)
i_q	induction motor stator current for the quadrature axis
m	number of industries in the sector or the number of different types of flexible loads available for control
M_t	total production of the good over a calendric year (tons)
n	total number of electrical drives in the process, or total number of hours used to determine average electricity consumption, or number of hours the facility is operating and/or producing goods, or load describing constant
o	total number of hours used to determine average electricity consumption
p	number of office building in the sector

$P(s)$	probability of the scenario s
P_{AS}	TSO's required minimum ancillary service load level (MW)
$p_{av,i}$	average price of the last 24 hours
P_{DSM}	service provider's offered (aggregated) DSR load for DSM (MW)
P_{DSR}	(aggregated) load used for DSR (MW)
P_e	input electrical active power for the induction motor
p_i	price at time i
$P_{i,j}$	total electricity consumption for n hours at m industry companies
$P_i^1 \ldots P_i^m$	total flexible load at hour n
P_i^{total}	total electricity consumption at hour n
$P_{k,j}$	electricity consumption for o hours at p office buildings
P_m	output mechanical power for the induction motor
$P_{N,m}$	rated power of the specific drive
P_P	marginal profit of the product per unit (euros per ton
P_t	electricity price for time period t
P_{FCL}^{DSM}	"freely" controllable load used for DSM
P_{CCL}^{DSM}	"conditionally" controllable load used for DSM
$\overline{P_{Industry}^{DSM}}$	DSM potential of an industry
$\overline{W_{el}}$	average hourly electricity consumption over a studied period (Wh/h)
Q_e	input electrical reactive power for the induction motor
Q_t	wood chipper's production volume for time period t
R_s	induction motor stator resistance
T_0'	transient open-circuit time constant
t_{DSM}	duration of the ordered DSR service (hours)
T_{l0}	load torque constant
T_{max}	maximum allowed temperature
T_{min}	minimum allowed temperature ranges
T_{set}	default temperature set-point
$T_{set,i}$	new set-point calculated according to the price
v_d	induction motor stator voltage for the direct axis
V_{DSM}	price of providing DSR service for the TSO (euros per MWh)
W_{el}	total electricity consumption over a studied period (Wh)
v_q	induction motor stator voltage for the quadrature axis
X'	induction motor transient reactance
X_m	induction motor magnetizing reactance
X_r	induction motor rotor reactance
X_s	induction motor stator reactance
δ	reserve production capacity factor
σ_m	loading factor of the specific drive
φ	flexible load capacity factor
ω_r	rotor rotating speed
ω_s	stator field rotating speed

Units

°C	degree Celsius
h	hour, time
m	meter, length
p.u	per unit
s	second, time
V	volt, voltage
W	watt, active power
VA	volt-ampere, apparent power
var	volt-ampere reactive, reactive power
Wh	watt-hour, unit of energy
Wh/h	watt-hour per hour, average energy consumption per hour

Metric prefix

m	milli, 10^{-3}
k	kilo, 10^{3}
M	mega, 10^{6}
G	giga, 10^{9}
T	tera, 10^{12}

1. Introduction

1.1 Motivation and background

According to the European Union (EU) Energy Efficiency Directive, article 15.8 [1], all member states are obliged to support access of demand side response (DSR) service providers to the electricity and ancillary service markets. The governmental regulatory institutions for the energy sector together with all market participants are required to work out the necessary technical requirements and parameters for enabling DSR services access to markets [1]. However, the ancillary service regulations that would allow DSR service provision have remained unchanged since they were established for generators. As using loads by ancillary service providers is unregulated, demand side management (DSM) utilization in the power systems is rare. In socio-economic terms, this means hundreds of millions of euros of loss for the society.

Currently out of 28 member states, only 5 have regulatory and/or contractual measures that allow or promote different DSR measures to be used for power system control. Finland, Belgium, Austria, Great Britain, Ireland, Germany, and France are revising their legislation, which should promote the usage of DSR in those countries [2]. The aim of this thesis research is to address the DSM potential in three main economic fields in Estonia and to research a novel approach to utilize DSM as a voltage support service in weak parts of the transmission system. The possibility to utilize DSM to provide system services in weak parts of the transmission system is becoming more actual as demand centres are shifting towards urban areas, leaving some parts of the transmission system inevitably in a weaker configuration.

Over the period of 2013-2014, the author of this thesis was responsible at the Estonian transmission system operator (TSO) to carry out a research project [3] in order to map the potential of the Estonian power system to include DSR in power system services provision. In addition to ancillary service provision, energy management and energy efficiency issues from the customer side were assessed to provide potentially beneficial options for the customers. Three different types of consumers (industrial, commercial and public services) were analysed that included on-site measurements and interviews with the representatives.

Within that context, the author of this thesis carried out comprehensive studies that included on-site measurements and energy analyses at different large electricity consumers. The information gathered from the studies were then incorporated in a reduced power system model to assess the possibility to model and utilize DSM in power system planning and operations studies, the results are summarized in this thesis. The main aim of this research was to show and prove that there is an unused technical potential and willingness from the consumers to provide DSR and not only for price based load control but also for system and ancillary services (DSM). Based on the results presented here it is possible to improve the power system modelling quality with dynamic loads in order to determine possible DSM related services and their impact on the Estonian power system operation and security. The thesis can be also a source for future research topics in the field of load modelling and DSM.

1.2 Main objectives and tasks of the thesis

The main objective of the thesis is to map the potential of DSR in different economic sectors in Estonia and determine the potential of using these loads for system ancillary services, taking into account also the technical and economic constraints from both the system and the service provider aspects.

Another objective of the studies was to determine through modelling the possibility and impact of using loads as a reactive power reserve for voltage support to the power system.

The main research tasks of the PhD thesis were as follows:

- to analyse the existing know-how about DSR and DSM usage for power system ancillary services;
- to analyse the existing capacities and costs of the Estonian power system ancillary services;
- to map and analyse the restrictions, potential and willingness of different economic sectors to participate in DSR and DSM actions;
- to study and determine the possibility to model the DSM in power system studies with power system modelling software PSS/E;
- to assess the possibility to use the DSM as a reactive power reserve for voltage support in the power system.

1.3 Contribution of the thesis and dissemination

Theoretical originality of the work

- It is based on a wide-scale analysis in terms of the field of activity.
- The DSM potential is mapped from two perspectives:
    - covering the needs and possibilities for the power system;
    - covering the consumer benefits.
- Benefits cover not only economic motivation but also technological improvements and optimization possibilities, which lead to possible economic benefits.
- Simple methodologies for DSM potential evaluation for different consumers are derived that help analyse small areas/countries composed of homogeneous consumers and load profiles.

Practical originality of the work

- The research provides comparison of different load modelling principles and models to incorporate DSM in everyday power system planning studies.
- The modelling concept is based on a real industrial consumer facility connected to a relatively weak part of the transmission system.

- The used model represents a real part of the Estonian transmission system and its interconnection strengths to the main 330 kV transmission system.

Novelty

The relevance of the thesis topic is growing along with the operation of the power system becoming more challenging by every day. With the increasing need for ancillary services for power system safe operation and mothballing of old generating units, the gap between demand and supply of these services is also increasing. Load and DSR could help to fill this gap between demand and supply with its yet undiscovered potential. The key factors that distinguish these studies are:

- The proposed DSM evaluation methodology can also be used in countries with similar climatic conditions, load distribution and consumer profiles.
- The research incorporates the benefits of the open electricity market and available resources (energy storages) at the consumer's site. This increases the consumer's awareness about their potential and helps to maximize the utilization of their resources and if possible, provide additional services for the power system.
- The research proposes a new modelling methodology to incorporate DSM in the studies of power system planning during weak transmission grid configurations targeted to providing voltage support.

Dissemination of the research work

This thesis has been composed and compiled from six research publications. Two of the articles have been published and presented in the world's largest IEEE conferences (IEEE Power and Energy Society General Meeting and IEEE PowerTech). The topics have proved relevant and researchers have shown interest in the presentations and its results. Paper [V] has been published in a peer reviewed journal. Chapter 5 of this thesis is being prepared for publication in a peer reviewed journal.

1.4 Thesis outline

The thesis is divided into four major sections: Chapter 2 covers the previous research and potential of the DSM in power systems, Chapter 3 introduces the methods used to map the DSR potential in Estonia, and Chapter 4 summarizes the DSM potential. Chapter 5 addresses a modelling principle to incorporate DSM actions in power system modelling with PSS/E. The chapter concludes the modelled impacts on the power system operation and proposes to use loads as a source of reactive power reserve to provide voltage support during weak system configurations. Finally, Chapter 6 provides a conclusion about the results together with recommendations for future research topics.

The conclusive list of references consists of 68 external publications and 6 author's publications.

2. Demand side response and the power system

Today's electrical loads are more predictable and controllable, giving a new opportunity to manage the power system all together through DSM. The current system includes already hundreds of thousands potential end consumers who would be able to provide different system and ancillary services through DSR for the system operator at any level. The loads have been successfully incorporated to provide long and short-term frequency reserves. In addition, there are new market driven DSM services widely and successfully incorporated for many system operators in the United States.

The classification of DSR and/or DSM can remain vague due to the large number of different definitions and understandings. Definitions provided in [4] divide DSM measures into two major categories: static and dynamic measures.

Impacts of static measures appear over a longer period and are mainly tied to energy efficiency. Depending on whether the measure is initiated via regulation or through consumer choice, it is divided into passive and active measures respectively. Measures are interesting mainly for those sectors where energy efficiency gives remarkable savings on (operating) costs, i.e. in households and in the commercial and public services sector. At the same time, the aggregated level of energy efficiency helps to reach national targets set by legislation. Through improved energy efficiency also some energy conservation is achieved.

Dynamic measures, on the other hand, are tied to short-term actions, which aim to provide services for the electricity market and system. The effects of these actions are short-term and no remarkable energy saving is derived, main aim of these services is to improve market and system efficiency. Dynamic services can only be provided by large unit consumers (e.g. industries) or aggregated consumer groups who are able to affect the system and at the same time, can be controlled centrally and simultaneously. Dynamic measures, for example, include price based load control or ancillary service provision for the system operator. Once again the service provision can be divided into two categories: active, i.e. the initiative for activating or implementing the measure comes from the customer (e.g. price based load control), and passive if the initiative is triggered by a third party, such as TSO/DSO (e.g. ancillary service, voltage support, etc.). A summary of the measures is provided in Table 1.

Both DSM measures described above have been used in this research to help determine potential benefits for the consumer. This is essential for making DSR and DSM attractive for potential service providers and users. However, for the sake of uniformity in terminology for power system related services, in this thesis, the classification of DSM and DSR refers mainly to the ENTSO-E's classification in the policy paper for DSR [5] published in September 2014. This classification is much simpler and helps the author to describe the research more clearly. According to ENTSO-E's terminology, **DSR** refers to load demand that can be actively changed by a trigger and that is initiated by the consumer. **DSM**, on the other hand, is the utilization of DSR loads for power system related services such as system security (e.g. balancing and congestion), or system adequacy.

Table 1. DSM measures, their classification, duration and examples [4]

<table>
<tr><td></td><td colspan="4">Demand side management</td></tr>
<tr><td>Action</td><td colspan="2">Static (Long term)</td><td colspan="2">Dynamic (Short term)</td></tr>
<tr><td>Macro level impact</td><td colspan="2">Improved energy efficiency and some energy conservation</td><td colspan="2">Improved market efficiency and system control. Some impact on energy efficiency and conservation</td></tr>
<tr><td>Customer involvement</td><td>Passive (Regulation or via 3rd party)</td><td>Active (Customer choice)</td><td>Passive (Automation/ Contract)</td><td>Active (Customer response)</td></tr>
<tr><td rowspan="5">Demand side action or programme terminology in common use</td><td>Energy Efficiency (regulation)</td><td>Energy Efficiency (customer investments)</td><td>Demand Side Management (DSM)</td><td>Demand Side Participation (DSP)</td></tr>
<tr><td>Energy Conservation (regulation)</td><td rowspan="4">Energy Conservation (customer limits energy use)</td><td>Demand Response (Initiated by TSO)</td><td>Demand Response (Initiated by price signals)</td></tr>
<tr><td>Integrated Resource Planning (IRP)</td><td rowspan="3">Demand-Side Control</td><td>Real-time pricing</td></tr>
<tr><td rowspan="2">Energy Performance Contracting (EPC)</td><td>Time of use pricing (TOU)</td></tr>
<tr><td>Critical peak pricing</td></tr>
<tr><td>Example</td><td>Energy efficiency standards in appliances</td><td>Installing loft insulation</td><td>Interruptible loads used to provide reserves</td><td>Load shifting in response to high prices</td></tr>
<tr><td rowspan="2">Level of customer participation required</td><td>low/medium</td><td>medium</td><td>medium/high</td><td>high</td></tr>
<tr><td>Overall customer demand is controlled by regulation of third party activities.</td><td>Customer makes an occasional or one-off decision, resulting in long-term energy efficiency.</td><td>Customer demand is controlled by third party; this can involve routine variation of service.</td><td>Customer regularly adjusts own energy use in response to price and system signals.</td></tr>
</table>

2.1 Overview of DSR for balancing and ancillary services

System or ancillary services are usually initialized by a third party, such as a TSO, DSO or a balance provider who orders it from service providers. 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 [II]. Nowadays electrical loads are more predictable and controllable, giving a new opportunity to manage the power system all together through DSM. The current system includes already hundreds of thousands of potential end consumers who would be able to provide different system and ancillary services through DSR for the TSO. However, as grid tariffs prevail in the cost of electricity, the cost and possible economic gain from providing energy and system services do not reach the traditional end user. At the same time, when having aggregated effect, these local consumers could provide the necessary system support at critical time periods if not for the TSO, then for the DSO, e.g. to prevent outages in the power system or participate in the system control (balancing), as well as optimal development of the network [6]-[8].

Torriti *et al.* in [9] give an overview of the DSR experience in different European countries. Although there are numerous DSR programmes and initiatives within EU Member States, the EU-wide DSR initiative is missing mainly due to the inexistence of a single European energy market. Most of the DSR programmes in EU Member States are focused mainly on large industrial users and miss the possible benefits from a more comprehensive approach to the DSR, including commercial and household consumers. It was observed that customers lack means and adequate incentives to respond to the DSR requirements. Nevertheless, recent developments have reshaped the DSR programmes, which are starting to focus on commercial and residential customers rather than industries. For example, the *Electricite´ de France's* Tempo tariff is a programme that offers small businesses and residential customers different prices according to the weather conditions. The system uses colours to indicate the price and whether it is an off-peak hour or not [10]. A Danish study has proposed to aggregate 260 MW (6% of the Danish peak load) DSR loads from approximately 125 000 households through their electrical heating. As a result of the pilot study, it was found that a household could provide up to 5 kW of controllable loads [11].

Palensky and Dietrich in [12] point out that DSM's main advantage is that it is financially and economically more promising to incorporate consumer loads for providing balancing services than to build new power plants or install energy storage units. DSR and demand shifting could be used more effectively for system-wide services through a platform, which would give the consumers necessary information, such as actual need for regulating power in addition to simple price incentives, for scheduling their processes.

According to Bradley et al. in [13], deploying DSR in the market can bring a positive economic effect and increase the economic welfare for the society. The authors report that DSR can have different positive impacts 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 the grid and plants can be displaced. Several studies reported in [13] also indicate vast interest (participation over 75%) from the customer side to participate in those programmes. However, large-scale participation in DSR may be low without an appropriate sharing of benefits among the parties, and at the same time, incentives are needed to lower the participation costs in such programmes.

The future balancing market should not be built solely on the traditional generating capacities but should also integrate the possibilities of consumers and renewable energy producers. The restructuring or development of a new balancing market is essential to enable the integration of DSR and DSM on a wider scale. The future balancing market should define the most essential parameters for ancillary services in a way that all service providers independent of whether they are producers, consumers or storages could participate in the new market [2]. The parameters could be, e.g., capacity, minimum duration, minimum run-up time, such that the service buyer could fix the necessary parameters for its balancing requirement rather than the source of this service. A further step here would not be to define a specific name for the market, as it could affiliate services of all kinds, i.e., balancing, ancillary services, emergency reserves, and other services. This, in return, would also eliminate the issue of harmonizing the definitions of reserves and services in different countries, as suggested in [5].

As described in [5], DSM offers flexibility for the TSO to maintain security of supply, optimize the utilization of infrastructure, investments, and system adequacy. The vast potential is lying around the grid and is unused, although in many cases it can be a more competitive alternative than generation. In many cases, loads are used as a last resort in emergency situations to avert system failure [5], [14]. At the same time, the need for reserves to maintain a secure system is growing by the increase of weather-influenced generation. Up to today, these reserves have been met with large synchronous machines in fossil fuel fired power plants that are being decommissioned due to the strict environmental regulations or the incapability to compete on the market with the renewable resources, as described in [I].

The increasing need for balancing services would require large investments into new generation needed for its power rather than for its produced energy, making the investment unreasonable [15]. DSM could be the necessary missing resource to cover the need for additional balancing services at a reasonably competitive cost without the need for additional power plants for ancillary services. In addition to the provided services, it is predicted that DSM would also enable integrating securely more renewable energy sources [5], as not only shortage of power supply may result in a power system blackout, but an oversupply can also lead to frequency and voltage instability problems leading to blackouts [16], [17]. The following sections analyse the possibilities to incorporate DSR in frequency and voltage related services.

2.1.1 Frequency control

Keeping the system frequency in specific ranges is essential for modern electrical machines that are designed to work within specific frequency limits. Frequency reserves are one of the main ancillary system services that a TSO has to guarantee and the DSM has the potential to cover several frequency reserve requirements.

According to [17] and [18], the DSM can make a significant and reliable contribution into the primary frequency response through the principle of maximizing the social welfare by dynamic loading. It means that for up-regulation, the power consumption with the lowest welfare contribution to the society is shut down and for down-regulation, loads that produce the most welfare for the society are activated. As a result, a certain part of loading is frequency dependent. The frequency could be measured locally near the device and this could serve as the control signal for the device, serving as an alternative control method for two-way communication. Different types of demands, i.e. refrigerators, HVAC, heaters and different types of industrial motors, could be allocated for frequency control [18]-[21].

In [21] the author proposes a method to implement industrial loads as frequency restoration reserves to relieve frequency containment reserves that are fast switching and aim to stabilize the frequency deviation quickly [22]. From the power system point of view, increasing active power production in system corresponds to a decrease in load demand and vice versa. It is concluded in [21] and [II] that industrial loads are suitable for the DSM due to their variability, size, production line structure and the infrastructure already installed that requires low or no investment for the DSR service to be allocated for DSM.

In [23] an approach of load shedding is presented where only the secondary loads (i.e., devices for those operations that are not urgent and can be shifted in time, such as boilers, refrigerators, HVAC) are managed in the entire distribution network. As soon as the disturbance is overcome, the loads can be smoothly/seamlessly re-committed, skipping long restoration procedures. The proposed mechanism exploits the capability of selective distributed load shedding on the customer level.

Although today the frequency of the Estonian power system is controlled centrally from the Russian power system, no separate agreements or reserves are maintained by the TSO. Nevertheless, the capability is required already today by the national grid code. It is assumed that in the long-term development plans, where the Baltic power systems could be desynchronized from the Russian power system, the demand to maintain different balancing and control reserves locally in the geographical region will significantly increase.

With the liberalization of the electricity market and asynchronous connections to the Nordic countries, first steps have been taken to modernize the power system and electricity markets. The next logical step is to develop a transparent balancing and control system and market in the Baltic region. This would enable the versatility of regulating and balancing service providers by utilizing the existing potential hidden in the power system today.

2.1.2 Voltage control and stability

Another quantity that describes the power system's operation is voltage. From voltage control mechanisms, the following factors influence the voltages in the power systems: terminal voltage of synchronous machines, line impedances, turns ratios in transformers, and transmitted reactive and active power (load) [24].

From the previous listing, load is one of the main factors that affects voltage stability in the power system. According to [24], voltage instability is caused by the power system's inability to meet the demand for reactive power. The main reason is that a voltage drop occurs when active and reactive power flows through the system. In extreme contingency cases, this flow of power can lead to voltage collapse.

Voltage instability is mainly a local phenomenon in the power system but can lead to a system-wide incident [24]. According to [25], load characteristic is one of the most important factors affecting voltage stability. Resulting from the analysis of the mechanism of voltage instability considering the load characteristic, the authors of [25] made the following conclusions:

- increase of the slip in induction motors worsens the system stability;
- different proportions of constant impedance load and dynamic load impact the static voltage stability;
- increase in the share of constant impedance load is helpful to voltage stability, however it is essential to keep a reasonable load proportion to avoid power unbalance and enhance transmission efficiency.

The load type has a strong impact on possible voltage instability incidents, i.e. it has the necessary potential to provide voltage control services for the system operator. Traditional measures for local voltage control include transformers with tap changers and stationary reactive power consumers or producers installed at the substation bay. However, these units are usually limited by their physical limits in providing reactive power or voltage support and in certain contingencies, the effect of these devices is insufficient. Another issue from the system planning point of view is the seasonal voltage control variability and need in certain points of the grid.

Installing voltage control/support devices is usually a time consuming project that may not be reasonable because of occasional short periods of voltage control. From this aspect, DSR is an unused potential for local voltage control and could prove a reliable and essential measure for controlling voltages under normal as well as extreme conditions. The requirement of additional variable voltage control has been analysed in [III] from the large-scale electric vehicle (EV) integration aspect. The need for additional voltage control arises in weaker and distant parts of the grid without strong connection to the main transmission system and/or requires voltage support occasionally. The latter case is analysed in detail in Chapter 5.

2.2 The Estonian power system

The Estonian power system connects Estonian power stations, network operators, and electricity consumers, while operating in parallel with the Integrated Power System and Unified Power System of Russia (in literature and public communication also addressed as IPS/UPS). Estonia has three 330 kV lines connected with Russia, two running from Narva towards St. Petersburg and one linking Tartu and Pskov. As of 2016, Estonia has officially two AC connections to Latvia from south Estonia. The line running through the Pskov region to North-Eastern Latvia can be also considered as an alternative interconnection to Latvia. A third AC interconnection is planned to be commissioned by 2020. In addition, the Estonian power system is connected to the Nordic power systems via two DC links (EstLink 1 and EstLink 2).

Although the Estonian power system is relatively small compared to the IPS/UPS system, the Estonian TSO is still responsible for planning the system functioning and management to guarantee safe and reliable operation of the network in all interconnection directions. In addition to enabling the transmission of electricity, the TSO is also responsible for managing the balance between the load and generation of its system at all times. The transmission grid of Estonia (illustrated in Figure 1) consists of:

- 1 702 km of 330 kV lines;
- 158 km of 220 kV lines;
- 3 479 km of 110 kV lines;
- 61 km of 35 kV lines;
- 139 km of DC lines with two converter stations;
- 146 substations.

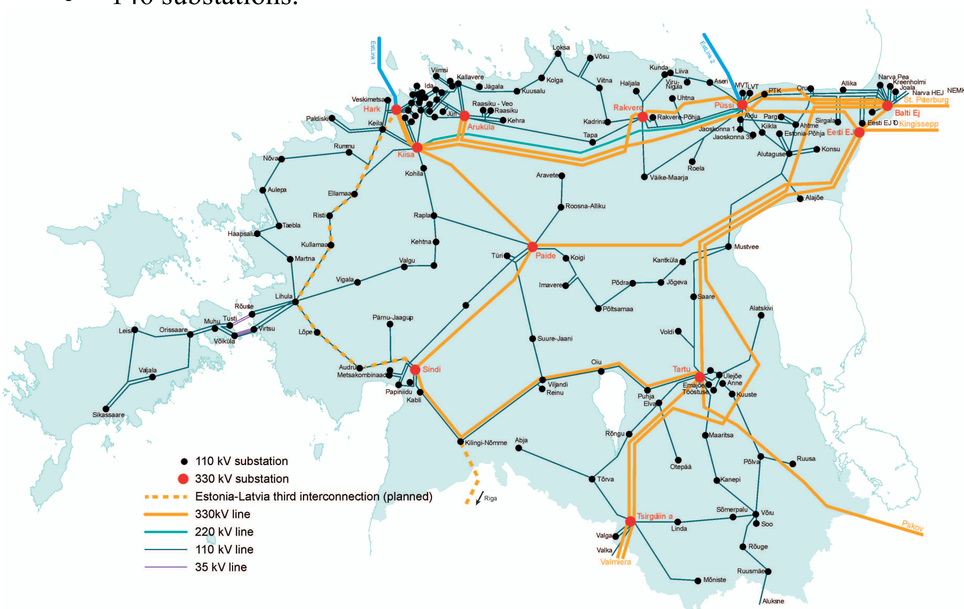


Figure 1. Estonian power system and its interconnections. [26]

The large deviation of load capacity in different parts of the power system can clearly indicate also the strength of the grid at those locations. Although the grid was once developed for higher consumption, then due to the modern society's development and urbanization, an area that once was a load centre has become, for example, a region for summer cottages with low consumption. Due to this the development of the grid has been halted, meaning that when the area becomes once again prospective, for example, for wood and forest industry, the situation of the transmission grid may inhibit the developments in that area due to high investments needed to upgrade the electricity system. The load distribution between different parts of the country is strongly tilted towards urbanized and industrialized regions, as analysed in [III] and illustrated in Figure 2.

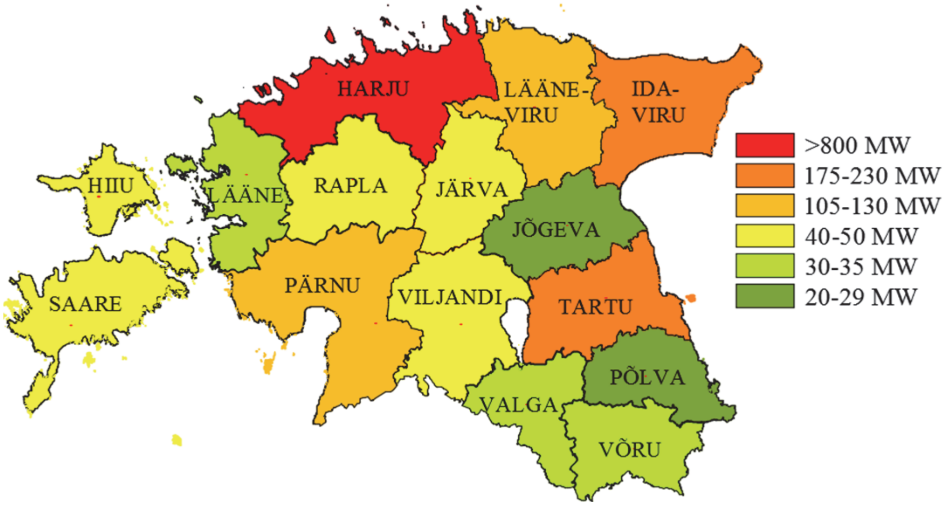


Figure 2. Peak load distribution in different counties in the Estonian power system.

Electricity consumption (including network losses) in Estonia in 2014 was approximately 8.3 TWh. The national consumption profile can be equally divided between three groups of consumers: industrial, commercial (including public sector) and domestic. Industrial consumers cover also the transportation, agricultural and construction industry. The share of the three sectors of consumption and network losses is illustrated in Figure 3.

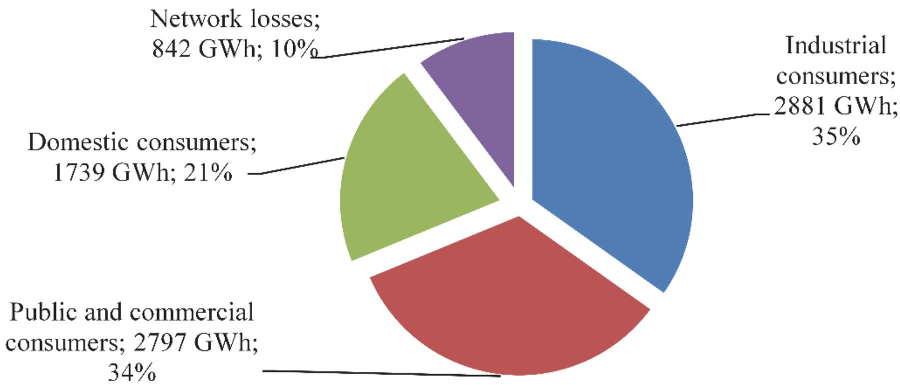


Figure 3. Electricity consumption in Estonia in 2014.

According to the TSO’s forecast, the annual electricity consumption growth will remain around 1.1% up to 2030, complying with the forecast for the EU (0.4% to 1%) [27]. Recent electricity consumption trends are indicating that although the overall electricity consumption might increase over the years, the peak consumption growth is slower or smaller. In the last decade, the peak consumption of the Estonian power system has remained between 1 500 MW and 1 600 MW.

Power system planning and operation in Estonia takes into account ±10% error in the peak consumption forecast, mainly due to the possible wide temperature fluctuation range. In extremely cold winters, a 10% offset in the forecasted peak consumption can be expected easily. It is assumed that the system peak consumption will not change until 2020 and remains around 1 600 MW. An additional 100 MW increase can be expected by 2030. The average peak consumption growth will remain around 0.7% per year, with prevailing influence from the climatic conditions. As of the beginning of 2016, 2 676 MW of generators have been connected to the Estonian power system, including:

- 1 945 MW condensing thermal power plants;
- 281 MW CHPs;
- 62 MW small and industrial CHPs;
- 7.8 MW run-of-river type hydro power plants;
- 375 MW wind power plants;
- 5.2 MW micro power plants (including solar, hydro and wind).

2.2.1 Regulation services in Estonian power system

Regulation services of the Estonian power system can be divided into two categories. **System services** are technical measures for the power system, which ensure the working reliability of the system, the security of supply, and transmission quality. System services include maintaining the frequency, ensuring the existence of reserve capacity, keeping the balance for active and reactive power, regulating voltage and other similar services. **Balancing services** help the TSO maintain balance in the power system at any time, certain power regulation actions (up and down balancing service) must be performed at every hour to maintain stability and safe operation of the power system. These actions are triggered by market participants who cannot maintain balance between their production and consumption during market operation hours and their shortfalls and excess of energy must be covered and purchased by the TSO. These services also include activating emergency reserves in case a cross-border link fails.

All the power system emergency reserves necessary for the Estonian power system are either owned by the national TSO or available to be ordered from neighbouring power systems through corresponding agreements. To minimize the costs and necessary capacities of these reserves, they are shared and maintained together with neighbouring power systems. Over the period of 2012 to 2014, the Estonian TSO built a new emergency reserve power plant (250 MW) due to the increased need for reserve capacities and the increasing cost of keeping it elsewhere, mainly outside Estonia.

To balance large mismatches between demand and supply, the TSO can order regulation services (balancing service), so far used to either increase or decrease the electricity production to balance the system. This service is realized 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 [28]. 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. Both system and balancing services can be in theory also provided by consumers. However, the minimum capacity that can be offered for regulation is 5 MW. In addition, all the offers have to be submitted two hours prior to the possible request for service. [II]

2.2.2 Historical overview of regulation services

The following overview of different regulation services in the Estonian power system covers the period between 01.01.2011 and 30.10.2014. Although both up- and down-regulation were analysed, it resulted from interviews of potential service providers that from the DSM point of view, only up-regulation is of current interest and therefore under discussion. This is because consumption decrease preceding a short notification can be managed rather easily but a sudden load increase involves risks to the industry and its employees.

The requirement for system services through up-regulation has varied over the studied period significantly. In 2011, system services were ordered only on 264 hours, in the following years, 2012 and 2013, they increased to 1 984 and 1 877 hours respectively, constituting around 1 000 hours in 2014. Majority of the ordered regulations remained below 40 MW and constituted merely 35% of the total costs on up-regulation system services (Figure 4). Over the period, the cost of MWh system service has increased by 35%, to 71 euros but the price variation range has doubled from the maximum price of 65 euros to 126 euros (Figure 5).

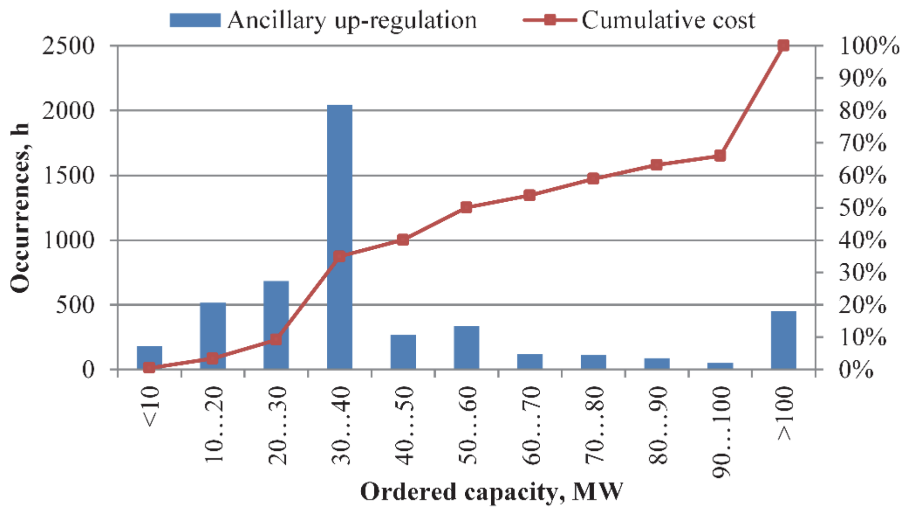


Figure 4. System service occurrences by capacity and their cumulative cost over the period 2011-2014.

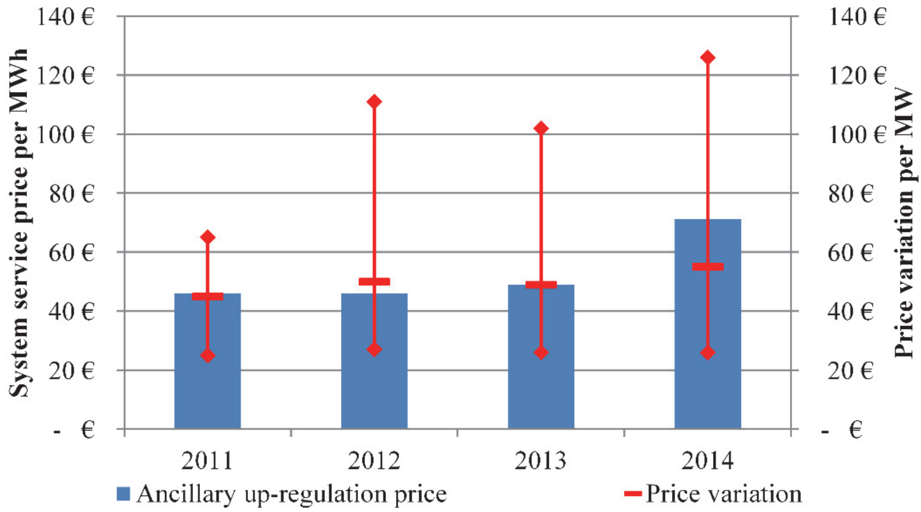


Figure 5. System service prices and their variation over the period 2011-2014.

Over the years, the requirement for balancing services through up-regulation and emergency reserves has stayed rather constant or even decreased (emergency reserves). Up-regulation for balancing has occurred around 600 to 700 hours a year, except for 2012, with 320 hours. At the same time, emergency reserve activation has decreased from 953 hours in 2011 to around 100 hours in 2014. Most (86%) of the ordered regulations remained below 60 MW and constituted 72% of the total costs on up-regulation balancing services (Figure 6). Half (55%) of the required emergency reserve activations take place at capacities over 60 MW but 47% of the total cost is constituted by regulations over 100 MW (Figure 7).

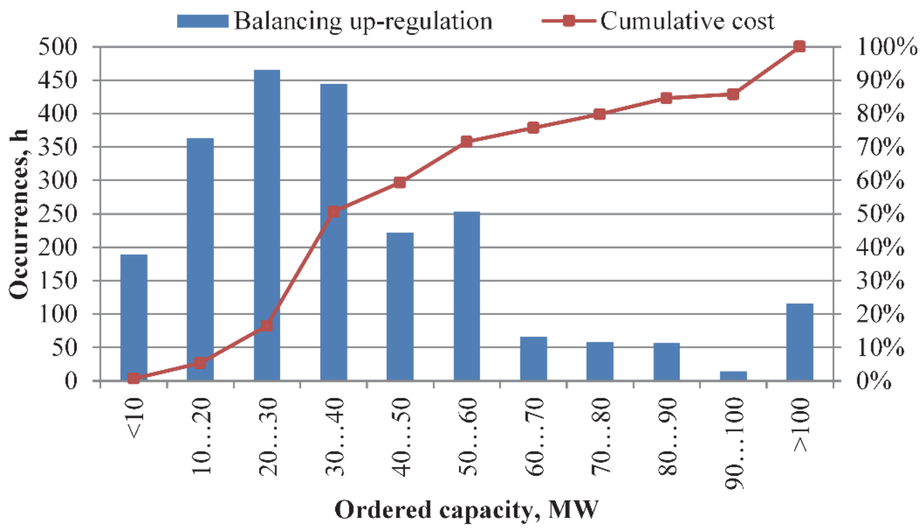


Figure 6. Balancing service occurrences by capacity and their cumulative cost over the period 2011-2014.

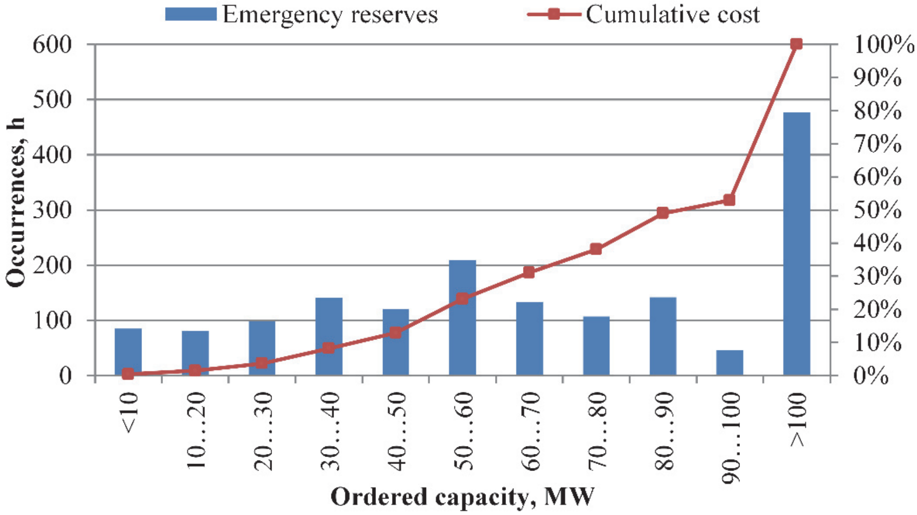


Figure 7. Emergency reserve activations by capacity and their cumulative cost over the period 2011-2014.

The cost of MWh balancing service has not changed significantly over the last four years, remaining around 60 euros, neither has the price variation range indicated any significant changes, remaining between 30 euros and 100 euros, except for 2013 when the price range was between 18 euros and 227 euros (Figure 8).

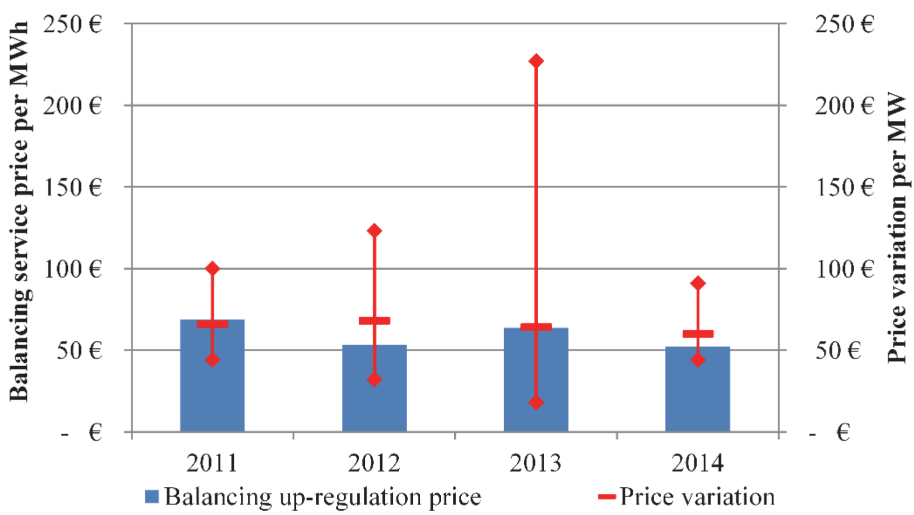


Figure 8. Balancing service prices and their variation over the period 2011-2014.

The total cost of emergency reserves, on the other hand, has decreased compared to 2011 from 4.1 million euros to 1.4 million euros in 2012 and 2013. The first 10 months of 2014 indicate a further drop, remaining below 0.5 million euros (Figure 9). Resulting from the latter, the TSO owned emergency reserve power plant has lowered the costs for emergency reserves as in previous years, this reserve was held in neighbouring countries.

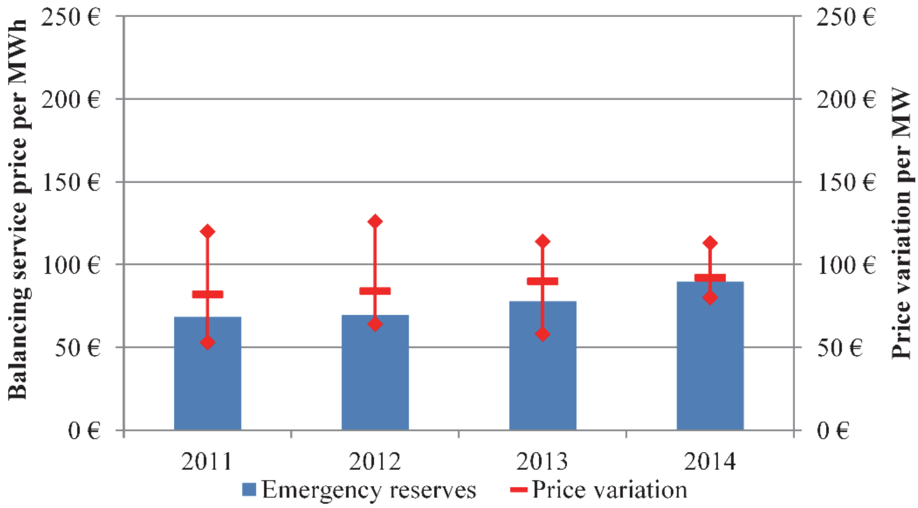


Figure 9. Emergency reserve activation prices and their variation over the period 2011-2014.

From the analysis above, it results that a potential for the consumers exists to participate already today either for the balancing service or system service provision. 85% of the balancing services and more than 60% of the system services are ordered by capacities below 60 MW and 40 MW, respectively. The cost of these services in the capacity range 40 MW to 60 MW over the last four years was approximately 9 million euros. Although the price per MW is low, the consumers are flexible to participate in competition with the generators.

Government policies and EU strategies are favouring massive integration of dispersed loads (e.g. EVs) but also generation that makes operating and controlling the system more unpredictable and complex. At the same time, the additional dispersed generation replaces large centralized units, but tends to be weather influenced, and increases further the requirements for rapid dynamic reserves that can compensate the concurring fluctuations between demand and supply. As old generation units used today for reserves are decommissioned, there is a gap of reserves to be replaced. These reserves have already been integrated into the power system as different types of loads and could be easily integrated into the ancillary service markets whether as dispersed storage units in the form of EVs or as dynamic controllable loads as a source for voltage or frequency support.

3. Research of demand side response potential in Estonia

The following discussion focuses mainly on the DSR in the industry, public and commercial sectors in compliance with the interest of the research and the definition of DSR and DSM from the power system point of view. Households are rather small unit consumers and would require a larger aggregation level to provide the services under investigation for the TSO. In addition, household electricity consumption and the willingness to allocate loads for DSR are influenced by comfort and values rather than technical and economic feasibility. Therefore, the analysis of household consumers would be a social study rather than a techno-economic analysis. The aspects how to determine DSR potential for different economic sectors that constitute up to 60% of the total electricity consumption in Estonia is discussed. The results and methodology have been published in papers [IV], [V] and [VI].

3.1 Mapping methodology of DSR

The following DSR mapping methodology was used under the research project to study the processes and electricity consumption of different sectors. The mapping methodology includes other aspects of DSR, besides the DSM potential, which is targeted for the TSO/DSO that are beneficial also for the consumer, e.g. energy efficiency and local generation that should motivate the consumer to participate in any form of DSR action. In addition, the proposed methodology can give the consumer additional incentives and business cases to reduce its energy intensity and engage in DSR actions. The description of the methodology is summarized in Figure 10.

1. Detailed mapping of the consumer
- Installed capacities
- Loading of the electrical drives
- Intemediate storages and their capacities
- Structure of the production/ consumption process

2. Electricity consumption analysis
- Analysis of the existing data
- Defining the necessary measurements
- Measuring
- Load pattern analysis

3. Analysis of the energy efficiency potential
- Static DSM measures and their implementation

4. Analysis of the DSM potential
- Dynamic DSM measures and their implementation

5. Renewable energy and local generation

Figure 10. Summary of the used DSR potential mapping methodology.

The aim of the first step is to provide a comprehensive overview of the consumer as a basis for the rest of the study. This step helps to divide the production processes or consumer groups into smaller sub-processes that can be handled as a single load from the DSR point of view as described in section 3.1.1.

The data acquired under this step characterize the electricity consumption, installed capacities, existence and capacities of the intermediate storages and the electrical installation. As a result, focus will be on the most energy intensive parts of the specific sector and their share in the total electricity consumption with the possibility to allocate them for DSR.

The second step of the methodology aims to determine in more detail the correlation between energy intensity and load patterns of the possible controllable loads or sub-processes that could be allocated for DSR. An example is also described in section 3.1.2. In this step it is less time consuming to utilize maximally the data available from site e.g. revenue metering in point of common coupling with the grid, historical production logs, bookkeeping, and etc. This reduces the need to carry out time-consuming measurements.

In the third step of the methodology static DSM measures are analysed from the customer perspective to determine if there are possibilities to lower the energy intensity of certain parts of its production line, e.g. reactive power compensation, installing additional frequency drives, etc. This step of the methodology is solely included for motivating consumers to participate in any DSR actions and to prove them that DSR includes real benefits for them. In addition, it is essential to have all possible static DSR measures incorporated before dynamic measures are engaged.

In the fourth step the possibility to engage in different dynamic DSR actions is analysed together with the consumer. The first three steps should by then provide the necessary constraints that have determined if it is possible for the consumer to engage in active and/or passive measures. Engaging in active measures depends on the existing infrastructure and control system readiness to incorporate DSR control principles described in section 3.3. The possibility to participate in passive measures depends on the TSO/DSO requirements and legislation and constraints determined by the consumer.

The fifth step is once again targeted for the consumer, as local generation can improve the energy efficiency and provide a separate business case for the consumer, but also add additional flexibility and capacity for providing DSR services.

3.1.1 Control methodology for DSR loads

The control methodology of loads aims to divide the production processes or consumer groups into smaller sub-processes (see Figure 11) that can be handled as a single load from the DSR point of view. As a result, the most energy intensive parts of the specific sector and their share in the total electricity consumption with the possibility to allocate them for DSR will be reviewed. The controllability or the possibility to use these processes for DSR are determined together with a customer's representative capable of establishing the specific limitations.

The main principle for a possible shift of certain processes or sub-processes at an industrial consumer is based on the existence and capacity of intermediate storages after the controllable load. The aim of this limitation is to remove the DSR impact on the final production or normal operation of the establishment.

Intermediate storages were selected in the industry because they can be used as on-site energy storages to shift the electricity consumption of certain parts of the production process. The “electrical” storage capacity of such units is determined by the physical size of the intermediate storage and its coherence with the following sub-process. The following chart in Figure 11 illustrates the results of mapping a production process with the production capacity of each sub-process in the industry.

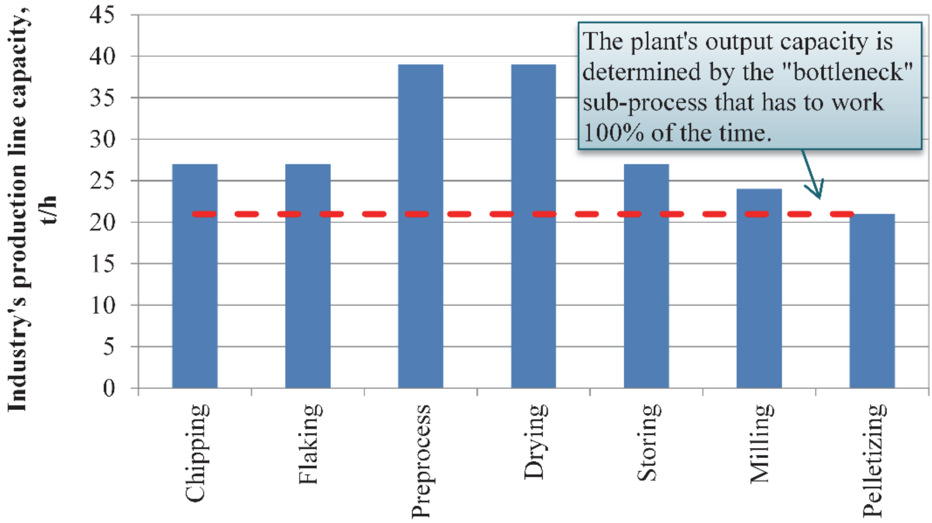


Figure 11. Controllable loads and their potential for DSR.

This kind of production structure allows optimizing energy consumption of each sub-process, taking into account the specific production capacity and the state of the following intermediate storage. Thus, the optimization can take place such that the production of the final process line does not decrease. The higher the production capacity and the following intermediate storage of the optimizable sub-process compared to the consecutive process, the longer it is possible to deploy the DSR in that process.

In commercial and public institutions, the main storage possibilities lie in thermal storage and control; as there are not many processes to shift, the DSR reverts mainly to temperature control. The only constraint for the DSR is derived from the (working) environment requirements for the employees and customers.

3.1.2 Electricity consumption analysis

Data acquisition under this step gives information about the electricity consumption, installed capacities, existence and capacities of the intermediate storages and the electrical installation. As a result of the analysis of electricity consumption data, relations between electricity consumption and controllable processes can be found. In addition, the analysis of the sub-processes of consumption provides the controllable load share and the duration of the possible load shedding from the capacity of the intermediate repository that acts as an energy storage from load shifting perspective.

It was found in the following example that if the industrial facility's daily production exceeds 200 tons, then the correlation between production and electricity consumption is clearly linear – 1 ton of produced industrial goods requires 0.19 MWh of electricity. This is described with a correlation factor $R^2 = 0.79$, illustrated in Figure 12.

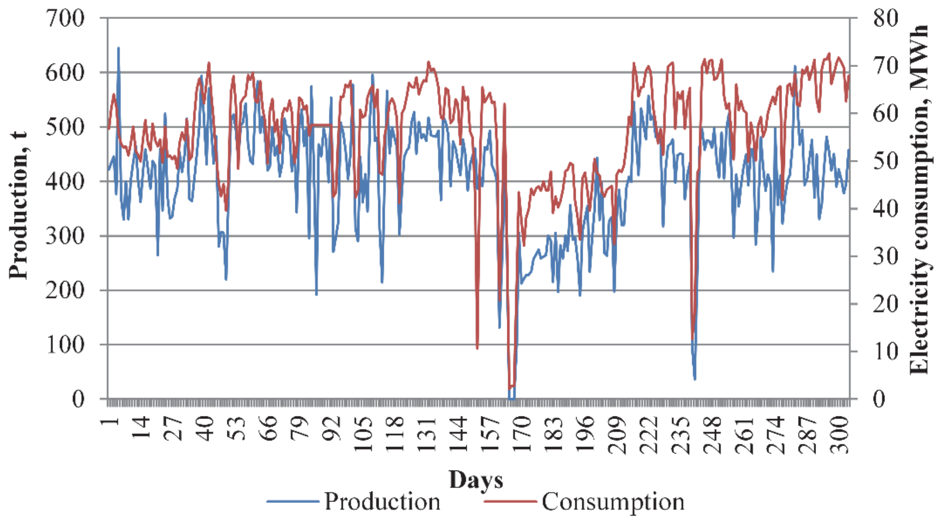


Figure 12. Correlation between industry's production and electricity consumption.

The analysis of the sub-processes of consumption determines the controllable load share and the duration of the possible load shedding from the capacity of the intermediate storage. An example based on the analysed industry is summarized in Table 2.

Table 2. DSR potential mapping results in the studied wood industry

Sub-process	**Capacity, kW**	**Controllable**	**Controllable load, kW**	**Storage**	**Storage capacity, h**
Chipping	900	yes	700	yes	70
Flaking	700	yes	400	yes	150
Drying	1 500	no	0	yes	24
Milling	900	yes	500	yes	2
Pelletizing	2 100	no	0	no	0
Packaging	50	yes	50*	no	0
TOTAL	**6 150**	**-**	**1 600**	**-**	**-**

* Due to variable working cycle not considered as controllable

3.2 Price sensitivity as a DSR driver

The planning of electricity costs ahead has become more complex in the liberalized market situation. Considering the volatility of electricity markets, in the future, the company may have to consider whether to keep production or stop the facility. On the other hand, stopping of the production line could be considered if it counts as an ancillary service for the TSO and the price paid for it covers the lost profit.

When electricity costs make up a significant share of the operational costs, the consumer will be motivated to optimize these costs when possible. By use of the day-ahead market information, the customers are able to some extent schedule or optimize certain manufacturing processes or electrical loads such that it will reduce the overall costs on electricity. The main driver for DSR is the customer's price sensitivity. Additionally, the price sensitivity information could provide necessary information about the possibility to include those consumers in providing DSR based services to the TSO or the DSO.

The aim of any company is to earn a profit; therefore, the customer makes its main decisions based on the marginal profit, which ensures that the company is not earning a negative profit. The following formula (2.1) is used to determine the electricity price cap for an industry but the principle can be adjusted to any other type of a consumer:

$$P_{cap} = \left(P_P - (C_v - C_{iV})\right) \cdot \frac{M_t}{E_t}\ , \tag{2.1}$$

where
P_P is the marginal profit of the product per unit (euros per ton),
C_v is the variable cost for the production (euros per ton),
C_{iV} is the inelastic variable cost for the production (euros per ton),
M_t is the total production of goods over a calendar year (tons), and
E_t is the total electricity consumption over a calendar year (MWh).

The variable costs can be calculated according to (2.2) and (2.3):

$$C_v = C_l + C_d + C_{rm} + C_e + C_t + C_o\ , \tag{2.2}$$

$$C_{iV} = C_l + C_d\ , \tag{2.3}$$

where
marginal cost C (euros per ton) is marked with the following indexes:
l – labour,
d – drying,
rm – raw material,
e – electricity excluding energy,
t – transport,
o – other costs.

In the following example, two scenarios were analysed. In the first scenario, the electricity price for the zero marginal profit was calculated without negative profit earned. In the second scenario, the electricity price is calculated where the negative profit earned is equal to the fixed costs of stopping the whole production facility. It was found that the zero marginal price of electricity is 296 euros per MWh and it is beneficial to stop the whole production for a short period at 387 euros per MWh. However, short-term outage of the consumer might not always be a cost for the company, as short-term maintenance could be planned for those periods. The calculated marginal prices could be the basis for providing DSR services. Table 3 summarizes the determined marginal price occurrences in the Estonian Nord Pool Spot market area over the years.

Table 3. DSR potential mapping results in the studied wood industry

Year	**>387 euros per MWh**	**>296 euros per MWh**	**maximum price (euros per MWh)**
2010	5	8	2000
2011	0	0	90.96
2012	0	0	183.5
2013	0	0	210.01
2014	0	0	210.08
2015	0	0	150.06

The described price sensitivity analysis is a good basis for any other (industrial) consumer if it can determine the marginal prices at which it is more beneficial to lower its electricity consumption. In addition, the analysis could provide the information necessary to include those consumers in DSM provision. The results of the analysed example case show that at today's market prices (except 2010), lower production capacity at the analysed consumer cannot be allowed under any circumstances without bearing any losses. Although the whole production cannot be stopped, it would be still possible to optimize and control certain parts of the production line and its electricity consumption, as mentioned earlier.

3.3 DSR load control in different economic sectors

DSR load control methodology studied by the author under the PhD research in the proposed three economic sectors is analysed in the following subsections.

3.3.1 Processing industry

According to Statistics Estonia definition, the processing industry deals with "*the mechanical, physical or chemical transformation or processing of materials, substances or components to make new products*". The processing industry comprises the following branches: chemical, engineering, construction, electronics, energy engineering, food industry, metal industry, plastic industry, textile industry, wood and paper industry, etc. The most important processing industry in Estonia is the mechanical industry (providing about 25% of manufacturing production); the second important branch is the wood and paper industry (20%), the third - the food industry (15%), the fourth - the metal industry (13%), the chemical industry provides about 10%, and the light industry less than 5%.

The Estonian wood and paper industry consists of more than 2 000 companies that comprise the whole wood processing chain from forestry to wood processing and furniture production. The Estonian wood and paper industry provides together more than 20% of the Estonian processing industry's turnout, which is more than in any of the surrounding countries (except Russia). The wood and paper industry is also one of the main stabilizers of the Estonian foreign trade, e.g. in 2012 the sector's export amounted to about 1.5 billion euros, providing 12% of the total goods exported. In 2011, the sector's value added comprised 4% of the Estonian gross domestic product [29]. According to Statistics Estonia, the total electricity consumption of this sector is 35% of the processing industries and 8% of the total electricity consumed in Estonia, making it an interesting and possible source of DSR (see Figure 13).

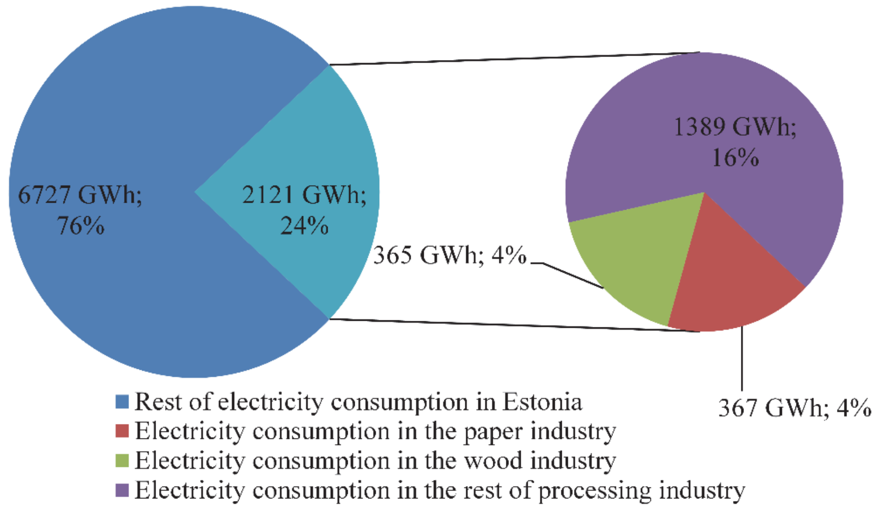


Figure 13. Electricity consumption in the processing industry in Estonia in 2014.

Depending on the produced goods, electricity cost can make up to 4% to 12% of the manufacturing costs of the final product in the wood industry [30], [31]. One of the most perspective DSR measures is optimizing the factory's electricity costs according to the spot market price. This is considered to be one of the key elements lowering the production costs in the industry; the proposed methodology and results have been published in papers [IV] and [VI]. However, when implementing DSR amongst industrial consumers, main limitations arise from technological constraints and financial losses related to load reduction or shifting.

DSR can be implemented and preferred if it is possible to use some sort of energy storage within production line processes that consume electricity. In case it is possible to store the final product, then it will be theoretically possible to shift the whole industry's electricity consumption. If it is possible to store only the intermediate storage, then DSR is applicable only on the sub-processes that have intermediate product storages. The existence of energy and/or intermediate storages guarantees no financial benefit from DSR and DSM, as the external costs (e.g. personnel and start-up costs) of such actions should also be taken into account. A similar principle can be applied to the other sectors as well; however, the storage possibilities and controllable loads are more limited.

In the following example, a wood chipper line is analysed [IV]. The production line is semi-automatic and works continuously (for 24/7). The production process is constrained by the final product output of the plant, which is constant. The industry's process line with the corresponding consumption loads is illustrated in Figure 14.

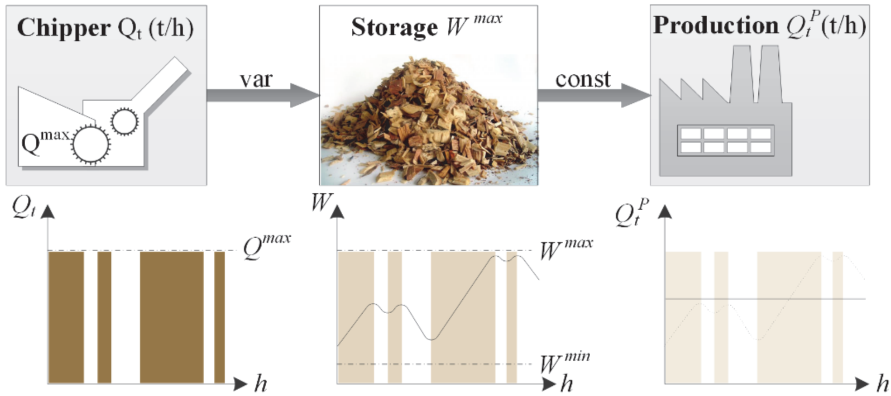


Figure 14. A wood industry's production process and the corresponding indicators (work cycle, storage capacity, final product output) and their correlation. [IV]

Since the production needs a constant flow of an intermediate product that is constrained by the storage capacity and by the required chipping volume, the control flexibility is determined by the maximum output of the chipper and the following storage capacity. Thus, it is rather obvious that higher chipper productivity and storage capacity gives higher control flexibility for the industry. Stops in the production process, as illustrated in Figure 11, are mainly caused by the individual needs of certain customers that require, e.g. other types of wood for their product. If 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. [IV]

It was found in [IV] that the electricity cost *E*, which is a stochastic parameter, for a single load under investigation can be minimized according to scenarios *s* with (2.4):

$$\min_{Q_t} \sum_s \sum_t P_t^s \cdot C^{CH}(Q_t) \cdot P(s) + C^E(Q_t)\,, \tag{2.4}$$

where

P_t is the electricity price for time period t,
Q_t is the wood chipper's production volume for time period t,
C^{CH} is the output power of the chipper,
$P(s)$ is a probability of the scenario s,
C^E is the external cost of the load shifting, e.g. start-up costs, labour costs, etc.

Two scenarios were analysed for the industry under investigation [IV]. In the first scenario, the production plan was adjusted according to the historical average spot market 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 behaviour of the production according to the fixed plan of the wood chipper. It allows even in the low tech industry to optimize machine production costs.

Since actual spot price dips and peaks might not be in the predicted range and time, in addition, the second approach utilizes the day-ahead price indications. This gives the industry a higher cost optimization possibility because it enables use of the most optimal production plan for a specific day. The precondition of that approach is installing an information and communication technology platform that calculates, executes and analyses the optimized production plan according to the available market price information. A simplified production control principle is illustrated in Figure 15.

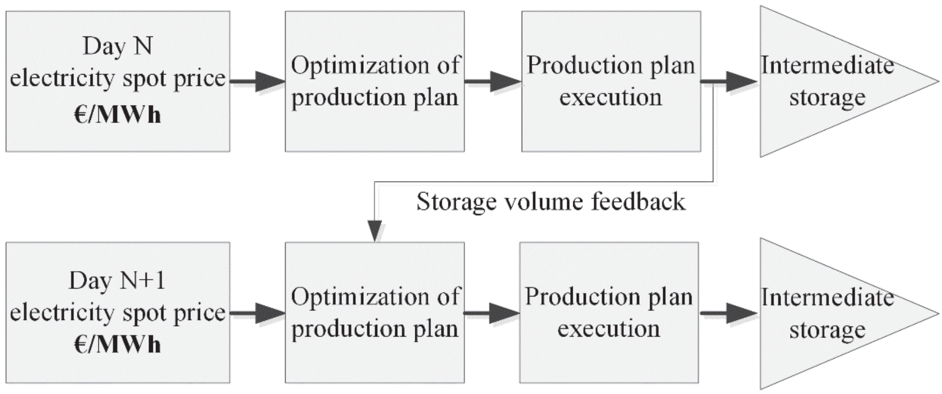


Figure 15. Simplified production control with day-ahead optimization of the wood chipper's operation schedule. [IV]

Automatic load control of the system is required in order to implement it on a larger scale; moreover, it excludes any 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 production plan. In technical implementations, the machines of the controllable loads require also frequency converters or soft starters, which allow starting and stopping the machines frequently with short start up times. Input information about the market price and the feedback from the machines and storages about the volumes available in the storages need to be added to the control system. In any additional commercial limits, the required maximum production and sales volume is necessary, as described in [VI].

It was calculated in [IV] hat the specific cost of the studied wood chipper's product before optimization was 0.27 euros per ton. By implementing the average historical price optimization algorithm, the unit's specific cost could be reduced to 0.24 euros per ton. With this scenario, the annual electricity cost reduction for the studied load would thus be 11% lower than an existing, non-optimized production schedule. Figure 16 illustrates the daily optimal working schedule for the wood chipper and changes in the storage volume depending on the average historical electricity spot price.

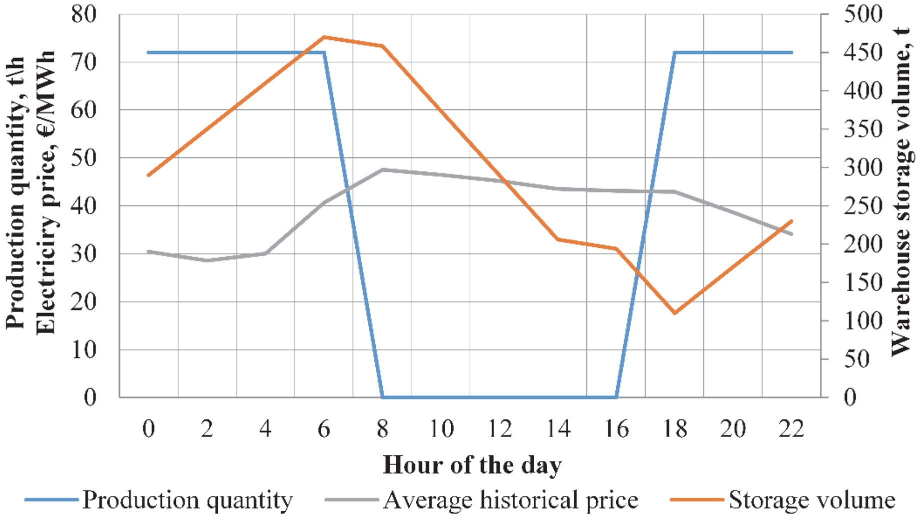


Figure 16. The optimized production characteristics with the changing stored volumes of the product according to the spot market average price. [IV]

By implementing additionally the day-ahead market price optimization algorithm, the specific cost could be lowered to 0.23 euros per ton. As a result, the specific electricity cost of the studied sub-process could be lowered by 17% compared to the base case scenario. From the whole production facility's point of view, this single optimization could decrease the factory's total electricity costs by 2% to 4% [IV], [VI]. Since the current operational market entity in the Baltic States (Nord Pool Spot) provides prices only day-ahead, the model cannot take into account possible changes that might occur in the longer future. Without any additional forecasting model, the optimization will be therefore limited, since it cannot take into account longer price variations. However, using historical electricity market price data, it can be shown that further optimization is possible and should be considered as one option. Figure 17 illustrates the storage capacity changes over a calendar year if long-term prices are known.

Since the storage of physical medium can act as a kind of energy storage for the industry, long-term scheduling according to optimization could prove even more cost-effective for the industry. Long-term ahead price information on the electricity market could help to determine the most profitable shifting periods. During load shifts on peak hours and days, the required wood will be taken from the storage. Additional benefit could be gained by planning the annual or regular maintenance stops to the peak periods when the storages are full and no additional production is required.

Taking into account that most of the Estonian processing industries operate sequential production lines that are non-optimized, it can be affirmed that this economic sector has a vast potential for implementing some type of DSR. Addition of an assumption here that the facilities have an intermediate product storage, DSR could be offered as a service also for the system operators without any economic loss. Nevertheless, it is required to promote DSR as an unexploited potential for the industrial electricity consumers, market participants, and system operators.

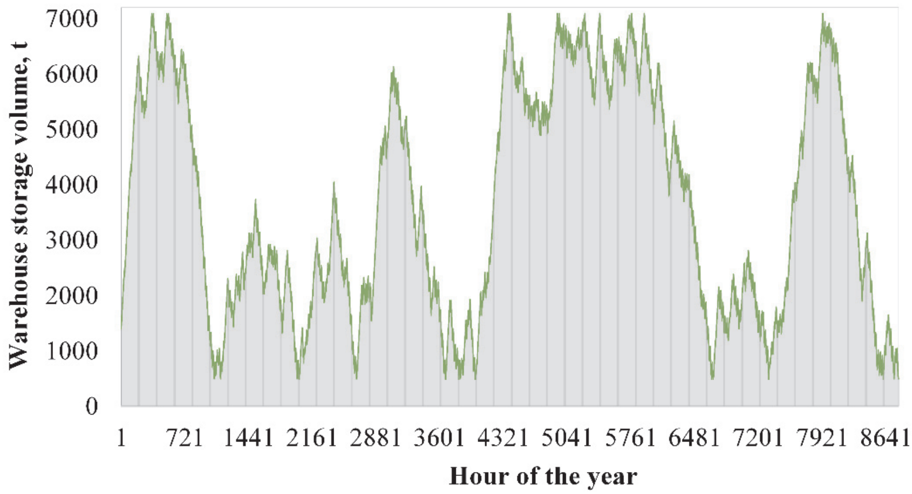


Figure 17. Warehouse storage volume fluctuation over a calendar year according to historical market price variations. [IV]

3.3.2 Public and commercial sector

The public sector in the scope of this research is defined as services provided for the society, e.g. banking, postal, utilities, and other services. Electricity consumption in this sector is used mainly in office buildings that can be divided into two principle groups: regular offices (8/5 type) that are occupied approximately 8 hours a day for 5 days a week and 24/7 type office buildings that are occupied constantly and work is organized according to scheduled shifts. The latter buildings have relatively constant electricity consumption profiles. On the other hand, the commercial sector has been defined as the businesses that deal with wholesale and retail, or more commonly known as shopping centres. In Estonia, a majority of shopping institutions operate on a fixed working schedule from 7-8 o'clock to 22-23 o'clock.

Office buildings constitute approximately 67% of the electricity consumption from the whole public and commercial sector's electricity consumption and approximately 22% from the total electricity consumption in Estonia. Shopping institutions, on the other hand, constitute approximately 26% of the electricity consumption from the whole public and commercial sector's electricity consumption and approximately 9% from the total electricity consumption in

Estonia. Figure 18 illustrates the electricity consumption share of different parts of the public and commercial sector's electricity consumption in 2014.

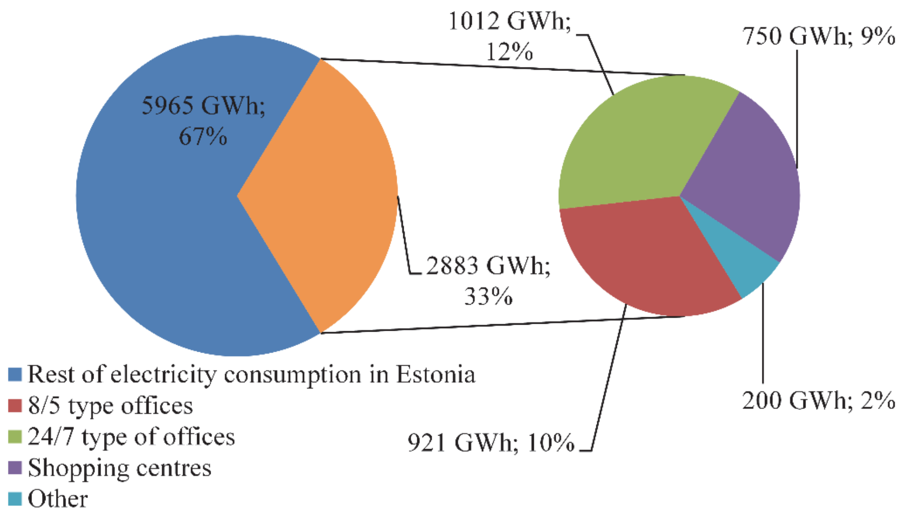


Figure 18. Electricity consumption in the public and commercial sector in Estonia in 2014.

3.3.2.1 Office buildings

The analysis included a set of office buildings, of which one was an 8/5 type and the other 24/7 type. The 8/5 type building was a regular office building, connected to the district heating network and with a traditional set up of office equipment. The 24/7 type office building, on the other hand, included a data centre and the heating system was a stand-alone system based on electrical heaters. The electricity consumption of the analysed buildings over the period of February 2011 until January 2012 was 2.49 GWh.

The aggregated load profile of the set of buildings is relatively stable, the base load over the calendar year is 225 kW and peak consumption remained around 400 kW. The load profile can be described as traditional: higher during the day and lower during nights and weekends.

According to the load analysis in the 8/5 type office buildings, lighting constitutes 43% of the electricity consumption [V]. Second largest electricity consumer groups are electrical heating (i.e. sauna stoves and floor heating in the bathrooms) with 27% and HVAC with 22%. In the 24/7 type office building, on the other hand, 46% of load is due to the data centre, followed by HVAC 32% and direct electrical heating with 14%. The aggregated load shares in the two office buildings are illustrated in Figure 19.

As seen from the following figure (Figure 19), loads that could be allocated for DSR seem negligible. The data centre that constitutes almost half of the consumption in the analysed office buildings cannot be allocated for any kind of DSR, as it is the basis for providing vital services. In this case, office and other small units that could be assumed to constitute majority of the electrical consumption have an insignificant share. The only load type that could be allocated for any kind of DSR is the electrical heating and HVAC system. Lighting could be allocated to DSR to some extent, however it would mainly serve as an energy efficiency measure.

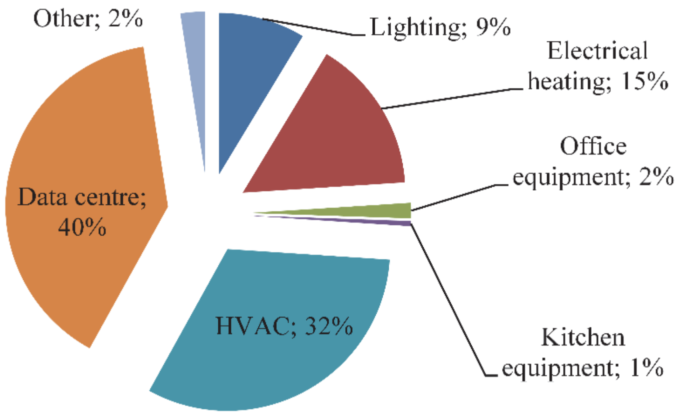


Figure 19. Electricity consumption distribution between different types of loads in the analysed office buildings.

Electrical heating and HVAC could be allocated for DSR through some kind of temperature control either for load shifting or price based control. There are several price based load control models for office buildings. Depending on the model and its parameters, different results in the cost and energy efficiency can be obtained. According to the price based control of the HVAC system, at higher price periods, the air flow to the rooms is reduced or the cooling element is allowed to work at higher set-points, e.g. the room temperature is kept between 20 ºC to 26 ºC [32]. In other heating equipment, i.e. water boilers, the water in the boilers has to be kept at least at 55 ºC to 60 ºC to prevent bacteria from growing [33]. The price based temperature control algorithm is as follows:

$$T_{set,i} = \begin{cases} p_i - p_{av,i} = 0, T_{set} \\ p_i - p_{av,i} \neq 0, \begin{cases} T_{set,i} \geq T_{\max}, T_{\max} \\ T_{\min} < T_{set,i} < T_{\max} \\ T_{set,i} \leq T_{\min}, T_{\min} \end{cases} \end{cases}, \qquad (2.5)$$

where
T_{set} is the default temperature set-point,
$T_{set,i}$ is the new set-point calculated according to the price,
p_i is the price at time i,
$p_{av,i}$ is the average price of the last 24 hours,
T_{max} and T_{min} are the allowed temperature ranges.

The control set-points can be calculated for heating and cooling as indicated in the following equation (2.6)

$$T_{set,i} = T_{\max} \mp (p_i - p_{\min,i}) \cdot \frac{T_{\max} - T_{\min}}{p_{\max,i} - p_{\min,i}}, \tag{2.6}$$

where
$T_{set,i}$ is the new set-point according to the price,
p_i is the price at time i,
T_{max} and T_{min} represent the temperature ranges.

According to the control algorithm, the actual hourly price is checked against the last 24-hour average price. If the prices are equal, no control is performed; however, if there is a price difference, a new set-point is set according to the price difference [34].

It was determined in the studied buildings that by applying price based load control, the electricity cost reduction and increase in the energy efficiency can be up to 8%. The average room temperature reduction remains between 1.4 ºC and 1.7 ºC, depending on the weekday. A similar control principle can be achieved by controlling the indoor lighting but instead of temperature ranges, brightness of the light is controlled. By reducing the lighting brightness by 50% over the periods when the price is above the average market price, energy costs can be lowered by 25% during working days and 5% over the weekends. At the same time, energy consumption is reduced on the average approximately by 19%.

3.3.2.2 Wholesale and retail buildings

The analysis included a relatively recently built shopping centre in the city of Rakvere. According to the data analysis and performed on-site measurements, the largest load share is due to lighting (45%), followed by the central cooling station with 29% and other undefinable loads, including catering associated loads, with 16 %. Figure 20 illustrates the distribution of load shares in the analysed shopping centre.

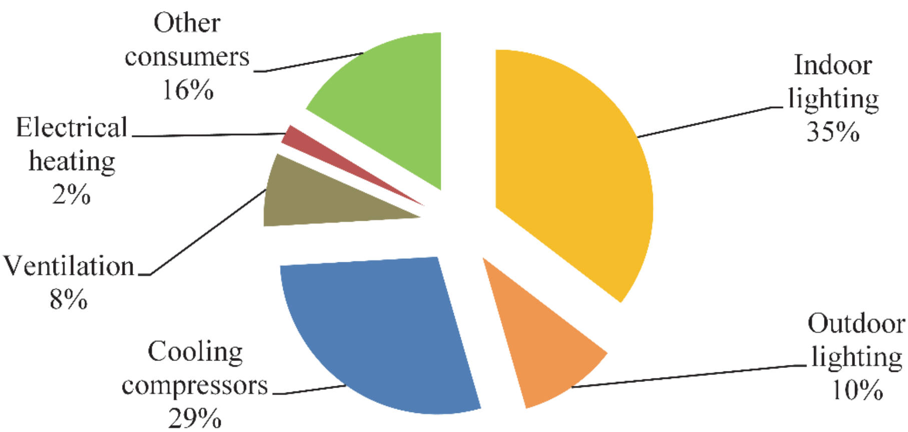


Figure 20. Distribution of electricity consumption between different types of loads in the analysed shopping centre.

The annual (March 2013 until March 2014) electricity consumption of the analysed buildings was approximately 2.67 GWh. The peak consumption was 484 kW and the base load remained around 100 kW to 130 kW. No seasonal fluctuations were found and the loads are assumed to be uniform throughout the year. The building is heated by a local natural gas fired boiler house, producing water required both for central heating and for hot water. The residual heat from the central cooling units is partly utilized for the heating of the building. 67% of the HVAC units are with regenerative heat exchangers.

No central air conditioning unit has been installed in the building. The central cooling station is purely used to maintain the necessary temperature in the food court's freezers and refrigerators. The central cooling station is divided into two parts. The first part with five compressors services the refrigerators, where the temperature is kept around +2 °C to +6 °C and the residual heat is reused in the ventilation units. The second part is composed of three compressors servicing the freezers, where the temperature is kept around -20 °C to -18 °C.

The most probable controllable load in the shopping centre was found to be the central cooling station for the freezers and refrigerators; all the other electrical loads (e.g. lighting, computers, etc.) were considered either as essential for operation or marginal to the possible effects. Load control was considered from three aspects of DSR:

- price based load control;
- peak shaving and load smoothing;
- load shifting.

Peak shaving and load smoothing are based on the assumption that there is a correlation between electricity consumption and temperature setting. Peak shaving or load smoothing could be performed by installing a cold storage that is cooled down over the night period by running the cold compressors at higher power. Possible load pattern of the analysed cooling station is illustrated in Figure 21.

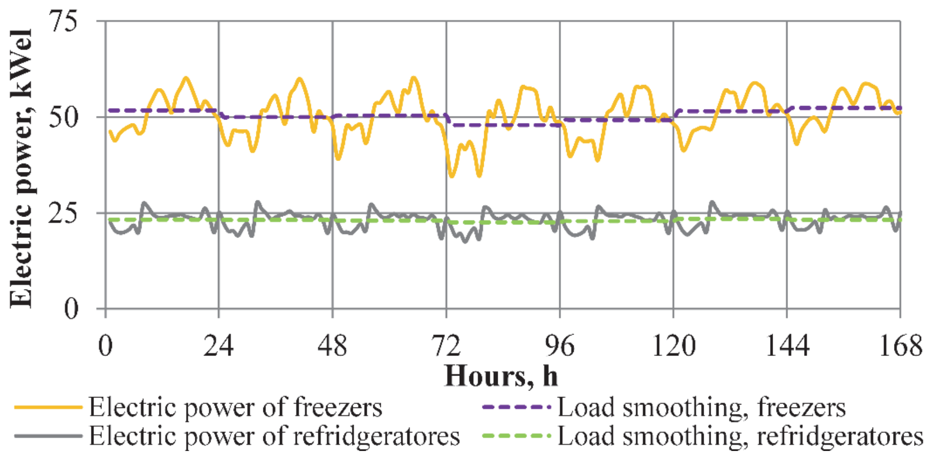


Figure 21. Load patterns of the cooling station before (measured) DSR and after implementing load smoothing and peak shaving (calculated).

During working hours, the compressors are run at a lower power, smoothing out the load profile. Cold additionally required is taken from the storage. It was calculated by a simple cost benefit analysis that the cold storage for regular food refrigerators has approximately 2.5 times longer payback time than for the freezers mainly due to the difference in the coefficient of compressors' performance (1.4 vs 2.75, respectively). On average, 5 to 15 year payback time is achievable with moderate investments, depending on the price differences during peak and off-peak hours.

Price based load control neglects the cold storage and utilizes directly the benefits from the correlation between electricity consumption and temperature settings. The authors in [35] calculated the correlation factor between the temperature and the electricity consumption $R^2 = 0.87$. In addition, it was stated that a 0.55 °C (or 1 °F) change in the freezer zone air temperature would change the energy consumption of the analysed freezers air handler by approximately 50 kWh. Assuming that the refrigerators' operating set-points are by default between +6 °C to +2 °C and freezers between -18 °C to -22 °C, modifying these set-points correspondingly to +6 °C to +5 °C for refrigerators and -18 °C to -19 °C for freezers, then without having a cold storage, the estimated energy savings per year could be up to 9%. This, in return, can be reduced to a 24 h period, meaning approximately 9% lower capacity requirement for the cooling stations over a certain period.

Load shifting utilizes the cold storage such that the total required cooling capacity is taken during the working hours from the cold storage and the storage is charged during the low price period (i.e. night). Possible load pattern of an actually analysed cooling station is illustrated in Figure 22.

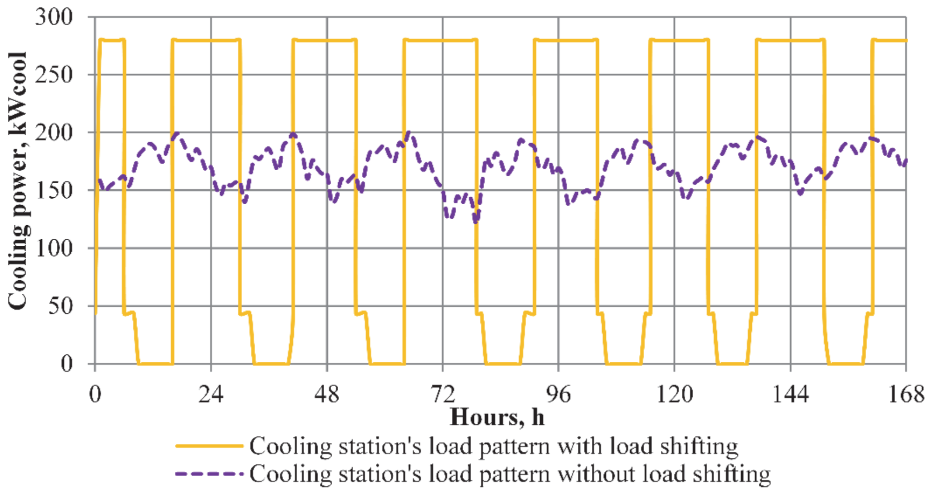


Figure 22. Cooling station's load patterns before (measured) DSR and after implementing load shifting (calculated).

The results of the cost benefit analysis showed that with this DSR measure, the cold storage for regular food refrigerators has approximately five times longer payback period than for the freezers.

4. Assessment of demand side management potential in Estonia

DSM is the utilization of DSR for such purposes as system security (balancing and congestion) or system adequacy. These measures can help keep load profiles and local electricity peak loads under control. Additionally, it can support balance in demand and supply, i.e. balance in large renewable power sources or counteract sudden changes in the power system (due to an outage of some power generation in the power system) as well as provide, for example, local voltage support, as demonstrated further in the thesis. Loads allocated for DSR can be either single (in case of large consumers) or a group of loads aggregated from a variety of consumers connected to the network from single or multiple geographical locations irrespective of their classification or economic sector [II].

4.1 Technical and economic constraints

Due to technical limitations of the existing SCADA system, the Estonian TSO accepts regulating service offers starting from 5 MW (eligibly 10 MW). In addition, it is required to submit all the offers two hours prior to the possible request for service. Single loads with such capacities are very rare in the Estonian power system and if they exist, then they are usually tied to an industry's main process, thus making it uncontrollable from the customer's point of view. Therefore, the load capacities necessary for ancillary services could be aggregated from smaller controllable loads. One possible aggregated load profile for a consumer controllable sub-process during a load shift or shed is illustrated in Figure 23.

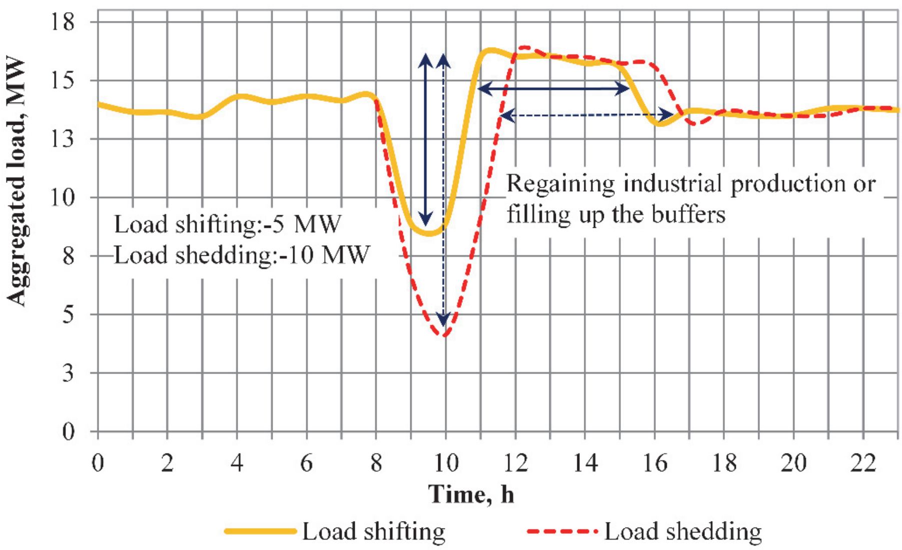


Figure 23. Aggregated demand profile of the consumer providing regulating service for the TSO (before, during and after service provision). [II]

While with load shifting in the case of an industrial consumer it is possible to catch up the production target by increasing the demand for a couple of hours, with load shedding, the increased consumption after regulation can only fill up the buffers in the production line but there will be some financial and product quantity loss for the consumer. Total load shed is be also possible, however its cost is directly tied to the cost of the lost production target and the additionally occurring external costs. [II]

From the system point of view, load forecasting issues might arise. Forecasting aggregate DSR activated events (shedding, shifting) from the system level can help to foresee more accurately system (and regional) load profiles and manage better transmission capacities, system security as well as balances. This is an especially important aspect for a TSO's planning and control system, regarding a small power system operation as an island or having strict rules for keeping intra-hour AC balance. Since the minimum load of the Estonian power system is around 480 MW and the peak load was 1 553 MW (as of winter 2015/2016), it is expected to have a negligible effect in general on the forecasted load profile, based on individual examples in this work. Therefore, system load forecasting error will be disregarded in the further discussion.

Nevertheless, considering a potentially large aggregation effect of the DSR on the predicted load profile, both shedding and shifting could affect forecasted power curve significantly, which in turn, can have influence on system security and transmission capacities if not correctly accounted in the planning phase. The behaviour and activities of end-users (individuals, groups) that affect their electricity demand characteristics have no certain pattern, e.g. when an office type of end-users participates in DSR events, the aggregate effect could not be easily predicted and accounted in the system load profile forecast. Therefore, with large-scale implementation of DSR, it is required to account the events separately in order to take them into account in the system planning phase.

Criteria for providing DSR related services are analysed in detail in papers [II] and [VI]. Based on the interviews with potential customers and the Estonian TSO, three main factors need to be addressed to qualify as a DSR service provider. The first criterion (3.1) describes the minimum regulating power acceptable by the TSO:

$$P_{DSM} \geq P_{AS}, \tag{3.1}$$

where

P_{DSM} describes the service provider's offered (aggregated) DSR load (MW),

P_{AS} is the TSO's required minimum ancillary service load level (MW).

The second criterion (3.2) takes into account the response time of the service provider:

$$\Delta t_{DSM} \leq \Delta t_{AS}, \tag{3.2}$$

where

Δt_{DSM} is the service provider's response time (minutes) for providing DSR,

Δt_{AS} describes the TSO's maximum response time allowed for ancillary service.

The final criterion (3.3) takes into account the duration of the regulation:

$$t_{DSM} \geq t_{AS}\ , \tag{3.3}$$

where

t_{DSM} is the service provider's capability (hours) to provide DSR,
t_{AS} is the TSO's minimum required ancillary service duration.

The pricing principle is reasonably based on the possibly lost profit, however it could additionally also incorporate a risk factor from the consumer side. The value of lost profit could be used to determine the cost of service through load shedding and the risk of losing production could be the basis for service through load shifting. Therefore, whenever the ancillary service prices exceed the consumer's determined price cap for the service provision, the DSR service could be engaged. Large electricity consumers who have no specific constraints are expected to act in a rational way, i.e. it can be assumed that they will provide the DSR service if they find it cost-effective [8]. The price for the DSM service through DSR could be expressed with (3.4):

$$V_{DSM} = \frac{\sum_{t=1}^{n}(I_{P/S,t} - C_{V,t}) + C^{E}}{P_{DSM} \cdot t_{DSM}}\ , \tag{3.4}$$

where

V_{DSM} is the value (price) of providing DSR service for the TSO (euros per MWh),
$I_{P/S}$ is the value of lost income due to production or service interruption (euros),
C_V is the spared variable cost (euros),
C^E is the external cost (euros),
P_{DSM} is the DSR load provided for DSM (MW),
t_{DSM} is the duration of the ordered DSR service (hours).

To implement DSR and DSM on a wider scale, new information and communication technology (ICT) and market platforms need to be developed for controlling and managing these services centrally. The ICT and market platforms need to be able to aggregate consumers at any power/energy level to make the provided services easily accessible for all interested parties. A new market platform is necessary to make the consumers equally competitive with traditional large power producing units. From the previous analysis it can be seen that in the Estonian case, the most feasible market for DSM services could be the balancing market, as it would be available not only for the TSO but also for different balance providers.

4.2 Potential of ancillary services from wood industries

The main precondition for industrial consumers for providing DSR for system services (DSM) is that the final production targets cannot be affected by that service. In order to ensure maximum output rate from the industry, the part of the process line with the lowest productivity must be loaded maximally (Figure 11). Controllable loads are divided into three categories taking into account that the industry will bear minimal losses when allocating its loads for DSM. Similar classification of loads will be used to describe other consumers analysed for DSR. The studied wood industry's rated and theoretical potential for providing DSM measures is summarized in Figure 24.

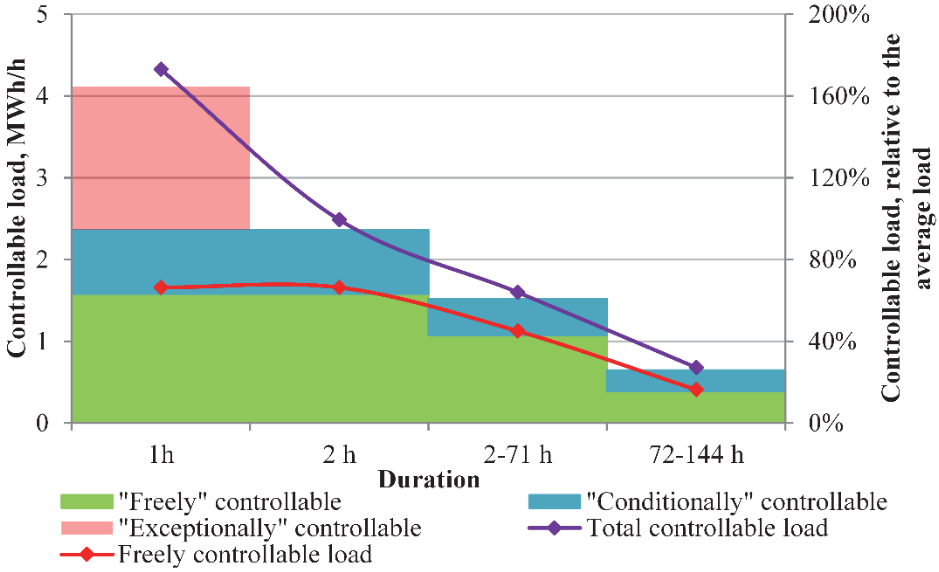


Figure 24. DSM potential in the wood industry with x-axis representing the duration and y-axis the relative capacity of the controllable load.

Resulting from the interviews with the customers and analysis of the consumption data, the controllable loads are divided into three categories based on the industrial consumers. A similar classification of loads will be used also to describe the other consumers' potential for the DSM.

"Freely" controllable load (FCL) is the load of the processes that can be allocated for DSM measures at any time. In the case of an industrial consumer, the load depends strongly on the load factor of the electrical machines, remaining around 50% to 60% from the rated power (P_N) for mechanical processes and can be calculated with (3.5):

$$P_{FCL}^{DSM} = \sum_{m=1}^{n} \left(\sigma_m \cdot P_{N,m} \right), \tag{3.5}$$

where

n is the total number of electrical drives in the process,

$P_{N,m}$ is the rated power of the specific drive,

σ_m represents the loading factor of the specific drive.

"Conditionally" controllable load (CCL) is the load of the processes that can be controlled under certain conditions or at certain times. This load depends on the process that runs with variable load, increasing under certain conditions the FCL service provision up to 40%. CCL can be calculated with (3.6):

$$P_{CCL}^{DSM} = \sum_{m=1}^{n} \left[(1-\sigma_m) \cdot P_{N,m} \right]. \tag{3.6}$$

“Exceptionally” controllable load (ECL) takes into account also loads that are uncontrollable under normal condition and can be allocated for control under extreme conditions, i.e. load shedding during emergencies in the power system or when the service price is high enough to cover the expenses occurring with DSM measures.

Based on two studied wood industry’s consumers, the DSM potential was expressed in relative units to extend the calculations over the whole sector. It was estimated that on average, the paper and wood industry could engage at least 20% from their average electricity consumption in DSR. This could be offered to the TSO as system services (DSM). The author’s estimated capacity corresponds well to the results from the study of the wood and forest industry sector carried out by the Foundation Enterprise Estonia [29]. According to the study, every company in the sector has on average 27% of free reserve production capacity, as illustrated in Figure 25.

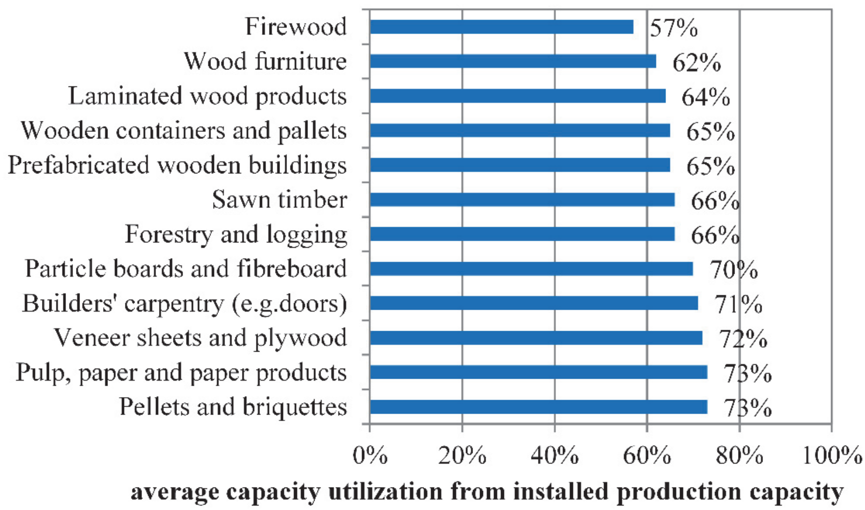


Figure 25. Average utilization of installed production capacity in different wood industry activities.

To estimate the DSM potential from the available electricity consumption data for the wood and paper industry, it was assumed that the wood and paper industry operates in a 24/7 regime. To determine the DSM potential, the industry’s average hourly electricity consumption was derived from its last three year’s total electricity consumption. These assumptions should be precise enough to provide the calculated capacities for short-term periods, e.g. 1 to 2 h. The possible DSM potential of the whole industry was calculated with (3.7):

$$\overline{P_{Industry}^{DSM}} = \frac{\delta}{m \cdot n} \sum_{j=1}^{m} \sum_{i=1}^{n} P_{i,j} , \tag{3.7}$$

where

m is the number of industries in the sector,
n is the total number of hours used to determine average electricity consumption,
$P_{i,j}$ is the total electricity consumption for n hours at m industry companies, and
δ is the reserve production capacity factor.

According to the estimation, the Estonian wood industry can provide on average at least 24 MW and the paper industry 8 MW of ancillary services. Results are summarized in Table 4.

Table 4. Total estimated DSM potential in the wood and paper industry

	Estimated capacity, MWh/h (% of average load)		
	FCL	**CCL**	**ECL**
Paper	8 (**21%**)	3 (**8%**)	25 (**63%**)
Wood	24 (**66%**)	12 (**33%**)	27 (**74%**)

Based on the data available from on-site measurements, interviews with industrial consumers and the study of Enterprise Estonia, a rough estimation on the other Estonian industrial consumers can be also assessed based on the following assumptions:

- industrial consumers are in continuous operation (24/7);
- average hourly consumption is based on their total electricity consumption from public databases;
- the load is eligible for DSR for 1 h minimally;
- production lines are at least 20% under-loaded.

To assess the DSR potential in other industries, average hourly electricity consumption data have to be acquired, e.g. as described in (3.8):

$$\overline{W_{el}} = \frac{1}{n}\sum_{i=1}^{n} W_{el,i} = \frac{\sum W_{el}}{n}, \tag{3.8}$$

where
$\overline{W_{el}}$ is the average hourly electricity consumption over a studied period (Wh/h),
W_{el} is the total electricity consumption over a studied period (Wh),
n is the number of hours the facility is operating and/or producing goods.

The final required information to calculate the possible DSR potential in an industry is its spare capacity factor S_C. S_C determines the quantity of spare capacity to be utilized by the industry compared to its installed capacity. DSR potential is then calculated as in (3.9):

$$P_{DSR} \approx P_{DSM} = \overline{W_{el}} \cdot S_C . \tag{3.9}$$

Assuming that all processing industries are over-dimensioned in their production capacities at least by 20% (except the wood industry) and by knowing their average annual electricity consumption in the last three years, it can be estimated that the Estonian processing industry would be able to provide FCL up to 67 MW for ancillary services to the TSO through DSM. Table 5 summarizes the estimation results.

Table 5. Total estimated DSM potential in the processing industry

	Estimated capacity, MWh/h		
	FCL	**CCL**	**ECL**
Iron and steel industry	0	0	0
Chemical industry	5	2	15
Production of non-ferrous metals	0	0	0
Production of other non-metallic mineral products	5	2	14
Production of transport equipment	1	1	4
Machinery	7	3	20
Mining and quarrying	0	0	1
Food processing, beverages and tobacco	7	3	21
Pulp, paper and printing industry	8	3	25
Production of wood and wood products	24	12	27
Construction	2	1	6
Textile, leather and clothing industry	3	1	9
Other industries	5	2	14
Total	**67**	**29**	**157**

4.3 Potential of ancillary services from office buildings

The main assumption for DSM in office buildings is that the loads allocated for DSR would be switched to a lower consumption profile in order to maintain the work of essential equipment and assure minimal requirements for the working environment and employee comfort. The analysed 8/5 type office building (OB) would be able to allocate the following loads (on average 25 kW) to system service provision by lowering the consumption over 1 h, as shown in Table 6. Prolonged (up to 8 h) DSM could be implemented additionally also on lighting (7.5 kW) and office/kitchen equipment (1 kW).

The analysed 24/7 type office building would be capable of allocating approximately 38 kW of lowered electrical consumption for DSM. The loads allocated for 1 h would consist of the components described in Table 6. Prolonged (up to 8 h) DSM measures could be implemented in addition also on lighting (6 kW) and office/kitchen equipment (1 kW).

Table 6. Service provision by lowering the consumption over 1 hour

	8/5 OB, kW	**24/7 OB, kW**
ventilation	7.5	22
electrical heating	9	9
unessential lighting	7.5	6
office and kitchen equipment	1	1

The DSM potential is based on the flexible load capacity factor φ, as calculated with (3.10) and denotes the loads that can be controlled in a flexible manner. Based on the electricity consumption of similar office buildings, the possible DSM potential for a 8/5 and 24/7 building is calculated according to (3.11).

$$\varphi = \frac{1}{n}\sum_{i}^{n}\frac{P_i^1 + P_i^2 + ... + P_i^m}{P_i^{total}} . \quad (3.10)$$

$$\overline{P_{OB}^{DSM}} = \frac{\varphi}{p \cdot o}\sum_{k=1}^{p}\sum_{j=1}^{o} P_{k,j} . \quad (3.11)$$

where

n is the total number of hours used to determine average electricity consumption,
m is the number of different types of flexible loads available for control,
P_i^{total} is the total electricity consumption at hour n,
$P_i^1 ... P_i^m$ is the total flexible load at hour n,
φ is the flexible load capacity factor,
p is the number of office building in the sector,
o is the total number of hours used to determine average electricity consumption,
$P_{k,j}$ is the electricity consumption for o hours at p office buildings.

Assuming that all buildings, in accordance with their purpose and usage, in the public services sector in Estonia are similar to the two analysed office buildings, then by using Eq. (3.10) and (3.11) we can estimate DSM potential for the whole sector. According to this hypothesis it would be possible to use on average up to 86 MW of regulating power for ancillary services for a period of one hour. Over a prolonged period (2 h to 8 h), the average controllable load would be up to 26 MW. Results are summarized in Table 7.

Table 7. Total estimated DSM potential in the office buildings

Duration of the control (hours)	**FCL (% of average load)**	
	8/5 OB, MWh/h	**24/7 OB, MWh/h**
1	72 (**73%**)	14 (**14%**)
2…8	24 (**25%**)	2.3 (**2%**)

4.4 Potential of ancillary services in the commercial sector

The author determined in the studies presented in [3] and [V] that using cold storage and controlling the ventilation system according to the price, 34% of the average consumption capacity could be allocated for ancillary service provision from shopping centres up to two hours. In a 3- to 8-hour period, it is possible to allocate 24% of the average consumption capacity and in 9 to 13 hours, approximately 16% of the average consumption capacity. The following loads were determined during the study to qualify allocation for DSM based on their maximum usage time:

- up to 2 h - ventilation (30 kW), refrigerator compressors (50 kW) and freezer compressors (23 kW);
- up to 8 h - refrigerator compressors (50 kW) and freezer compressors (23 kW);
- up to 13 h - refrigerator compressors (50 kW).

Based on the analysis, it was determined that in the best case scenario, in addition, it would be possible to flexibly control 20% to 25% of the lighting.

Therefore, the ECL in shopping centres would increase the controllable load by 30 kW up to 8 h during daylight. The results with cold storage are summarized in Figure 26.

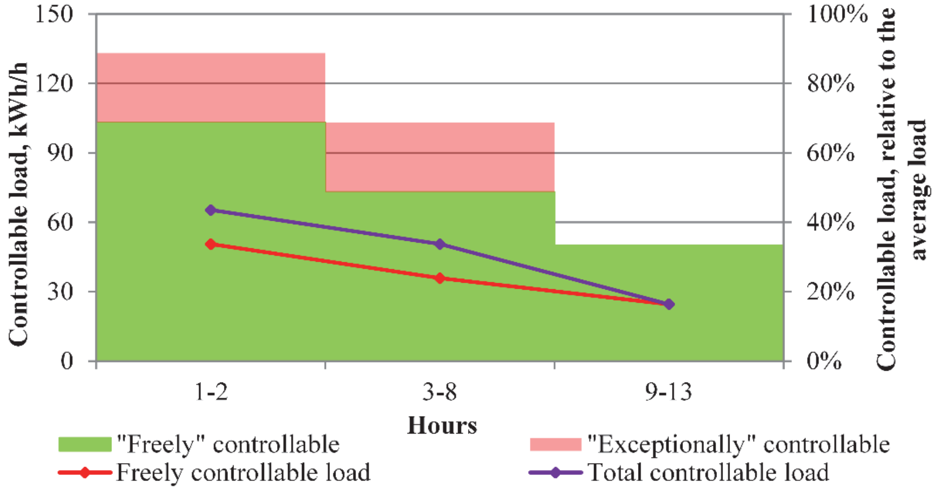


Figure 26. DSM potential in the shopping centre (with cold storage and lighting) with x-axis representing the duration and y-axis the relative capacity of the controllable load.

In case cold storage cannot be used as an energy storage over two hours, it is possible to allocate ventilation for DSM approximately with 30 kW of capacities. This means that on average 10% of the hourly load is allocated for DSM services. In exceptional cases, additional DSM service can be provided with lighting control and adjusting the central storage set-points. Lighting can be controlled in these cases up to 8 h with 30 kW capacities. By adjusting the control set points for the central cooling (i.e. price based load control), additional 6.6 kW of capacities could be allocated for DSM. The results are summarized in Figure 27.

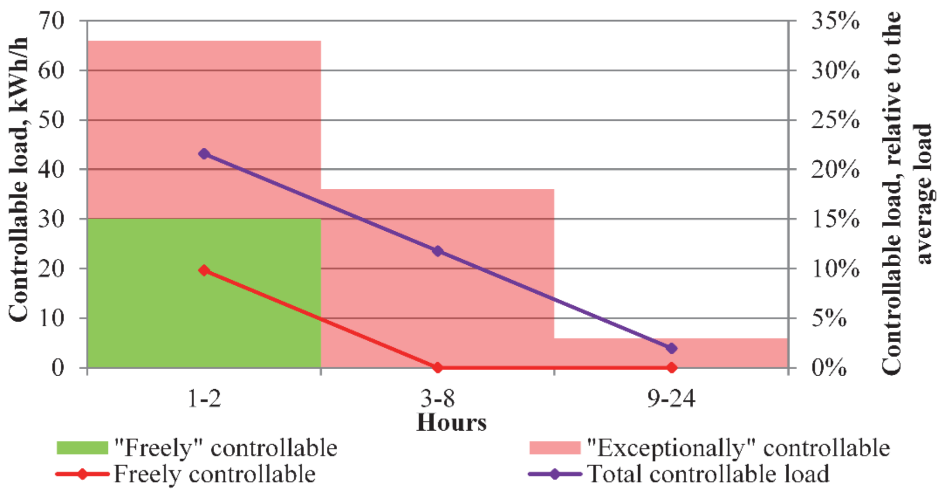


Figure 27. DSM potential in the shopping centre (with ventilation and lighting control and without cold storage) with x-axis representing the duration and y-axis the relative capacity of the controllable load.

The total DSM potential for the whole sector with or without cold storage can be estimated in a similar manner as for office buildings with (3.10) and (3.11). The results are summarized in Table 8.

Table 8. Total estimated DSM potential in the wholesale and retail sector

Duration of the control (hours)	**Flexibility with storage (% of average consumption)**		**Flexibility without storage (% of average consumption)**	
	FCL, MWh/h	**ECL, MWh/h**	**FCL, MWh/h**	**ECL, MWh/h**
1…2	26 (**34%**)	8 (**10%**)	7 (**9%**)	9 (**12%**)
3…8	18 (**24%**)	8 (**10%**)	0	9 (**12%**)
9…13	13 (**16%**)	0	0	1 (**2%**)

Taking into account data from the previous sections, the whole sector has a potential to provide on average 26 MW of ancillary service power over a period of two hours and in exceptional cases, additional 8 MW. This assumes that the sector implements energy storage on a wide scale. Without the usage of cold storages as energy storage, the sector's contribution remains moderate. In this case, the sector is able to provide on average FCL at 7 MW for DSM services up to two hours and as ECL at an additional 9 MW.

It should be noted that due to the nature of the controlled loads, demand shifting with cold storage would increase the additional power requirement and thus the average electrical consumption outside the DSM measure timeframe 1.5 times (from 75 kW to 115 kW to 120 kW in the studied cases).

5. Demand side management as a voltage support service

Due to increased share of weather influenced power generation, deregulation and market driven operation in today's power systems operate closer to their voltage stability limits [36]. With the emergence of smart grids and large scale integration of ICT into power system control at all levels of the system, several reactive power and/or voltage related problems could be addressed in a "smarter" way. This thesis proposes a novel but simple approach to provide reactive power support for ancillary services through controlled or targeted load shedding.

Reactive power and voltage stability related problems are primarily a localized issues and in many cases originate from weaker parts of the power grid where reserves are scarce [37], [38]. However, large consumers such as industrial factories have a variety of types of loads that could release different levels of active and/or reactive capacities specifically to support the grid when needed. This chapter focuses on the analysis of dynamic reactive power reserve provision through DSM. In addition, the impact of different aspects of loads to be involved in providing emergency reserves is described, i.e. the existence and impact of power factor correction (PFC) on the high voltage side of the grid transformer and the impact of load type shares in the studied load composition. The proposed approach was modelled with power system modelling software PSS/E on an actual simplified network model that represents the south-east Estonian 110 kV transmission grid. Additionally, the potential of providing seasonal voltage control services in weak parts of the grid is discussed.

5.1 DSM as a source for reactive power ancillary service

Different measures for increasing reactive power reserves are proposed in the literature. Majority of the papers, e.g. [37]-[40], focus on the VQ-curve method for assessing the reactive power reserves either from the load or generator side. Authors of [41] and [42] introduce also a time domain aspect because of transformer on-load tap changer (OLTC) and generator excitation systems to reactive power optimization. In 2000, CIGRE working group 39/11 [43] presented a comprehensive overview of the issues and possibilities of incorporating reactive power reserves into a market based trading entity. Most of the problems pointed out in the paper (e.g. reactive power metering and localized monopolies) have been overcome by now. Several studies, e.g. [44]-[48], have discussed the possibilities and existing practices, including reactive power resources on a market based trading platform and different financial compensation mechanisms around the world. Nevertheless, in many countries (including Estonia), the power system voltage stability issue is still addressed through bulk load shedding in emergency situations, e.g. [42], [49], and [50]. Although in all cases, the purpose is to minimize load shedding, this approach is still somewhat outdated.

Although the authors in [49] argue that their utilization is costly compared to traditional compensators installed at area buses, in fact, near voltage collapse situations are uncommon in power systems. In addition, if controlled load management rather than bulk load shedding is applied, they could compete with traditional measures. Braun in [51] compares provision of reactive power with distributed generation and traditional measures. It was found that provision of reactive power control through distributed generation results in two cost aspects: additional investment and additional operation costs. From the load point of view, only the additional operational costs are of interest, as additional investment costs include mainly updating and connecting the plant's control system into the link with the power system operator's network. It is therefore incomparable with an investment cost of new compensators. Table 9 shows additional investment and operational costs for traditional reactive power control, including those from distributed generators.

Table 9. Investment and operational costs for traditional reactive power control (including distributed generators) [51]

<table>
<tr><th rowspan="2">Device</th><th rowspan="2">Initial investment cost, euro/kVA (euro/kvar)</th><th rowspan="2">Additional investment cost, euro/kvar (euro/kVA)</th><th colspan="4">Operation and maintenance costs, eurocents/kvarh</th></tr>
<tr></tr>
<tr><td rowspan="2">DGs:
Inverter
DFIG
SG</td><td rowspan="2">
150-300
155-85
120-50</td><td rowspan="2">
34.9-68.5
12.5-19.9
6.90-15.4</td><td>PV</td><td>Wind</td><td>Hydro</td><td>CHP</td></tr>
<tr><td>0-3.0</td><td>0-0.2</td><td>0-0.3</td><td>0-0.4</td></tr>
<tr><td>Transformer</td><td>N/A</td><td>(10.0-30.0)</td><td colspan="4">N/A</td></tr>
<tr><td>Static compensator (Mvar)</td><td>1 (30-75)</td><td>N/A</td><td colspan="4">0.20-0.40</td></tr>
<tr><td>Synchronous condenser</td><td>1 (27-69)</td><td>N/A</td><td colspan="4">0.30[1]</td></tr>
<tr><td>Capacitor, (10 kvar)</td><td>(150)</td><td>N/A</td><td colspan="4" rowspan="6">0.015[2]</td></tr>
<tr><td>Reactor, (10 kvar)</td><td>(180)</td><td>N/A</td></tr>
<tr><td>Capacitor, (100 kvar)</td><td>(31.0)</td><td>N/A</td></tr>
<tr><td>Reactor, (100 kvar)</td><td>(37.2)</td><td>N/A</td></tr>
<tr><td>Capacitor, (200 Mvar)</td><td>(14.0)</td><td>N/A</td></tr>
<tr><td>Reactor, (200 Mvar)</td><td>(16.8)</td><td>N/A</td></tr>
</table>

[1] based on 60 Mvar unit with 3% losses or 0.03 kWh/kvarh and energy purchase 10 eurocents/kWh [52]

[2] based on losses 0.0015 kWh/kvarh and energy purchase 10 eurocents/kWh

Similar costs can be also calculated for industrial consumers and additional and operational costs for industrial loads are described in detail in section 5.1.3. Nevertheless, automation level in the majority of industrial plants is quite high and load management can be connected into the power system operations easily.

In contrast, installation of new equipment into substations that may be needed on a seasonal basis needs more effort. In the author’s opinion, load based reactive power services are mainly hindered by the lack of legislation and market platforms, as loads for primary and secondary frequency reserves are in use already today [21]. Instead of using loads as a last measure by system protection, they could possibly be used as a new type of system service for the system operator.

5.1.1 Load composition

This thesis research analyses a wood processing plant that is somewhat similar to the plant in Chapter 3 where some of the production line parts are semi-automatic, others are automatic but the production facility itself works continuously. As the industry is based on the mechanical processing of wood, the electrical drives that run those processes make it relatively energy intensive. The illustrative outline of the production facility with the installed loads (P_i) and PFC capacities (Q_{comp}) is shown in Figure 28.

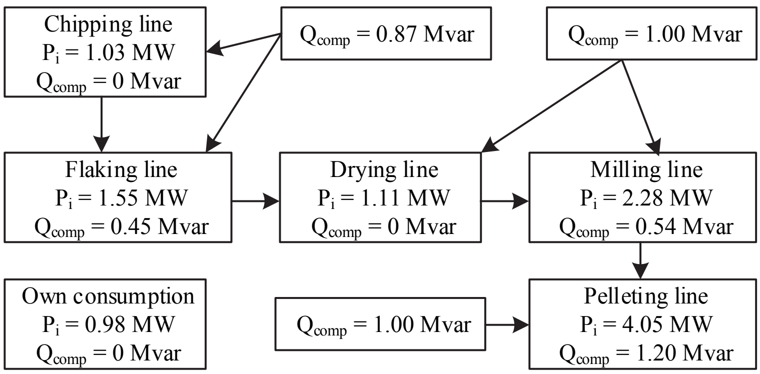


Figure 28. Layout of production facility capacities.

95% of the total electricity load is constituted by the induction motors. Majority (16) of the largest motors (>350 kW) are started via soft-starter, one of the main motors is operated through a frequency converter and the largest motor (500 kW) is started via a star-delta starter. From the rest of the installed capacity of electrical motors, approximately 15% are fed through a frequency converter, and 25% are started either direct-on-line or star-delta. Total installed capacity of the plant is approximately 11 MW, including only 5% for lighting, electrical heating, electronic office loads, etc. The facility has also reactive power compensation devices with installed capacity of approximately 5.1 Mvar. Peak demand capacity of the industrial consumer is approximately 9.5 MW, however the average consumption per hour remains around 8 MW. Load composition is summarized in Table 10.

As it was found in [II] and [IV], the main constraint from the consumer side is the objective to maintain constant production output from the plant. For load control, this would assume the availability of some kind of energy storage. In the industrial plant, a simple bulk material storage between different parts of the production lines would enable control of loads without affecting the production output. However, in emergency situations, circumstances may occur when selective load control from the consumer part is not enough for the power system. In order to avoid unselective bulk load shedding from the SPS enforced in power systems, this research aims to determine the impact of the industrial load targeted shedding on the system's voltage level and reactive power balance during emergencies in the power system and when the system configuration is weak.

Table 10. Load composition in the plant

Load Type	**Value, kW**	**Share**	**Reactive load, kvar**	
			Without compensation	**With compensation**
Electrical drives (induction motors)*	8 520	80%	5 060	410
Electrical drives (as electronic load)	1 615	15%	0	0
Cooling (air conditioners)	175	1.5%	35**	
Electrical heating	100	1%	0	0
Lighting (electronic load)	200	2%	95	
Office equipment + miscellaneous (electronic load)***	60	0.5%	0	0
TOTAL	**10 671**	**100%**		

*Assuming that a motor's average cos φ = 0.86 and after compensation cos φ = 0.99
**Measured value during spring time, when the load factor for the air conditioners is low (~30%)
***Due to the marginal share of loads cos φ is assumed to be 1

5.1.2 Theoretical potential of offered reactive power reserve with induction motors

Induction motor usage in under voltage load shedding (UVLS) for support to the grid has been analysed in detail in [53]. The author emphasizes that traditional load shedding schemes in power system modelling, e.g. generic load models, overlook the complex coupling between real and reactive power consumption. Therefore, the system settling trajectory can differ significantly from the real situation, especially for loads with high shares of induction motors. In real life, the reactive power dynamics cannot be considered separately or independent of the active power, especially for induction motors due to the coupling between them and the influence of phase angle dynamics [53]. Simple induction motor models do not cover its behaviour over the whole operating region, instead they cover only a small part of the motor's characteristic curve. The author of [53] concludes that the generic models are suitable only for usage during normal operation modes and not during or after system disturbances.

As induction motors constitute a majority of the dynamic load models that have a significant impact on the transient voltage stability [54], in addition to UVLS possibilities, the author of this thesis proposes to study how to prevent voltage collapse by the use of induction motor load shedding and provide reactive power reserves and voltage control. This is in many ways similar to the UVLS scheme proposed in [53], as it takes into account the reactive power consumption behaviour of induction motors during low voltages and the effect of capacitor banks used to supply the reactive power demand of motors.

When the induction machine is analysed in stability studies, it is common to disregard stator transients [24]. In this case, the machine can be modelled with the following system of differential equations:

$$\frac{d}{dt}e_d = (\omega_s - \omega_r)\cdot e_q - \frac{1}{T_0'}\cdot\left[e_d + (X - X')\cdot i_q\right], \tag{5.1}$$

$$\frac{d}{dt}e_q = -(\omega_s - \omega_r)\cdot e_d - \frac{1}{T_0'}\cdot\left[e_q - (X - X')\cdot i_d\right], \tag{5.2}$$

$$\frac{d}{dt}\omega_r = \frac{\omega_s}{2\cdot H}\cdot(P_e - P_m), \tag{5.3}$$

where

$$i_d = \frac{R_s\cdot(v_d - e_d) + X'\cdot(v_q - e_q)}{R_s^2 + X'^2}, \tag{5.4}$$

$$i_q = \frac{R_s\cdot(v_q - e_q) - X'\cdot(v_d - e_d)}{R_s^2 + X'^2}, \tag{5.5}$$

$$P_e = v_d\cdot i_d + v_q\cdot i_q, \tag{5.6}$$

$$P_m = T_{l0}\cdot\left(\frac{\omega_r}{\omega_s}\right)^n, \tag{5.7}$$

$$X = X_s + X_m, \tag{5.8}$$

$$X' = X_s + \frac{X_r\cdot X_m}{X_r + X_m}, \tag{5.9}$$

$$T_0' = \frac{X_r + X_m}{\omega_s\cdot R_r}. \tag{5.10}$$

The quantities v_d, v_q, i_d, and i_q are the stator voltage and current in the *dq* transformation domain, while e_d and e_q represent the voltage behind the transient impedance (rotor currents are eliminated and the relationship between stator voltage and current is expressed in terms of this voltage [24]). Power P_e is the input electrical power and P_m is the output mechanical power, where T_{l0} is the load torque constant [55]. Input reactive power can be expressed as follows:

$$Q_e = v_q\cdot i_d - v_d\cdot i_q. \tag{5.11}$$

Machine parameters may be given in terms of the common induction machine equivalent circuit (i.e. R_s, X_s, X_m, X_r, etc.) or as the set of R_s, X, X', and T_0'. If the former is the case, Eqs. (5.8)-(5.10) apply. The stator resistance R_s and the reactance X' combined give the transient impedance. T_0' is referred to as the transient open-circuit time constant and is expressed in radians. H is the combined inertia time constant of the motor and the load, while the exponent n is a constant characteristic of the load describing the torque's dependency from the speed (usually with a value of either 0, 1, or 2). Rotational speeds ω_s and ω_r correspond to the stator and rotor, respectively [24].

When the machine is in steady state, the voltage behind the transient impedance and rotational speed remain constant in time. In this case, the derivatives on the left hand sides of Eqs. (5.1)-(5.3) can be equated to zero and the system of equations is solved for certain steady state conditions. For different values of stator voltage, static active and reactive power characteristics can be computed for a given induction motor. For motors described in [66] and used later for modelling purposes in section 5.2.2.3, the static characteristics are plotted in Figure 29. For reactive power, additional characteristics are plotted which include compensation from shunt capacitors. The shunt capacitor is assumed to be dependent on supply voltage, which is equated to the stator voltage. The compensation at rated values is configured to achieve cos φ = 0.99.

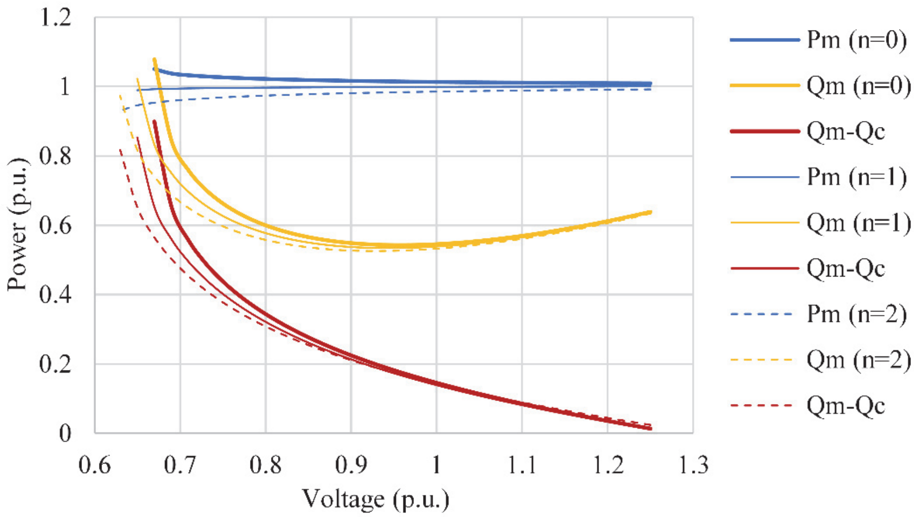


Figure 29. PV and QV static characteristics for different induction motors with and without reactive power compensation.

The increase in reactive power demand from the induction motors is caused by the increase in reactive current when the supply voltage has decreased. In order to maintain speed and power, the motor tries to compensate the loss of power by increasing the magnetizing flux, which is dependent on the supply voltage inside the motor with higher magnetizing current. When PFC is present in the system, the decreasing voltage on the terminal also decreases the output of these devices and thus increases the demand of reactive power from the grid. From Figure 29 it can be seen that during low voltage situations, the induction motor's reactive power demand together with the inverse voltage effect on the installed PFC device can dramatically increase the reactive power demand from the grid. During a low voltage situation where the voltage drops to 0.7 p.u. and the transformer OLTC does not switch the steps fast enough, the reactive power demand can increase 200% to 300% as compared to the normal situation.

5.1.3 Technical and economic aspects

In the introduction, additional investment and operational costs for traditional reactive power resources together with DGs were compared. A somewhat similar analysis can be done also for the consumer providing reactive power reserves. From the consumer point of view, the majority of the operating costs of providing a reactive power reserve will comprise mainly costs due to stoppage of the production facility, as described in Chapter 3. Additional losses for transferring the reactive power, similar to DGs, is usually not an issue as physical reactive power is not transferred to the gird during normal operation.

Theoretically, the compensating capacitors of reactive power could be turned on to transfer reactive power also into the grid when no consumption occurs. In this case, the capacity would be 5.3 Mvar (see Figure 28) and electrical losses in the internal network should be considered as well. However, this would require the modification of the control logic of the PFC devices, as in the normal mode, it controls the power factor at the 0.4 kV system. In addition to the loss of profit, some additional alternative costs will arise due to some specifics of the production line. Finally, also additional investment costs need to be considered in order to update the plant control interface so that certain services could be started remotely by the service purchaser.

Due to the specifics of the production facility discussed in more detail in [II] and [IV], stopping the whole production facility is possible, but the restarting of the production line is somewhat complicated. In any case, the cost of stopping the whole facility would mean loss of a fixed profit of approximately 900 euros per hour for the company. Due to the specifics of the technology, it is required to take into account a fixed cost per stoppage of about 30 to 40 euros. Additional time delays before start up need to be considered also because of the need to clean the conveyor belts and due to cooling the reheating of the drying line. This increases the cost of DSR service and stopping of the whole production facility may not prove so competitive in relation to traditional methods implemented in the power system. The summary of operational costs for providing DSM related ancillary services from a customer side are given in Table 11.

Table 11. Operational cost for providing DSM related theoretical reactive power support based on an industrial consumer

<table>
<tr><th colspan="2"></th><th>Reactive power support, Mvar</th></tr>
<tr><td>Additional investment cost, euros per facility</td><td>10 000</td><td>N/A</td></tr>
<tr><td>Stopping the whole production, euros per hour</td><td>900</td><td rowspan="2">5.3</td></tr>
<tr><td>Fixed cost, euros per stoppage</td><td>30-40</td></tr>
<tr><td>Partial stopping of the production, euros per hour*</td><td>13.2</td><td>1.3</td></tr>
</table>

*In the assumption that diesel fuel costs 1.1 euros per litre

Nevertheless, the production facility before the drying line can be stopped relatively easily and the costs involved would contain only the alternative operating costs. While chipping and flaking lines are offline, it is required to transfer raw material to the following processing lines from the bulk storages via diesel operated bulldozers. The alternative operating cost would include the cost of fuel needed to operate the machinery that on average is approximately 12 litres per hour. Additional investment costs include upgrading of the plant's control computer in order to accommodate the necessary capability to provide DSM as a service to other parties. This cost includes the installation and creation of the necessary communication and control channels within the facility's equipment, e.g. loads, capacitors, and their respective control equipment, together with programming and if necessary, with some minor upgrades in ICT hardware.

In the author's view, two theoretical solutions exist for the DSM users to initiate ancillary services from industrial consumers. It should be noted that the proposed solutions are based on an actual working system that is only missing the necessary links to enable DSM, as illustrated in Figure 30 and Figure 31.

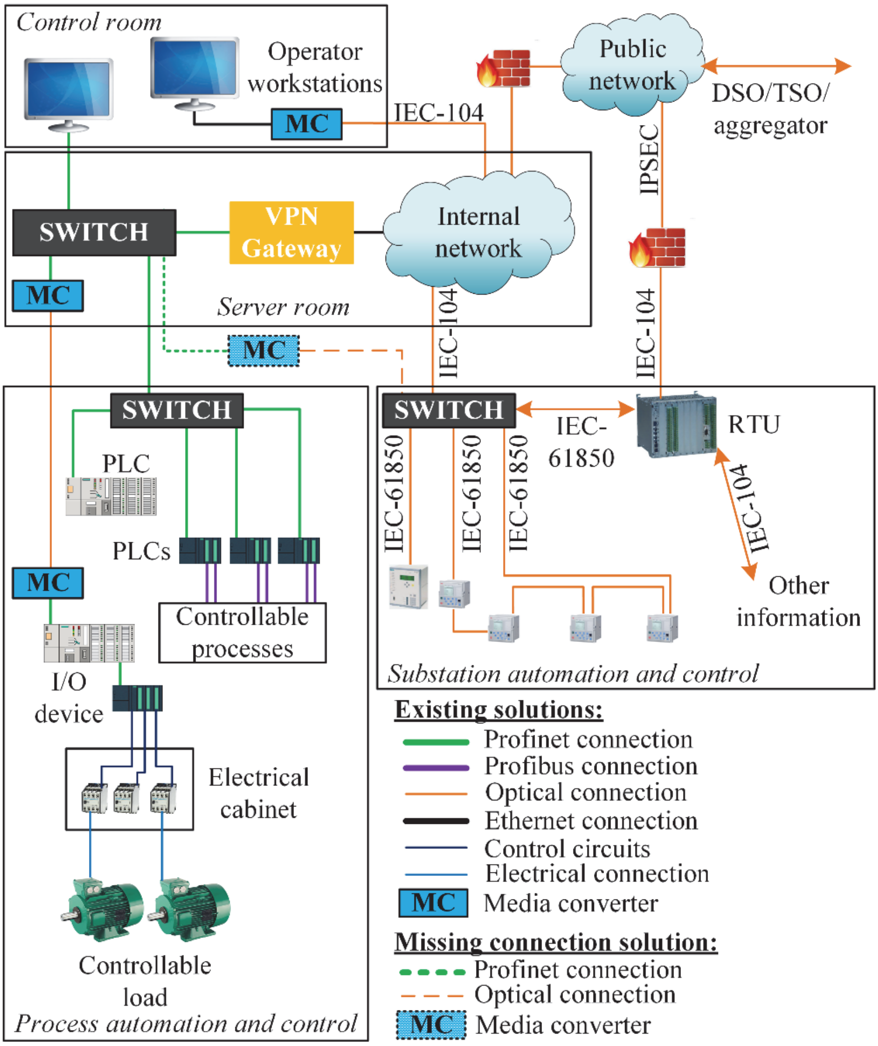


Figure 30. Communication solution for DSM service provision (direct access).

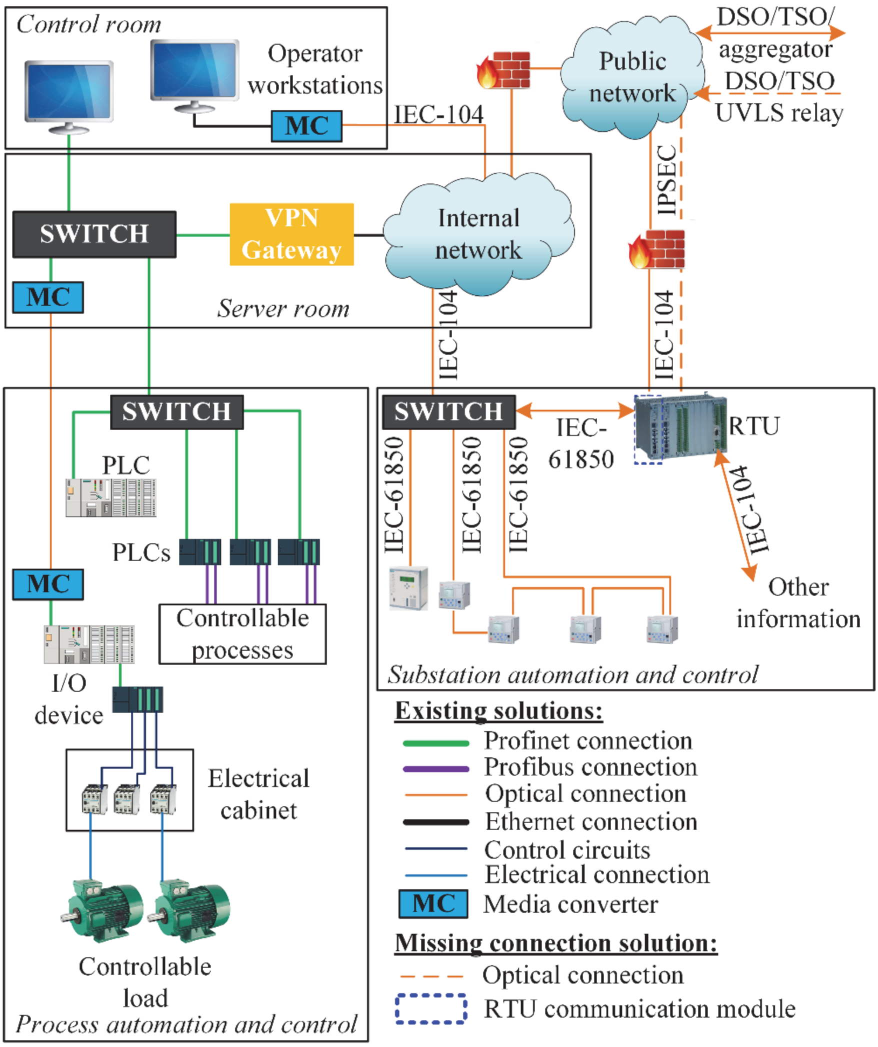


Figure 31. Control and communication principle (SPS) of DSM service provision.

The first solution, illustrated in Figure 30, is based on direct control access by TSO/DSO or any other interested party. The solution could be incorporated to an existing or planned market platform; however, it works also based on bilateral agreements. In this way, the DSM service provider has a direct communication channel to its facilities' control computer, which enables the service user to remotely control predetermined parts of its load whenever the service is required. The control access could be enabled, for example, by an ask-bid price agreement. If an agreement is reached, the remote control is enabled. As the system would be integrated into the existing operator workstation, the operator would have an overview about the actions performed or services ordered/initiated.

The second solution, illustrated in Figure 31, is based on a modified UVLS relay (SPS) solution. As discussed at the beginning of this chapter, unselective load shedding could in theory worsen the recovery process from a fault. UVLS today is based on two to three parameters: voltage, time delay and (pre-determined) load shedding feeders on the medium voltage side. In order to incorporate this solution, the UVLS relay should be slightly modified with an additional (first) control stage before the standard UVLS action. The first stage that is at least an order of magnitude faster than the standard stage of the relay would have once again a direct connection to the DSM service provider's facility to trip critical loads or parts of loads predetermined by the grid operator to impose the largest impact.

Although the proposed solutions are currently only theoretical, as they have not been tested yet in real life, then in the assumption that both the DSM service provider and the service user possess the necessary infrastructure and network communications to activate this service, two solutions proposed could be implemented. Today's relays are relatively flexible in terms of programming its functions, so adding one additional step to it should not be an issue. Nevertheless, this solution assumes that a comprehensive load composition and dynamic analysis has been carried out by the TSO and critical load types for specific load areas have been determined in order to trip only the most critical loads.

5.2 Case study to determine the DSM's applicability for voltage support services

In order to study the voltage support service applicability in the Estonian power system, the TSO's long-term transmission system planning model in PSS/E is adopted and modified. As this approach is novel and has not yet been used in the TSO's planning and modelling policies, some simplifications and modifications of the model are required. In addition a suitable load model that would adequately simulate the DSM action needs to be determined. The modelling is carried out with PSS/E, which is the main tool for the Estonian TSO (but also for other Baltic TSO's) for network modelling.

The case study is based on the 110 kV transmission grid of south-east Estonia. The reason for selecting this part of the network is load increase in that specific part on the transmission system that is related with new large industrial consumers expanding to that region. As the grid can operate in relatively weak configurations, it provides also a good source for testing the proposed methods on a real part of the system. The system incorporates an actual industrial consumer's load in bus 24, which has been described with more detail in section 5.1.1.

The studied part of the system is tied to the main 330 kV transmission system through two substations (load bus 1 and load bus 28) and the 110 kV part is operated in two separate control areas during normal conditions, as illustrated in Figure 33. This configuration avoids unnecessary loop flows with the 330 kV transmission grid operating in parallel with the 110 kV system. Due to confidential nature of network data and to avoid possible problems because of model quality, the test system is reduced to only represent the 110 kV part of the studied system. The links to the 330 kV network are modelled with two lines with parameters representing the Thevenin's equivalent parameters for the rest of the network (source), as illustrated in Figure 32 and parameters presented in Table 12. The reduced model is in accordance with modelling practices [56] and also accepted by the Estonian TSO as an adequate model reducing method.

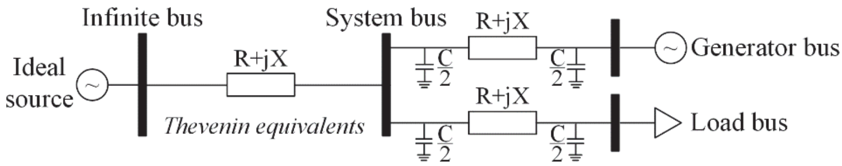


Figure 32. System equivalent modelling with Thevenin's equivalents.

Table 12. System equivalent parameters used in the modelling (during normal operating conditions) and describing the system strength

Substation	Faulted Bus	Short Circuit Power, MVA	*Thevenin* equivalents, ohms	
			R_{pos}	X_{pos}
Load bus 24	Load bus 24	435	**10.6**	**27.9**
Load bus 28	Load bus 28	1 066	**1.31**	**12.7**
Load bus 1	Load bus 1	3 113	**0.75**	**4.47**

The reduced model's contains 50 buses with one distributed generator and the system "source" is modelled with a single classical generator model. The model also includes 30 load points totalling at 212 MW and 43.7 Mvar. The only distributed generator is modelled as a GENSAL synchronous generator model with IEEE type 1 exciter, and with IEEE type PSS2A dual-input signal stabilizer model. OLTC model has been added to the studied industrial consumer's (load bus 24) transformer with parameters suggested in [56] and presented in Table 13.

Table 13. OLTC model parameters used for the studied industry's main transformer

CONs	Value	Description
J	**10**	TD, time delay (s)
J+1	**5**	TC, time constant of tap changer (s)
J+2	**7.5**	TSD, time before subsequent tap signal sent (s)

As a simplification, all loads in the reduced model are modelled as simple loads (except the studied industrial consumer's load in bus 24), only taking into account the transformer losses. No specific load models are assigned to these loads. This is because the model has been previously used for long-term power system planning and dynamic simulations, where transformer and load modelling has been considered unimportant and therefore either removed or neglected from the original model by the TSO. The latter one is most probably tied with the studies' objectives to determine transit power flow and angle stability related issues rather than voltage control and support. Nevertheless, in this particular case, the new industrial consumer is modelled in more detail until the 0.4 kV bus bars where also the PFC devices are modelled. This industrial consumer's load will be used for benchmarking the most suitable load model for DSM studies.

Loads at 0.4 kV bus bar are represented in the load flow as aggregated loads in constant MVA form. Loading capacity is determined based on the average actual load rather than on installed capacity that represents the actual instead of boundary situations. The general outlay of the model used in the case study is illustrated in Figure 33.

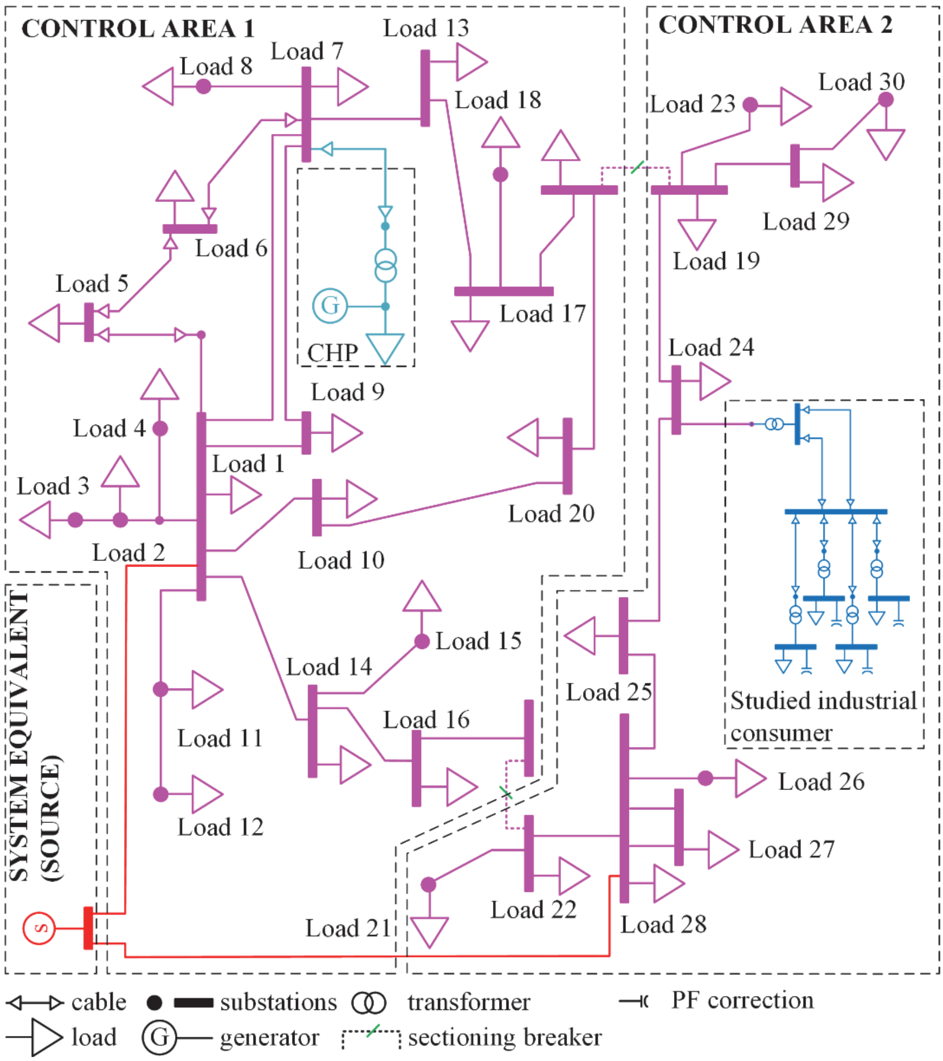


Figure 33. Single line diagram of the study system.

5.2.1 QV analysis

In the first step of the case study, a QV analysis was performed for the study bus. Here, the aim was to determine maximum Mvar demand at any different system configuration possible before voltage collapse could occur and the corresponding contingency would trigger the event. As it was described in the previous section, the 110 kV network is operated as two separate control areas

(Figure 33) via the sectioning breakers in load bus 19 and 22. Therefore, from the load bus 24 perspective, seven system configurations were considered viable and analysed based on the status of links to the main transmission network and sectioning breakers. The following scenarios (S1, S2, and S3) for each configuration were analysed:

S1. QV analysis with the base case and without a new industrial consumer;
S2. QV analysis with a new industrial consumer and with power factor correction;
S3. QV analysis with a new industrial consumer and without power factor correction.

Results of the QV analysis under different system conditions are summarized in Table 14.

Table 14. Results of the QV analysis

		(COO)*	(CCC)	(OCC)	(OCO)
S1	Base (Mvar)	-110.23	-246.42	**-157.31**	-120.35
	N-1 (Mvar)	-110.13	-122.24	**-43.257**	-60.927
	Contingency	Trip line 28-26	Trip line 24-19	Trip line 24-19	Trip line 7-13
S2	Base (Mvar)	-106.94	-242.89	**-153.64**	-116.50
	N-1 (Mvar)	-106.84	-119.06	**-39.260**	-56.210
	Contingency	Trip line 28-26	Trip line 24-19	Trip line 24-19	Trip line 7-13
S3	Base (Mvar)	-105.18	-240.61	**-151.45**	-114.33
	N-1 (Mvar)	-105.08	-117.25	**-37.110**	-54.090
	Contingency	Trip line 28-26	Trip line 24-19	Trip line 24-19	Trip line 7-13

*(COO): 1st position - status of system link; 2nd position - status of sectioning breaker at load bus 19; 3rd position - status of sectioning breaker at load bus 22;
C - closed, link in operation; O - open, link is offline. Configuration (COO) represents the normal operating condition for the studied region.

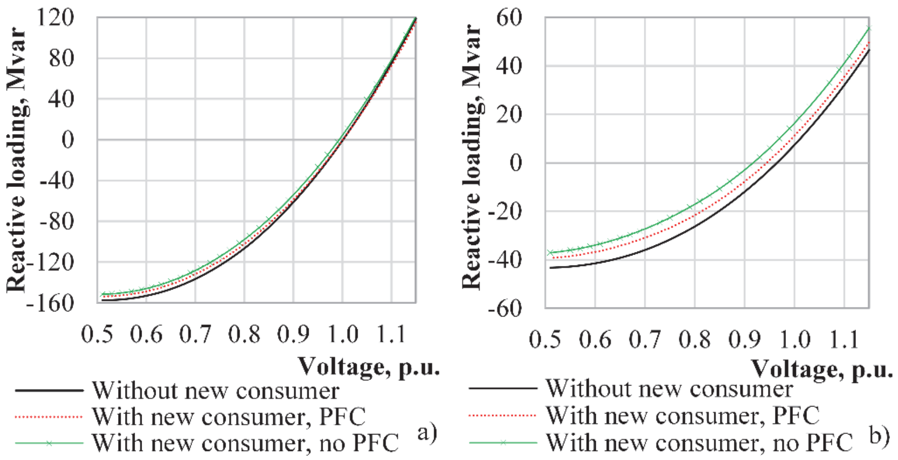


Figure 34. QV curves for load bus 24 during grid configuration 3 with and without a new consumer and PFC, a – normal operation mode, b – N-1 contingency applied.

The analysis results show that the worst case scenario occurs with “configuration 3”. This represents a situation where load bus 28 link to the main 330 kV transmission is out of service due to transformer maintenance. This configuration would give the highest Mvar loading reserve for the area and studied load bus. However, if an additional contingency (N-1-1 situation) occurs due to some unforeseen event that trips an additional line (in this case, line from bus 24 to bus 19), then the allowable reactive power loading margin would decrease almost fourfold. The analysis results are illustrated in Figure 34

According to the load flow study of this configuration and scenario, the system voltage would be around 110 kV and the medium voltage 9.85 kV, which are in a reasonable range. However, the voltage at the customer’s 0.4 kV bus bars would have decreased by 10% from 410 V to 370 V and as a result, also the reactive compensation level would have decreased by at least 15%, meaning a higher reactive load for the system. As induction motors are not modelled in the load flow scenarios, the actual impact is also not seen due to the aggregated nature of the loads. In reality, in addition to the general power factor correction devices (seen in Figure 33 at the 0.4 kV bus bars), the motors include a supplementary power factor improving capacitors directly connected to the motor control circuit itself, as illustrated in Figure 35.

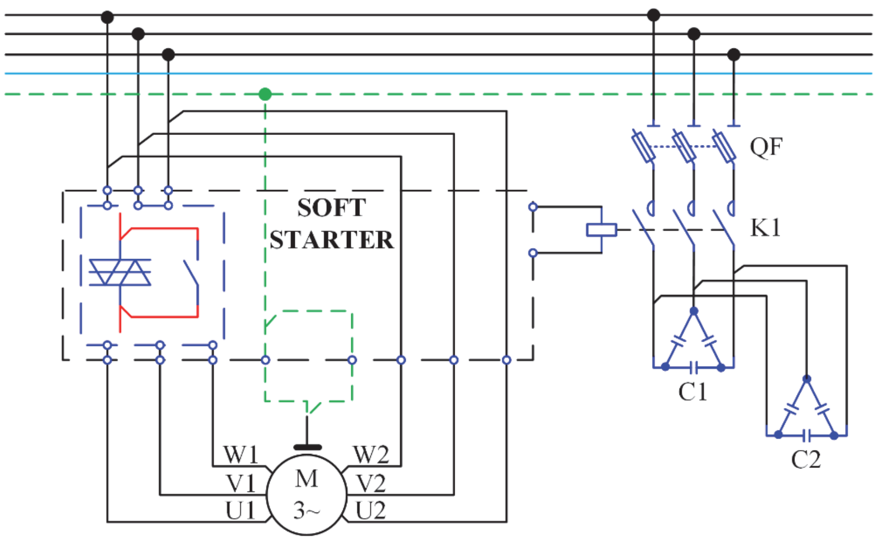


Figure 35. Motor load control circuit with supplementary power factor improvement at low voltage buses.

According to the induction motor theory, this part of the voltage recovery process is the most critical regarding the motor behaviour. The reason lies in the process itself. If it takes too long, the induction motor might trigger the under voltage protection or stall, leading to a longer recovery process or voltage collapse in the worst case scenario [57]. The induction motor poses special interest regarding to the ancillary reserves because it tends to draw different amounts of reactive power during and after a fault in the power system.

Depending on the motor size and mechanical load behaviour, the induction motor will draw little or no reactive power during fault but after fault clearing, the reactive power demand can be two to five times higher than under normal conditions over a period of 0.2 to 0.7 s after the fault [57]. The effect of reactive demand increase in induction motors and decrease from capacitor supply has been described in section 5.1.2. As a result, it can be speculated that due to the inadequate modelling level of loads, reactive power demand may rise threefold at low voltage situations as compared to base cases without contingencies and static load flow situations.

The QV analysis shows that the potential for reactive power reserve provision through DSM remains between 3.7 Mvar (with PFC) and 5.5 Mvar (without PFC), depending on the grid configuration and availability of PFC. Although the number does not seem high, during emergencies, it can raise the transmission system voltage by up to 6% in the studied system. On a larger scale where loads are higher, the potential should be also higher in the order of magnitude. At the same time, PFC is important at the customer level together with the level of detail used for modelling. The described effects diminish with each simplification made in load modelling, and therefore, different models should be maintained by the TSO for different studies and aims, e.g. long-term transmission capacity planning model intended for wide-area studies is not sufficient to model voltage control related issues on local level. Even the presented results are based on a simplified load flow study that does not take into account the actual behaviour of induction machines and capacitors during low voltage situations in time domain. Therefore, after the QV analysis, a series of dynamic simulations should be run in order to plot the voltage profile over a specific contingency and with different load modelling principles applied.

5.2.2 Applicable load models

According to the literature, voltage and its stability are a local issue. The voltage recovery after a disturbance is affected by many different characteristics, i.e. OLTCs, under excitation limiters and over excitation limiters of generators but also load dynamics. According to [58], load characteristics are the most active factor of those mentioned that affect the dynamic voltage change and the process of voltage collapse in extreme situations. These characteristics become even more important in weaker parts of the power system where the availability of reactive power reserves, especially fast acting [57], may be scarce and their installation too costly. Nevertheless, over the years, loads in power system models have been represented in a least accurate way [59] compared to other elements, i.e. generators, exciters, OLTC, etc. Only in recent years and because of power systems operated closer to their limits, improving the modelling of loads has become an area more widely studied. However, according to [60] only 8% of Europe's power system/network operators use detailed composite loads, and around 30% of users prefer to use constant power load models in dynamic studies. This section of the thesis concentrates on the modelling step to determine the impact of different load modelling methodologies during dynamic simulations and the impact of controlled load shedding. The default way for dynamic simulations with PSS/E instructs to convert the constant MVA loads used in the power flow studies to the following shares:

- the active part of loads should be converted as 100% constant current (I) representation;
- the reactive part of loads as 100% constant admittance (B).

This approach has been and is still used in TSOs mainly to run angle stability studies. Although in the author's opinion, this approach is not completely wrong, it limits the results that could be misinterpreted due to load voltage characteristics and could give false reinsurance of safe states of the power system. In addition, when other types of power system analysis for long-term planning or dynamic stability are required, this approach is very limited.

The standard approach for voltage control and under-voltage load shedding includes installing reactive power control devices (e.g. in Estonia, shunt capacitors and reactors) and in emergencies, disconnecting loads unselectively. These approaches are expensive and ineffective as voltage control may be needed only seasonally and in case of potential voltage collapse events, unselective load shedding may not support the recovery from it as a valuable load is lost, increasing the shortage of reactive power furthermore.

In this thesis a more selective approach is proposed for load shedding where only critical loads are shed, thus increasing the odds to recover from a possible voltage collapse event. In addition, a similar principle of selective load shedding could be implemented for providing valuable reactive power support for the weak parts of the grid at times when needed, e.g. from a seasonal off-peak voltage control point of view. The following three load modelling methods will be used on the test model to compare the results and impact of exact load modelling on voltage recovery:

- standard modelling without load models;
- complex load models;
- composite load models.

All three models have their pros and cons, however using any kind of load models instead of the standard PSS/E static load models gives better results for different stability studies. In addition, the possibilities of controlled load shedding as a source of reactive power resource have been studied, as areas with high concentration of induction motors tend to decrease the voltage stability margins in the weaker parts of the grid [61]. There are two options to cope with a situation like this, plan A is to install dynamic var devices or plan B use selective and controlled load shedding (DSM) and compensate the concurring costs.

5.2.2.1 Standard modelling without load models

In the standard modelling case, the standard PSS/E static load modelling method is used. As described before, this is achieved by converting the active loads to 100% (I) and reactive loads to 100% (B) loads without any specific dynamic load models. This serves as a reference case about the behaviour of active power, reactive power and voltages in the system during and after faults.

The method is most commonly used in modelling amongst the Baltic TSOs; however according to [60], only a minority of TSOs (8% for active power and 16% for reactive power) prefer this modelling method, majority of users (~30%) prefer to model the loads as constant MVA loads.

The power system configuration looks identical to the system layout illustrated in Figure 33. In addition to the presented system layout, a more simplified modelling method was used. Loads were aggregated on the 110 kV bus for an additional reference case about differences and impact of modelling methodologies on the system voltage recovery profile from a contingency. The latter example would mean replacing the more detailed representation of the studied industrial consumer's load with the traditional modelling method, i.e. one constant MVA load at the system bus.

5.2.2.2 Complex load models

The easiest possibility to receive any adequate dynamic response from a load is to use the PSS/E standard library's model for complex loads (CLODxx). This model is ideal if no detailed data are available for exact representation of loads in the study. However, the basic information about load composition is available.

Several papers have been published either with extensive analysed data [62] or with parameter estimation [63] and [64] about different consumer groups that could be used for modelling. The complex load model includes load behaviour for large and small motors, discharge lighting and constant MVA loads, with the possibility to model distribution grid equivalents and transformer saturation parameters [65]. Based on available information together with some assumptions about load distribution according to the available parameters, the data available can be incorporated to the complex load model illustrated in Figure 36.

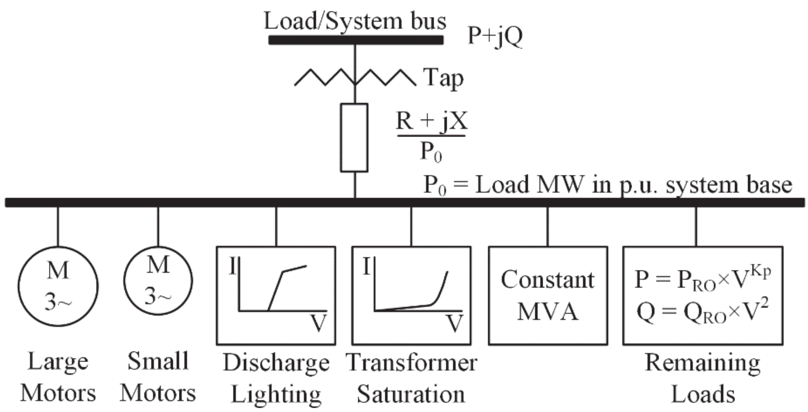


Figure 36. Description of the CLODxx load model. [56]

In the present case, the studied industrial consumer load is represented as a complex load at the 110 kV system bus, as illustrated in Figure 37. The model parameters used are described in Table 15.

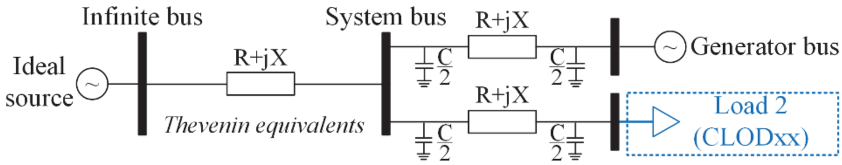


Figure 37. Industrial consumer load representation in PSS/E with CLODxx model.

Table 15. CLODxx model parameters used for the studied industry's load composition

CONs	Value	Description
J	**30**	% large motor
J+1	**47.5**	% small motor
J+2	**0.007**	% transformer exciting current
J+3	**2**	% discharge lighting
J+4	**1**	% constant power
J+5	**2**	K_P of remaining
J+6	**0.0016**	Branch R (p.u. on load MW base)
J+7	**0.0025**	Branch X (p.u. on load MW base)

5.2.2.3 Composite load models

A special load modelling taskforce at the WECC was created in 2002 in order to develop a composite load model that would represent more accurately the load responses to voltage and frequency disturbances and at the same time give more realistic behaviour during transmission system faults. Slow voltage recovery after a transmission line fault may initiate the operation of SPS or motor stalling, leading eventually to a loss of load and socio-economic loss for the society [59].

The WECC's dynamic composite load model (CMPLDW, seen in Figure 38) comprises the following types of loads [66]:

- Three-phase induction motors with constant torque (type A);
- Induction motors with high inertia and speed-dependant loads (type B);
- Induction motors with low inertia and speed-dependant loads (type C);
- Single-phase induction motors representing residential air-conditioners and heat pumps (type D);
- Loads with power electronics (computers and variable frequency drives);
- Static loads (resistive heating elements, incandescent lights, etc.).

The studied industrial consumer's load is represented as a user written WECC composite load model. The model for the specific consumer is built by using a special LMDT program created specifically for WECC to help write custom load models for PSS/E and General Electric's modelling software (PSLF) formats. In [67] several industrial consumers are pre-modelled, wherefrom the paper mill (thermo-mechanical process) industrial model (IND_PMT) was chosen to represent the current industrial consumer. Although the model does not include two levels of voltage transformers as in real life, the LMDT enables setting the far end of the distribution network voltage level to 0.4 kV, as in real life together with the minimum power factor setting that simulates the actions of the PFC devices. These simplifications are currently most close to the reality model available for this study, as no detailed information is available that would enable modelling the industry in more detail. However, this simplification should be viable due to the similarity of the processes – thermo-mechanical transformation of wood into a product. Due to the large number of variables in the model, the parameters used in the various models are listed in APPENDIX A – Parameters for CMLDBLU1 models.

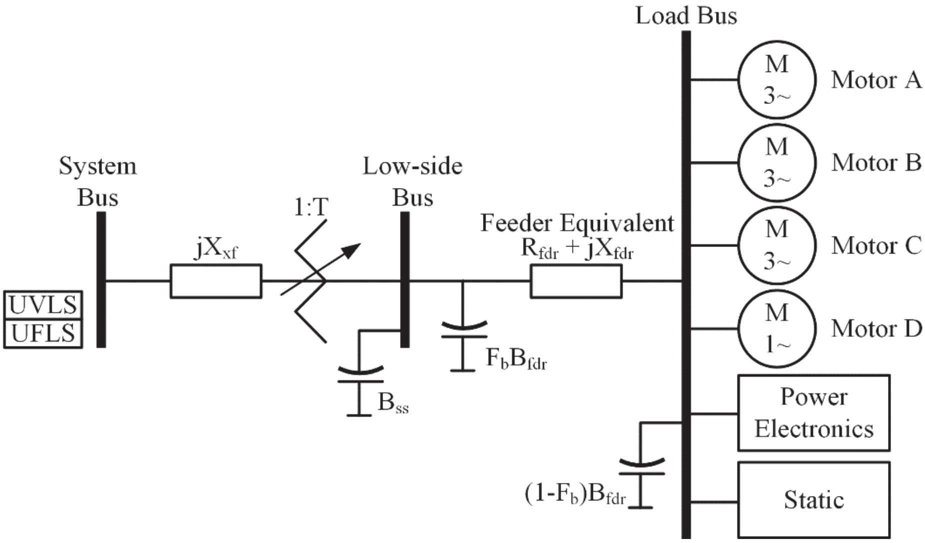


Figure 38. WECC composite dynamic load representation principle in PSS/E as CMLDxxU1 model, UVLS relay, UFLS – under frequency load shedding relay. [66]

5.2.3 Load modelling cases

Based on the models proposed for use in this study, six different cases were simulated. The chosen cases describe in a relatively wide range the impact of different load models on the transient response of different system parameters after a disturbance, i.e. active and reactive power consumption and voltage at the PCC for the consumer. The cases are as follow:

1. Aggregated load at the PCC without any load model. A transient response is expected from passing a severe voltage dip and recovering on a lower voltage level due to the change of system equilibrium.
2. Loads are aggregated at the consumer's low voltage bus bars. This model includes two levels of voltage transformation together with PFC at the 0.4 kV level and OLTC on the high voltage transformer. Effects of additional transient response are expected in voltage due to the operation of the OLTC.
3. Aggregated load at the PCC with a CLODxx load model that represents approximately the consumer distribution network equivalent circuit and load composition. A more realistic transient response from the load side is expected.
4. Aggregated load at the PCC with a WECC composite dynamic load model CMLDxxU. This model includes models of high level of detail

prepared with the LMDT. In this scenario, no parameters have been changed and the model is in its original form. The following shares of loads are tripped indefinitely by the model:

   a. Motor type A – 100% of the load is shed within 0.05 s after the voltage drops below 0.7 p.u.
   b. Motor type B – 30% of the load is shed within 0.02 s after the voltage drops below 0.7 p.u.
   c. Motor type C – 30% of the load is shed within 0.02 s after the voltage drops below 0.7 p.u.

5. The standard WECC composite dynamic load model has been modified to model restoration of some tripped loads due to consumer action (M1). Previously indefinitely tripped shares of motors type B and C are restored due to the following changes in the parameters:
   a. Reconnection voltage threshold has been lowered from 1.0 p.u. to 0.9 p.u.
   b. Reconnection delay time has been set to 40 s and 50 s, respectively, for motors type C and type B enabling the model to restore loads after the voltage has recovered to at least the level of 0.9 p.u.
6. The final scenario tries to imitate the situation when for an "unknown" reason, the UVLS fails to operate in time and attempts are made for the disconnected load to restore to the pre-fault levels due to consumer or faulty relay actions (M2). The following changes are applied to the UVLS relay:
   a. Load shedding time delays have been extended as follows:
      i. Motor type A – time delay has been changed from 0.05 s to 0.2 s;
      ii. Motor type B:
         1. 1st load shedding time delay has been changed from 0.05 s to 0.5 s;
         2. 2nd load shedding time delay has been changed from 0.02 s to 0.2 s.
      iii. Motor type C:
         1. 1st load shedding time delay has been changed from 0.05 s to 0.5 s;
         2. 2nd load shedding time delay has been changed from 0.02 s to 0.2 s.
   b. Reconnection voltage threshold has been lowered to 0.9 p.u.
   c. Reconnection delay time has been changed as follows:
      i. Motor type A – time delay has been set to 20 s;
      ii. Motor type B – time delay has been set to 5 s;
      iii. Motor type C – time delay has been set to 6 s.

The chosen time delays should adequately represent either programming errors in the UVLS relays or PLCs used for process control, or also in some cases, operator actions trying to restart the process. The modelling algorithm is composed so that the final grid situation would resemble the weakest possible situation for the study bus described in Table 14. The modelling steps are summarized on the following flowchart illustrated in Figure 39.

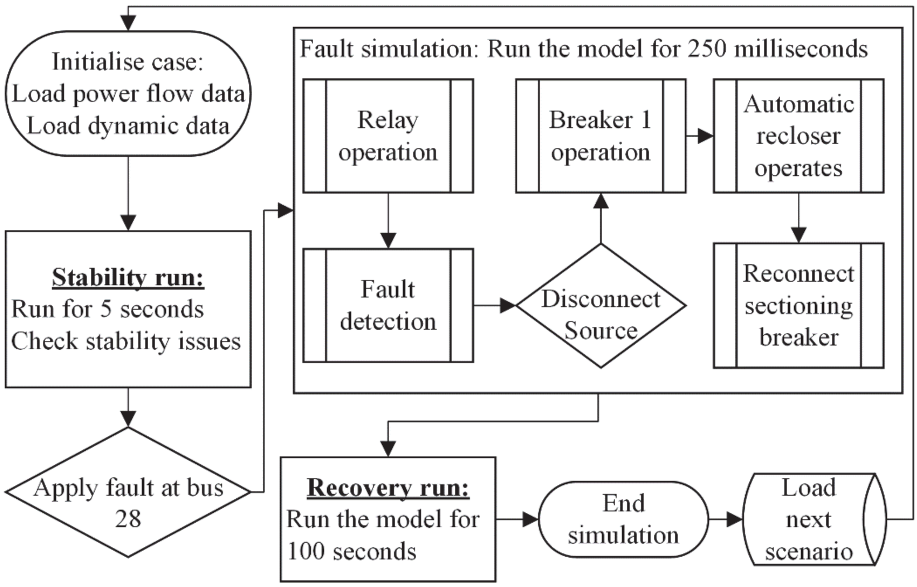


Figure 39. Modelling algorithm and changes applied to the power system.

The fault simulation duration (250 ms) is based on the requirements of the Estonian Grid Code [14], which states that all generators connected to the Estonian transmission system network have to withstand a short circuit at their PCC. This duration of 250 ms is derived from the longest possible disconnection of a short-circuited element from the grid, including fault detection, relay operation delay, circuit breaker operation, failure of circuit breaker and operation of the next substation's relay protection and circuit breakers. Usually, the fault clearance remains well below the simulated 250 ms.

The results of the simulations should give an overview of the impacts of different load models on the system behaviour after fault clearance and the possibility to incorporate DSM into reactive power reserve provision. The modelling is done with a time step of 1 ms, which is determined by the smallest time constant used in the model, and every 5th value is plotted. The reason is that the simulation is run for 100 s, making the plot file too large to process and export the data. A test was performed to validate this simplification and it was found that no viable data were lost during plotting.

5.3 Study results

The following results demonstrate a severely weakened network, meaning that the system is more than two times weaker than in normal operation conditions (see Table 19). This is one possible operation mode of the real system represented in the model. The network equivalent and short circuit power at the studied load bus 24 is summarized in Table 16.

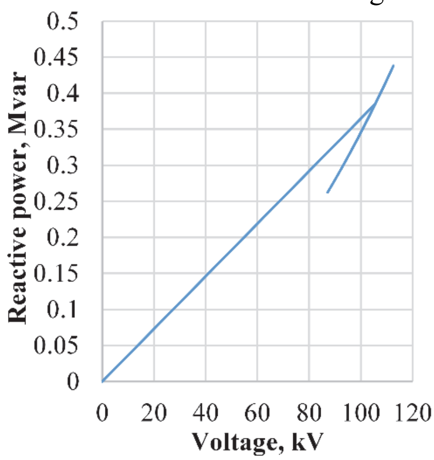
Table 16. System equivalents and short circuit power at the studied load bus after the applied fault

Substation	Faulted Bus	Short Circuit Power, MVA	Thevenin equivalents, ohms	
			R_{pos}	X_{pos}
Load bus 24	Load bus 24	196	33.3	46.1

The results obtained are presented based on the listed modelling scenarios and used models. Although there are numerous possibilities to plot different data parameters over the simulation, only three parameters (active and reactive power and voltage) are observed, plotted and analysed from the system performance and DSM point of view.

5.3.1 Aggregated load at the PCC without any load model

The post-fault system trajectory on the VQ plane is presented on the left in Figure 40, together with the transient changes in voltage on the right. The results clearly illustrate the expected response of the reactive load to the changes in voltage due to the initial model conversion process of loads, where the constant reactive power was converted into constant admittance load. Unfortunately, as PSS/E was not developed for simulating fast transients, the first "fast" transition from 0 kV and 0 Mvar to 105 kV and 0.39 Mvar that happened over a 1 ms period is a direct result of the modelling methodology in steps.



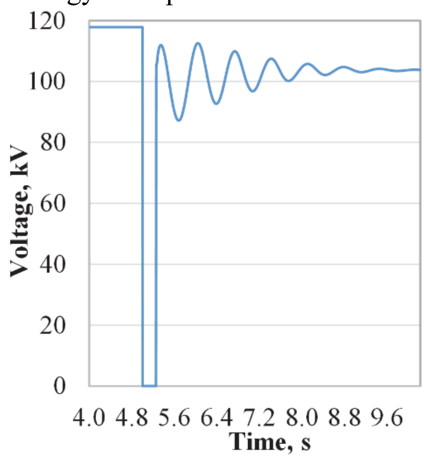


Figure 40. The post-fault trajectory of the system after fault clearance on the VQ plane (left) and voltage recovery profile before, during and after fault situation (right).

Nevertheless, the settling transient after fault clearance is almost linear like the dependency on the fluctuating voltage magnitude during the settling period that is caused by the constant admittance behaviour of the reactive load. The active power part of load (I) settles around 4.6 MW (pre-fault level was 5.2 MW) due to the lower end system voltage and constant current type load. The results of this methodology used for load modelling are rather simplistic and fail to resemble in any way the actual behaviour of induction motors during and after fault situations. Using this methodology for DSM modelling would not give us the results expected, as it overlooks the actual reactive power coupling to the voltage. The modelling methodology is suitable for simple angle stability studies where the load impact is considered insignificant. Expected voltage support for the grid cannot be determined in an adequate way.

5.3.2 Aggregated load at the consumer 0.4 kV bus

The post-fault system trajectory on the VQ plane is presented on the left in Figure 41, together with the transient changes in voltage on the right.

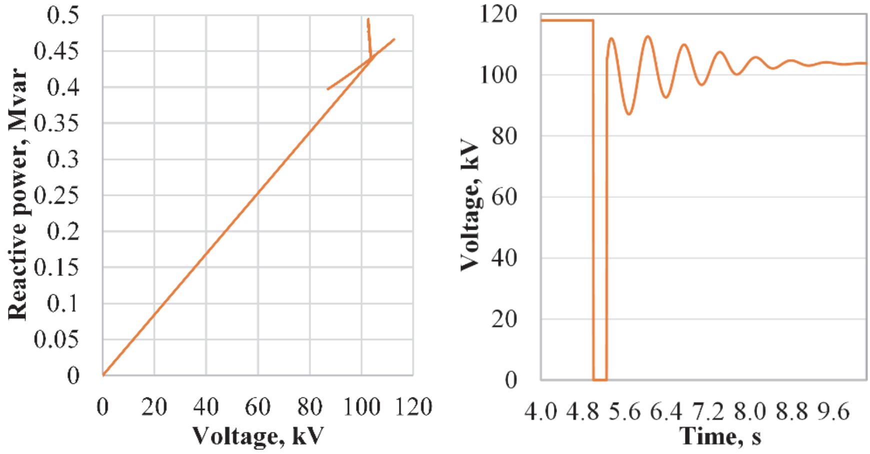


Figure 41. The post-fault trajectory of the system after fault clearance on the VQ plane (left) and voltage recovery profile before, during and after fault situation (right) with the model including OLTC.

In comparison with the previous results, both active and reactive power flow are restored to their pre-fault levels after fault clearance due to the action of the tap changer that raises the voltage at the customer end to its normal operating point (10.5 kV in the medium voltage and 0.4 kV in the low voltage). As the voltage at the customer side is restored, then for obvious reasons, no active or reactive power is lost as compared to the pre-fault levels and previous modelling methodology.

System voltage is 0.93 kV lower than in the previous modelling results, which can be explained by the difference in reactive power end-consumption that has increased from 0.37 Mvar (no model) to 0.48 Mvar (with OLTC) model. Although using this methodology for load modelling provides still rather simplistic response from the load side, it already starts to show the behaviour from the consumer side (reactive balance and its impact on the voltage), which is relevant to providing ancillary services through DSM. Load restoration to the pre-fault level can be considered a key factor to be taken into account when voltage-related issues are studied. The voltage profile is illustrated in Figure 42.

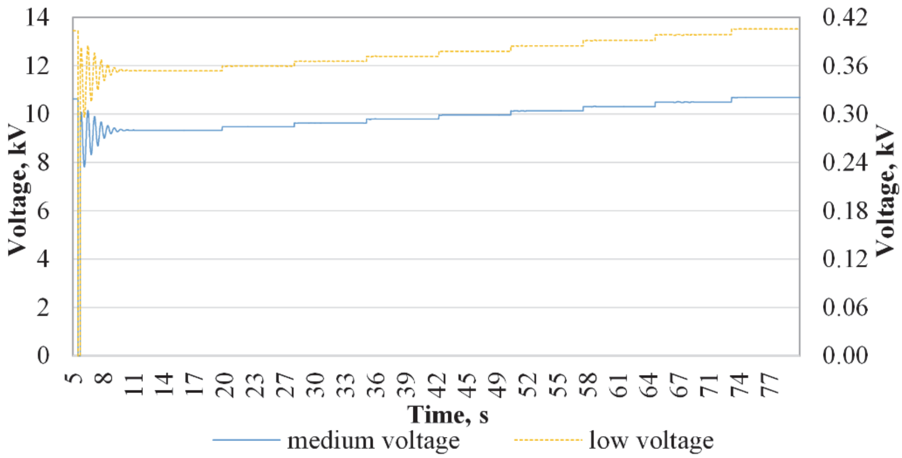


Figure 42. The voltage profile at the consumer end with OLTC modelling.

5.3.3 Complex load model CLODxx

The post-fault system trajectory on the VQ plane is presented on the left in Figure 43, together with the transient changes in the voltage on the right.

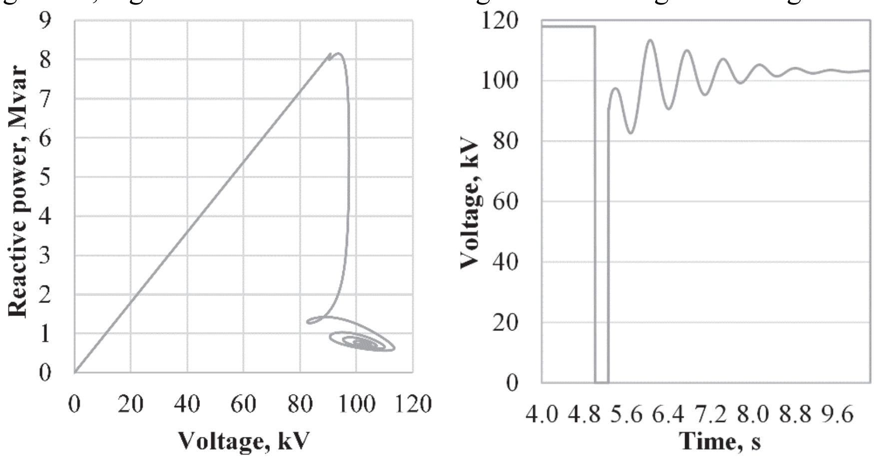


Figure 43. The post-fault trajectory of the system after fault clearance on the VQ plane (left) and voltage recovery profile before, during and after fault situation (right) with the CLODxx load model.

As the third modelling principle used is an induction motor centric, the reactive power response of the system after fault clearance resembles the situation described in the induction motor theory, i.e. motors can consume from two to seven times more reactive power after fault situations than in normal conditions. Due to the high initial reactive power consumption (~8 Mvar), the first voltage "swing" is at much lower level than in the previous models. The final voltage level settles at the lowest level (102.89 kV) in comparison with the OLTC model (104.34 kV) and with the first model (103.65 kV). This could be explained by the almost twice as high reactive power consumption level (0.73 Mvar) after fault clearance. In addition, a more complex link between voltage and reactive power changes at the end of the transient process can be observed. The latter is probably caused by the square function of the reactive power part that describes the non-motor loads.

Although the results of the model look promising in comparison to the previous two simulation cases, it only covers one aspect of the required behaviour of the load model that could be used in further analysis of the DSM possibilities. Additionally, it fails to model the OLTC response and the consequent load restoration phenomenon. With regard to the model description, it should be present. The final load level is higher than in the first (no load model) modelling scenario, but some of the load is still lost over the modelling period. As the model has no load shedding mechanism incorporated, a simplistic load shed would disconnect only the active part and reactive part of the load, without any significant impact on the system state.

5.3.4 Composite dynamic load model CMLDxxU

The post-fault system trajectory on the VQ plane for the original unchanged model is presented on the left in Figure 44, together with the transient changes in the voltage on the right.

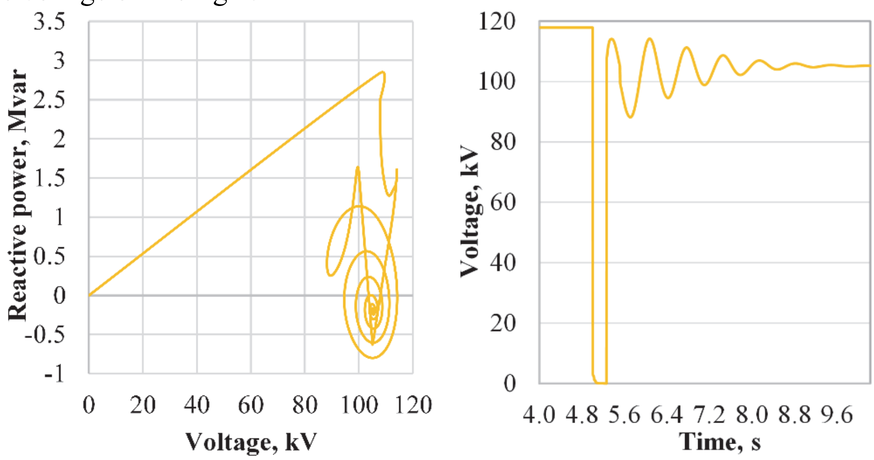


Figure 44. The post-fault trajectory of the system after fault clearance on the VQ plane (left) and voltage recovery profile before, during and after fault situation (right) with CMLDxxU load model.

As the used model remained unchanged after it was created with the LMDT, several aspects of the model need to be taken into account. OLTC was disabled as the model was created so that its low end voltage represents customer’s end voltage (0.4 kV) with PFC. In addition, 5% (Type A motors) and 24% of initial load (Type B and Type C motors) are shed 50 ms into the fault without the possibility for reclosing. 40% of the load (Type B and Type C motors) is shed during the transient recovery, however it is restored after voltage level rises above 0.75 p.u. The reactive load response is illustrated in Figure 45.

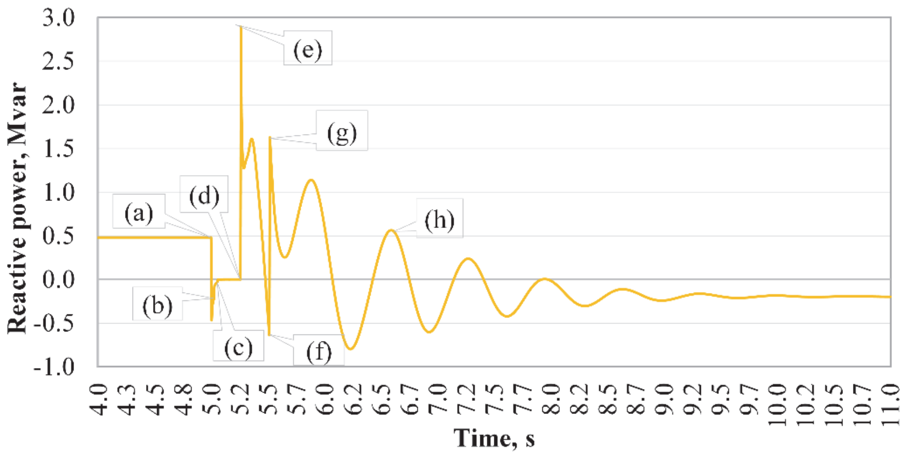


Figure 45. The studied industrial consumer's reactive load response to the applied system disturbance.

At time point (**a**), a fault is applied to the study system that creates a voltage dip with 0% residual voltage. Due to UVLS relay settings at time point (**b**), 50% of both type B and C motors are tripped, followed by an additional load shed at time point (**c**) when 100% of type A and 30% of type B and C motors are tripped. At time point (**d**), the fault is cleared from the system and the system enters into a post-fault recovery. At the first time step after fault clearance (**e**), a high reactive power draw is registered from the remaining motor load due to low voltage (0.93 p.u. at the system level). As the system voltage recovers, further the reactive power demand decreases until time point (**f**). At this point, the UVLS relay reconnects the tripped 50% of type B and C motors because the system voltage has restored to at least 0.75 p.u. for 0.25 s, which causes the voltage to a sudden decrease by 5% and consequently, increase in the reactive power demand of the motors (**g**). After the induction motor transients processes have ended, the system enters into an aperiodic transient process (**h**) that finally settles at -0.22 Mvar.

It can be speculated that the source of reactive power generation is probably the PFC device at the consumer's end, i.e. as 29% of the load has been disconnected, the bus shunts exceed the pre-fault requirements of reactive power compensation, which is now higher and thus starts flowing towards the system. In comparison with the previous models, the results clearly illustrate a more complex response from the load after fault clearance in the system. As load shedding has been incorporated into the model, an opportunity is given to study its effects on the system and the possible impacts and benefit if the controlled DSM is used to provide system services such as reactive power (voltage) support.

5.3.4.1 Modified composite dynamic load models

The post-fault system trajectory on the VQ plane for the modified models, described in more detail in section 5.3.4 that includes higher load restoration levels with delayed load shedding is presented in Figure 46.

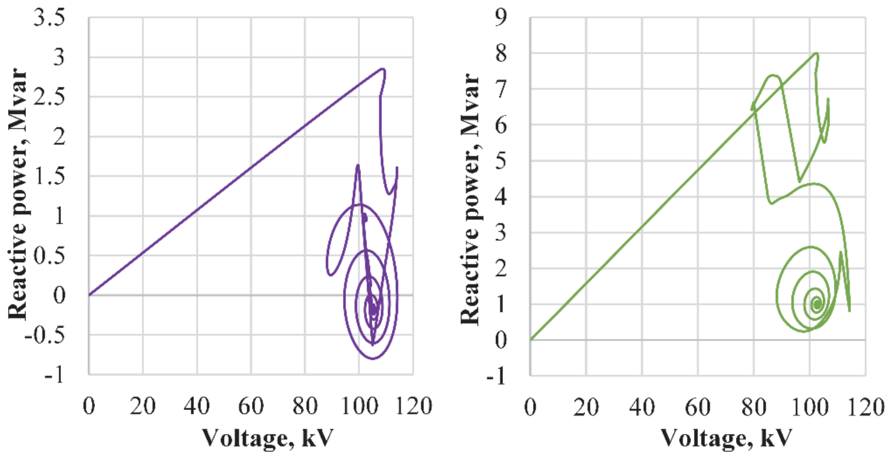


Figure 46. The post-fault trajectory of the system after fault clearance with modified CMLDxxU models. Load reconnection modelled on the left together with "faulty" relay settings on the right.

The left image illustrates the model (M1) where the initially indefinitely tripped 24% of load (30% of type B and C motors) is reconnected respectively 40 s and 50 s after the voltage has restored to at least 0.9 p.u., see section 5.2.3. The simulated situation aims to imitate the consumer's action of restarting manually some tripped loads. The right-hand image describes the model (M2) that in addition to the load reconnection combines also "faulty" relay settings where the load trip is delayed. Although the model M2 parameters allow reclosing the lost share of type A motors, then as the voltage settled below the set parameter (0.9 p.u.), the load was not restored. Both simulations end around 102.63 kV and 0.95 Mvar reactive power consumption. The higher reactive power demand in comparison to the initial situation is caused by the lower voltage, which in return increases the reactive power demand, see Figure 47.

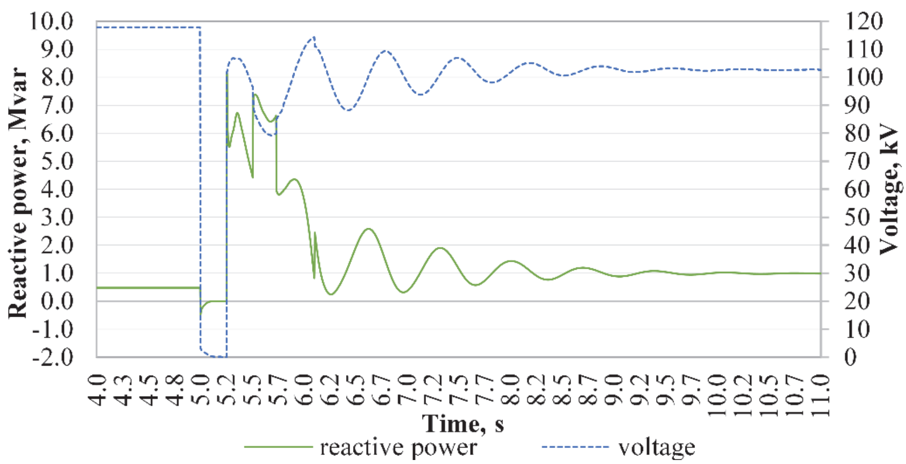


Figure 47. Industrial consumer's modified load model (M2) voltage and reactive power response to the applied system disturbance.

Due to the delayed tripping of induction motors in model M2, the initial reactive power demand after fault clearance jumps to almost 8 Mvar, which is similar to the initial behaviour of the CLODxx model. In addition to the extremely high instantaneous reactive power demand, the delay in motor tripping together with fast restarting of the motors creates a dangerous situation during which the system voltage drops below 80 kV (0.7 p.u.). The low voltages cause type B and C motors to trip twice during the recovery process. In similar situations, the SPS of the power system would probably have disconnected the loads in buses where UVLS is configured. An example of settings for UVLS is summarized in Table 17.

Table 17. SPS settings for UVLS in the studied region

Bus	U/V trip, kV	U/V trip delay, seconds	U/V trip reclose, seconds
Load bus 28	**102**	4.9	N/A
Load bus 19	**98**	5	5

As seen from the table below (Table 18) only two of the models used are suitable for DSM modelling. However, the used CLODxx model is applicable only in principle, as it disconnects the whole load from the system, whereas the more complex CMLDxxU model gives the user the possibility to control the volume and the part of the load to be used specifically for DSM. Therefore, in further DSM evaluation, the CMLDxxU model is used from the perspective of possible reactive power reserve provision. The comparison of the models and their suitability for DSM modelling from the perspective of reactive power support are summarized in Table 18.

Table 18. Comparison and evaluation of performance for different models used

	Voltage, kV*	Reactive power, Mvar*	Active power, MW*	Load shed?	DSM?
No model	103.65	0.37	4.58	No	**No**
OLTC	102.72	0.48	5.24	No	**No**
CLODxx	102.89	0.73	4.96	No	**Plausible**
CMLDxxU	105.13	-0.22	3.74	Yes	**Yes**
(M1)	102.63	0.96	5.02		
(M2)	102.63	0.96	5.02		

*Initial values: U = 117.89 kV, Q = 0.48 Mvar, P = 5.21 MW

5.4 Using DSM to provide voltage control

The used CMLDxxU model was modified in order to imitate a DSM action. For this, a two-stage load shedding relay was modified so that the initial load shed of motors type B and C during voltage dip is higher and the second stage of the relay is used to imitate the action of the controlled load shed. In addition to the initially shed 100% share of type A motors, due to the action of DSM, 100% of the type B and C is shed 30 s after the fault. The post-fault system trajectory on the VQ plane for the DSM model is compared to the standard behaviour of the model in Figure 48.

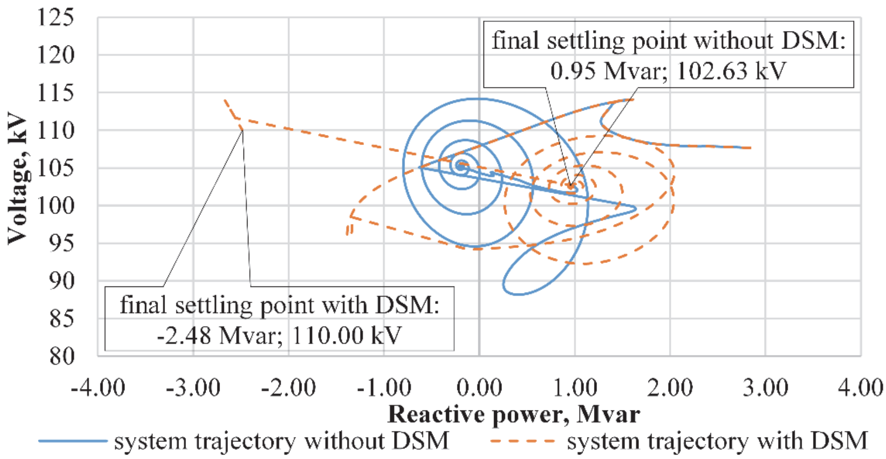


Figure 48. The post-fault trajectory of the system after fault clearance on the VQ plane with and without DSM.

As seen from the figure, due to DSM, the system settling point moves from a lower voltage level (0.89 p.u.) to almost normal operational condition (0.96 p.u.). The reactive power balance at the PCC has shifted to the grid direction, with almost 2.5 Mvar being produced by the consumer. These numbers correspond to the load profile and theoretical capabilities of the real consumers. At the same time, the results originate from the weakest grid configuration possible (parameters provided in Table 16). In order to adequately assess the DSM effect, three additional simulations were carried out:

1. Simulation was carried out in a stronger grid situation, i.e. instead of the sectioning breaker at load bus 22, the breaker at bus 19 was used, this in return, changed the short-circuit power of the system and made the grid a little stronger. Exact system parameters are provided in Table 19 and results illustrated in Figure 49.
2. The studied industrial load was increased by 100%, which corresponds to the consumer's perspective load after expansion of the production facility. The results are illustrated in Figure 49.
3. In order to simulate the possibility to provide simple voltage control, one additional simulation was run with transition from a strong grid to a weak configuration without any faults, e.g. during system maintenance when some of the circuits are switched off for regular maintenance. DSM is implemented within 30 s to provide voltage control service for the TSO. System voltage and load reactive power demand change during simple voltage control is illustrated in Figure 50.

Table 19. System equivalents and short circuit power during stronger grid configuration

Substation	Faulted Bus	Short Circuit Power, MVA	Thevenin equivalents, ohms	
			R_{pos}	X_{pos}
Load bus 24	Load bus 24	515	11.5	21.5

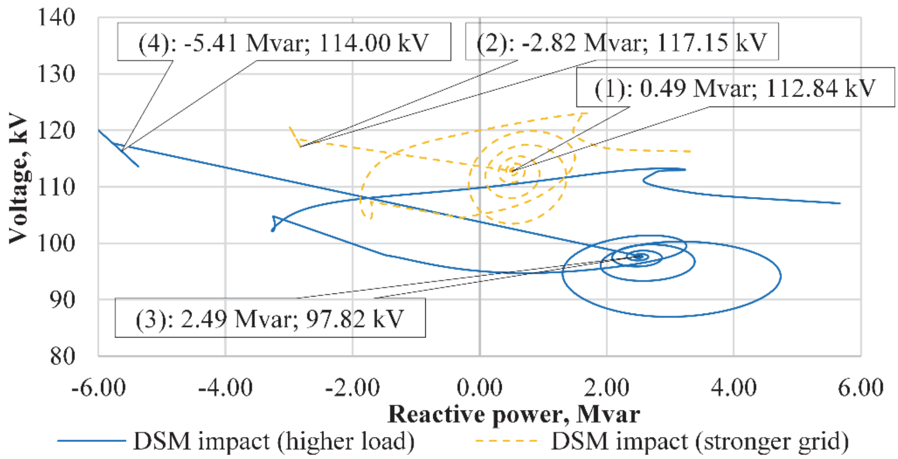


Figure 49. The post-fault trajectory of the system after fault clearance on the VQ plane with higher loads or a stronger grid. Points (1) and (3) represent the settling point without DSM, points (2) and (4) the new settling point after DSM actions.

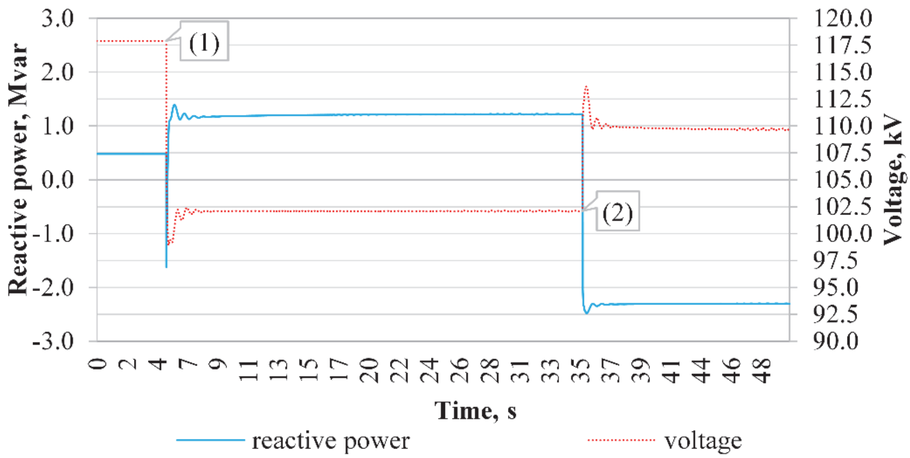


Figure 50. System voltage and load reactive power demand change with DSM applied for voltage control. (1) – change in system state, (2) – DSM action for additional voltage support.

As seen from the figures above, all different system conditions simulated prove to have an impact on the PCC bus voltage. Even without simulated faults or during stronger grid connections, the post-DSM system voltage is increased by the load control actions. Figure 50 illustrates the possibility to use loads for temporary voltage support. In point **(1)** the system goes into a weakened state, e.g. temporary maintenance configuration, and at time point **(2)** DSM is activated to provide voltage support. The end results from DSM actions during different simulation scenarios are compared and summarized in Table 20.

As seen from the table, the highest impact on the system voltage is achieved with higher load values. If we compare the results, lost-load levels together with reactive power support levels between the DSM in weak and strong grid situation with DSM initiated for voltage control, we can see that they remain in the same range for all three cases. Difference comes out only in the actual voltage support level. In stronger grid situations, the impact on the voltage is smaller, yet still noticeable, as the residual voltage is already higher after disturbance clearance.

Table 20. Comparison and summary of the impact of DSM actions on the power system voltage and reactive power flow at the PCC

		DSM (weak grid)	**DSM (strong grid)**	**DSM (double load)**	**DSM (voltage control)**
Before fault	U, kV	117.9	117.9	117.2	117.9
	P, MW	5.210	5.210	10.420	5.210
	Q, Mvar	0.480	0.480	0.960	0.480
After fault	U, kV	102.6	112.8	97.8	102.1
	P, MW	5.020	5.010	10.120	5.290
	Q, Mvar	0.960	0.490	2.490	1.220
After DSM	U, kV	110.0	117.2	114.0	109.7
	P, MW	0.779	0.779	1.570	1.040
	Q, Mvar	-2.480	-2.820	-5.410	-2.300
Impact	U, kV	**7.370**	**4.320**	**16.18**	**7.600**
	P, MW	**-4.241**	**-4.231**	**-8.550**	**-4.250**
	Q, Mvar	**-3.440**	**-3.310**	**-7.900**	**-3.520**

To demonstrate the alternatives to reactive power reserves from DSM, the following two alternatives and their concurring costs were compared. The modelled results of the impact of DSM on the system voltage could be measured and compared with those of a capacitor bank (5 Mvar) that would have an initial investment cost of approximately 150 000 euros (including one substation bay). Another alternative would be to install an additional transformer (330/110 kV) at the load bus 28 that would make the connection to the main 330 kV grid stronger and eliminate the need to operate in the simulated network configuration. Total concurring costs of installing an additional transformer can reach up to 3 500 000 euros (including substation bays and other related devices). However, if the investments are needed irrespective of the existing situation, e.g. due to the development plans of the region, the problem would be solved. At the same time, if the actual situation in the region does not favour large investments and voltage control is required only occasionally, then the solution from DSM would be more competitive even with the concurring high operational costs in comparison to traditional methods (see for reference Table 9 and Table 11).

6. Conclusion and future work

This thesis has presented a discussion on DSR and DSM potential in Estonia together with the existing limitations and barriers. Together with the author's contribution in the study [3] and the follow-up report of [68], Estonia has gained valuable information and insight to its DSR potential both for consumers and for the system operators. Although there is today a lack of understanding from the consumers, majority of them are willing to implement DSR if it possesses a business case for them. And even if DSR is not interesting for the system operators, there are direct economic benefits for the consumer through price based load control and optimization. In addition, even if DSR is implemented only for the benefit of customers, it inevitably has also a relieving impact on the power system. This is achieved through the price signal that is used to trigger load control and at the same time also gives a direct indication about the state of the system.

As more dispersed and weather-influenced generation replaces large centralized units the requirements for rapid dynamic reserves that can compensate the concurring fluctuations between demand and supply increases. With old generation units used today for reserves being decommissioned, there is a gap of reserves to be replaced. These unused reserves are integrated into the power system as different types of flexible and controllable loads that could be integrated into the ancillary service markets. The thesis has presented a historical overview about the Estonian ancillary services, indicating that 85% of the balancing services and more than 60% of the system services are ordered by capacities below 60 MW and 40 MW, respectively. These capacities are relatively small and could be acquired easily through aggregation. In addition, the analysed samples of loads could possibly provide a high durational range and variety of services for the TSO.

The thesis provides a comprehensive discussion about the methodology how to determine DSR potential for three main economic sectors that constitute up to 60% of the total electricity consumption in Estonia. The industry, public and commercial sectors are determined to be the most promising and prompt resource of DSR and DSM from the power system point of view. Although households incorporate possibly even substantial potential for DSR and DSM services, then they were determined to be rather small unit consumers that would require a larger aggregation level to provide services under investigation for the system operators. In addition, household electricity consumption and the willingness to allocate loads for DSR are influenced more by comfort and values rather than technical and economic feasibility.

The DSM potential from the commercial and public services sector (shopping centres and office buildings) have been determined to remain between 93 MW to 112 MW, depending on whether cold storage is implemented or not. From the determined potential 93 MW can be provided steadily throughout the year mainly through temperature control of HVAC devices. The most promising source of DSM in Estonia is seen in the industrial sector due to its energy intensity and relatively large units of loads that can be allocated for aggregated control relatively easily. The industry's production line is usually segmented, allowing more flexibility for control and less inconvenience for the consumer. In addition, as the industry incorporates a relatively high level of automation, meaning that the allocating parts of its production lines for aggregation and integration into market platforms could be arranged with at relatively low costs. Also, the internal power system of the studied industrial consumer includes necessary prerequisites for variable DSM services through load control. These include:

- intermediate bulk material storages that could be used as an energy storage for load shifting, without loss of productivity;
- the necessary types of loads that have significant impact on the power system reactive power balance, i.e. large share of induction motors and reactive power compensation devices suitable for voltage support services;
- high level of automation and ICT systems to control the loads and PFC devices remotely or automatically to provide different DSM related services for the grid.

It is estimated that the DSR potential from the whole Estonian industry can be around 65 MW, whereas approximately 1/3 originates from the wood and paper industry. Small changes and upgrades to the control system would enable the smart control of these loads for the different ancillary services. The necessary changes to the control system both in investment and operational costs can be considered relatively competitive with the possible alternatives.

The analysis indicates that if DSR could be implemented for providing system services, the potential of DSM would be in the range of 160 MW to 180 MW. The analysis determined that the average price for emergency, ancillary and balancing reserves in Estonia has stayed in the recent years between 50 euros to 80 euros per MWh and it occurs around 2 200 times (h) per year. In the assumption that on average up to 150 MW of DSR capacities could be provided for the region's ancillary services markets at least 1 h to 3 h per day, then the Estonian DSM market value would be up to 13 million euros.

In addition to mapping the Estonian DSM potential, the thesis also proposes a novel approach to provide voltage support for the power system through DSM. Using DSM as a source of reactive power reserve has been analysed through network modelling with power system simulation software PSS/E. The modelling has been carried out with an actual part of a real network together with real information about loads and their profiles. In addition, different load modelling principles and models have been compared to determine the best practice for DSM modelling in power system studies. The results obtained with the WECC composite dynamic load model have proven to be most suitable model for DSM related simulations, as it already incorporates the possibility to shed certain types and shares of loads within the simulation.

The results of this research clearly illustrates that DSM could be a viable source of reactive power (reserve) during different disturbances and conditions in the grid. Although the best performance for voltage support was achieved during weak configurations of the grid, the results also indicate that smart load control could be successfully used also for voltage control services during normal operations. The research also determined that special load models have a more significant impact on the post-fault system settling trajectory and voltage levels than the constant current and constant admittance load modelling methodology provides. Therefore, system operators should incorporate more detailed load models at least in the studies of voltage stability and reactive power to receive realistic responses also from the load side. The methodologies proposed in this thesis can be easily implemented for similar research in other countries and systems, where the DSM potential is unmapped or DSM modelling is required.

Although the results of the modelling look promising and the theory behind is supportive, the author still wishes to stress that several assumptions and simplifications were used, i.e. only one load bus was studied with a composite load model and the results of the model used have not yet been validated in an actual system. As the relevance of the topic of additional ancillary services or controllable loads is growing due to the increase of distributed generation and heavier strains on the power system operation modes, the potential to use DSM in the everyday operation and maintenance of the electricity network could be a large source of untapped resources. Therefore, the author feels with strong confidence that possibilities and topics for further studies to ancillary services through DSM need to be addressed. For future research author sees four possibilities:

- Aggregation of loads and their applicability for different services;
- Legislative barriers removal to provide DSR freely for ancillary services;
- Determination of the possibility to use the customers PFC devices for the power system benefit;
- Develop load models that could be easily incorporated to the (Estonian) power system model.

Although there are some technical limitations for DSM implementation, the analysis of the Estonian power system regulation services indicated that electricity consumers can be incorporated to the system service provision already today. The only problem is that currently it is more convenient and financially cheaper to order services from generating units. This is due to the lack of aggregation services that would collect the necessary loads to a single portfolio and supply them to the necessary party. As the analysed samples of loads could possibly provide a high durational range of services for the system operators, a research subject to be addressed is an aggregation model or service that could be implemented into the existing balancing market in Estonia. The research topic proposed in this field should determine the existing legislative barriers and propose solutions to remove them. In addition, a reasonable incentive mechanism should be developed to favour incorporating loads into these service provision.

From the technical aspects, it seems questionable whether the PFC capacitors located at the 0.4 kV system could be used for the proposed service, as their primary function is completely different from the proposed usage. Although in the presented case study, the PFC devices are relatively close to the transmission system that may not be the case for other types of consumers in different regions. Nevertheless, the modelling has shown that the proposed approach is viable, as reactive power resource is a resource irrespective of its location and no technical barriers from the control point of view are present. Therefore, the author proposes to investigate further the potential problem of electrical distance of low voltage PFC devices from the main system and possible problems induced by the high voltage at the 0.4 kV bus bars that could harm sensitive electronics.

The author acknowledges that the used models could be too simplified from the studied industry perspective. However, it should be also stressed that the idea was not to develop a specific model but rather to prove if the existing load modelling principles are suitable for DSM modelling. Therefore, the author proposes a future research topic to develop a methodology for creating specific consumer based models for the Estonian electricity system by using the CMLDxxU models in PSS/E.

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Abstract

Demand Side Management Possibilities and Viability for Voltage Support Services in Estonia

According to the European Union's Energy Efficiency Directive, all member states are obliged to support access of DSR services providers to the electricity and ancillary service markets, but the actual situation is that the ancillary service regulations that would allow DSR service provision have not changed since they were developed for generators. At the same time, the need for emergency reserves and balancing services is increasing together with the increasing integration of dispersed and weather-influenced generation and decommissioning of large existing power plants used to support these services until now. The main objective of this doctoral thesis is to map the potential of DSR in different economic sectors in Estonia and determine the possibility of using these loads to cover the increasing need for system ancillary services.

This thesis presents a historical overview about the Estonian ancillary services, indicating that 85% of the balancing services and more than 60% of the system services are ordered by capacities below 60 MW and 40 MW, respectively. These capacities are relatively small and could be acquired easily through load aggregation. The analysed samples of loads could possibly provide a high durational range and variety of services for the system operators.

A comprehensive discussion is provided about the methodology how to determine DSR potential for three main economic sectors that constitute up to 60% of the total electricity consumption in Estonia. The key factor that determines the large-scale implementation of DSR is the availability of energy storages in any from (e.g. heat, cold, intermediate bulk material storage, etc.). The DSM potential from the commercial and public services sector is estimated to remain between 93 MW to 112 MW, depending on whether cold storage is implemented or not. The DSM potential from the Estonian industry can remain around 65 MW, whereas approximately 1/3 originates from the wood and paper industry.

The thesis proposes a novel approach to provide voltage support for the power system through DSM. The proposed approach is based on the induction motor's increased reactive power demand phenomenon during low voltage situations. Together with the installed PFC devices the reactive power demand of induction motor dominant loads before and post contingency can increase two to three times. In weaker parts of the grid such high reactive power demand change can lead to extremely low voltages or in worst case UVLS relay operation. With DSM

The proposed approach has been validated through network modelling with power system simulation software PSS/E on model representing an actual part of the Estonian power system. The research determines that special load models have a more significant impact on the post-fault system settling trajectory and voltage levels than the constant current and constant admittance load modelling methodology provides. Therefore, system operators should incorporate more detailed load models for voltage stability and reactive power related studies.

Kokkuvõte

Tarbimise juhtimise võimaluste uurimine ning selle rakendatavus pinge reguleerimise teenusteks

Vastavalt Euroopa Liidu energiasäästu direktiivile, on kõik liikmesriigid kohustatud toetama tarbimise juhtimisega seonduvate teenuste integreerimist elektriturgudele. Tegelikult pole süsteemi- ja bilansiteenuste regulatsioonid, mis võimaldaksid tarbimise juhtimise integreerimist turgudele, suures jaos muutunud sellest ajast peale, kui need töötati välja tootmisseadmetel. Seejuures kasvab elektrisüsteemides nõudlus bilansi- ja süsteemiteenuste järgi, kuna üha rohkem liitub elektrivõrkudega taastuvenergial põhinevaid hajuselektrijaamu ning paralleelselt suletakse ka vanasid jaamasid, mida kasutatakse just süsteemiteenuste pakkumiseks. Käesoleva doktoritöö eesmärgiks on kaardistada tarbimise juhtimise potentsiaal Eesti energiamahukates majandusharudes ning selle rakendatavus bilansi- ja süsteemiteenuste pakkumiseks.

Töös analüüsitud ajalooliste bilansi- ja süsteemiteenuste andmete kohaselt jäävad ligi 85% tellitud bilansi- ja 60% süsteemiteenustest alla 60. MW. Sellised koormused on suhteliselt väikesed ning peaksid olema saavutatavad ka koormuste agregeerimise teel. Seejuures on töö käigus tuvastatud koormustüübid võimelised pakkuma bilansi- ja süsteemiteenusteks väga laia võimsuste vahemikke aga ka teenuse kestusi.

Töös käsitletakse põhjalikult metoodikat, mida kasutati tarbimise juhtimise potentsiaali kaardistamiseks. Põhifaktor, mis määrab tulevikus tarbimise juhtimise laialdase kasutuselevõtu, on mistahes energiasalvesti olemasuolu tarbija paigaldises. Selleks võib olla nii reaalne energiasalvesti kui ka tahke materjali (toorme) vaheladu tööstuses. Analüüsi tulemusena selgus, et Eesti tarbimise juhtimise potentsiaal äri- ja avaliku teenuse sektoris on 93-112 MW, sõltuvalt energiasalvestite olemasolust. Tarbimise juhtimise potentsiaal Eesti tööstuses võib jääda 65 MW juurde, millest ligi 1/3 annab puidu- ja paberitööstus.

Doktoritöö pakub uudse lahendusena välja ka võimaluse pakkuda tarbimise juhtimise kaudu pinge reguleerimise teenust. Lahendus põhineb asünkroonmootorite suurenenud reaktiivenergia tarbimise nähtusel madalatel pingenivoodel. Koos reaktiivenergia kompenseerimisega võib suure mootorite osakaaluga tarbija reaktiivenergia nõudlus kasvada võrguavariide korral kaks kuni kolm korda. Nõrkades elektrisüsteemi osades võib selline hetkeline reaktiivvõimsuse muutus viia eriti madalate pingeteni või koormuste välja lülitumiseni. Tarbimise juhtimisega lülitataks välja ainult kriitilised koormused (näiteks asünkroonmootorid), mille tulemusena pakutaks süsteemile pingetuge.

Pinge reguleerimise teenuse lahendus on valideeritud modelleerimistarkvaraga PSS/E, milles kasutati vähendatud Eesti elektrisüsteemi mudelit. Modelleerimistulemustest selgus, et koormusmudelitel on oluline roll süsteemi avariijärgsete siirdeprotsesside kujutamisel. Sellest lähtuvalt on doktoritöö üheks soovituseks võrguettevõtjatele kasutada kindlasti pinge- ja reaktiivenergiaga seotud analüüsideks võimalikult täpseid koormusmudeleid.

Curriculum Vitae

1.Personal data

Name: Imre Drovtar
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2.Education

Educational institution	Graduation year	Education (field of study/degree)
Tallinna Pääsküla gümnaasium	2006	Secondary education
Tallinn University of Technology	2009	Bachelor of Science in Engineering
Tallinn University of Technology	2011	Master of Science in Engineering

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

Language	Level
Hungarian	Fluent
Estonian	Fluent
English	Fluent
Russian	Average
German	Basic skills

4. Special courses

Period	Educational or other organisation
2009 winter semester	Fachhochschule (University of Applied Sciences) Stralsund, Germany

5. Professional employment

Period	Organization	Position
2010-2015	AS Elering	Power System Analyst
2015-…	AS Graanul Invest	Specialist of Power Engineering

6.Research activity, including honours and theses supervised

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2.Hariduskäik

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Tallinna Pääsküla gümnaasium	2006	Keskharidus
Tallinna Tehnikaülikool	2009	Tehnikateaduse bakalaureus
Tallinna Tehnikaülikool	2011	Tehnikateaduse magister

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

Keel	Tase
Ungari keel	Kõrgtase
Eesti keel	Kõrgtase
Inglise keel	Kõrgtase
Vene keel	Kesktase
Saksa keel	Algtase

4. Täiendusõpe

Õppimise aeg	Täiendusõppe korraldaja nimetus
2009 kevadsemester	Fachhochschule (University of Applied Sciences) Stralsund, Saksamaa

5. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2010-2015	AS Elering	Elektrisüsteemi analüütik
2015-…	AS Graanul Invest	Elektripaigaldise spetsialist

6. Teadustegevus, sh tunnustused ja juhendatud lõputööd

Juhendatud lõputööd

Kristina Kiivramees, magistrikraad, 2012, (juh) Imre Drovtar, Electricity Consumption Analysis of Two Office Buildings and the Possibilities to Integrate Renewable Energy Sources for Energy Efficiency Improvement (Kahe ärihoone elektritarbimise analüüs ja võimalused kasutada taastuvenergiaallikaid energiatõhususe eesmärgil), Tallinna Tehnikaülikool, energeetikateaduskond, elektriajamite ja jõuelektroonika instituut, elektriajamite ja elektrivarustuse õppetool.

APPENDIX A – Parameters for CMLDBLU1 models

Appendix A. 1. CMLDBLU1 model parameters used during simulations

Model (M1)	Model (M2)	Model (DSM)	Original value	Description
-1	-1	-1	-1	Load MVA base
0	0	0	0	Substation shunt b (p.u. of MVA base)
0	0	0	0	R_{fdr} - Feeder R (p.u. of Load MVA base)
0.01	0.01	0.01	0.01	X_{fdr} - Feeder X (p.u. of Load MVA base)
1	1	1	1	F_b - Fraction of Feeder Compensation at substation end
0.08	0.08	0.08	0.08	X_{xf} - Transformer Reactance – p.u. of load MVA base
1	1	1	1	T_{fixhs} - High side fixed transformer tap
1	1	1	1	T_{fixls} - Low side fixed transformer tap
0	0	0	0	OLTC - OLTC flag (1=active, 0=inactive)
0.9	0.9	0.9	0.9	T_{min} - OLTC min tap (on low side)
1.1	1.1	1.1	1.1	T_{max} - OLTC max tap (on low side)
0.0063	0.0063	0.0063	0.0063	Step - OLTC T_{step} (on low side)
1.025	1.025	1.025	1.025	V_{min} - OLTC V_{min} tap (low side p.u.)
1.04	1.04	1.04	1.04	V_{max} - OLTC V_{max} tap (low side p.u.)
0	0	0	0	T_D - OLTC Control time delay (s)
0	0	0	0	TC - OLTC Tap adjustment time delay (s)
0	0	0	0	R_{cmp} - LTC R_{comp} (p.u. of load MVA base)
0	0	0	0	X_{cmp} - LTC X_{comp} (p.u. of load MVA base)
0.05	0.05	0.05	0.05	F_{mA} - Motor A Fraction
0.55	0.55	0.55	0.55	F_{mB} - Motor B Fraction
0.25	0.25	0.25	0.25	F_{mC} - Motor C Fraction
0	0	0	0	F_{mD} - Motor D Fraction
0.12	0.12	0.12	0.12	F_{el} - Electronic Device Fraction
1	1	1	1	PF_{el} - PF of Electronic Load
0.72	0.72	0.72	0.72	V_{d1} - Voltage at which electronic loads start to drop
0.52	0.52	0.52	0.52	V_{d2} - Voltage at which all electronic loads have dropped
1	1	1	1	PF_s - Static Load Power Factor
2	2	2	2	P_{1e} - P_1 exponent
0	0	0	0	P_{1c} - P_1 coefficient
1	1	1	1	P_{2e} - P_2 exponent
1	1	1	1	P_{2c} - P_2 coefficient
0	0	0	0	P_{frq} - Frequency sensitivity
2	2	2	2	Q_{1e} - Q_1 exponent
1	1	1	1	Q_{1c} - Q_1 coefficient
1	1	1	1	Q_{2e} - Q_2 exponent
0	0	0	0	Q_{2c} - Q_2 coefficient
-1	-1	-1	-1	Q_{frq} - Frequency sensitivity

Model (M1)	Model (M2)	Model (DSM)	Original value	Description
3	3	3	3	M_{typA} - Motor type
0.85	0.85	0.85	0.85	LF_{mA} - Loading factor (MW/MVA rating)
0.01	0.01	0.01	0.01	R_{aA} - Stator resistance
3.1	3.1	3.1	3.1	L_{sA} - Synchronous reactance
0.2	0.2	0.2	0.2	L_{pA} - Transient reactance
0.165	0.165	0.165	0.165	L_{ppA} - Sub-transient reactance
0.8	0.8	0.8	0.8	T_{poA} - Transient open circuit time constant
0.0026	0.0026	0.0026	0.0026	T_{ppoA} - Sub-transient open circuit time constant
0.15	0.15	0.15	0.15	H_A - Inertia constant
0	0	0	0	$etrq_A$ - Torque speed exponent
0.7	0.7	0.7	0.7	V_{tr1A} - U/V $trip_1$ V (p.u.)
0.25	0.05	0.05	0.05	T_{tr1A} - U/V $trip_1$ time (s)
1	1	1	1	F_{tr1A} - U/V $trip_1$ fraction
0.9	1	1	1	V_{rc1A} - U/V $trip_1$ reclose V (p.u.)
20	9999	9999	9999	T_{rc1A} - U/V $trip_1$ reclose time (s)
0.6	0.6	0.6	0.6	V_{tr2A} - U/V $trip_2$ V (p.u.)
0.02	0.02	0.02	0.02	T_{tr2A} - U/V $trip_2$ time (s)
0	0	0	0	F_{tr2A} - U/V trip2 fraction
1	1	1	1	V_{rc2A} - U/V trip2 reclose V (p.u.)
99999	99999	99999	99999	T_{rc2A} - U/V $trip_2$ reclose time (s)
3	3	3	3	M_{typB} - Motor type
0.85	0.85	0.85	0.85	LF_{mB} - Loading factor (MW/MVA rating)
0.01	0.01	0.01	0.01	R_{aB} - Stator resistance
3.1	3.1	3.1	3.1	L_{sB} - Synchronous reactance
0.2	0.2	0.2	0.2	L_{pB} - Transient reactance
0.165	0.165	0.165	0.165	L_{ppB} - Sub-transient reactance
0.8	0.8	0.8	0.8	T_{poB} - Transient open circuit time constant
0.0026	0.0026	0.0026	0.0026	T_{ppoB} - Sub-transient open circuit time constant
1	1	1	1	H_B - Inertia constant
2	2	2	2	$etrq_B$ - Torque speed exponent
0.7	0.7	0.6	0.7	V_{tr1B} - U/V $trip_1$ V (p.u.)
0.5	0.05	0.02	0.05	T_{tr1B} - U/V $trip_1$ time (s)
0.3	0.3	0.8	0.3	F_{tr1B} - U/V $trip_1$ fraction
0.9	0.9	0.75	1	V_{rc1B} - U/V $trip_1$ reclose V (p.u.)
5	50	0.5	9999	T_{rc1B} - U/V $trip_1$ reclose time (s)
0.6	0.6	0.9	0.6	V_{tr2B} - U/V $trip_2$ V (p.u.)
0.2	0.02	30	0.02	T_{tr2B} - U/V $trip_2$ time (s)
0.5	0.5	1	0.5	F_{tr2B} - U/V $trip_2$ fraction
0.75	0.75	1	0.75	V_{rc2B} - U/V $trip_2$ reclose V (p.u.)
0.25	0.25	9999	0.25	T_{rc2B} - U/V $trip_2$ reclose time (s)
3	3	3	3	M_{typC} - Motor type
0.85	0.85	0.85	0.85	LF_{mC} - Loading factor (MW/MVA rating)

Model (M1)	Model (M2)	Model (DSM)	Original value	Description
0.01	0.01	0.01	0.01	R_{aC} - Stator resistance
3.1	3.1	3.1	3.1	L_{sC} - Synchronous reactance
0.2	0.2	0.2	0.2	L_{pC} - Transient reactance
0.165	0.165	0.165	0.165	L_{ppC} - Sub-transient reactance
0.8	0.8	0.8	0.8	T_{poC} - Transient open circuit time constant
0.0026	0.0026	0.0026	0.0026	T_{ppoC} - Sub-transient open circuit time constant
0.2	0.2	0.2	0.2	H_C - Inertia constant
2	2	2	2	$etrq_C$ - Torque speed exponent
0.7	0.7	0.6	0.7	V_{tr1C} - U/V $trip_1$ V (p.u.)
0.5	0.05	0.02	0.05	T_{tr1C} - U/V $trip_1$ time (s)
0.3	0.3	0.8	0.3	F_{tr1C} - U/V $trip_1$ fraction
0.9	0.9	0.75	1	V_{rc1C} - U/V $trip_1$ reclose V (p.u.)
6	40	0.5	9999	T_{rc1C} - U/V $trip_1$ reclose time (s)
0.6	0.6	0.9	0.6	V_{tr2C} - U/V $trip_2$ V (p.u.)
0.2	0.02	30	0.02	T_{tr2C} - U/V $trip_2$ time (s)
0.5	0.5	1	0.5	F_{tr2C} - U/V $trip_2$ fraction
0.75	0.75	1	0.75	$V_{rc}2C$ - U/V $trip_2$ reclose V (p.u.)
0.25	0.25	9999	0.25	T_{rc2C} - U/V $trip_2$ reclose time (s)
0	0	0	0	T_{stall} - Stall delay (s)
0	0	0	0	$T_{restart}$ - Restart delay (s)
0.02	0.02	0.02	0.02	T_v - Voltage input time constant(s)
0.05	0.05	0.05	0.05	T_f - Frequency input time constant(s)
0	0	0	0	$Comp_{LF}$ - Compressor load factor, p.u. of rated power
0	0	0	0	$Comp_{PF}$ - Compressor power factor at 1.0 p.u. voltage
0	0	0	0	V_{stall} - Compressor stall voltage at base condition (p.u.)
0	0	0	0	R_{stall} - Compressor motor res. with 1.0 p.u. current
0	0	0	0	X_{stall} - Compressor motor stall reactance - unsaturated
0	0	0	0	LF_{adj} - Load factor adjustment to stall voltage
0	0	0	0	K_{p1} - Real power constant for running state 1
1	1	1	1	N_{p1} - Real power exponent for running state 1
6	6	6	6	K_{q1} - Reactive power constant for running state 1
2	2	2	2	N_{q1} - Reactive power exponent for running state 1
12	12	12	12	K_{p2} - Real power constant for running state 2

Model (M1)	Model (M2)	Model (DSM)	Original value	Description
3.2	3.2	3.2	3.2	N_{p2} - Real power exponent for running state 2
11	11	11	11	K_{q2} - Reactive power constant for running state 2
2.5	2.5	2.5	2.5	N_{q2} - Reactive power exponent for running state 2
0.86	0.86	0.86	0.86	V_{brk} - Compressor motor "break-down" voltage (p.u.)
0	0	0	0	F_{rst} - Fraction of motors capable of restart
0	0	0	0	V_{rst} - Voltage at which motors can restart (p.u.)
1	1	1	1	Cmp_{Kpf} - Real power constant for frequency dependency
-3.3	-3.3	-3.3	-3.3	Cmp_{Kqf} - Reactive power constant for frequency dependency
0	0	0	0	V_{c1off} - Voltage 1 at which contactors start dropping out (p.u.)
0	0	0	0	V_{c2off} - Voltage 2 at which all contactors drop out (p.u.)
0	0	0	0	V_{c1on} - Voltage 1 at which all contactors reclose (p.u.)
0	0	0	0	V_{c2on} - Voltage 2 at which contactors start reclosing (p.u.)
0	0	0	0	T_{th} - Compressor motor heating time constant(s)
0	0	0	0	T_{h1t} - Temperature at which compressor motor begins tripping
0	0	0	0	T_{h2t} - Temperature at which compressor all motors are tripped
0	0	0	0	F_{uvr} - Fraction of compressor motors with under voltage relays
0	0	0	0	UV_{tr1} - 1st voltage pick-up (p.u.)
0	0	0	0	T_{tr1} - 1st definite time voltage pick-up (s)
0	0	0	0	UV_{tr2} - 2nd voltage pick-up (p.u.)
0	0	0	0	T_{tr2} - 2nd definite time voltage pick-up (s)

APPENDIX B – Original publications

Paper I

Drovtar, I.; Landsberg, M; Kilter, J.; Rosin, A., "Impacts of large scale wind integration on the Baltic region's thermal power plant economics and electricity market in 2025," *Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2012 International Symposium on*, Sorrento, 2012, pp. 684-689.
doi: 10.1109/SPEEDAM.2012.6264591

2012
International Symposium on Power Electronics,
Electrical Drives, Automation and Motion

Impacts of Large Scale Wind Integration on the Baltic Region's Thermal Power Plant Economics and Electricity Market in 2025

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***Abstract*--This paper covers the analysis methods and results of the increasing wind integration impacts on the Baltic region's electricity market participants and power plant economics. The scope of the study is 2025 – when mayor decrease in generation capacities has occurred. The final part of the paper addresses the key findings that large scale wind integration might have on the economics of different generation technologies, with and without renewable electricity subsidies.**

***Index Terms*—electricity supply industry deregulation, power generation economics, wind energy.**

I. Introduction

Society's continuously growing need for energy and the alleged climate changes taken place in the last couple of decades have inevitably raised the question, whether the current trends in energy consumption and available technologies together are a sustainable way for the future. Even though the leaders of the world have not yet agreed upon what happens after Kyoto, there are clear indications of developments towards more clean and sustainable power technologies. The European Union (EU) has taken a political decision to restructure the power industry to a less carbon-intensive one (Fig. 1a and Fig. 1b) [1].

Contrary to the world's trend, the EU's electricity production from coal is forecasted to decrease and the bulk of new generating capacity additions result from renewable technology. According to the International Energy Agency's (IEA) forecasts [1], EU has planned to invest by 2035 in new power plants over 2.4 trillion (10^{12}) euros, from which more than 70% is destined for renewable technology.

The EU's policy pressures mainly those countries whose energy portfolios are based on fossil fuel operated large thermal power plants, e.g. the Baltic States. Restructuring the whole power industry in Estonia, Latvia and Lithuania with new power plants, covering the peak demand and fulfilling the EU's objectives, seems at least in the following decades more than impossible without additional supporting mechanisms.

This work was supported by the European Social Fund's Doctoral Studies and Internationalisation Programme DoRa, Estonian Archimedes Foundation programme "Doctoral School of Energy and Geotechnology II" and the Estonian Ministry of Education and Research (Project SF0140016s11).

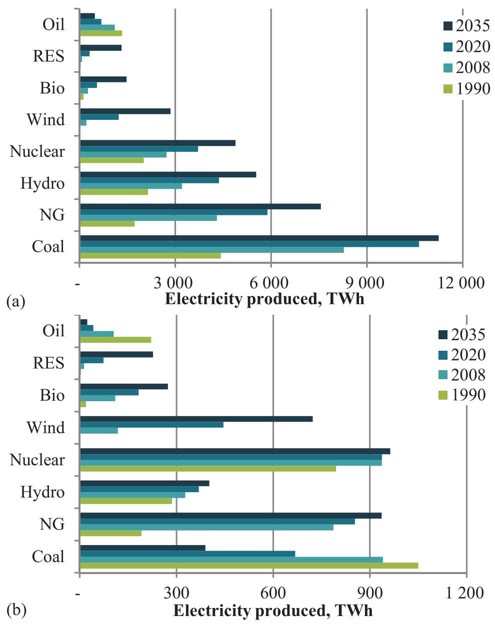

Fig. 1. Power industry outlook comparison, (a) World, (b) EU

Even though there is a growing interest in installing new renewable capacities in all three Baltic Statesit does not solve the problem of increasing capacity deficit in the region. For example in Estonia investors have shown interest in integrating wind capacities up to 4000 MW into a power system which peak demand is 1587 MW [2]. Wind power is by nature stochastic and unpredictable, and even though it supplies with electricity and is able to replace the output of conventional power plants, wind turbines are not able to provide capacity during peak hours, as it is described by Palu in [3] and by Boyle in [4].

This paper covers the methods and results of the analysis carried out to determine the impacts that large scale wind integration has on the Baltic region's electricity market and power generation in 2025. Although the Estonian TSO is currently using a Balmorel market modelling software for analysing power flows and market prices in the future from the power system development point of view, there is no tool currently in use for analysing how the increasing wind capacities and

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renewable supporting mechanisms actually influence the region's power plant economics. The model and methods described in this paper are unique in the sence, that it covers all the region's power plants and their economic aspects as close to reality as possible.

The paper has been divided into five sections, which cover overviews of the previous works published on large scale wind integration, the modelling methodology and finally the results and key findings.

II. Previous Studies Covering Large Scale Wind Integration

In [5] Olsina *et al.* developed a method to evaluate the optimal wind capacity that could be profitably integrated into system with liberalised electricity market. The model was based on the variables that determine the market price (supply and demand) and probabilistic factors that influence those variables. The results showed that large scale wind integration might significantly reduce the electricity price on the market, which in the short-term might be positive for the society but in the long term it jeopardizes the economic viability of conventional generators. As new capacities are built based on their profitability, then this might also affect the security of supply. Olsina concluded that due to high investment costs large scale wind capacity deployment on a deregulated market is possible only in case of high fossil fuel prices or with additional financial incentives (lower investment costs or subsidies).

Lamont in [6] described with his work that introducing intermittent generation to the market tended to decrease the overall marginal costs of the system. This was achieved through avoiding fuel and variable costs of conventional (dispatchable) generation. However, in the long term it makes the conventional technology unreasonable and thus reduces the security of supply, giving an incentive to restructure the generation mix to meet the new power system configuration requirements with less base capacities.

On the other hand, as intermittent generation, especially wind, is unpredictable, new costs will arise in the future, as more spinning or fast switching reserves are required to cope with the higher number of fluctuations occurring in the system, consequently increasing the intermittent and peak capacities. Increased wind integration thus restructures the power system's capacity allocation. However, it is doubtful that it will fully replace conventional units that are able to cover peak loads. Boyle in [4] states that the total dispatchable capacity in a system will never be less than the peak load irrespective the amount if integrated intermittent generation.

MacCormack *et al.*, in [7] examined the effects that large wind capacities have on the electricity price, reliability of supply and dispatchable suppliers' economics. The results showed similarly to Olsina's results that in medium term, large integration of wind power can lead to reduced market prices. In addition, increased reliability of supply was observed due to the dispersion of wind power plants in the power system. However, increasing average costs were observed for conventional technology, due to the decreased utilization hours. In the long term, revenues collected from the market should be equal to the average cost of production, or sufficient dispatchable capacities will not be built.

III. The Electricity Market Model

To analyse the large scale wind integration impacts on the Baltic region's electricity market a simplistic electricity market model was created. The model described here, has been adopted from [8] and modified to carry out a more detailed analysis on how subsidising methods (implemented in 2010) and increasing wind capacities might affect the market and market players. The working principle and inputs of the model used in this research is elaborated in the following subsections.

A. Assumptions and Inputs

The model assumes that the electricity market operates under perfect competition and all three countries of the Baltic States are trading in one fictive price area. To neglect the neighbouring systems' influence and to evaluate the feasibilities of different technologies in the region, the Baltic States are assumed to operate separately in a so called "island mode" and thus have no actual power exchange with any of their neighbouring power systems.

The hourly capacity factors of onshore and offshore technology and large hydro power plants are based on statistical data provided by each country's transmission system operator (TSO) for the wind study [9], which analysed the possibilities and limitations for integrating wind capacities into the Baltic power system. The availability and sudden failures of other generating technologies are taken into account by applying the availability factor from the literature [10]. The model disregards the technical-mechanical restrictions of large thermal power plants that set limits to the minimum on and off time between shutdowns.

The demand model is based on the region's latest hourly consumption patterns in 2010, provided by the Estonian TSO. 2025 consumption data was achieved by applying forecasted growth per cents [11] for each hour of the year. 2025 fuel prices are based on the Estonian TSO's modelling results using IEA's reference data, see Table I.

Table I. Projected Fuel Prices for 2025 [2]

Fuel	Coal	HFO[1]	Oil shale	NG[2]	Woodchips
Price, €/GJ	2.93	12.64	2.51	8.52	6.95
Price,€/MWh_{fuel}	10.53	45.51	9.02	30.66	25.02

To take into account the impacts of externalities, the model includes an implemented CO_2 tax 25 €/ t_{CO_2}, based on the ENTSO-E market database scenario and subsidies, which are elaborated in subsection C.

B. Mathematical Formulation of the Model

The modelling methodology is based on the electricity

[1] HFO – heavy fuel oil
[2] NG – natural gas

pool principle described in many power system economics handbooks [12, 13]. All the producers bid on the market according to their short-run marginal costs (SRMC). After all the bids have been submitted and the gate for the trading hour has been closed the bids are arranged from the smallest to the highest. This list of arranged bids gives the merit order curve of dispatching units at the trading hour. The system's marginal price (SMP) or electricity price at a specific trading hour is determined by the last unit that covers the demand forecast (Fig. 2).

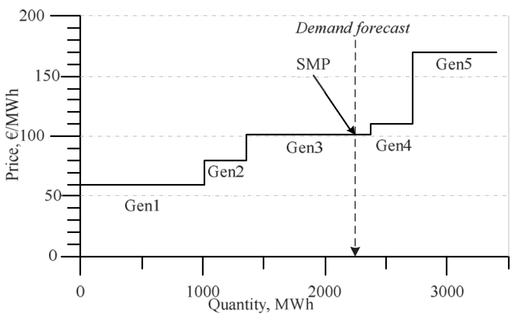

Fig. 2. The used modelling principle of electricity pool [12]

Based on the theory in literature [12, 13] the authors have formulated the SRMC as follows:

$$\mathrm{SRMC} = \frac{\mathrm{FC} + \mathrm{EC}}{\eta_{\mathrm{PP}}} + \mathrm{VC} \tag{1}$$

where *SRMC* is the short-run marginal cost of the unit, *FC* is the forecasted price of the fuel used, *EC* is the external cost[3] of production, η_{PP} is the power plant's efficiency and *VC* is the variable cost of production.

Results obtained from the first stage of modelling are then used for the economic evaluation, which is based on comparing the long-run marginal cost (LRMC) of the power plant with the revenues collected from the market. For the power plants to be economically viable the revenues from the market should be greater than its long-run costs, this is formulated in equation (2).

$$\frac{\sum_{i=1}^{8760} \mathrm{MR}_i}{\sum_{l=1}^{8760} \mathrm{E}_l} > \mathrm{LRMC} \Rightarrow \begin{cases} \text{FALSE, economically not viable} \\ \text{TRUE, economically viable} \end{cases} \tag{2}$$

where *LRMC* is the long-run marginal cost of the unit, MR_i is the hourly revenue collected from the market and EP_l is the hourly supplied energy to the market.

LRMC takes into account additionally to the SRMC also the capital (operation and maintenance) and investment costs. The following formulation of the LRMC was used in the model:

$$\mathrm{LRMC} = \mathrm{SRMC} + \frac{\mathrm{IC}}{\mathrm{EP_a}} + \frac{\mathrm{CF}}{\mathrm{EP_a}} \tag{3}$$

where *IC* is the annual discounted investment cost during the unit's technical life time, *CF* is the annual fixed costs occurring irrespective of the unit's utilization time and EP_a is the total energy produced in one year.

The necessary technology specific data for calculating the above mentioned costs are based on either literature [10, 14, and 15] or in case of oil shale technology data available and provided by the Estonian TSO.

C. Analysed Scenarios

The following two market scenarios, each with two different wind integrations levels, have been used:

a) 2025 market with currently implemented subsidies;

b) 2025 market without subsidies.

The wind integration levels were chosen taking into account the results of the wind integration study [9]. Equal wind integration levels for both technologies and all countries were chosen, because it enables to analyse and compare them taking into account country specific factors. The following wind integration levels for each country were thus used:

a) low wind integration level 250 MW offshore capacities and 250 MW onshore capacities – total installed wind capacity in the Baltic States power system 1500 MW;

b) high wind integration level 450 MW offshore capacities and 450 MW onshore capacities – total installed wind capacity in the Baltic States power system 2700 MW. This represents the maximum possible integration of wind power into the Baltic electricity system without grid reinforcements or wind curtailment [9].

The values of the subsidies used in the model are based on either the current legislation in Estonia [16] or statistics of actually paid subsidies in 2010 provided by the TSOs [17]. The Estonian subsidies remain between 32 €/MWh for conventional combined head and power plants (CHPs) and 53.7 €/MWh for wind power. Biomass fuelled CHPs got additional revenue of 50.67 €/MWh. Latvia subsidies were between 67.75 €/MWh for wind power and biomass fuelled CHPs and 79.88 €/MWh for biogas power plants. As the Lithuanian supporting mechanisms data in [17] for the year 2010 was inconclusive, it was assumed that the paid premium is equal to the power plant's SRMC.

It should be noted that the subsidies are only taken into account in the calculation of the marginal cost with what the power plant bids on the market. Assuming that the ensured subsidy is subtracted from the actual SRMC of the unit whilst bidding on the market, it pushes the specific unit upward in the merit order curve and hence increases its chances to sell its electricity on the market.

The generation portfolios (except wind power) for each country in 2025 were created according to the TSOs national development plans described in [2], [9], and [18].

[3] External costs are calculated by multiplying the CO_2 tax (€/t_{CO_2}) and the fuel's carbon content (t_{CO_2}/MWh_{fuel})

IV. Results

A. Impacts on Market Price

The impacts that increasing wind penetration into the power system has on the average market prices, with and without subsidies, are summarized in Table II.

TABLE II. Wind Integration Impacts on Market Price

Wind integration level	Market price without subsidies, €/MWh	Market price with subsidies, €/MWh
1500 MW	76.08	73.31
2700 MW	68.05	64.57

The increasing capacity of wind power in the system decreases the electricity prices on the market by altering the merit order curve of dispatching. The last unit that determines the SMP might be shifted in the curve due to increased wind capacity, which thus lowers the price at some trading hours. Depending on the level of wind integration, the annual average market price is lowered.

Although the table suggests that applying subsidies lowers the market prices but this is deceptive. The average market price is actually lowered, but only if assumed (like in this case) that some producers distort the market by bidding to the market with lower prices than their actual SRMC. The renewable electricity producers (such as biomass and biogas), that otherwise would have higher marginal costs with what they bid on the market, are shifted frontward in the curve. This inevitable lowers the average market price as at higher demands the SMP is now lower than it would be in unsubsidised situations. In literature this is referred to as market distortion.

B. Impacts on Utilization Factors

Impacts on utilization factors by technology are summarized in Table III. Note that a utilization factor of 1 corresponds to 8760 working hours.

TABLE III. Wind Integration Impacts on Utilization Factors

Technology	Wind integration level	Without subsidies	With subsidies
Oil shale CFB[4]	1500 MW	0.970	0.954
	2700 MW	0.892	0.868
Coal CFB	1500 MW	0.986	0.942
	2700 MW	0.923	0.812
CCGT[5]	1500 MW	0.749	0.689
	2700 MW	0.587	0.527
Biomass	1500 MW	0.851	1.000
	2700 MW	0.690	1.000
Biogas	1500 MW	0.310	1.000
	2700 MW	0.192	0.999

The analysis showed that if subsidies are used, large scale wind integration impacts the most those technologies that utilize more expensive fuels (i.e., natural gas). If no subsidies have been applied the situation changes – biogas and biomass technologies will be shifted backward in the merit order curve and their utilization hours decrease. Utilization hours might be reduced up to 38%, depending on the type of technology.

[4] CFB – circulating fluidized bed combustion technology
[5] CCGT – combined-cycle gas turbine technology

The modelling results show that even if externalities, such as CO_2 taxes, have been implemented, the key factor determining the economic feasibility of a technology is the fuel price. The units using the cheapest fuel will have a significant leverage over their competitors. The same advantage can be observed with increasing wind integration. Without subsidies alternative renewable technology has thus the biggest disadvantage on the market. However, this depends strongly on the level of externalities – at higher CO_2 tax levels (e.g. 90 €/t_{CO2}) the less carbon-intensive technology has the advantage.

C. Economics of Conventional Power Plants

A simplistic method is used to evaluate the economic feasibility of power plants: the idea is to compare the total revenues from the market in one year with the LRMC (2). The modelling results with implemented subsidies are summarized on Fig. 3

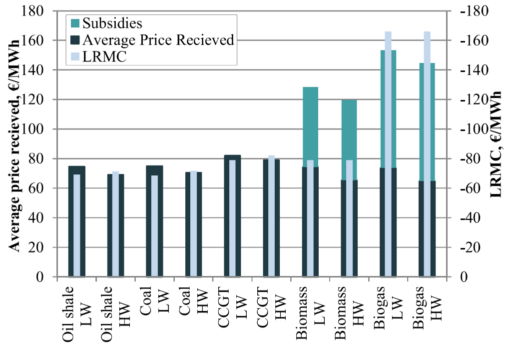

Fig. 3. Economics of different technologies with implemented subsidies; LW – low wind integration; HW – high wind integration

The results show that oil shale, coal and CCGT technologies might become economically not feasible in the long run with the increasing wind integration. Biomass technology on the other hand is almost not affected by the increase in wind capacities – this is ensured by the subsidies. However, the level of subsidies in some cases is abnormally high compared to the actual costs, giving a significant leverage for this type of technology. On the other hand, biogas technology's costs are still higher than the revenues even with additional subsidies and with the increased wind integration level the gap between costs and revenues increases.

Without subsidies the situation is somewhat similar, but due to the higher market prices most of the technologies are economically viable even with the increased wind capacities. Even though, there was one externality (CO_2) implemented, most of thermal power plant technologies turned out to be quite competitive and relatively feasible on the open market and without additional subsidies. The increasing wind integration level affected mainly biomass and –gas technologies. The results and cost calculations indicated that biogas technology is relatively expensive and for it to become feasible it requires higher utilization factors and some additional financial support. The modelling results without implemented subsidies are represented on Fig. 4.

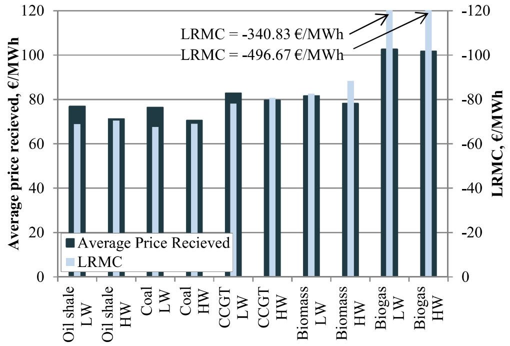

Fig. 4. Economics of different technologies without implemented subsidies

The advantage of modelling the market without subsidies was that it brought out the real competitiveness of different technologies. In addition, it gave an overview which technologies should be financially supported and which should not be.

D. *Economics of Wind Power Plants*

Wind power is the key factor that affects the market and the market participants. Nevertheless, the modelling results showed that increasing wind integration also affects its own economics. Olsina *et al.* in [5] described, that there is a maximum level of wind power capacity that could be profitably deployed under full market conditions. Fig. 5 and Fig. 6 summarize the modelling results for onshore and offshore wind capacities in a market with subsidies.

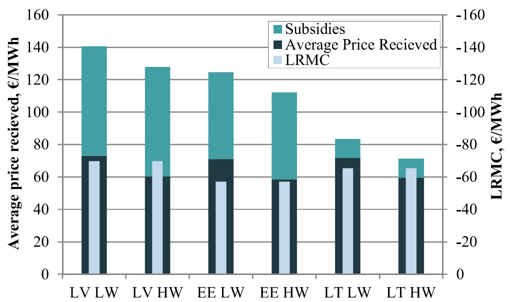

Fig. 5. Economics of onshore wind technology in LV – Latvia, EE – Estonia, LT – Lithuania with subsidies

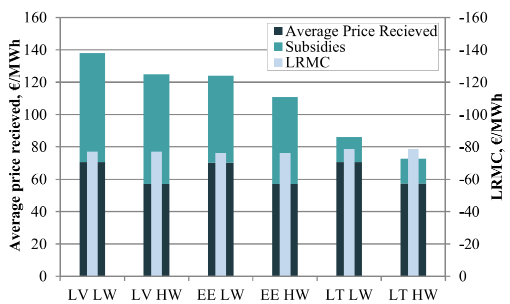

Fig. 6. Economics of offshore wind technology with subsidies

The results indicate that deploying wind capacities under full market conditions can significantly increase their incomes compared to the regulated market with a fixed price. Therefore, maintaining the subsidies as high as on the regulated market is unfounded. On the one hand it is an extra cost for the society and creates market distortions by favouring certain technologies. On the other hand this might jeopardize the investments into conventional technologies which are less profitable on the market.

The modelling results indicated that once the onshore wind capacities have been deployed under full market conditions they have the potential to become economically feasible even without subsidies. According to the European Wind Energy Association (EWEA) offshore wind power started to develop rapidly only in the last couple of years and at the same time onshore capacity additions have decreased [19] – meaning that onshore technology has reached it maturity and does not require substantial subsidizing anymore. At the same time offshore technology is still emerging, which makes it more expensive to develop and integrate than onshore technology [10]. Thus additional financial incentives might be founded even under full market conditions. However if the wind integration level increases even the onshore technology might lose its feasibility, implying that the maximum level of economically dispatchable wind power [5] has been exceeded. It should be stressed that this happens only if the wind generation portfolio consists of 50% of either technologies. Fig. 7 and Fig. 8 describe the modelling results without subsidies.

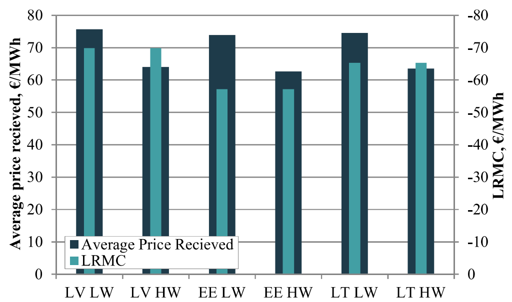

Fig. 7. Economics of onshore wind technology without subsidies

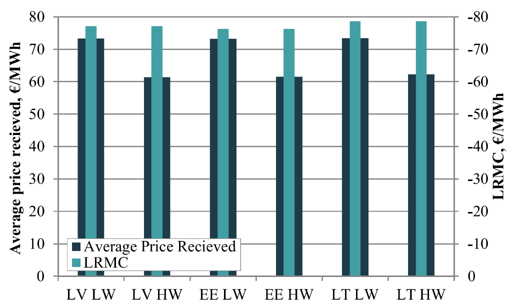

Fig. 8. Economics of offshore wind technology without subsidies

The results show that subsidies have the least influence on the economics of wind power. The economic situation has stayed almost similar in both cases. This is because wind power has almost negligible short-run costs and thus produces electricity for the market. There is a marginal difference between the average prices received from the market with and without subsidies – this is caused by the shifts in the merit order curve discussed previously. The economic threshold up to what it is feasible to deploy either technology also varies by country because of the different wind resources available. So theoretically it should be possible to reach a mix of technologies in the wind generation portfolio that would be economically feasible in both market situations. However, the specific situation used in this model and analysis gives a chance to compare the two technologies in equal country specific conditions.

V. Conclusions

The rapid increase of wind power in the system can cause severe problems and deterioration of the security of supply through changes in market conditions. This paper analyses, the impacts of large-scale wind integration on the local electricity market and power generation in 2025. The developed fictive market model allowed investigating the impacts of renewable supporting mechanisms and increasing wind capacity impacts on the market and economics of different generation technologies. The model provides a variety of technology specific information, e.g., changes in the utilization hours, shifts in the merit order curve of dispatch, changes in revenues collected from the market, and etc. This data enables to estimate the economic feasibility of different technologies. The economic viability of technologies is evaluated by the difference between the LRMC and the average price and additional revenues received from the market during a one year period.

The created model confirmed the results of similar studies carried out on other countries – increasing capacity of wind power in the system inevitably decrease the electricity price on the market. Amongst other things the model also indicated that subsidies might seemingly lower the market price, but this is deceptive and this lower market price will not reach the end-consumers.

In the utilization hour sensitivity analysis the model suggested that even if some externalities (CO_2 taxes) have been introduced on the market, the increase of wind integration levels in the power system have the biggest impact on the technologies utilizing more expensive fuels. Hence, in a system where there are no significant hydro resources, the key factor determining the success of a technology on the open market is the fuel price and introduced external costs.

The market model without subsidies brought out the real competitiveness of different generators and showed that most of the technologies do not require additional financial support. However, it is extremely important to analyse the mix of wind technologies deployed on the market, to ensure its feasibility.

The presented paper should give the regulatory bodies in the Baltic States directions and facts to consider in developing new energy policies. Taking into account the region's peculiarities and the need to assure the security of supply for the consumers, in the short run the policies should ensure the equality for different market players and in the long run ensure the development towards new innovative and sustainable solutions in the power system.

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Paper II

Drovtar, I.; Uuemaa, P.; Rosin, A.; Kilter, J.; Valtin, J., "Using demand side management in energy-intensive industries for providing balancing power - The Estonian case study," *Power and Energy Society General Meeting (PES), 2013 IEEE*, pp.1,5, 21-25 July 2013. doi: 10.1109/PESMG.2013.6672418

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

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***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

This study is supported by the European Social Fund's Doctoral Studies and Internationalization Programme DoRa, Estonian Archimedes Foundation programme "Doctoral School of Energy and Geotechnology II", the Estonian Ministry of Education and Research (Project SF0140016s11) and by the Estonian TSO, Elering AS.

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

978-1-4799-1303-9/13/$31.00 ©2013 IEEE

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].

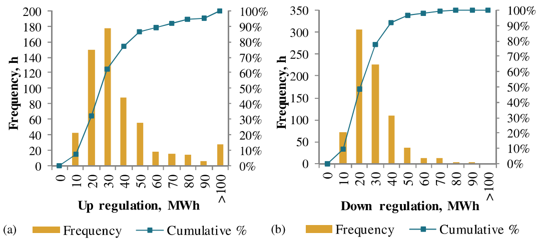

Fig. 1. Required balancing energy in the Estonian power system in 2011, (a) up regulation or positive tertiary regulation and (b) down regulation or negative tertiary regulation [6].

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.

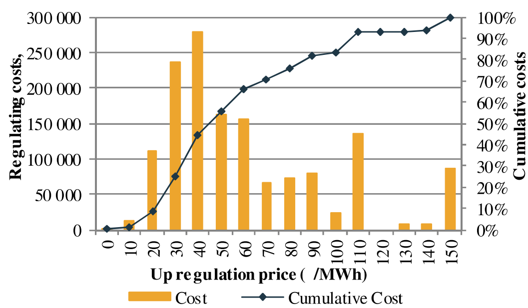

Fig. 2. Estonian TSO's up regulation costs in 2011.

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.

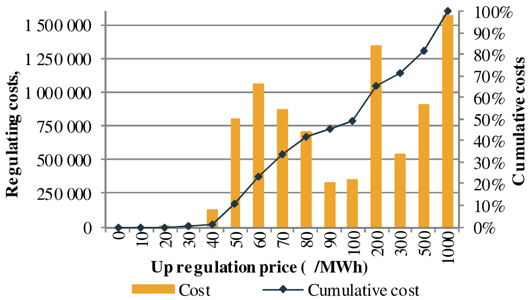

Fig. 3. Finnish TSO's up regulation costs in 2011 [13].

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.

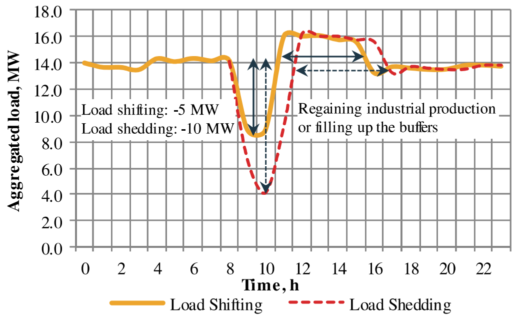

Fig. 4. Aggregated demand profile of the consumer providing regulating service for the TSO (before, during and after service provision).

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.

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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 III

Drovtar, I.; Rosin, A.; Landsberg, M; Kilter, J., "Large scale electric vehicle integration and its impact on the Estonian power system," *PowerTech (POWERTECH), 2013 IEEE Grenoble*, Grenoble, 2013, pp. 1-6.
doi: 10.1109/PTC.2013.6652181

Large Scale Electric Vehicle Integration and its Impact on the Estonian Power System

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Abstract—**This paper presents the main aspects of the study about large scale electric vehicle (EV) integration impacts in Estonia. The complex impact of EV charging and the resulting additional load demand on the Estonian power system is discussed. Two different charging principles are analysed – controlled and unmanaged. Standard and quick charging impacts are assessed together with the preheating strategies due to the climatic conditions. The aim of the paper is to model the impacts of EVs on the Estonian power system at sub regional level and to give an input for the Estonian TSO for its network development plans concerning e-mobility integration.**

***Index Terms*-- electric vehicles, charge profile, power system development, power system operation**

I. Introduction

According to the European Commission (EC) [1] the European Union's (EU) road transportation contributes about 20% of the total emissions of carbon dioxide (CO2). The CO2 emissions derived from road transport increased almost 23% over two decades since 1990, and without the financial crisis that started in 2010 the growth could have been even bigger. Transportation is the only major sector in the EU where greenhouse gas emissions are still rising. In addition, to the climate concerns, the high traffic concentrations inside cities are sources for health problems caused by poor air quality. In order to improve the air quality in cities and to decrease the CO_2 emissions in the transportation sector, one solution is thought to be the large scale integration of electric transportation in the urban areas.

In 2011, the Estonian government made a contract with the Mitsubishi Corporation to sell 10 million Assigned Amount Unit (AAU) of Kyoto carbon credit to initiate the Estonian electromobility program (ELMO [2]). ELMO programme aims to promote emission free personal transportation and electric cars in order to achieve better city environment, energy efficiency and fuel independence. The program consists of three parts: in the first part 507 Mitsubishi iMiEV EVs will be given into the usage of Ministry of Social Affairs as an example, Ministry of Economic Affairs and Communications will develop a grant system for private persons to support the purchase of EVs and finally a quick charging (<30 minutes) infrastructure that covers the whole Estonian territory has been developed by the end of 2012. With these steps Estonia has become the first country in the world that has an EV quick charging infrastructure that covers the whole country. This in return enables the large-scale usage of EVs and/or plug-in hybrid electric vehicles (PHEV).

Within this context, the authors are investigating the large scale usage of EVs potential impact on the Estonian power system and its operation. The results of this paper will cover a scenario analysis of the year 2030 and the possible impact on additional load in different counties. The results of this analysis will be used to update the Estonian power system development plans for the year 2030. The paper has been divided into five sections, with section II giving an overview of the possible penetration levels of EV till 2030 and the power system loads without large scale EV integration. Section III describes the methods and calculations of the additional load in the power system associated with the considered vehicle fleet. Section IV will describe the power system model (PSS/E) and assumptions used to simulate the operation of the Estonian power system. Finally, section V concludes the main results of the paper and discusses the future works.

II. Base Case Scenarios

International Energy Agency's (IEA) Energy Technology Perspectives forecasts that the EU's EVs or PHEVs passenger vehicle sales in 2030 will remain depending on the scenario between 6.6% and 23.5% of the total passenger vehicles sales [3]. Another study [4] has indicated that in 2030 the electrical car fleet in the European Union might remain between 10% and 30%. Additionally, the authors of [5] have indicated that in the best case scenario the EV and PHEV fleet would reach 50% of the total number of vehicles. This paper will emanate from the assumption that the EV and fleet in Estonia remains between 10% and 30% of the total number of passenger cars.

This study is supported by the Estonian Science Foundation (Project SF0140016s11 and Grant 9350), by the Estonian TSO (Elering AS), the European Social Fund's Doctoral Studies and Internationalisation Programme DoRa and by the programme "Doctoral School of Energy and Geotechnology II", which are carried out by the Foundation Archimedes.

For the load impact analysis the Estonian TSO forecast is used. According to the data provided by the TSO the power system peak load and consumption will grow annually approximately 2.0% and 2.3% respectively. The winter peak load in 2030 (WP2030) will be around 2.2 GW and consumption around 12 TWh.

A. Road Transportation Development until 2030

According to Eurostat, in 2009, the number of passenger vehicles per 1000 inhabitants in Estonia reached 407, while the European average remained around 473 cars [6]. In the end of 2011 this number reached 435 [7]. The actual distribution of vehicles in 2011 is presented in Table I [8].

TABLE I. NUMBER OF VEHICLES IN ESTONIA (2011)

Year	Passenger cars	Buses	Trucks	Motorcycles	Mopeds
2011	574 000	4 200	84 300	21 100	2 100

The Estonian Road Administration (ERA) has ordered several studies [7; 9] to predict the long term road transportation development in Estonia. According to the studies, the number of passenger cars in Estonian will exceed 520 vehicles per 1 000 inhabitants by 2030. Together with the Estonian population growth and the ERA forecasts, it can be estimated that there will be around 681 000 passenger cars, 4 400 buses and 85 000 trucks in 2030.

B. Power System Load Curve in 2030

Due to the Estonian geographical location the power system loads within one year can differ significantly. The spring-autumn (900 MW) and summer (720 MW) seasons' average loads can be 25% to 40% lower than the loads during winter (1200 MW). From this study's point of view the authors are only interested of the winter peak load curves and the possible additional load during that period on localized levels. Usually the planning looks also at the generation adequacy, however in this case the authors are only interested in the additional load and its impact on the technical infrastructure. Winter peak load is ideal for this, because during that time the power system is already under great stress and pushed to the limits.

III. METHODS AND CALCULATIONS

A. Base Data for Calculations

Table II summarizes the main data describing today commercially available EVs from three different classes: eco, standard and sports. From the factory datasheet it can be assumed that the average power consumption of an EV would remain around 170 Wh/km however, Vee in [10] has proven that due to the Estonian geographical and climatic conditions the actual consumption of an EV could be up to 40% higher than indicated by the manufacturer. Because of the extra energy required by the heating during winter periods the Mitsubishi iMiEV's power consumption per km peaked at 190 Wh (compared to the 135 Wh indicated by the producer) during the test period. For further calculations the authors have assumed that the power consumption of an EV during winter time would be thus 235 Wh/km and the average daily mileage, based on the ERA prognosis, 41 km.

TABLE II. MAIN DATA DESCRIBING EVS IN 2012[1]

	Mitsubishi iMiEV	Nissan Leaf	Tesla Model S
Power consumption [Wh/km]	135	173	155-176
Range [km]	150	175	250-480
Top speed [km/h]	130	145	177-201
Acceleration 0 - 100 km/h [s]	15.9	11.9	5.6-6.5
Power bank [kWh]	16	24	40-85

For the EV's to reach a significant share of the passenger car fleet, the power bank technology would need a technological breakthrough so that it could compete with the internal combustion engine (ICE) car's range. The authors have thus assumed that by 2030 the average EV would have power bank with the capacity of 100 kWh.

B. EV Charging

According to IEA [11], in Finland, approximately 60% of the cars have an engine block heater[2], with a slight modification these block heaters could also be used for EV charging. For the large scale EV integration to succeed, Estonia will need to reach at least the same level of block heater/charging infrastructure per passenger vehicle by 2030. This way most of the EV owners would have an access to a standard charger and this would be the main way for charging plug-in vehicles, as indicated by several studies [12; 13]. Due to the limited parking space in high population density city districts, approximately 75% of EV owners would have full time access to this type of charging. Rest of the EV owners are assumed to use the quick charging infrastructure.

To calculate the possible charging impact on the load, it has been divided into three levels: standard charging, comfort charging or preheat and quick charging. Standard charging is assumed to be influenced mainly by the electricity market price.

Standard charging takes into account the market price fluctuations and the traffic intensity. Market price impacts are based on the 2010-2011 Nord Pool Spot (NPS) market price analysis, which determined the prime time for charging between 20:00 to 6:00[3], however this can be modified according to the user's specifications. Equation (1) is used to calculate the hourly load impact (MWh/h) of standard charging outside the prime time charging period.

[1] Data based on manufacturer datasheets.
[2] Block heaters are used for preheating the ICE cars during winter seasons due to extreme cold temperatures.
[3] During this period of time the NPS system's average hourly market price during the winter season remained below 68 €/MWh.

$$E_{\underset{h=7...19}{C_h}} = \frac{\sum_{l=20}^{6} d \cdot \rho_{T_h} \cdot E_d}{\sum_{i=7}^{19} 1_i} \cdot \Delta V_{P_h}, \quad (1)$$

where h represents the hour of the day, l defines the prime time hours, i represents the time period outside the prime charging time, E_{Ch} the charging energy of the hour, d is the total daily distance covered by EVs (km), ρ_{Th} is hourly traffic density, E_d is the energy consumption per distance covered ($2.35 \cdot 10^{-5}$ MWh/km) and ΔV_{Ph} is the relative change in the number of parking EVs to the average parking EVs over the observed hours of the day (%/h). The values of h, l and i, used in the equation, should match the prime time selection.

Equation (2) is used to calculate the hourly impact of standard charging during the prime time.

$$E_{\underset{h=20...6}{C_h}} = a \cdot d \cdot E_d \cdot D(MP)_h, \quad (2)$$

where h represents the hour of the day, E_{Ch} the charging energy of the hour, a is the share of EV owners (%) who have access to a standard charging station (block heater), d is the total daily distance covered by EVs, E_d is the energy consumption per distance covered and $D(MP)_h$ is charging distribution coefficient during the prime charging time (%/h). The values of h used in the equation should match the prime time selection.

Comfort charging is the energy used for preheating the car and the battery 2 hours prior to usage, in order to maximize the battery usage for driving and not to heat the cabin. The preheating is assumed to have an energy intensity of $3 \cdot 10^{-3}$ MWh[4] per car in one hour. Equation (3) describes how to calculate the hourly energy required for preheating.

$$E_{P_h} = (\Delta V_{(h+2)} \cdot E_H)\big|_{h<(h_n-1)} + (\Delta V_{(h+1)} \cdot E_H)\big|_{h>(h_{m-2})}, \quad (3)$$

where h represents the hour of the day, $E_{Ph}$the preheating energy of the hour, ΔV_h represents the change of vehicles in traffic during observed hour (1/h), E_H represents the hourly consumption of the preheaters, h_m represents the hour when the increase of traffic intensity starts and h_n represents the last hour of the cycle when the traffic intensity has increased.

Quick charging takes into account the car users who do not have a full time access to standard chargers and thus need to utilize the quick charging infrastructure. This load is assumed to be proportional to the traffic intensity and calculated with (4).

$$E_{\underset{h=0...23}{Q_h}} = (d \cdot E_d - E_C) \cdot \rho_{T_h}, \quad (4)$$

where h represents the hour of the day, E_{Qh} the charging energy of the hour, d is the total daily distance covered by EVs, E_C is the total energy charged via the standard chargers and ρ_{Th} is the hourly traffic density (%/h).

C. Impact on the Power System Load Curve

Two separate charging impacts were considered:

1) the first assuming that charging is managed according to the signals coming from the electricity market,.

2) the second without any aim to control the charging and assuming that due to the extreme weather conditions 75% of the cars parked will be plugged in.

The calculated hourly energy demand (by type) of EVs in case of controlled charging is illustrated on Fig. 1.

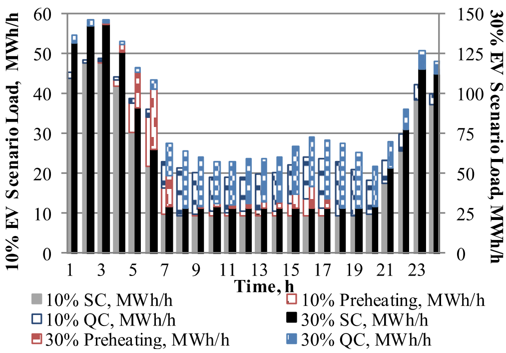

Figure 1. Additional energy demand of EVs by type in the case of controlled charging; SC – standard charging, QC – quick charging.

Calculations, assuming that the charging is dependent on the market price, indicated that the average additional load that large scale EV integration adds to the power system remains between 30 MWh/h and 90 MWh/h, depending on the number of EVs. Higher load increase can be observed during off peak times but during peak hours 1.3…3.8% of additional load should be expected, depending on the vehicle integration level. On a daily basis the integration of EVs would increase the energy demand between 2% and 5%. The possible impact range of EVs on the power system load is illustrated on Fig. 2.

In the case there is no control over the charging of the vehicle fleet, the average increase of load in the power system remains approximately the same as in the previous case. The difference is revealed in the distribution of the impact. In the

[4] For example, according to the manufacturer and field tests, the Nissan Leaf's heater power remains between 1.5 kW and 3 kW. 3 kW is assumed to be optimal, in order to minimize the heater's impact on the battery capacity during driving and at the same it does not overstress the power outlets, which have a maximum power of 3.6 kW.

previous case the higher impact on the power system occurs during off peak hours. In the case of uncontrolled charging the bigger increase of load can be observed during peak hours. The calculated hourly energy demand (by type) of EVs in case of uncontrolled charging is illustrated on Fig. 3.

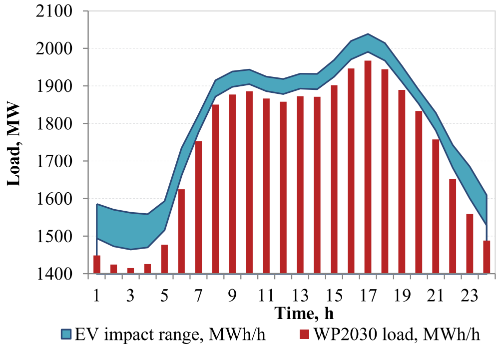

Figure 2. Possible impact of EVs on the power system load curve in the case of controlled charging.

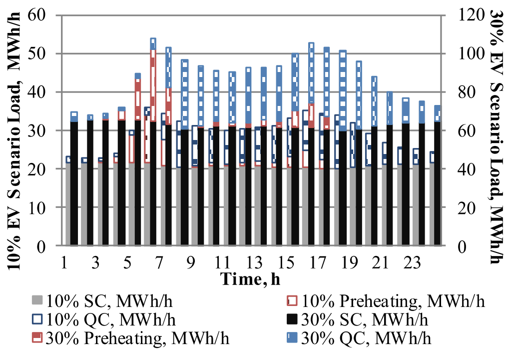

Figure 3. Additional energy demand of EVs by type in the case of unmanaged charging.

Highest impact on the load curve can be observed between 4 and 6 o'clock in the evening. This is in correspondence with the ending of the working day and the traffic intensity changes. During peak hours 1.8…5.2% of additional load should be expected, depending on the vehicle integration level. The possible impact range of EVs on the power system load is illustrated on Fig. 4.

Although the increase in peak load might seem insignificant on the whole system perspective, then due to the different concentration of EVs in urban and countryside areas, the impacts in different parts of the grid are expected. The following section gives an overview about the possible EV charging impact in different parts of the Estonian power system.

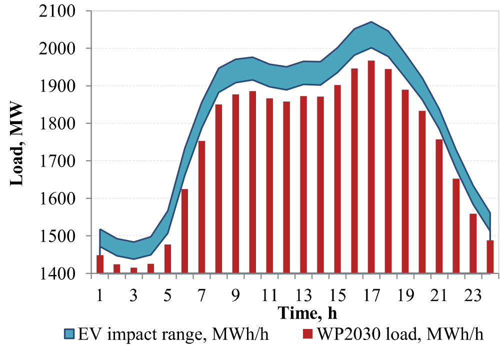

Figure 4. Possible impact of EVs on the power system load curve in the case of unmanaged charging.

IV. Power System Modelling

In order to model the impacts of charging on a localized level the analysis of passenger car distribution and load distribution in Estonia was carried out. The aim of the load distribution analysis was to get an overview of the grid, where the large scale integration of EVs could cause problems. Areas with lower peak loads most probably do not have a strong electricity grid and the increase of local peak load is higher. The load distribution in the Estonian power system with forecasted 2030 peak loads is summarized in Fig. 5. Note that Saare and Hiiu counties are analysed as one load area.

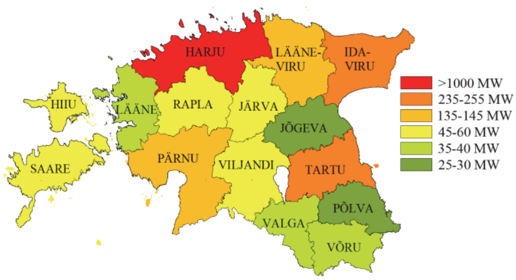

Figure 5. Load distribution forecast in different counties in Estonia in 2030 winter.

The passenger car distribution analysis was used to determine the localized increase of peak loads due to EV charging. This is based on the assumption that the distribution of the EVs in Estonia will follow the same pattern as regular vehicles. The calculations of the increased peak loads were based on the 30% integration scenario, as it represents the highest possible increase of peak load, which should be used in the power system studies. The results confirm the previous hypothesis that higher impacts can be expected in areas where the peak load is lower. The possible increase of peak loads in different Estonian counties is summarized in Table III.

TABLE III. RELATIVE INCREASE OF PEAK LOAD IN DIFFERENT ESTONIAN COUNTIES

County	30% EVs, controlled charging	30% EVs, unmanaged charging
Harju	2.4%	3.4%
Ida-Viru	2.6%	3.8%
Jõgeva	7.8%	11.2%
Järva	4.7%	6.7%
Lääne	4.9%	7.0%
Lääne-Viru	2.6%	3.8%
Põlva	10.5%	15.2%
Pärnu	3.5%	5.1%
Rapla	4.2%	6.1%
Saare and Hiiu	5.8%	8.4%
Tartu	3.0%	4.4%
Valga	5.8%	8.4%
Viljandi	7.4%	10.7%
Võru	6.4%	9.3%

A. *The Estonian Power System Model*

The Power System Simulator for Engineering (PSS/E) software package is used for the power system modelling. The winter peak model for the year 2030 is the basis for the analysis. All the Estonian TSO's development plans until 2030 with the forecasted peak load are already included in the model. The model represents identically the actual Estonian power system, with all of its generators, 110 kV and 330 kV overhead lines (OHL), and the loads behind each of the 110 kV substations (SS).

The EV's impact will be modelled by scaling up the load in preselected load centre 110 kV SS according to the projected load increase presented in Table III. The preselected SS that will take on the additional load from the EV charging are selected according to the proximity of residential areas, such as downtown and midtown districts, where majority of the population is situated. The two charging scenarios' models will be compared against the base case scenario (without the EVs). The impact study of EV's will include determining overloading of power lines and localized voltage problem analysis based on fulfilling the N-1 criterion[5] in the system. The criterions which the model has to fulfil are as follows[6]:

- OHL loading in normal conditions <80%;
- OHL loading in N-1 fault conditions <92%;
- bus voltages in normal conditions 115…122 kV;
- bus voltages in N-1 fault conditions 105…123 kV.

B. *Modelling Results of the Controlled Charging*

The increased load lowered the bus voltages in the counties' monitored SS 1…2 kV, remaining within the pre-set limits defined in subsection A of this section. 9 regions out of 14 (including the counties with low loads) did not encounter any other problems, besides the lowered voltages. The results indicated a close to the limits low voltage (105.1 kV) only in the Jõgeva County. If measures, e.g., installing shunt capacitors, will be taken to improve the voltage situation in the region then the installed devices should have slightly higher reserve margin than planned. Although the voltage criterions were not violated in any of the studied cases, then it should be taken into account that due to the lower voltages higher losses in 110 kV grid can be expected. In the current case the power system losses (110 kV and 330 kV) have increased 2.3% compared to the base case.

There was only one line loading violation caused by the increase of load by the EVs, which occurred in the Pärnu County. During a fault on either of the lines that close the electrical loop inside the city, the lines feeding the mayor load centres suffer under overloading (see Fig. 6. and Fig. 7.).

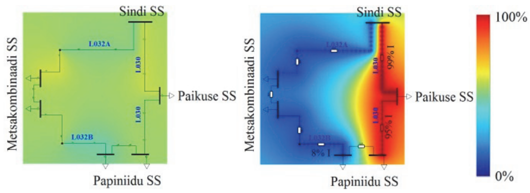

Figure 6. Loading of the lines before (left) and after (right) the fault on line L032A (screenshot from PSS/E).

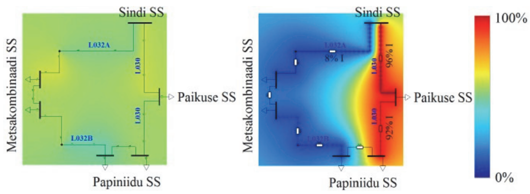

Figure 7. Loading of the lines before (left) and after (right) the fault on line L032B (screenshot from PSS/E).

The results also suggested that if the upper branch of the L030 line (between Sindi and Paikuse) should be faulty, then in certain situations the L032A/B lines would also over load. This is because the L032A and L032B lines use two different types of conductors. In order to solve this issue, the above shown electrical loop should be strengthened, which means reconstructing the lines to a higher transmission capacity.

Other issues found during modelling include power transformers, which can be conditionally divided into two categories. The first issue discovered is connected with the fact that in some SS the two transformers are with different MVA ratings. In the case when something should happen to the transformer with the higher rating, the smaller would overload. The second issue is simply tied with the MVA ratings of the transformers, which will over load in case there is a fault with the other transformer.

[5] The N-1 criterion describes the ability of the power system to lose an element (overhead line, transformer, generator, and etc.) without causing an overload or system failure elsewhere in the grid.
[6] Criterions are based on the national grid code.

C. *Modelling Results of the Uncontrolled Charging*

Generally, the increase of load in the system does not raise any additional issues. The voltages over the system have decreased slightly compared to the previous scenario but this increases the losses in the system by 3.1% compared to the base case scenario. No additional transformer or lines over loading issues were detected. Nevertheless, the Pärnu County's OHLs within the described city loop should be all reconstructed to a higher transmission capacity, as the increased load causes in any fault over loading on all of the lines. The voltage issue in the Jõgeva County addressed in the previous subsection has become more severe. Põltsamaa SS bus voltages will drop below the predetermined limit of 105 kV, in the case when the line L132C should encounters a fault (see Fig. 8.).

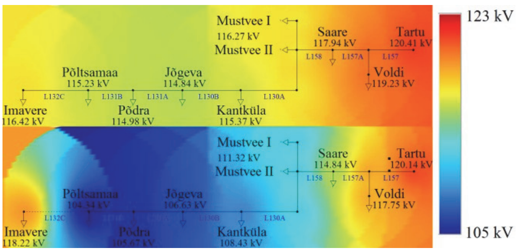

Figure 8. Voltages in the Jõgeva County before (uper) and after (lower) the fault on line L132C (screenshot from PSS/E).

In addition the results also indicated that one of the lines in the City of Tartu (in Tartu County) is reaching its transmission limit by loading in an N-1 fault up to 89%.

V. Conclusions And Future Work

The preliminary study has shown that with the EV integration remaining between 10% and 30% from the total passenger car fleet in Estonia would have minor impact on power system operation from a central point of view. Assuming that the main charging of vehicles is driven by the market price fluctuations, the largest impact on power system load will be dispersed over the night period, having a load levelling effect and the increase of peak load will be around 4%. However, if the charging would not be driven by the market price, then a slightly higher impact (around 5%) would occur and there would be no levelling effect on the load curve.

Taking into account the development plans of the Estonian TSO, coping with the possible increase of peak load in power system should not be a problem. Only minor local issues with transformers, line loading and voltages were discovered with the power system modelling, that should be considered. The problems should provide an additional input for the TSO in its development plans that could help them to further improve and optimize the system planning, especially from the voltage point of view. In addition, as this analysis only covers the transmission part of the power system, then this study and its results should be an interest also for the distribution system operator, as the impacts of load increase might be more important and with bigger impact than it has on the transmission level.

Although a majority has not shown a vast interest in EVs so far, the government policy and EU strategies are favouring this. In addition to the impacts analysed in this paper, a fleet of EVs this size should be taken as an opportunity to use them as a dispersed storage unit to provide certain short term system services. Future work of the authors will include a more detailed analysis of the load levelling and system service possibilities of the EV fleet in the power system.

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Paper IV

Uuemaa, P.; **Drovtar, I.**; Puusepp, A.; Rosin, A.; Kilter, J.; Valtin, J., "Cost-effective optimization of load shifting in the industry by using intermediate storages," *Innovative Smart Grid Technologies Europe (ISGT EUROPE), 2013 4th IEEE/PES*, pp.1,5, 6-9 Oct. 2013. doi: 10.1109/ISGTEurope.2013.6695404

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

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***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.

This study is supported by the European Social Fund's Doctoral Studies and Internationalization Programme DoRa, Estonian Archimedes Foundation programme "Doctoral School of Energy and Geotechnology II", the Estonian Ministry of Education and Research (Project SF0140016s11) and by the Estonian TSO, Elering AS.

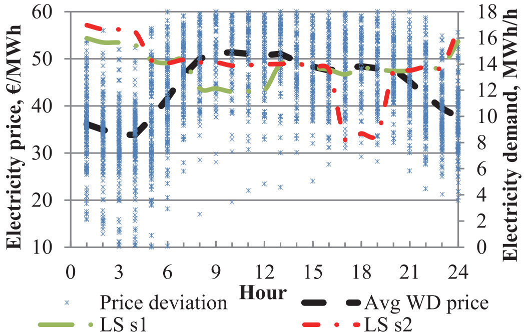

Figure 1. Dispersion of the stochastic market price allows two different load control methods; WD – work day, LS – load shift, s1 – scenario 1 and s2 – scenario 2.

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.

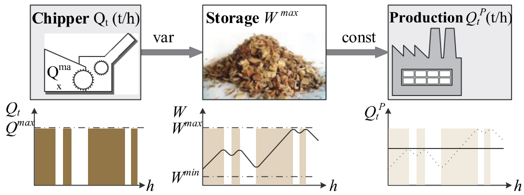

Figure 2. A wood industry's production process and the corresponding indicators (work cycle, storage capacity, final product output) and their correlation.

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).

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

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).

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

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).

$$0 \le Q_t \le Q^{\max}. \tag{3}$$

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).

$$W_{\min} \leq W_t \leq W^{\max}\ , \tag{4}$$

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.

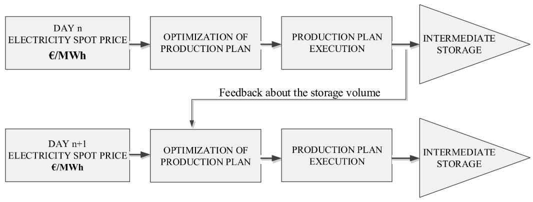

Figure 3. The simplified production control with day-ahead optimization of the wood chipper's operation schedule.

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.

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

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.

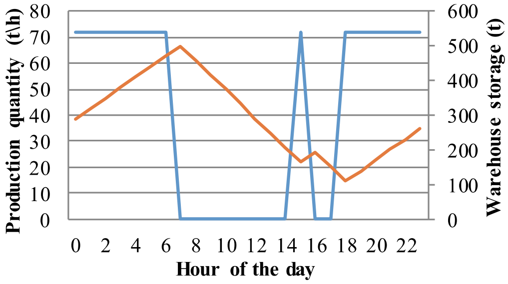

Figure 4. The optimized production characteristics with the changing storage volumes according to the sport market's average price (s1).

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.

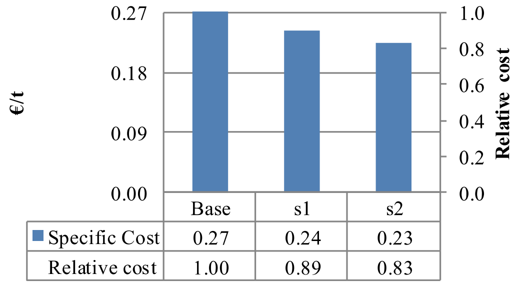

Figure 5. Comparison between different study cases; s1 – optimization based on historical market data, s2 – optimization based on day-ahead market data.

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.

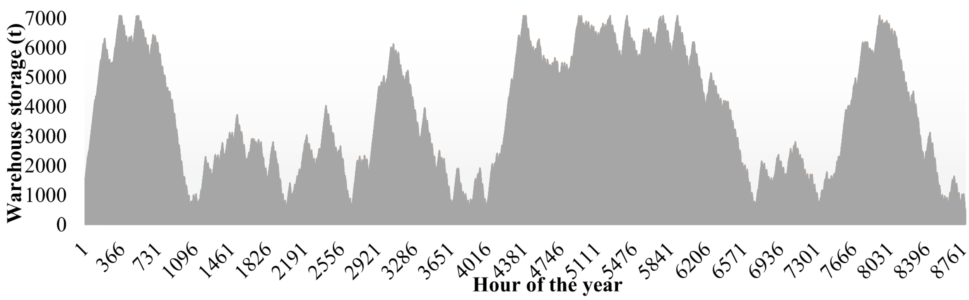

Figure 6. Warehouse storage dynamics according to s2 over on calendric year with preset storage limits and according to historical market data.

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.; Rosin, A.; Kilter, J., "Demand Side Management in Small Power Systems – The Estonian Case Study," *in ELEKTRONIKA IR ELEKTROTECHNIKA*, ISSN 1392-1215, pp. 13-19, vol. 22, no. 3, 2016.
doi: 10.5755/j01.eie.22.3.15308

http://dx.doi.org/10.5755/j01.eie.22.3.15308 ELEKTRONIKA IR ELEKTROTECHNIKA, ISSN 1392-1215, VOL. 22, NO. 3, 2016

Demand Side Management in Small Power Systems – The Estonian Case Study

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***Abstract*—The increasing amount of stochastic power generation connected to power system increases the need for additional ancillary reserves. Most of today's electricity consumers are relatively flexible and easily controllable, providing an already existing supplement for traditional power system ancillary services. The flexibility of loads depends on the number, type and size of consumers. In small power systems utilizing loads for power system services pose different challenges for the system operator than in larger systems. The main challenge lies in developing a business case and incentives for the customers to participate in such services. This paper discusses and analyses the Estonian three most energy intensive economic sectors potential for demand side response from a small power system point of view. Generally, it is determined that demand side flexibility provides incentives not only for the power system operator but also for the customer who is able optimize its processes to gain higher economic and energy efficiency and at the same time provide flexibility for the system operator.**

***Index Terms*—Load management; power grid; power system management; smart grids.**

I. INTRODUCTION

According to the European Union's Energy Efficiency Directive article 15.8, all member states are obliged to support access of demand side response (DSR) services providers to the electricity and ancillary service markets. The governmental regulatory institutions for the energy sector together with all market participants are required to work out the necessary technical requirements and parameters for enabling DSR services access to markets [1]. Currently from 28 member states only 5 have regulatory and/or contractual measures that allow or promote different DSR measures to be used for power system control. Finland, Belgium, Austria, Great Britain, Ireland, Germany and France are revising their legislation, which should promote the usage of DSR in those countries [2].

In comparison to the above listed countries, where peak demand can be measured in tens of gigawatts and population in tens of millions, the Estonian power system is a diminutive compared to them. The Estonian power system is operating in parallel with the integrated and unified power system (IPS/UPS) of Russia. In 2014, the total capacity of installed power plants was 2 713 MW, and the peak demand has stayed below 1 600 MW. Together with the other two Baltic States, Latvia and Lithuania, the total system capacity is approximately 6 GW and peak load 5 GW.

In the synchronous area of IPS/UPS the frequency control and its related reserves are maintained centrally in Russia. Although there are secondary and tertiary reserves within the Baltic States, then the required capacities are solidarily shared amongst all parties in the synchronous area to keep its operational and maintenance costs low. The increasing share of stochastic and weather-influenced generation in the system inevitably increases the need for additional balancing services to cover the possible mismatches between demand and supply. Using electrical loads as a source of flexibility is one way to solve the need for increasing reserves, however it will be challenging as due to the system's relative size the loads are small in unity and dispersed over the system.

The paper aims to discuss the unused technical potential and willingness from the consumers to provide DSR in small power systems. The results presented in this paper are the outcome of a two year research and cooperation with the Estonian large electricity consumers. Furthermore, as the Estonian power system operates synchronously with other Baltic States power systems, *i.e.*, Latvia and Lithuania, and is in many ways similar, the results and methodologies could be used as basis for future local and regional studies as well.

The paper has been divided into four major sections: the first provides an overview of the previous research and potential of DSR, the second discusses on existing regulation methods and capacities in Estonia, the third provides an assessment of methods used to map the DSR potential in small power systems, and the fourth section discusses and analyses the DSM potential available for power system support. Final section of the paper summarizes the results.

II. DSR AS A SOURCE OF FLEXIBILITY IN PREVIOUS RESEARCHES

In this paper the demand side management (DSM) and DSR use a classification according to the ENTSO-E's policy

Manuscript received 16 December, 2015; accepted 26 March, 2016.
This study was supported by the Estonian TSO, Elering AS and the Estonian Ministry of Education and Research (Project SF0140016s11).

paper for DSR [3] published in September 2014. DSR is load demand that can be actively changed by a trigger. DSM is the utilization of DSR for a purpose such as system security (*i.e*. balancing and congestion), or system adequacy.

Electrical loads are nowadays more predictable and controllable, giving a new opportunity to manage the power system all together through DSM *e.g*., to prevent outages in power system or participate in the system control (balancing), as well as optimal development of the network [4]–[6]. Torriti *et al*. in [7] give an overview of the DSR experience in different European countries. Recent developments have reshaped the DSR programs, which are starting to focus on commercial and residential customers rather than industries. For example the Electricite´ de France's Tempo tariff is one program that uses different prices according to the weather for small businesses and residential customers [8]. A Danish study determined to aggregate 260 MW (6 % of the Danish peak load) DSR loads from approximately 125 000 households with electric heating. The pilot study determined that a household could provide up to 5 kW of controllable loads per household [9].

Palensky and Dietrich in [10] 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. Bradley *et al*. in [11] bring out that deploying DSR 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 DSR 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. However, large scale participation in DSR may be low without the appropriate sharing of benefits among the parties. In addition, incentives are needed to lower the participation costs in such programs.

A. Services for the Transmission System Operator

As described in [3] DSR could offer the transmission system operator (TSO) additional ancillary reserve resource to securely integrate weather-influenced generation, maintain security of supply, and optimize the utilization of infrastructure and investments. However, in many cases loads are used as a last resort in emergency situations [3], [12]. On the other hand, investing in additional ancillary services power plants requires large investments into new generation that is needed for its power, not for its produced energy [13]. Besides balancing and shortage of power supply, the increasing renewable integration can lead to regional oversupply and the coinciding frequency and voltage instability problems [14], [15]. The following services through DSM would be of interest for the TSO.

Frequency control. DSR has the potential to cover several frequency reserve requirements. The authors of [15] and [16] bring out that DSR can make a significant and reliable contribution into primary frequency response through dynamic loading. The author in [17] proposes a method to implement industrial loads as frequency restoration reserves (FRR). FRRs are reserves that relieve frequency containment reserves (FCR) that are fast switching and aim to stabilize the frequency deviation [18]. In another paper [19] an approach for DSM was presented where only the secondary or non-essential loads were shed, *i.e.* boilers, refrigerators, heating, ventilation, and air conditioning (HVAC). As soon as the disturbance is over, the loads can be smoothly re-committed, skipping long restoration procedures.

Voltage control and stability is mainly affected by load when the power system is unable to meet the demand for reactive power. The phenomenon itself is mainly a local problem in the power system but can lead to system wide incidents [20]. According to [21] load characteristic is one of the most important factors affecting voltage stability. The variety of load types in the system enables the possibility to provide for example seasonal voltage control or other voltage stability related services through DSM.

III. ESTONIAN POWER SYSTEM REGULATION SERVICES

System services are technical measures for the electrical power system which ensure the reliability of the system, the security of supply, and power quality. System services include maintaining the frequency, ensuring the existence of reserve capacity, keeping the balance for active and reactive power, regulating voltage and other similar services.

Balancing services are power regulation actions covered by the TSO to balance out the shortfalls and excess of energy due to the actual market situations. These actions also include activating emergency reserves in case of cross-border link failures and generator outages. The services are ordered based on equal terms from the provider who offers the most techno-economically optimal price (pay-as-bid principle).

A. Historical Overview of Regulation Services

An overview of different regulation services (i.e. regulation capacities, occurrences and costs) is given for the Estonian power system over the period 01.01.2011… 30.10.2014. Although the analysis was done for both, up and down regulation, then it was determined by interviewing potential service providers that from the DSM point only up regulation (*i.e*. load shedding) is currently possible and therefore under discussion. Figure 1 illustrates the total requirement and total cost distribution for system services through up regulation over the period 2011 to 2014.

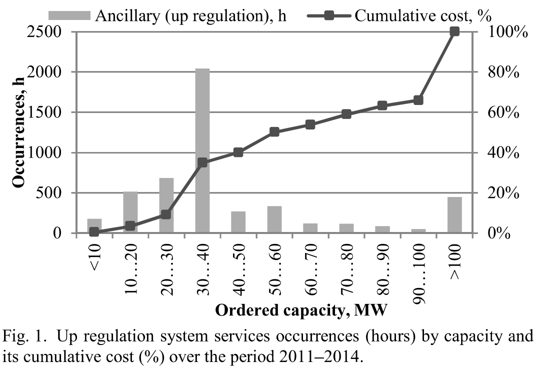

Fig. 1. Up regulation system services occurrences (hours) by capacity and its cumulative cost (%) over the period 2011–2014.

System services requirements have varied over the studied period significantly. In 2011 system services were ordered only on 264 hours, the following years, 2012 and 2013, it increased to 1 984 and 1 877 hours respectively, remaining around 1 000 hours in 2014. Majority of the ordered regulations remained below 40 MW and constituted merely 35 % of the total costs on system services through up regulation. The cost of MWh system service has increased over the observable period by 35 % to 71 euros but price variation range has doubled from maximum price of 65 euros to 126 euros.

On the other hand, the requirement for balancing services through up regulation and emergency reserves have stayed on a constant level or even decreased (emergency reserves). Up regulation have occurred around 600…700 hours in a year, 2012 being an exception with 320 hours. At the same time emergency reserve activation has decreased from 953 hours in 2011 to around 100 hours in 2014. Most (86 %) of the ordered regulations remained below 60 MW and constituted 72 % of the total costs for up regulation balancing services over the period from 2011 to 2014 (Fig. 2).

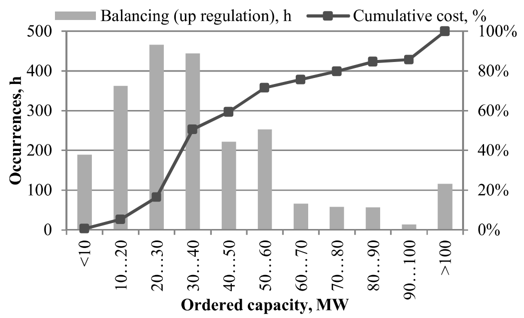

Fig. 2. Up regulation balancing services occurrences (hours) by capacity and its cumulative cost (%) over the period 2011–2014.

Half (55 %) of the required emergency reserve activations take place at capacities over 60 MW but 47 % of total cost is constituted by regulations over 100 MW (Fig. 3).

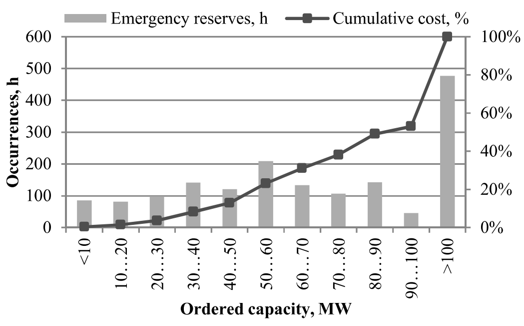

Fig. 3. Emergency reserves activations (hours) by capacity and its cumulative cost (%) over the period 2011–2014.

The cost of MWh balancing service has not changed significantly over the last four years remaining around 60 euros, also the price variation range does not indicate any significant changes remaining between 30 euros and 100 euros with an exception in 2013 when the price range was between 18 euros and 227 euros. The total cost of emergency reserves on the other hand has decreased compared to 2011 from 4.1 million to 1.4 million euros in 2012 and 2013. The first 10 months of 2014 indicate a further drop, remaining below 0.5 million euros.

From the analysis above it can be deduced that there is already today potential for the consumers to participate either for the balancing service or system service provision. 85 % of the balancing services and more than 60 % of the system services are order by capacities below 60 MW and 40 MW respectively. The cost of these services in the capacity range 40…60 MW over the last 4 years was approximately 9 million euros. Although the price per MW is low, the consumers have the possibility and potential to participate in these services.

B. *Technical Constraints*

Both, system and balancing services can be in theory also provided by consumers. However, due to technical limitations the Estonian TSO accepts regulating service offers starting from 5 MW (eligible 10 MW). In addition, all the offers have to be submitted two hours prior to the possible request for service. Single loads with such capacities are very rare in the Estonian power system and usually tied to an industry’s main process, thus making it uncontrollable from the customer’s point of view. Therefore the necessary load capacities for ancillary services could be aggregated from smaller controllable loads to meet the minimum criteria.

In the commercial sector case, total load shed cannot be discussed as the cost of lost man hours or working days is not rewardable through DSR. It should be noted that as a singular service provider these consumers are a minor players compared to the traditional service providers (i.e. power plants) and in addition the expected reward levels are far from today’s market situation where pay-as-bid system is used. Nevertheless, if they could be aggregated on a wider system level and a business case for motivating participation on such market would be in place, they could become quite competitive and eligible service providers.

In addition to the technical constraints, no means to aggregate or verify the ordered services exist. To implement DSR and DSM on a wider scale new information and communications technology together with market platforms need to be developed for controlling and managing these services. The main obstacle for today’s market is the service providers’ inability to aggregate consumers at any power/energy level to make the provided services easily accessible and verifiable for the necessary parties.

IV. Analysis of DSR Potential

In the following discussion the authors will mainly focus on the DSR in the industry, public and commercial sectors as they are seen as the most eligible service providers. The automation level and infrastructure needed for remote controlling is most probably already installed, meaning a relatively small need for additional investments. Households on the other hand are rather small unit consumers and would require bigger aggregation level and higher investments to provide the services under investigation for the TSO. In addition the households' electricity consumption and the willingness to allocate loads for DSR are more influenced by comfort and values rather than technical and economic feasibility. Therefore the analysis of the household consumer would be more of a social research rather than a techno-economic analysis. This section focuses on the aspects how to determine the DSR potential for different economic sectors where the initial investment for aggregation would be low and other measurable incentives for participation are available.

A. Control Methodology for DSR Loads

A classical large-scale electricity consumer is usually a business whose sole aim is to produce a profit to its owners. If DSR is deployed and the controllable load is critical for the business, then this might inhibit the primary goal of the business. Therefore, to implement DSR the risk of discomfort for the business owner should be minimized, otherwise the DSR development is halted.

Figure 4 illustrates as an example the results of a production process mapping with production capacity of each sub-process in an industry. As long as the most critical process's operation is guaranteed (in Figure 4 "Process 2"), the rest of the processes can be allocated for DSR. Minimizing the potential risks for the business owner can be achieved by utilizing the built-in intermediate storages as on-site energy storage to shift the electricity consumption of certain parts of the controllable process. The "electrical" storage capacity of such units is determined by the physical size of the intermediate storage and its coherence with the following sub-process [22]. The bigger the production capacity and the following intermediate storage of the optimizable sub-process are compared to the consecutive process, the longer it is possible to deploy DSR in that process.

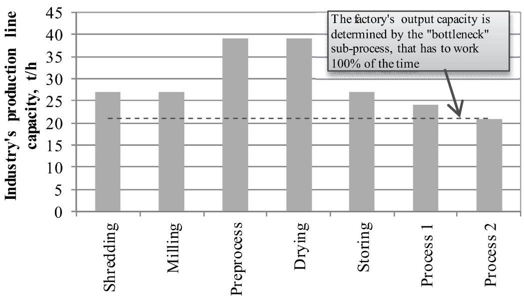

Fig. 4. Controllable loads and their potential for DSR.

Over the course of a related research [22], the authors determined a linear correlation between electricity consumption and product output in industries ($R^2 = 0.79$). The authors in [23] determined similar association between temperature and electricity consumption with a correlation factor $R^2 = 0.87$. In addition, it was stated that a 0.55 ˚C (or 1 ˚F) change in freezer zone air temperature would change the energy consumption of the analysed freezers air handler by approximately 50 kWh. At the same time other studies *e.g.*, [24] and [25] suggest an energy saving potential between 2 %…10 % with a 1 degree (˚C) temperature change. As there are not many processes to shift in the commercial and public institutions the main storage possibilities and therefore DSR potential lie in thermal storage and temperature control. These interdependencies provide the necessary bases for determining potential business cases for the consumers to motivate them participating in DSR and DSM.

B. Business Cases for DSR

In comparison to larger power systems, where DSR is measured in hundreds of megawatts and the rewarding system is in thousands of euros per megawatt, small power systems, such as Estonia, do not have the financial or technical potential to work on the same concepts. The business case for the Estonian customer should be based on other principles than the direct financial motivation of DSR and ancillary services markets in large power systems. Example business cases for different economic sectors are described in the following subsections.

Wood Industry

Depending on the produced goods, electricity cost can make up to 4 %…12 % of the manufacturing costs of the final product in the wood industry [26], [27]. One of the most perspective DSR measures is optimizing the factory's electricity costs according to the spot market price. This is considered to be one of the key elements lowering the production costs in the industry. The authors of [22] have determined that the electricity cost (E), which is a stochastic parameter, for a single load under investigation can be minimized according to scenarios s with (1)

$$\min_{Q_t} \sum_{s} \sum_{t} P_t^s \times C^L(Q_t) \times P(s) + C^E(Q_t), \tag{1}$$

where P_t is the electricity price for time period t, C^L is the output power of the load depending on the production volume Q_t, $P(s)$ is the probability of scenario s, and C^E is the external cost of the load shifting *e.g.* start-up costs, labor costs and *etc*.

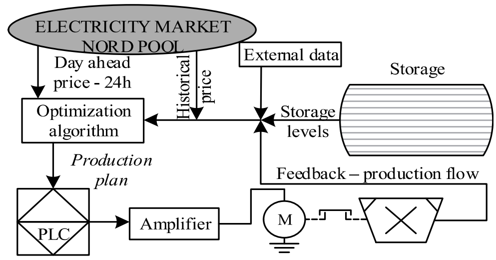

Fig. 5. A simplified production control with day-ahead optimization of the machines' operation schedule.

Two scenarios have been analysed for an industry. In the first scenario the production plan was adjusted according to the historical market prices. Since actual spot price dips and peaks might not be in the determined range and time then the second approach utilizes in addition the day-ahead price information. This enables the industrial consumer to use the most optimal production plan for the specific day. A simplified production control philosophy is illustrated in

Figure 5.

The authors of [22] determined that by applying the optimization according to the historical market price data, the load's annual electricity costs could be lowered up to 11 %. However, when implementing additionally the day-ahead market price optimization algorithm according to (1), the specific electricity cost of the studied sub-process could be lowered as much as 17 % compared to the base case. The same load control principle could be then applied for providing DSM.

Office Buildings and Shopping Centers

In the public (office buildings) and commercial (shopping centers) sector the business case is built solely on the concept of covering administrative charges (heating and ventilation related) through price based load control. Price based HVAC control is based on the principle that at higher price periods the air flow to the rooms is reduced or the cooling element is allowed to work at higher set-points *e.g.* the room temperature is kept between 20 ºC…26 ºC [28]. In case of controlling water heaters the water in the boilers has to be kept at least 55 ºC …60 ºC to prevent bacteria from growing [29].

The temperature control algorithm checks the actual hourly price against the last 24 hours average price. If the prices are equal, no control is performed, however if there is a price difference a new set-point is determined [30]. In shopping centers' the most probable controllable load was determined to be the central cooling station for the freezers and refrigerators, all other electrical loads (*i.e.* lighting, and *etc.*) were considered either as essential for operation or marginal to the possible effects.

The main constraint for DSM arises from the issue that loads allocated for DSR could be only switched to lower consumption profile in order to maintain the work of essential equipment and assure the minimal requirements for the safety, working environment and the comfort of the employees. However, it was determined that utilizing additionally a cold storage, the flexibility of freezers could be increased threefold.

V. Discussion of DSM Potential

Based on the interviews with the customers and analysis of the consumption data, the controllable loads are divided into three categories based on the industrial consumers. This assures that the customer would bare minimal losses when implementing DSM. Similar classification of loads will be used also to describe the other consumers potential for DSM.

"Freely" controllable load (FCL) is the load of the processes that can be allocated for DSM measures at any time. In the case of industrial consumer the load depends strongly on the load factor of the electrical machines, remaining around 50 %…60 % from rated power (P_N) for mechanical processes and can be calculated as follows

$$P_{FCL}^{DSM} = \sum_{m=1}^{n} (\sigma_m \times P_{N,m}), \tag{2}$$

where n is the total number of electrical drives in the process, σ_m represents the loading factor of the specific drive and $P_{N,m}$ is the rated power of the specific drive.

"Conditionally" controllable load (CCL) is the load of the processes that can be controlled under certain conditions or at certain times. This load depends from the process that runs with variable load, increasing under certain conditions the FCL service provision up to 40 %. CCL can be calculated as follows

$$P_{CCL}^{DSM} = \sum_{m=1}^{n} \left[(1-\sigma_m) \times P_{N,m} \right]. \tag{3}$$

"Exceptionally" controllable load (ECL) takes into account also loads that under normal condition are not controllable and can be allocated for control under extreme conditions *i.e.* load shedding during emergencies in the power system or when the service price is high enough to cover the expenses occurring with DSM measures.

A. Paper and Wood Industry

The main precondition for industrial consumers to partake in DSM is that the final production is not affected by it *e.g.* due to storage capacities after the controllable loads. The analysed wood industry's rated and theoretical potential for providing DSM measures with durations according to available storage capacities is summarized in Table I.

TABLE I. DSM POTENTIAL IN THE WOOD INDUSTRY.

Load shift, h	Estimated capacity (% of average consumption)			Total from average load
	FCL, MWh/h	CCL, MWh/h	ECL, MWh/h	
1	1.58 (66 %)	0.79 (33 %)	1.75 (73 %)	**173 %**
2	1.58 (66 %)	0.79 (33 %)	0.00	**99 %**
2-71	1.07 (45 %)	0.45 (19 %)	0.00	**64 %**
72-144	0.39 (16 %)	0.26 (11 %)	0.00	**27 %**

Based on the carried out interviews, analysis and measurements the authors estimate that on average the whole paper and wood industry could engage at least 20 % from their average electricity consumption in DSR, this estimation is also is affirmed in [31]. The study [31] brings out that every company in the Estonian wood and forestry sector has on average 27 % free unused production capacity (δ). This enables the industry to increase its production output for short periods of time higher than the usual production capacity, making it ideal for DSR and DSM.

From the available electricity consumption data for the wood and paper industry the total DSM potential can be then calculated. The calculations are based on the assumption that the industry is operated in a 24/7 regime and the DSM potential is calculated based on the industry's average hourly electricity consumption. These assumptions guarantee that the calculated capacities are available for short terms of period, *i.e.* 1…2 hours. The possible DSM potential of the whole industry is calculated as follows

$$\overline{P_{Industry}^{DSM}} = \frac{\delta}{m \times n} \sum_{j=1}^{m} \sum_{i=1}^{n} P_{i,j}, \tag{4}$$

where m represents the number of industries in the sector, n is the total number of hours used to determine average electricity consumption, $P_{i,j}$ represents the total electricity consumption for n hours at m industry companies, and δ is the reserve production capacity factor.

According to the estimation (4) it is possible that the Estonian wood industry can provide on average at least 22 MW of ancillary services and paper industry 8 MW. Results are summarized in Table II.

TABLE II. DSM POTENTIAL IN THE WOOD INDUSTRY.

	Estimated capacity, MWh/h (% of average load)		
	FCL	CCL	ECL
Paper	8 (**21%**)	3 (**8%**)	25 (**63%**)
Wood	22 (**66%**)	11 (**33%**)	25 (**74%**)

A rough estimation of DSM amongst Estonian industrial consumers is given by using (4). The estimation is based on the following assumptions:

- the industrial consumers are in continuous operation (24/7),
- the average hourly consumption is based on their total electricity consumption from public databases [32],
- the load is eligible for DSR for minimum 1 hour,
- the production lines are at least 20 % under loaded.

From this it can be estimated that the Estonian industrial sector would be additionally able to provide FCL up to 35 MW for ancillary services to the TSO through DSM.

B. *Office Buildings*

The DSM potential is based on the flexible load capacity factor φ as calculated in (5) and denotes the loads that can be flexibly controlled. Based on the electricity consumption of similar office buildings the possible DSM potential for 8/5 and 24/7 building is calculated according to (6):

$$\phi = \frac{1}{n}\sum_{i}^{n} \frac{P_i^1 + P_i^2 + ... + P_i^m}{P_i^{total}}, \tag{5}$$

$$\overline{P_{SC}^{DSM}} = \frac{\phi}{p \times o} \sum_{k=1}^{p} \sum_{j=1}^{o} P_{k,j}, \tag{6}$$

where n is the total number of hours used to determine average electricity consumption, m represents the number of different types of flexible loads available for control, P_i^{total} represents the total electricity consumption at hour n, $P_i^1 ... P_i^m$ represents the total flexible load at hour n, φ is the flexible load capacity factor, p represents the number of office building in the sector, o is the total number of hours used to determine average electricity consumption, $P_{k,j}$ represents the electricity consumption for o hours at p office buildings. The estimation (6) indicates that the Estonian public services sector would be able to provide for ancillary services over a period of 1 hour on average up to 86 MW of regulating power. Results are summarized in Table III.

TABLE III. TOTAL ESTIMATED DSM POTENTIAL IN OFFICE BUILDINGS (OB).

Duration of the control (h)	FCL (% of average load)	
	8/5 OB, MWh/h	24/7 OB, MWh/h
1	72 (73 %)	14 (14 %)
2…8	24 (25 %)	2.3 (2 %)

C. *Shopping Centres*

The study determined that using a cold storage and controlling the ventilation system according to the price, it would be possible to provide ancillary service power in shopping centers up to 2 hours and 34 % from the average consumption capacity. For a period of 3…8 hours it would be possible to allocate 24 % from the average consumption capacity and 9…13 hours approximately 16 % from the average consumption capacity. The total DSM potential with or without cold storage can be estimated in a similar manner as for office buildings with (5) and (6). The results are summarized in Table IV.

TABLE IV. TOTAL ESTIMATED DSM POTENTIAL IN SHOPPING CENTRES.

Duration of the control (h)	Flexibility with storage (% of average consumption)		Flexibility without storage (% of average consumption)	
	FCL, MWh/h	ECL, MWh/h	FCL, MWh/h	ECL, MWh/h
1…2	26 (**34 %**)	8 (**10 %**)	7 (**9 %**)	9 (**12 %**)
3…8	18 (**24 %**)	8 (**10 %**)	0	9 (**12 %**)
9…13	13 (**16 %**)	0	0	1 (**2 %**)

It should be noted that due to nature of the controlled loads demand shifting with cold storage would increase the additional power requirement and thus the average electrical consumption outside the DSM measure timeframe 1.5 times.

VI. CONCLUSIONS

The possibilities to use different consumers' loads for DSR and DSM were discussed. An analysis of the Estonian power system regulation services indicated that although there are some technical limitations for implementing DSM then actually it is already today possible to incorporate electricity consumers to the system service provision. Majority of the required capacities remain below 40 MW …60 MW. The analysed samples of loads could possibly provide a high durational range of services for the TSO. The total DSM potential estimation is summarized in Table V.

TABLE V. TOTAL ESTIMATED DSM POTENTIAL IN ESTONIA.

Sector	Average controllable load in one hour, MWh/h (% of average consumption)
Industry	65 (**26%**)
Offices (24/7)	14 (**14%**)
Offices (8/5)	72 (**73%**)
Wholesale and retail buildings	7…26 (**9...34%**)
TOTAL	**158…177 (18...20%)**

The largest potential for DSM is seen in the industrial sector, due to the relatively large unit consumers that can be allocated for aggregated control comparatively easy. In addition, the industry's production line is usually segmented allowing more flexibility for control. Also the high level of automation in the industry allows performing aggregation with relatively low costs. It is estimated that controllable DSR load in the industry can be around 65 MW, from what approximately half originates from the wood and paper industry. The controllable load potential in the commercial and institutional services sector (shopping centres and office buildings) remain between 93 MW…112 MW, depending on whether cold storage is implemented or not. This 93 MW can be provided steadily throughout the year. The largest potential constitutes from 8/5 type office buildings.

The analysis indicates that if DSR could be implemented for providing system services, the potential of DSM would be in the range of 160 MW…180 MW. The analysis determined that the average price for emergency, ancillary and balancing reserves in Estonia has stayed in the recent years between 50 euros…80 euros per MWh and it occurs around 2 200 times (hours) per year. In the assumption that on average up to 150 MW of DSR capacities could be provided for the region's ancillary services markets at least 1 hour…3 hour a day, then only the Estonian DSM market value would be up to 13 million euros.

Future work will focus on the analysis and modelling of possible voltage control related DSM services in small power systems. The aim of the study should determine the potential influence of load related voltage regulation services for the TSO. These should be at least in theory economically more feasible alternatives for voltage regulating devices that are required seasonally or on rare occasions.

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Paper VI

Uuemaa, P.; Puusepp, A.; **Drovtar, I.**; Valtin, J.; Kilter, J.; Rosin, A., "Load control implementation in the energy intensive industry," *Mediterranean Electrotechnical Conference (MELECON), 2014 17th IEEE*, pp.213,218, 13-16 April 2014. doi: 10.1109/MELCON.2014.6820534

17th IEEE Mediterranean Electrotechnical Conference, Beirut, Lebanon, 13-16 April 2014.

Load Control Implementation in the Energy Intensive Industry

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***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.**

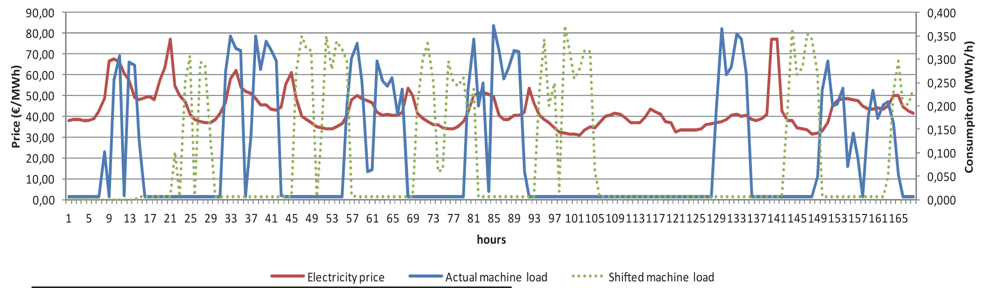
***Keywords* --Demand side management; load control; price based control of industrial processes; load shifting; peak demand.**

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.



This study is supported by the European Social Fund's Doctoral Studies and Internationalization Programme DoRa, Estonian Archimedes Foundation programme "Doctoral School of Energy and Geotechnology II", the Estonian Ministry of Education and Research (Project SF0140016s11) and by the Estonian TSO, Elering AS.

978-1-4799-2337-3/14/$31.00 ©2014 IEEE

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].

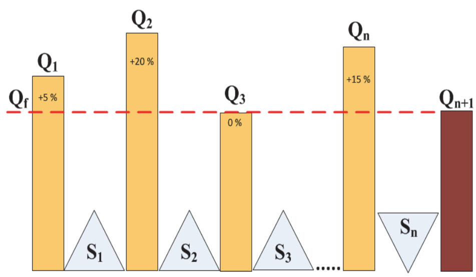
The current study is focused on optimizing the timing of a production process according to the market price. The process under investigation is the industry's production line which consists of several machine groups like chipping, drying milling, and etc. All these sub processes are considered as a single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

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

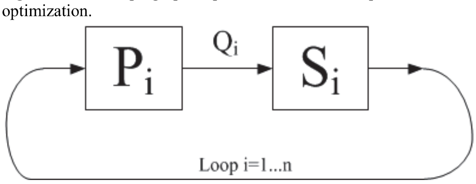
where $P(s)$ is a probability of the scenario s.

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):

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

Also the following conditions need to be fulfilled.

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

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

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

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

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.

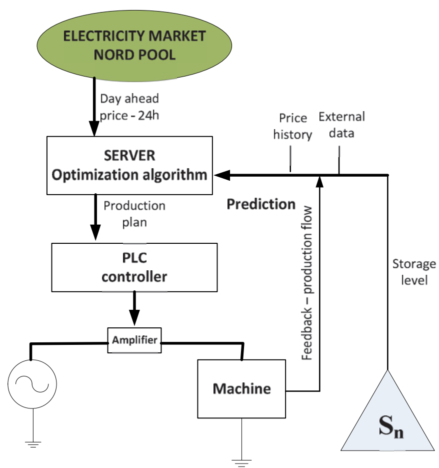
The subsystems of the process can be divided by the type of the consumers. The loads that act as a single cycle, which cannot be separated, form a controllable load. The single loads which have the medium storage between them do not depend from each other and therefore can be considered as a single aggregated 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.

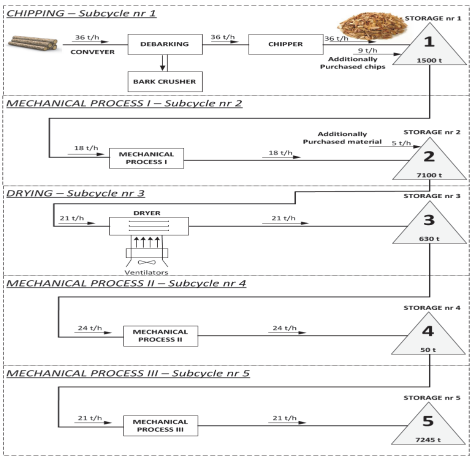
B. Wood Industry - Case Study

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^{t}). 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)	Controllable	Production capacity (t/h)	Additional purchase (t/h)	Storage (t)	Storage (h)	Energy consumption (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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