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Profitability of combined heat and power plants to participate in electrical power reserve markets

Juha Haakana, Jarmo Partanen, Ville Tikka and Jukka Lassila
Lappeenranta University of Technology
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Lappeenranta University of Technology
P.O. Box 20
FI-53851 Lappeenranta, Finland

LUT School of Energy Systems
Tel. +358 294 462 111
Fax. +358 5 411 7201

www.lut.fi
Business ID 0245904-2
VAT FI 02459042

Preface

This report includes the results of the work done as part of the project BEST (Sustainable Bioenergy Solution for Tomorrow). This work was done between during 2015 by the Electricity Market and Power Systems Research Group at Lappeenranta University of Technology (LUT), comprising Professor Jarmo Partanen, D.Sc. Juha Haakana, M.Sc. Ville Tikka, and D.Sc. Jukka Lassila.

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The Authors

Contents

1 Introduction

In the future electrical power production is based more on renewable energy sources such as solar, wind and biomass. Figure 1 and Figure 2 present different scenarios for photovoltaic and wind power production. Mutual for these are the estimated increase of installed capacity that seems to increase rapidly before 2030. This is good for the sustainability of the system. However, variation of power production will be high in solar and wind power plants that cause challenges for the electrical system. In the system the power production and consumption has to be in balance, and this is challenging to be arranged when the power production and consumption fluctuates. Thus, the electrical system has to contain balancing power to be able to respond to power fluctuation arising for instance from renewable power production or failure in the system. The power plants, which can regulate the output of electrical power, are vital for the electrical system. Example of controllable power plant is biomass based combined heat and power (CHP) plant. However, at present the benefits of CHP plants in power balancing are not utilized maximally.

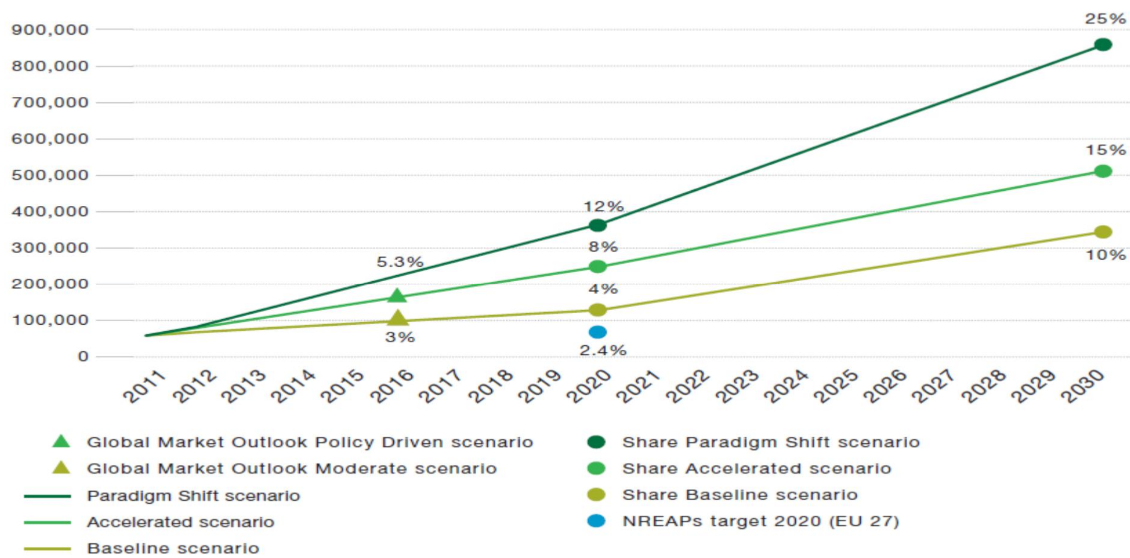

Figure 1. Projected penetration of PV in Europe until 2030 (MW) (EPIA 2012).

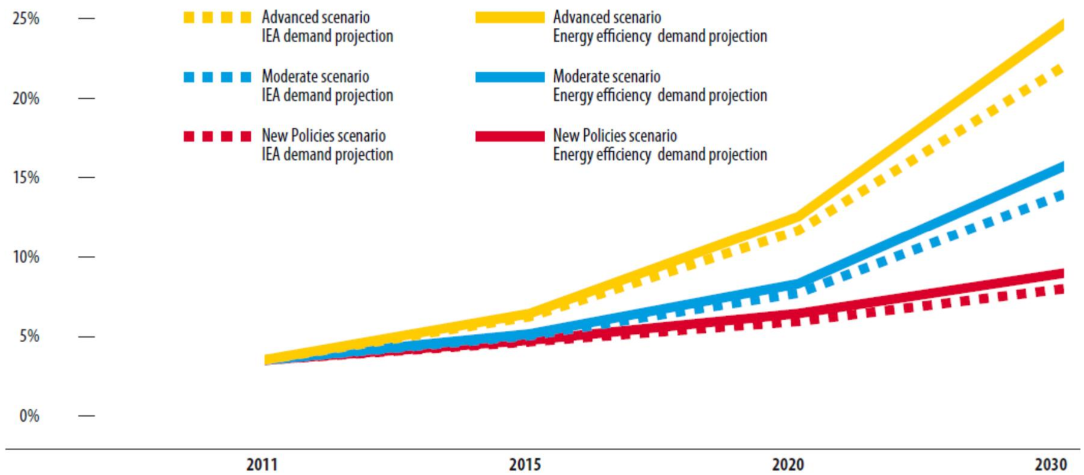

Figure 2. Wind Power proportion of global electricity demand until 2030 (GWEC 2012).

The motivator for increasing capacity of solar photo voltaic (PV) production is the decreasing costs of the PV panels. Within the past ten year period the PV prices have decreased from 5 000 €/kWp to level of 1 500 €/kWp. This is such a price that provides electricity end-users motivation to invest in PV without subsidies. The price trend of PVs (2006–2014) is illustrated in Figure 3. Different scenarios of PV in Europe have been presented in Figure 1. It shows that PV capacity is estimated to increase considerably next 15 years.

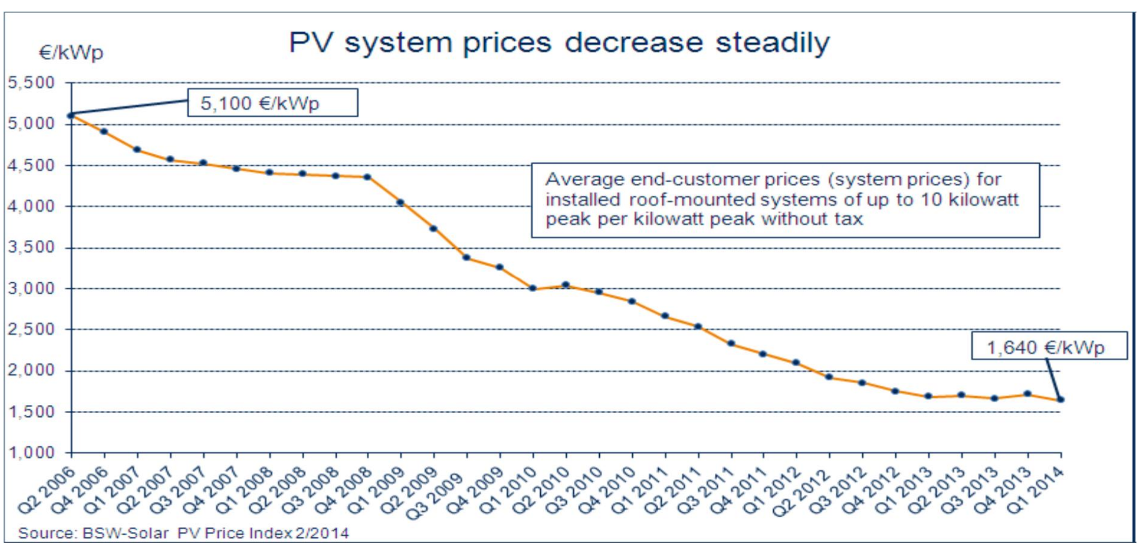

Figure 3. Price trend of PV panels between years 2006 – 2014 (BSW-Solar 2014).

2 Energy and power markets

The study is based on goal to maximize profit of CHP operator. The approach aims to find the best combination of both heat and electrical markets. The heat market provides stable revenue for the operator and electrical markets provide extra return of investment. The considered electricity markets in the study are Elspot market and frequency containment reserve (FCR) markets FCR-N that is the market to stabilize normal fluctuation of frequency and FCR-D market that is the market to response to unexpected frequency drops deriving, for instance, from sudden shortage in electrical power production. Reserve market products in Finnish electricity markets provided by Fingrid are shown in Figure 4.

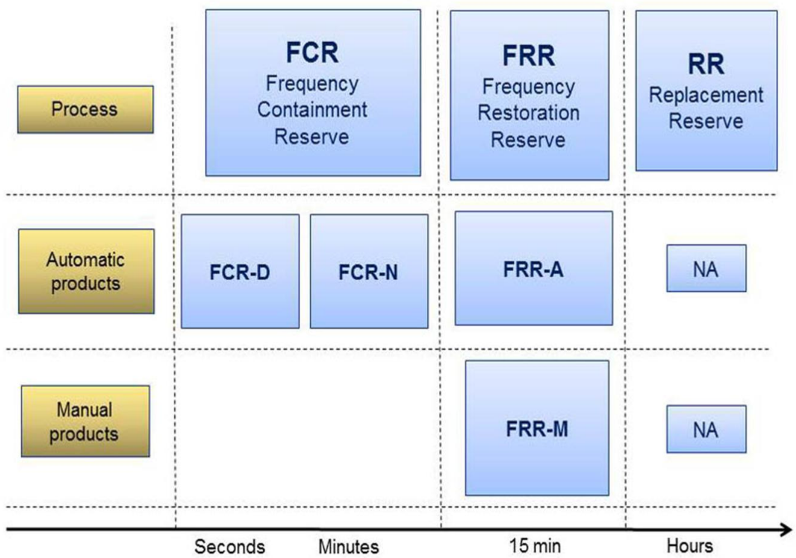

Figure 4. Electricity market products provided by Finnish national transmission system operator Fingrid. (Fingrid 2015a)

Elspot market is hourly day-ahead market provided by the Nordic electricity stock exchange Nordpool. Elspot market defines different price for each hour so that the market closes previous day at 13:00 Finnish time and the Nordpool publishes the accepted offers approximately at 14:00 Finnish time. The minimum offered capacity to Elspot market is 1 MW and the steps are 1 MW.

2.1 Frequency containment reserves

Frequency containment reserve (FCR) markets are both hourly and annual. In this study only the hourly market is considered. The FCR market is divided to two different market, which are normal market (FCR-N) and disturbance market (FCR-D). The operational boundary conditions for the use of FCRs are determined in the FCR agreement. For instance it determines the boundary values when the reserves have to start the operation. Both FCR-N and FCR-D are automatically adjustable reserves which react automatically if the system frequency exceeds the threshold. The FCR market closes previous day at 18:30 Finnish time. Thus there are few hours to do FCR-N and FCR-D offers after the Elspot offers are accepted.

2.1.1 FCR-N

The frequency containment reserve is the first reserve used to balance fluctuation in system frequency. The agreement of FCR determines that FCR-N has to respond to frequency fluctuation when frequency $f < 49.95$ Hz or $f > 50.05$ Hz. The full capacity of FCR-N has to be in use when $f \leq 49.90$ Hz or $f \geq 50.10$ Hz (Fingrid 2015b).

Minimum offered capacity to participate in FCR-N market is 0.1 MW and maximum capacity per one operator is 5 MW. At present to be able to participate in FCR-N market the operator has to provide both power up and down regulation. FCR-D

Disturbance reserve is the fast reserve to power up regulation that has to respond quickly to rapid frequency drops. The minimum capacity to participate in FCR-D market is 1 MW and maximum capacity per one operator is 10 MW. The operation of disturbance reserve has to begin when frequency decreases below 49.90 Hz. Moreover, the agreement determine that the full capacity has to be in operation when frequency is 49.50 Hz (Fingrid 2015b).

2.2 Participation to frequency regulation markets

Frequency of electrical power system variates in relation of power balance. When the power consumption is higher than production, frequency starts to decrease. When the power consumption is lower than production, frequency starts to increase. Frequency statistics of year 2013 are shown in Figure 5.

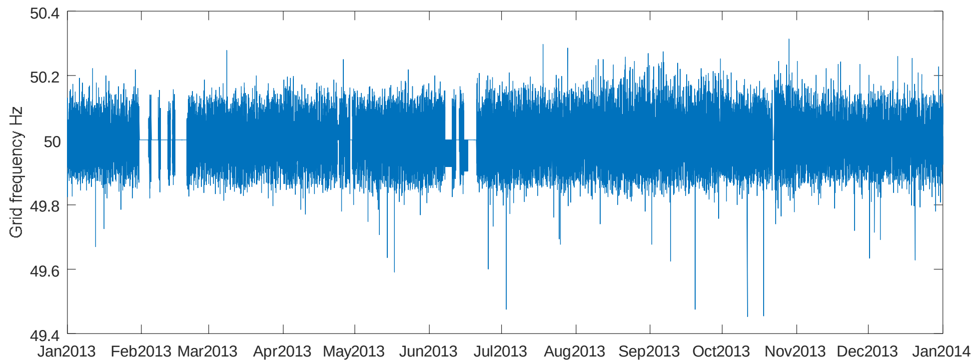

Figure 5. Measured frequency in electricity transmission system in 2013.

The data contain some periods when the frequency is not registered, and thus these periods are not taken into account in the study. However, the lengths of unregistered periods are relatively short. The figure shows that frequency remains most of the time between 49.85 and 50.15 Hz. Because of the fast changes in the frequency, the accurate distribution cannot be seen from Figure 5. Thus, it has been shown in Figure 6. It shows that most of the time frequency is between 49.95 and 50.05 Hz. This is also confirmed by the standard deviation that is approximately 4% each considered year.

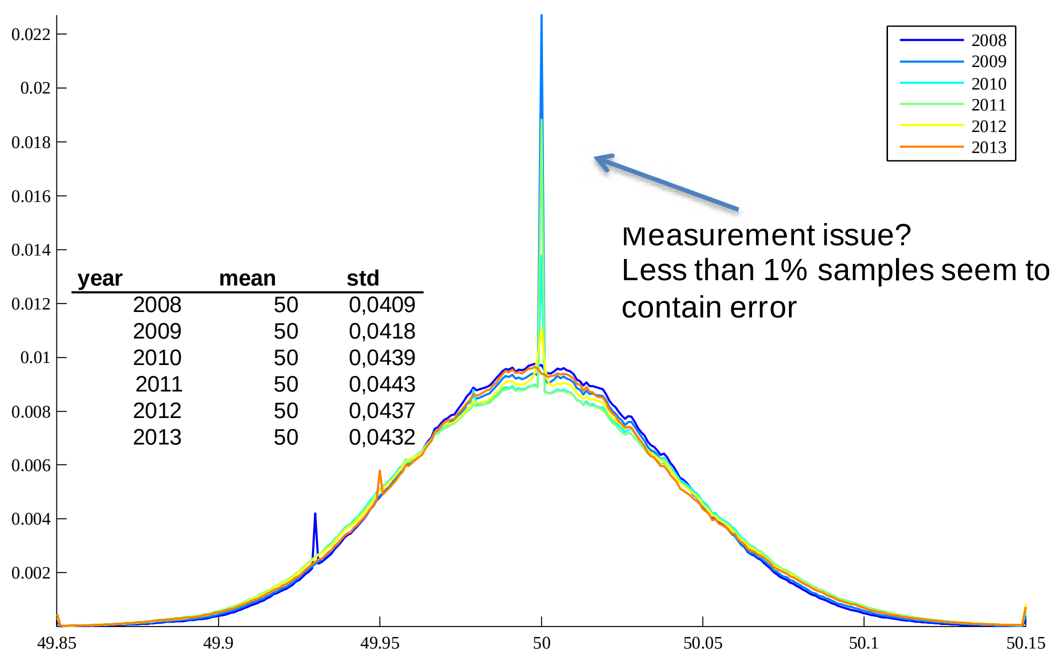

Figure 6. Distribution frequency in years 2008–2013.

The exceedings of the boundary values for FCRs given in section 2.1 are presented in Table 1. It can be noticed that frequency is either below 49.95 or above 50.05 Hz almost each hour during the year that means the operation of FCR-N. Moreover, it can be seen that frequency is below the limit 49.90 Hz almost 1/3 of the hours that means the operation of FCR-D.

Table 1. Numbers of exceeding the frequency limits.

	Occurrences (days) per year	**Occurrences (hour) per year**	
$f < 49.5$ Hz	4	4	few times per year
$f < 49.9$ Hz	341	2552	1/3 of hours
$f < 49.95$ Hz	344	6773	~every hour
$f > 50.05$ Hz	345	6576	~every hour

2.3 Prices in electrical markets

Prices of Elspot, FCR-N and FCR-D in years 2013 and 2014 are presented in Figure 7 - Figure 9. Elspot price is most of the time below 50 €/MWh (averagely 41.2 €/MWh). There are few price spikes but they are relatively rare. Variation of reserve market prices seems to be higher. For instance, in 2013 the prices have fluctuated from the beginning of April to end of August. Also it can be seen that the prices are the highest at the summer time.

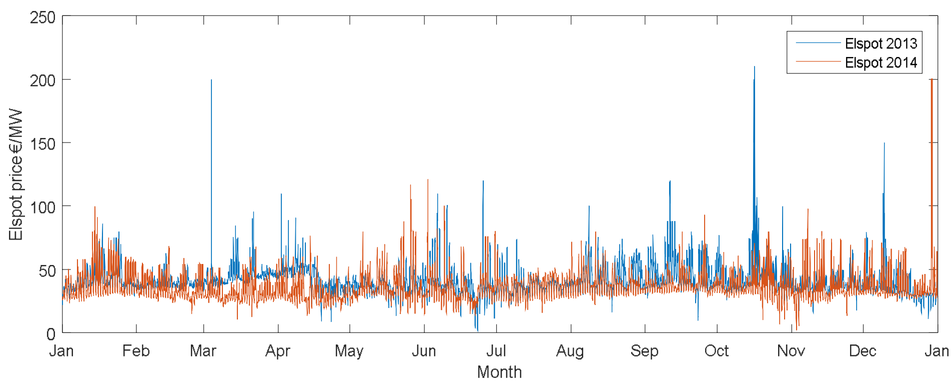

Figure 7. Elspot price in 2013 and 2014 (Nordpool).

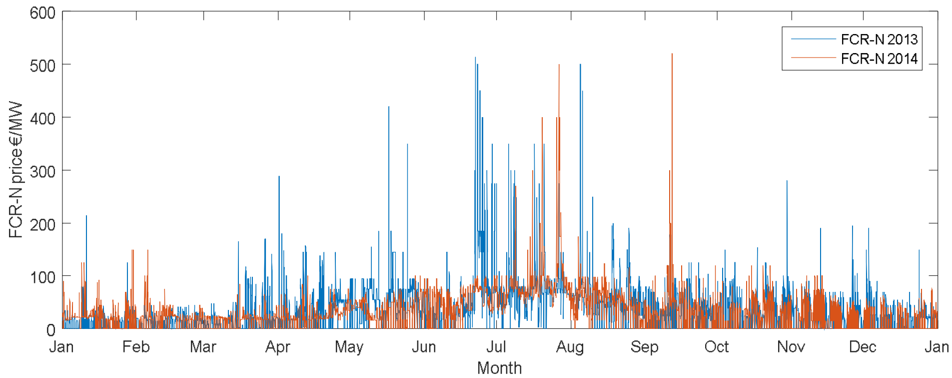

Figure 8. Price of frequency containment reserve in normal operation (Fingrid 2015c).

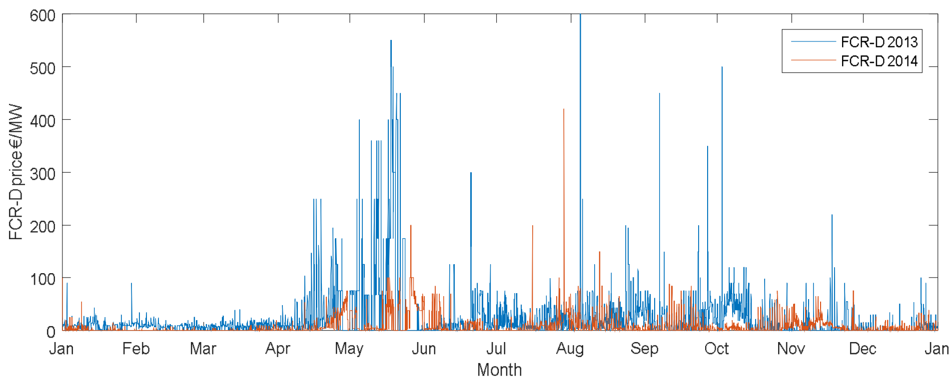

Figure 9 Price of frequency containment reserve for disturbances (Fingrid 2015c).

It can be seen from Figure 7–Figure 9 that the prices are averagely higher in each considered markets in year 2013 compared with year 2014. The average prices are presented in Table 2.

Table 2. Average prices in Elspot, FCR-N and FCR-D markets in years 2013 and 2014. FCR-N available and FCR-D available are the average prices of hours when the price is over zero i.e. on the market is required more regulation capacity.

	Elspot €/MWh	**FCR-N €/MW**	**FCR-N available €/MW**	**FCR-D €/MW**	**FCR-D available €/MW**
2013	41.2	36.3	50.8	23.4	32.1
2014	36	31.9	45.9	8	16.7

3 Operation simulation of CHP power plant

The operation of CHP power plant is simulated by a time series simulation model. The simulation is based on price statistics of years 2013 and 2014. The data consist of prices of Elspot market, FCR-N market and FCR-D market. The simulation is built in Matlab using Simulink libraries. The Simulink model is presented in Figure 10.

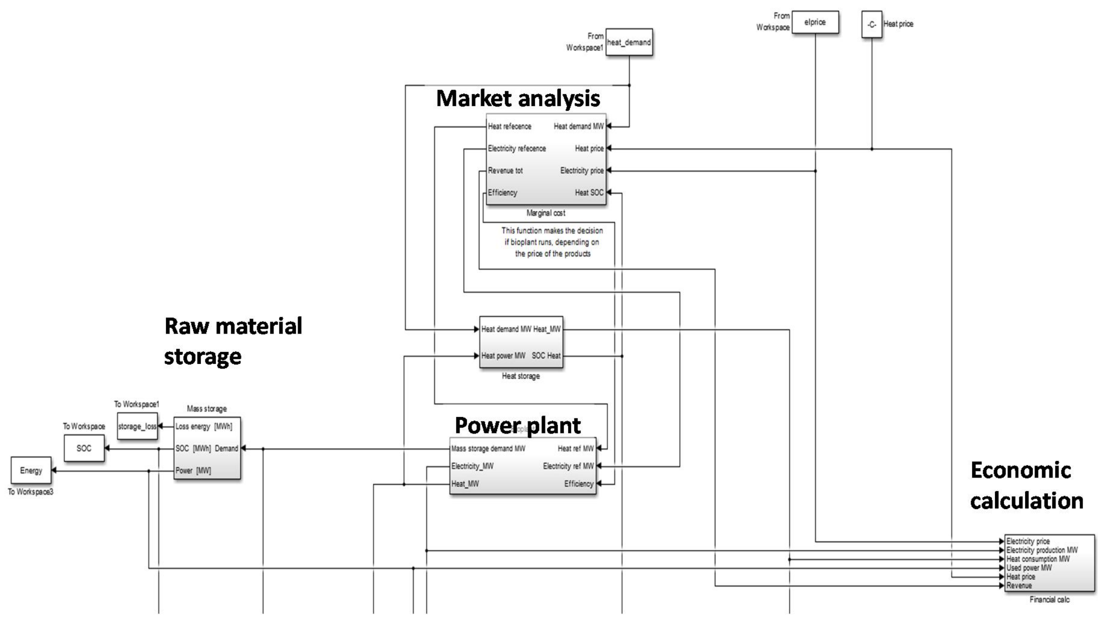

Figure 10. Simulation of model of CHP plant in the study.

3.1 Background study and assumptions of CHP plant

Study contains several assumptions such as price of heat and different efficiencies which are based on typical performance of CHP plants. The analysis is carried out for a 20 MW boiler powered CHP power plant. Parameters have listed as follows:

- Heat price is assumed constant 40 €/MWh
- Maximum efficiency of boiler 85% (Maximum output power 17 MW)
- Maximum efficiency of electricity production 30% (Maximum electricity output 6 MW)
- Minimum load of boiler in electricity production 60% (Minimum load 12 MW to produce electricity)
- Minimum load of boiler in pure heat production 30% (Minimum load 6 MW to produce heat)

- Rate of power change per time unit 1 MW / 10 minutes (when the output power rises, the boiler has to increase production beforehand)
- Power plant uses woodchips as raw material (24 €/m^3, 0.9 MWh/m^3)
- Raw material is stored for two week time period
- Losses of raw material (decay of woodchips in the material storage) is assumed to be 1% per week

Table 3. Efficiency characteristics of the example CHP plant (20 MW).

Heat power [MW] \ Electrical power [MW]	0	0.5	1	1.5	2	2.5	3
0	0 %	8 %	17 %	25 %	30 %	30 %	30 %
0.5	17 %	17 %	25 %	33 %	38 %	36 %	35 %
1	33 %	25 %	33 %	42 %	45 %	42 %	40 %
1.5	50 %	33 %	42 %	50 %	53 %	48 %	45 %
2	67 %	42 %	50 %	58 %	60 %	54 %	50 %
2.5	83 %	50 %	58 %	67 %	68 %	60 %	55 %
3	85 %	58 %	67 %	75 %	75 %	66 %	60 %
3.5	85 %	67 %	75 %	83 %	83 %	72 %	65 %
4	85 %	75 %	83 %	85 %	85 %	78 %	70 %
4.5	85 %	83 %	85 %	85 %	85 %	84 %	75 %
5	85 %	85 %	85 %	85 %	85 %	85 %	80 %
5.5	85 %	85 %	85 %	85 %	85 %	85 %	85 %
6	85 %	85 %	85 %	85 %	85 %	85 %	
6.5	85 %	85 %	85 %	85 %	85 %		
7	85 %	85 %	85 %	85 %			
7.5	85 %	85 %	85 %				
8	85 %	85 %					
8.5	85 %						

Best operation area

3.2 Utilization of reduction to improve opportunities of CHP plant

Reduction capability of CHP plant provides a new opportunity to make business with CHP plants. Usually the feature is not used in daily operation. Reduction makes it possible to change the ratio between heat and electricity production so that electricity output can vary between 0% and 100%. This is a precondition to participate in electricity reserve markets.

Traditionally the operation of CHP plant is planned so that full capacity of electrical power is generated from the steam processed in the boiler. However, a better profit may be provided for the CHP plant if it participates in electricity reserve markets. This is arranged by the reduction of the process. For instance, the plant offers only 50% (reduction 50%) of electricity capacity to electricity market (Elspot) and the rest capacity is sold as heat to district heat system. In this case, the rest capacity of electricity production (50%) remains in reserve and it can be transformed to electricity if the electrical system needs up regulation. In this case (up regulation) the reduction can be even 0% if the frequency falls below 49.90 Hz. Up regulation causes deficit to heat network, but averagely this is not a problem because in reserve market operation exists also the opposite functioning when the reduction has to be increased from 50% to 100%. This function is required when the electrical system needs power down regulation. An example of CHP plant operation is shown in Figure 11.

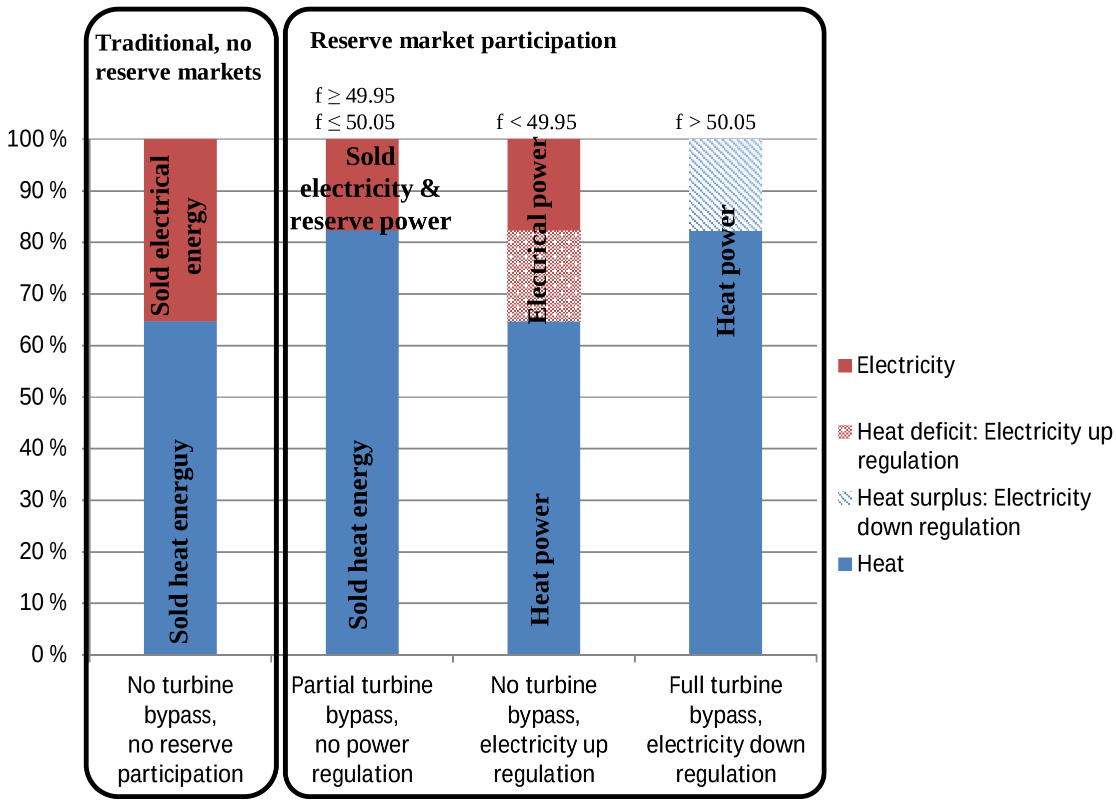

Figure 11. Different operation scenarios for CHP plant. 1) Traditional operation without electrical power reserve market participation that makes possible to produce electricity with max power-to-heat ratio, 2) Participation in reserve markets, when the power-to-heat ratio is selected so that electrical power output is restricted in normal operation by partial turbine bypass.

3.2.1 Co-operation with district heating system

District heating system provides a good buffer to changes in heat production. For instance, typically the district heating system can easily store energy corresponding heat demand of one hour. Thus, the capacity of district heat system provides opportunity to operate CHP plant in electricity reserve markets.

3.3 Participation procedure to energy markets

Principled procedure to participate electricity markets follows next steps, which are based on market analysis to get best profit for the operation:

- Heat production is carried out based on assumed heat demand curve
    - If heat demand is low, power plant is shut down
- 50 % of the maximum electricity capacity is offered to Elspot market with the marginal cost price
    - If the Elspot offer is accepted, the rest 50 % electricity capacity can be offered to reserve markets (FCR-N) with the marginal cost price
        - If the power plant operates with full power, the marginal cost is zero
        - If power plant operates with partial power, several offers can be played to market based on different marginal costs
    - If the Elspot offer is not accepted, the full electricity capacity can be offered to reserve markets (FCR-D) with the marginal cost price
        - If the power plant operates with full power, the marginal cost is zero
        - If power plant operates with partial power, several offers can be played to market based on different marginal costs
- Electricity derivative market is neglected in the analysis

Participation to heat market is modelled based on heat demand curve that is shown in Figure 12. The demand curve illustrates the variation of temperatures.

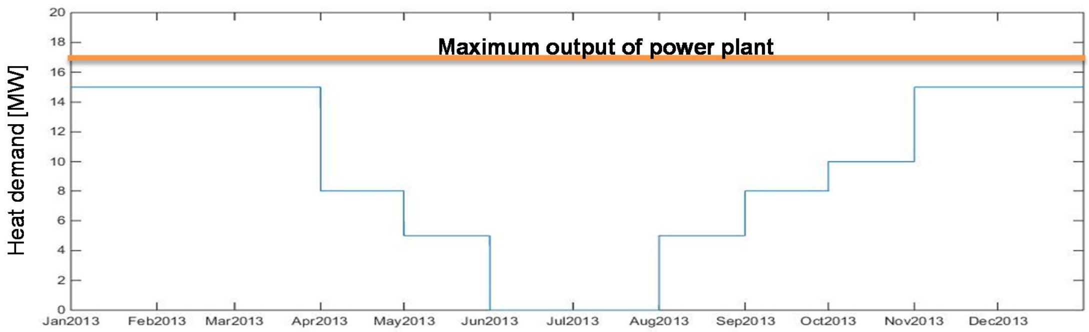

Figure 12. Heat demand curve.

4 Result of simulation

Study shows that CHP plants may have preconditions to participate on electrical power reserve markets. Table 4 illustrates the participation of the example CHP plant to different power and energy markets in years 2013 and 2014. It can be observed that year 2013 provided better profitability to participate in Elspot markets. This effects also on FCR-N market participation because the power plant also requires base power production that can be down regulated. Also the profitable hours to participate in FCR-D market exist more in year 2013.

Table 4. Participation in different power and energy markets in years 2013 and 2014.

	Heat (h)	**Elspot (h)**	**FCR-N (h)**	**FCR-D (h)**
2013	7296	5538	3513	2265
2014	7296	3512	2396	1165

Figure 13 presents the participation of CHP plant in FCR markets. It shows the sold balancing reserve for each hour in year 2013. Down regulation proportion (below zero) consists only of FCR-N but up regulation reserve is sum of both FCR-N and FCR-D. It can be seen that the provided FCR capacity is mainly between -2 and 2 MW. Moreover, the pure up regulation reserve FCR-D is focused more on winter time between November and March.

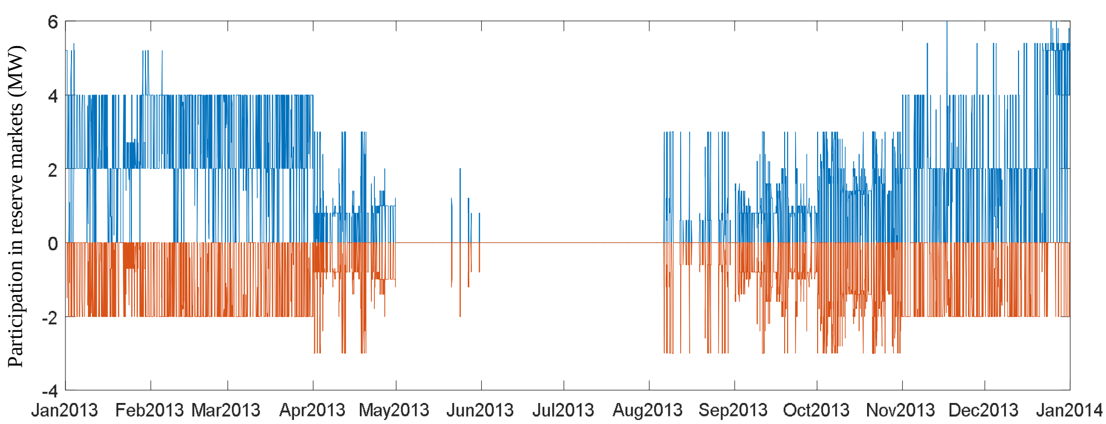

Figure 13. Participation in electrical power reserve markets in year 2013.

The operation in FCR markets is illustrated in Figure 14 that shows the regulation power provided by the CHP plant in the simulation. The simulation shows that provided FCR-N reserve is often fully used so that both down and up regulation is required to balance the electrical system frequency. Furthermore it can be seen that even the CHP plant participates in FCR-D reserve, the operation of FCR-D reserve does not realize often, at least with full capacity. For instance, within the considered year 2013 the highest operated FCR-D balancing power is 1.6 MW when the highest sold FCR-D capacity is 6 MW.

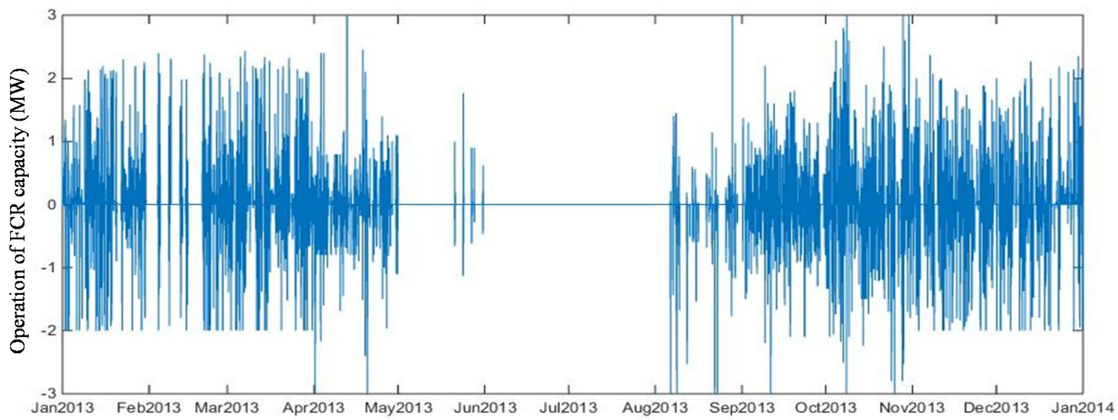

Figure 14. Operation in FCR-N and FCR-D markets.

4.1 Example day

An example of simulated daily (4.2.2013) participation in FCR markets is presented in Table 5. It can be seen that the sold FCR-N capacity is 2 MW excluding the first and last hours of the day and the FCR-D capacity is 2 MW for each hour.

Table 5. Simulated participation of CHP plant to frequency containment reserve (FCR) markets in the example day.

	FCR-N	FCR-D		FCR-N	FCR-D
4.2.2013 0:00	0.2	2	**4.2.2013 12:00**	2	2
4.2.2013 1:00	2	2	**4.2.2013 13:00**	2	2
4.2.2013 2:00	2	2	**4.2.2013 14:00**	2	2
4.2.2013 3:00	2	2	**4.2.2013 15:00**	2	2
4.2.2013 4:00	2	2	**4.2.2013 16:00**	2	2
4.2.2013 5:00	2	2	**4.2.2013 17:00**	2	2
4.2.2013 6:00	2	2	**4.2.2013 18:00**	2	2
4.2.2013 7:00	2	2	**4.2.2013 19:00**	2	2
4.2.2013 8:00	2	2	**4.2.2013 20:00**	0	2
4.2.2013 9:00	2	2	**4.2.2013 21:00**	0	2
4.2.2013 10:00	2	2	**4.2.2013 22:00**	1.5	2
4.2.2013 11:00	2	2	**4.2.2013 23:00**	1.5	2

Participation in FCR markets is illustrated in Figure 15 that shows the sold capacity of both FCR-N and FCR-D as up and down regulation capacity. The figure presents also the operation of FCR in the example day (4.2.2013) based on the measured frequency. For instance, in the morning (6:00–7:30) up regulation is required as well as at noon (11:00–15:00) and shortly in the evening (18:00–19:00). Down regulation seems to be mostly required in the morning (8:00-10:30) and afternoon (15:30–17:30). The highest operation power is in both up and down regulation 2 MW that is the maximum capacity sold to FCR-N markets. It indicates that frequency remains relatively long time around 49.9 Hz or 50.1 Hz, which produces a need to operate FCR-N with full capacity.

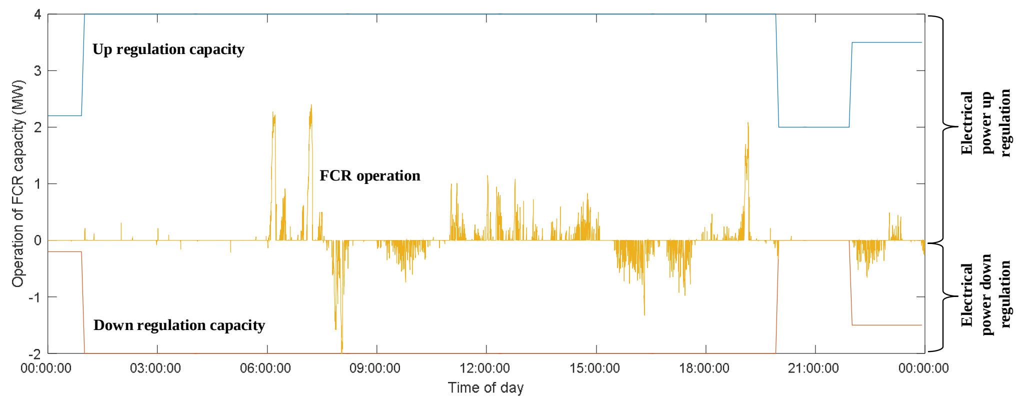

Figure 15. Provided up and down regulation capacities and FCR operation when participating in FCR-N and FCR-D markets in example day 4.2.2013.

4.2 The effects of participation in FCR market on heat balance

Operation of FCR effects on heat balance in the district heat system. If the CHP operator participates only in up regulation market such as FCR-D, the operation of the reserve causes deficit to heat balance. However, this is typically not a problem because FCR-D is operated relatively rarely. Instead of FCR-D, the FCR-N reserve is operated more frequently, which produces a risk that heat balance may be disturbed. Fortunately the operation of up and down regulation is typically fairly in balance, which means that high unbalance cannot exist. Figure 16 illustrates the daily variation of surplus heat energy when the considered 20 MW CHP plant participates in both FCR-N and FCR-D markets. It can be observed that the daily surplus varies between -2 MWh and 2.5 MWh that is quite low amount of energy compared with the daily produced heat energy in the cold winter day (15 MW x 24 h = 360 MWh). The highest surplus 2.5 MW means that CHP plant has produced more heat than is consumed in district heat system (electrical power has mainly down regulated) and value -2 MWh means that there are 2 MWh deficit in the system (more up regulation of electrical power). This number can be compared, for instance, with the energy committed in the district heating system. For instance, the rise of supply water temperature with 5 degrees corresponds 40 MWh in the district heating system of

Kotka that is a middle size Finnish city. A comparison shows that 2 MWh is only 5% of the compared 40 MWh.

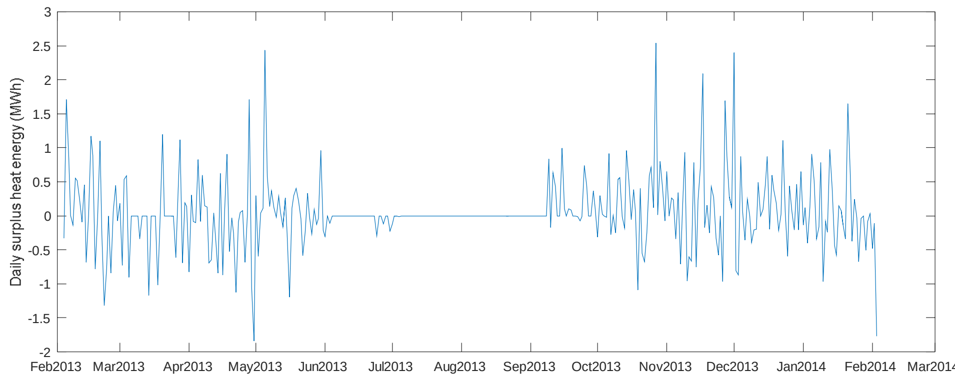

Figure 16. Daily variation of surplus heat energy when participating in FCR-N and FCR-D markets.

Another perspective to proportion the surplus or deficit is to compare it with produced heat. Figure 17 shows the daily surplus/deficit proportion of the heat production. It can be seen that the biggest deficit is below than 0.6% of the daily heat production of the CHP plant.

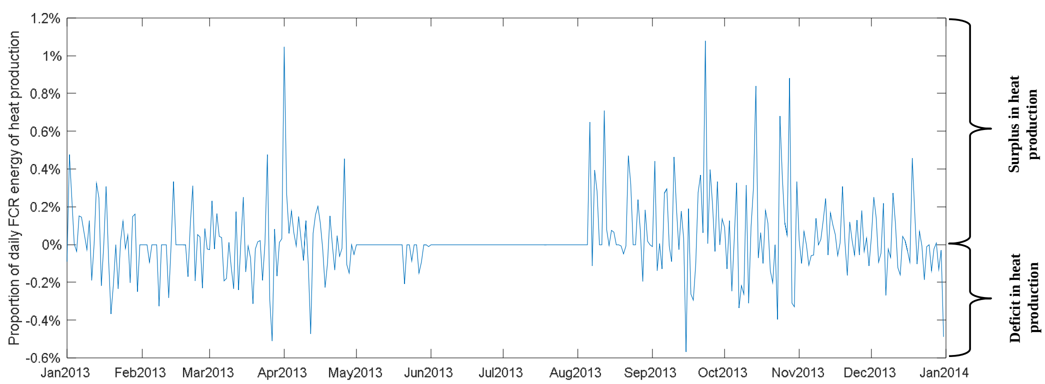

Figure 17. Proportion of daily surplus heat energy of daily heat production in percentages when participating in FCR-N and FCR-D markets.

4.3 Feasibility of CHP plant participation in electricity reserve markets

Participation of CHP plant on electrical power reserve markets seems to provide benefits to CHP operator. For instance, the data of both years 2013 and 2014 provide roughly 20% increase in operational profit compared with operation when the maximum electrical capacity can be sold to Elspot (no reserve market). The hourly revenue of year 2013 is presented in Figure 18.

It can be seen that the most part of the revenue comes from heat, the next biggest share comes Elspot, FCR-N and FCR-D, respectively.

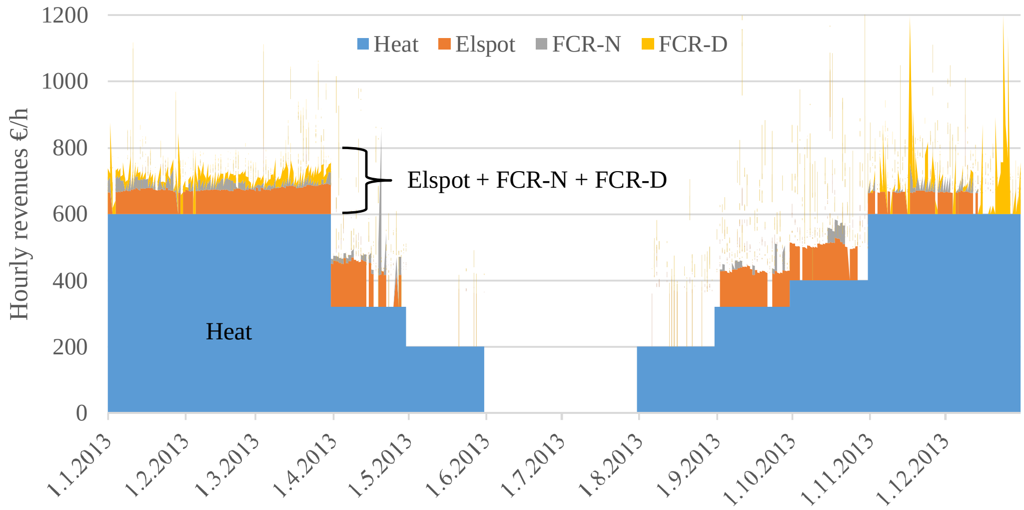

Figure 18. Different revenue sources of CHP operation.

Table 6 shows the revenues and costs of the different CHP operation, first with electrical power reserve market participation and second without reserve market participation. It can be seen that most part of the revenue comes from heat production. Elspot market provides approximately double revenue compared with reserve markets. However, even the proportion of reserve markets from the total revenue (3.3% in year 2013 and 2.8% in year 2014) is relatively low, their effect on profit of operation much stronger (23.4% in year 2013 and 20.5% in year 2014). Thus, it can be said that reserve markets provide a considerably opportunity to increase profit of CHP plants in energy and power production, and hence to balance fluctuation of electrical power production and consumption.

Table 6 Comparison of revenues and costs with different CHP operation scenarios, 1) with reserve market participation and 2) without reserve market participation.

	2013		2014	
	Reserve market	Without reserve market	Reserve market	Without reserve market
Revenue total	4 127 000 €	3 994 000 €	3 797 000 €	3 694 000 €
Heat	3 230 000 €	3 230 000 €	3 230 000 €	3 230 000 €
Elspot	595 000 €	764 000 €	362 000 €	464 000 €
FCR-N	233 000 €	0 €	153 000 €	0 €
FCR-D	69 000 €	0 €	52 000 €	0 €
Costs total	3 019 000 €	3 096 000 €	2 845 000 €	2 904 000 €
Fuel consumption	3 019 000 €	3 096 000 €	2 845 000 €	2 904 000 €
Profit	1 108 000 €	898 000 €	952 000 €	790 000 €

5 Conclusion

The study shows that electrical power reserve markets provide good opportunity to CHP operators to enhance profitability of the operation. The study contains simulation of CHP model with the market data of years 2013 and 2014. The results indicate that participation in reserve markets may increase the profit of CHP operator considerably, even 20% compared with the operation without reserve markets.

In the future the aim of the study is to fit an actual CHP power plant to simulation model and thus to model the profits in the real case. Furthermore, a task is to determine the potential of suitable CHP plants to participate in reserve markets in Finland and further in the world. Another task is to develop an operational algorithm to model the daily behavior of the CHP system containing also the variable heat demand.

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