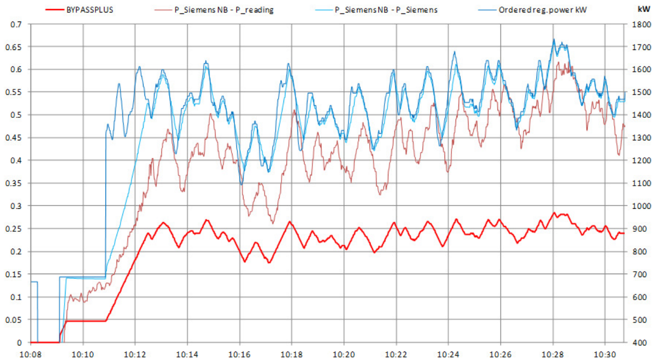

Demonstration of primary control from WtE plants

ForskEl 2012-1-10799

Index - Final Report

1. Final report

The final report must be prepared in English. Please fill in the following sections of the template.

1.1 Project details

Project title	Primary control (frequency reserves) from wte-plants
Project identification	Energinet.dk project no. 2012-1-10799
Name of the programme which has funded the project (ForskVE, ForskNG or ForskEL)	ForskEl
Name and address of the enterprises/institution responsible for the project	Weel & Sandvig Diplomvej, bygning 377 2800 Kgs. Lyngby
CVR (central business register)	2725 5817
Date for submission	25-10-2013

1.2 Executive summary

Mainly due to increasing amount of wind power in the Danish electricity grid the demand and challenge for controlling power production increases. Special and different markets regarding response time and activation are developed for handling control of the frequency and balancing power production in the electricity grid (see Figure 1).

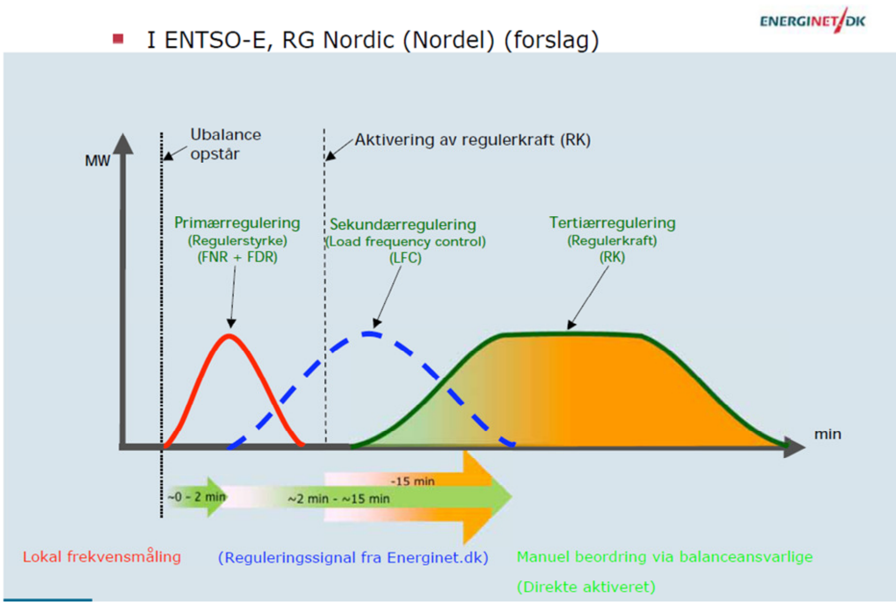

Figure 1. Response time for different markets for balancing the electricity grid (Source:energinet.dk)

The Danish electricity grid consists of two areas DK1 (West of Storebælt) and DK2 (East of Storebælt). The two areas are frequency separated each having its own markets, terms and conditions for grid system services including frequency control.

Before this project was initiated, the market for frequency control has, been characterized by few actors. Far the most of the primary control (frequency control) has been executed by the central power stations, owned by two companies (Dong Energy and Vattenfall). The payment for this service (especially down regulation in DK2) has until October 2012 been high compared to what can be estimated as the actual cost associated with providing such regulation. In that sense, the apparently high market price indicated lack of competition. The background for this project was to demonstrate that WtE plants can also provide frequency control and thereby enforce the competition.

As demonstration facility the WtE plant Nordforbrænding was selected. The plant is situated in Hørsholm and is connected to the electricity grid DK2 (East Denmark). In DK2, the market for handling regulation of power production or consumption in order to maintain a frequency in the electricity grid close to 50 Hz (between 49.9 and 50.1 Hz) is called FNR. Another market for frequency control in DK2 is FDR which is automatically activated when the frequency comes below 49.9 Hz. Relevant to this project is the FNR service. Alone for the FNR service between January 2010 and May 2011, Energinet.dk has paid around 150 Mill. DKK.

The purpose of the project has been to demonstrate that WtE (waste-to-energy) plants from a technically as well as from their own economically point of view can operate in the market for primary control (frequency reserves) of the power grid.

Most WtE plants can from normal operation apply down regulation of power production by partly bypassing the steam turbine.
Up regulation of power however, can also be applied. In this case it is necessary as a base to apply a certain amount of bypass of the turbine corresponding to a power reduction equal to the full amount of up regulation power. When up regulation is required, the basic bypass is reduced.
In the present project primarily down regulation has been focused, but the system can also handle up regulation.

Concerning the economical benefit for the individual WtE-plant, the WtE sector in Denmark is moving towards a more liberalized market. Therefore it was expected that the individual plants would have the incentive to act in the FNR-market when it is demonstrated to be both technically feasible and profitable, given the conditions present when this project was initiated.
WtE plants are characterized by having very high operating time throughout the year and can in most of the season reject extra heat either to the connected district heating system or to the surroundings via external heat exchangers.

Thereby, the WtE sector can increase the number of individual actors in the market as well as the amount of regulated power offered to the market, ensuring a more keen competition. As a consequence, the consumer cost related to operating services of the electricity grid is expected to drop.

Through preliminary investigations and analyses Weel & Sandvig has estimated that the WtE-sector can offer primary control to an extent of at least 10% of its electricity production rate, corresponding to primary control power of around +/- 20 MWe. This amount equals almost half of the actual daily demand for primary control.

The WtE plant in Hørsholm (Nordforbrænding) has a capacity of approximately 7.2 MW power and a bypass system of steam directly to the district heating condensers.

The bypass control has been implemented in such a way that the amount of bypass corresponds to a power reduction of the turbine equal to the amount required by the activated bid in the FNR market and the actual frequency in the electricity grid.

Based on test runs the characteristics of the bypass system and the marginal performance of the steam turbine have been mapped. During the first test runs some irregularities were identified that have caused problems of developing an unambiguous model.
A control model of the bypass valve based on mathematical modelling of the marginal turbine performance is implemented. The system response time complies with the terms and conditions for FNR.

During the project period (3.rd of October 2012), the conditions for FNR have changed, as the Danish market DK2 was merged with the Swedish market. The new conditions have lead to a significant reduction in the benefits for WtE plants including Nordforbrænding for operating in the new FNR market. The reduced benefits are mainly in terms of a significantly lower market price and in terms of merging the former separate FNR markets for up respectively down regulation into a symmetrical up and down FNR market.
In the present case at Nordforbrænding, the latter implies far more bypass of steam for operating in the market of FNR.

This report is mainly written before this change applied, and consequently the descriptions of the FNR conditions are no longer valid in all details.

The project has been delayed, for more reasons:

1. Nordforbrænding required time for setting up their system providing us the required access to various parameters, in the control system,
2. unforeseen turbine overhaul (damaged labyrinth sealing) in late 2012,
3. changed market conditions for FNR-regulation 3.rd of October 2012, significantly reducing the benefit for WtE plants to act in the market,
4. irregularities in terms of unexpected responses of bypass regulation during tests (observed in February 2013),
5. Gearbox failure (a new gear wheel is installed)
6. turbine reparation (again labyrinth sealings were damaged and the turbine was sent to Nürnberg).

When the market conditions changed in October 2012, the price level observed went down by a factor of approximately 7, meaning that in reality there was no incentive for Nordforbrænding acting in the FNR-market. Since then the price level has regained somewhat.

The observed irregularities have been difficult to explain. After more tests we concluded that the bypass valve was not able to apply reliable performance according to the specified valve characteristic in the low opening range.

As a consequence, we changed the control strategy for FNR-regulation by adding an offset to the FNR-controller, meaning that when applying FNR-regulation, an additional constant down regulation is applied in order to prevent the bypass valve position to operate in the almost closed position.

With this changed control strategy we have demonstrated good accordance between expected (model based calculation) power and observed power.
The drawback of this modified control strategy is an additional amount of bypass, which means income loss when electricity (for the facility) has a higher value than heat production to the district heating system.

An alternative methodology is to apply FNR-regulation by using the existing power control of the turbine. The reason for not choosing this methodology from the start was to apply as little bypass as possible for providing the FNR regulation. However, as things have turned out, in this case we need to apply a certain offset of the bypass valve implying more bypass than assumed from the start.
Similar bypass characteristic and limited operating range with high accuracy may be present in other WtE plants. This implies more bypass and consequently more expensive FNR-regulation when electricity for the WtE plant is more valuable than heat.
As FNR in DK2 now is symmetrical up and down and the price level has become much lower after the 3.rd of October 2012, we expect the potential for FNR-regulation from WtE plants now is much lower than in the beginning of the project.

In DK1 the price level has been quite stable for primary up regulation during the project period. Whereas the price level for down regulation (which requires far less bypass regulation) has decreased even further from an already low level, meaning that the benefits from down regulation are rather limited.
The market price for primary up regulation in DK1 is now higher (in average since October 2012) than a symmetrical FNR regulation in DK2. In that sense, we expect that WtE plants in DK1 now have greater incentive than WtE plants in DK2 for acting in the market for frequency control.

1.3 Project results

1.3.1 General conditions for WtE plants in Denmark

The average power production from WtE plants in Denmark is approximately 200 MWe. The WtE sector is characterized by having production 24 hours a day - 7 days a week and throughout the year, apart from scheduled periods for overhaul or eventually unplanned stop. In that sense, the plants are available in the electricity grid to a very high degree.

Most WtE plants in Denmark convert wastes into electricity and district heat. The electricity is generated in a Rankine process, where a steam turbine drives an electric generator. The steam, exiting the steam turbine at relatively low pressure and temperature, is normally condensed in a heat exchanger producing district heat. Some WtE plants may in hot summer periods be limited in rejecting heat to the district heating system. In order to maintain capacity for converting wastes and generate electricity in such hot periods, some plants have an external cooling system rejecting surplus of heat into the surroundings.

WtE plants have a system where the high pressure and high temperature steam from the boiler can be bypassed the steam turbine. The bypassed steam will not generate power, but only reject heat into the district heating system or eventually into the surroundings.

In normal operation, this bypass system is closed, in order to maximize electricity production, which usually is of more value than heat delivered to the district heating system.

However, for many WtE plants the marginal payment for heat and electricity is not that different in long periods, meaning that potential electricity production can be rejected by instead producing more district heating without significant income losses. This degree of freedom in producing electricity contra more or less heat is intended to be exploited in providing lower market prices for primary control in the electricity grid.

1.3.2 Conditions for grid system service: frequency control

The conditions described below apply to the conditions until 3.rd of October 2012. As mentioned in the summary, the Danish electricity grid is split up in two areas with individual frequencies. The one called DK1 is West of Storebælt and the other (DK2) is East of Storebælt. For this project the grid service in focus is automatically activated frequency control, by either up or down regulation. Down regulation can be applied by decreased power production or increased power consumption and vice versa for up regulation. The detailed terms and conditions for FNR can be found on the internet site: http://energinet.dk.

In DK1 the relevant market is called "Primær reserve" and in DK2 the service is called FNR ("frekvensstyret normaldriftsreserve").
Common to both markets is a minimum bid of 0.3 MW. Each bid in the market covers predefined 4-hour blocks and consists of amount of power regulation (MW) up or down and price.
A bid must be applied to Ediel (web site http://www.ediel.dk/ny/index.php) no later than 3:00 pm the day before.
Accepted bids will be announced at 3:30 pm together with the related payment (highest accepted bid in the market).
The power regulation should be applied automatically based on measured momentary frequency in the grid. The accuracy of the frequency measurement should be better than ±10 mHz and with a resolution better than 10 mHz.

The "Primær reserve" in DK1 regulates automatically power production or consumption in the frequency band 49.8 – 50.2 Hz. The market volume in 2011 is ±27 MW. The activated regulation should be applied linearly to the frequency deviation relative to 0.2 Hz. However, a dead band of up to ±20 mHz is allowed. The demanded output according to actual frequency is illustrated in Figure 2.
The response time is 15 seconds for applying the first half amount of the required regulation and the full amount of required regulation should be delivered after 30 seconds. The service provider should be able to maintain the full regulation for at least 15 minutes.

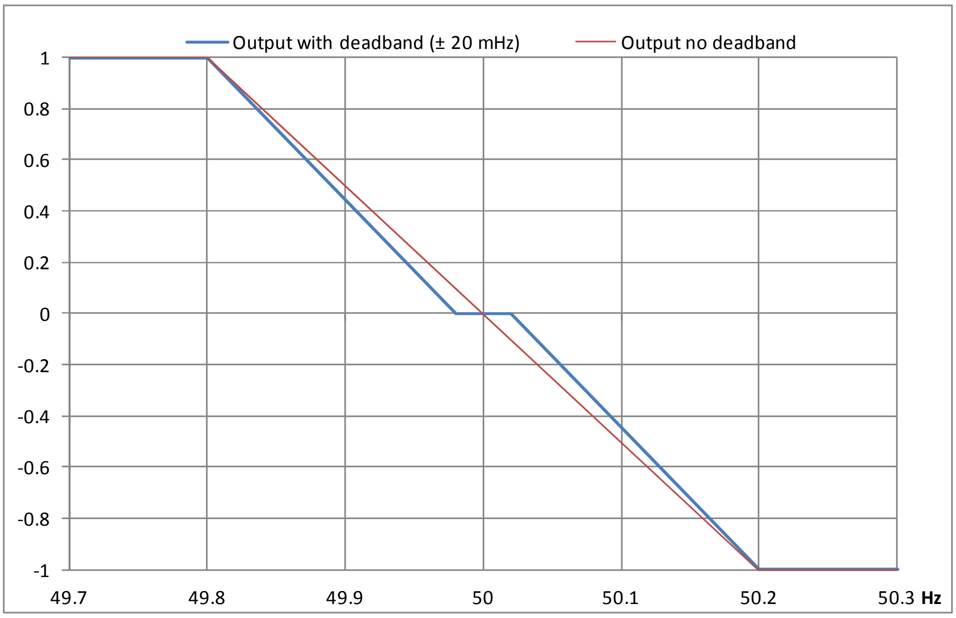

Figure 2. Required output in DK1 according to frequency with and without a deadband.

The FNR regulates power production or consumption when the frequency in the DK2 grid is between 49.9 and 50.1 Hz. The market volume in 2011 is ±23 MW
The activated regulation should be applied as minimum linearly to the frequency deviation relative to 0.1 Hz meaning that the full amount of down regulation should be applied when the frequency is 50.1 Hz or above and the full amount of up regulation should be applied when the frequency is 49.9 Hz or below. The FNR regulation should be delivered with no dead band and the regulation must be maintained continuously.

From the momentary frequency *f* in the DK2 grid, the demand for down regulation related to an accepted bid (FNR_{down}) in the market for down regulation can be calculated as follows:

$$FNR_{down,demand} = \frac{(f - 50\ Hz)}{0.1\ Hz} \cdot FNR_{down} \quad ; \ 50\ Hz < f < 50.1\ Hz$$

$$FNR_{down,demand} = FNR_{down} \quad ; \ f > 50.1\ Hz$$
$$FNR_{down,demand} = 0 \quad ; \ f < 50\ \ Hz$$

Similarly, the demand for up regulation according to a bid (FNR_{up}) in the market for up regulation is calculated as:

$$FNR_{up,demand} = \frac{(50\ Hz - f)}{0.1\ Hz} \cdot FNR_{up} \quad ; \ 49.9\ Hz < f < 50\ Hz$$

$$FNR_{up,demand} = FNR_{up} \quad ; \ f < 49.9\ Hz$$
$$FNR_{up,demand} = 0 \quad ; \ f > 50\ \ Hz$$

The full demanded FNR regulation up or down should be delivered within 150 seconds.

1.3.3 Registering of grid frequency

From the terms specified for FNR, it is understood that the accuracy of frequency measurement should be within ±10 mHz and the resolution better than 10 mHz.

For measurement of grid frequency in DK2 (Denmark East) an AC-monitor from PQube (see Figure 3) is installed at the plant. The local AC-monitor installation is directly connected with the FNR control system, installed on a local PC. The resolution of frequency measurement with this monitor is approximately 2.18 mHz, and consequently is sufficient. Range and accuracy of the unit is presented in Table 1, showing that the accuracy is as required.
An example of measurement of the grid frequency in DK2 with the PQube is presented in Figure 4.

Figure 3. PQube AC-monitor for measurement of grid frequency.

Frequency Measurement	
Range	40Hz to 70Hz and 320Hz to 560Hz
Accuracy	±0.01Hz, steady state
Method	Cycle-by-cycle zero-crossing detection on L1-E or L2-E (auto-selected). Firmware phase-locked for frequency slew rate up to 5 Hz/sec. For 50/60 Hz, measured through an 9-pole low-pass analog filter, 3-dB frequency 76 Hz. For 400 Hz, measured through 7-pole low-pass filter, 3-dB frequency 1 kHz. Poles and 3-dB frequency are auto-selected based on nominal frequency.

Table 1. Specification of range an accuracy regarding frequency measurement with PQube.

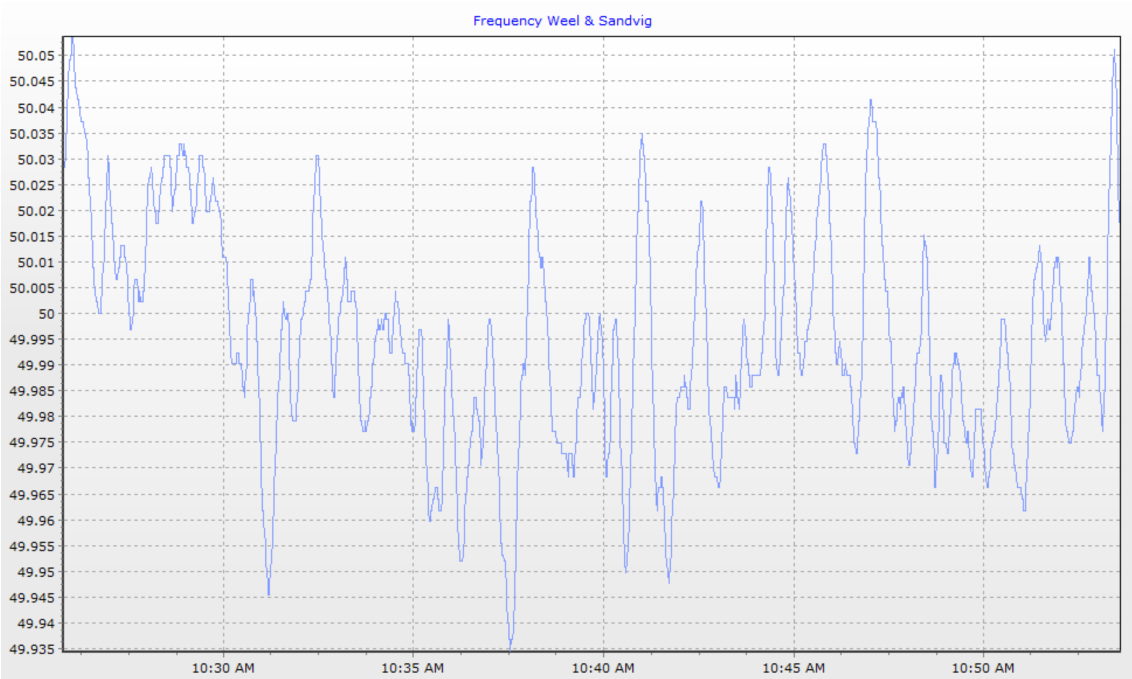

Figure 4. Measurement of grid frequency (DK2) with PQube (Date: 26.th of April 2012).

1.3.4 Evaluation of the measured grid frequency

Measurement of grid frequency in Örebro, Sweden has been compared with the measured frequency at the Weel & Sandvig office installation, as the two measurements are on the same grid (synchronic frequency). The measurement in the Swedish location is applied with the same unit (PQube) as the measurement applied by Weel & Sandvig.
The stored data from the Örebro measurement, were available in 1 minute time resolution only, however both as minimum, maximum and average values. Comparison with the Weel & Sandvig frequency measurements provided as 1 second values shows that the 1 minute based minimum and maximum values as well as the 1 minute average values from the Örebro measurements comply with our measurements (see Figure 5).

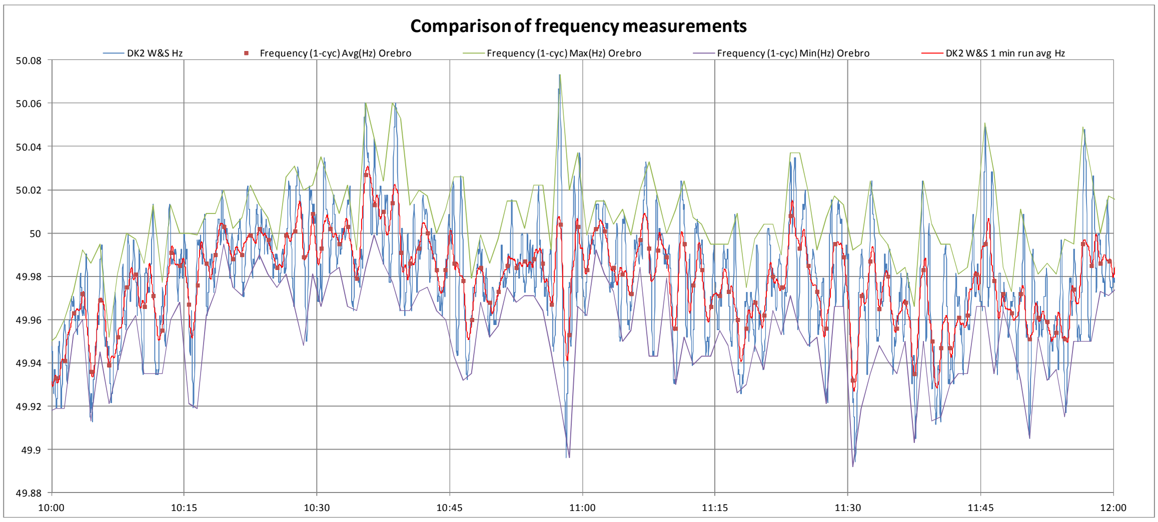

Figure 5. Comparison of frequency measured by a PQube unit installed at Weel & Sandvig office in Lyngby (DK2) and a similar PQube unit installed in Örebro in Sweden.

1.3.5 Description and conditions at the demonstration facility

As demonstration facility, the waste-to-energy (WtE) plant Nordforbrænding was selected. Nordforbrænding is situated approximately 20 km North of Copenhagen. Waste is incinerated and the heat generated is via a Rankine steam cycle converted into electricity. Heat rejected from the steam condensers is utilized in a district heating system. Similar to most WtE plants, the primary task is to handle (incinerate) waste from the local area, but also the production of heat is essential.

Normally Nordforbrænding rank its main activities as follows:

1. Receiving and incineration of waste.
2. Production of district heat (obligation for providing heat to the consumers in the district heating system).
3. Production of electricity.

This project mainly involves the heat and electricity production, as FNR regulation implies more heat production on the cost of a similar amount of electricity production. The capacity of handling waste however, normally will be unchanged.

By acting in the FNR market, the plant rejects potential power production to end up instead as heat in the district heating system or eventually in heat exchangers rejecting heat into surroundings (to air by dry coolers).

In periods during the hot season the heat demand in the connected district heating system might be so low that the capacity of the heat exchangers, rejecting heat into surroundings, is the bottleneck concerning capacity of handling waste. In this case, acting in the FNR market will imply a tighter bottleneck in capacity of handling waste, and as a consequence, might influence the bid price for FNR.

At Nordforbrænding there are three incinerators of different ages and a new line is under projection.

The present demonstration project involves Line 4 at Nordforbrænding. Some technical information is presented in Table 2.

Construction year	*1998*	
Steam capacity	*39.6*	*tons/h*
Boiler pressure	*50*	*baro*
Design power	*7.2*	*MW*
No. of district heaters (condensers)	*2*	
Condenser 1	*Bypass steam and turbine exit steam*	
Condenser 2	*Extraction 1 steam from turbine.*	
Deaerator	*Extraction 2 steam from turbine or live steam*	

Table 2. Technical data for Line 4, Nordforbrænding.

The steam turbine is manufactured by Siemens. Steam can be extracted from two pressure levels. The district heating water is heated successively in two steam condensers. The first heating takes place in "FV KONDENSATOR 1", in which the steam turbine exit flow is condensed. The second heating of district heating water takes place in "FV KONDENSATOR 2", in which steam extracted from the lowest extraction level ("Dampudtag 1") is condensed. The two-stage (steam pressures) heating arrangement is applied for increasing the power production of the turbine.

The deaerator is driven by steam extracted from the second extraction level ("Dampudtag 2"), or in case the pressure at this level is insufficient (at low turbine load), live steam is directed to the deaerator.

The performance (according to Siemens documentation) of the turbine in terms of steam consumption as function of power production (see Figure 6) can be correlated with a third degree polynomial.

Approximately 3 years ago there was an accident with the turbine and it was renovated at Siemens in Germany. The performance of the turbine might have changed slightly during this renovation.

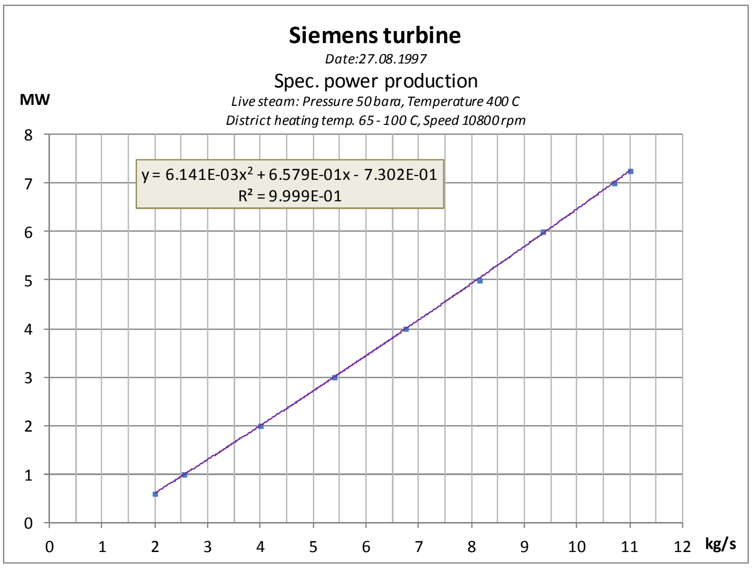

Figure 6. Performance of the steam turbine (from Siemens documentation).

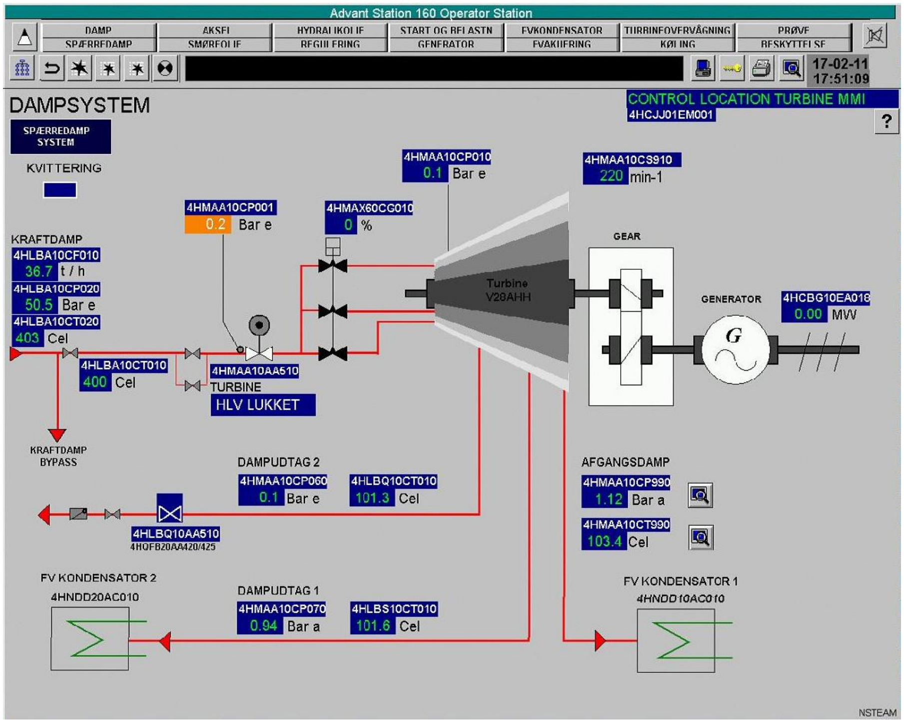

Figure 7. Screendump from ABB control-system of turbine with extraction to Condenser 2 ("FV Kondensator 2") and back-pressure Condenser 1 ("FV Kondensator 1").

1.3.5.1 Bypass system and valve characteristic

Upstream the turbine, steam can be bypassed the turbine via the bypass valve leading the steam directly to the first condenser named "FV KONDENSATOR 1" (see Figure 8 and Figure 9) on the district heating line. The bypass system among others is used if the power from the turbine is too large for the generator or if the turbine is out of service.
The bypass valve has an integrated water injection, for ensuring a suitable temperature of the steam before entering the condenser.
The valve is manufactured by HORA and is of the type "equal percentage" (see Figure 10).
This valve characteristic is described with a rangeability, in which the characteristic is "Equal percentage" and for an opening degree below this area the characteristic is linear.
This means that the valve characteristic at the transition point is not smooth but has a sharp shoulder. The rangeability of the valve is 40 corresponding to a relative capacity of 3% of the maximum Kv at the transition point, which in this case occurs at an opening degree of 5%.
The maximum valve coefficient (Kv) is according to specification 120.

It might not be ideal to use this valve for FNR in case only down regulation is active, as it can be expected that the valve in most of the time will operate close to and across this transition point.
This can be avoided by also acting with a suitable amount of FNR up regulation. The more up regulation the less time the valve will operate below the transition point.
As only symmetrical bid in the FNR market is allowed after the 3.rd of October 2012, this problem seems less where this

One unit of up regulation implies more than six times as much bypass as one unit of down regulation. Statistically one MW power of FNR implies approximately 14% in average power regulation meaning that 1 MW down regulation implies in average bypass of steam corresponding to a down regulation of power of in average 140 kW. Whereas 1 MW of up regulation implies holding back 1 MW power in the neutral condition and the net power reduction from bypass will correspond to in average 1000 kW-140 kW = 860 kW.
Another possibility to avoid the transition point operation is of course to change the valve characteristic.

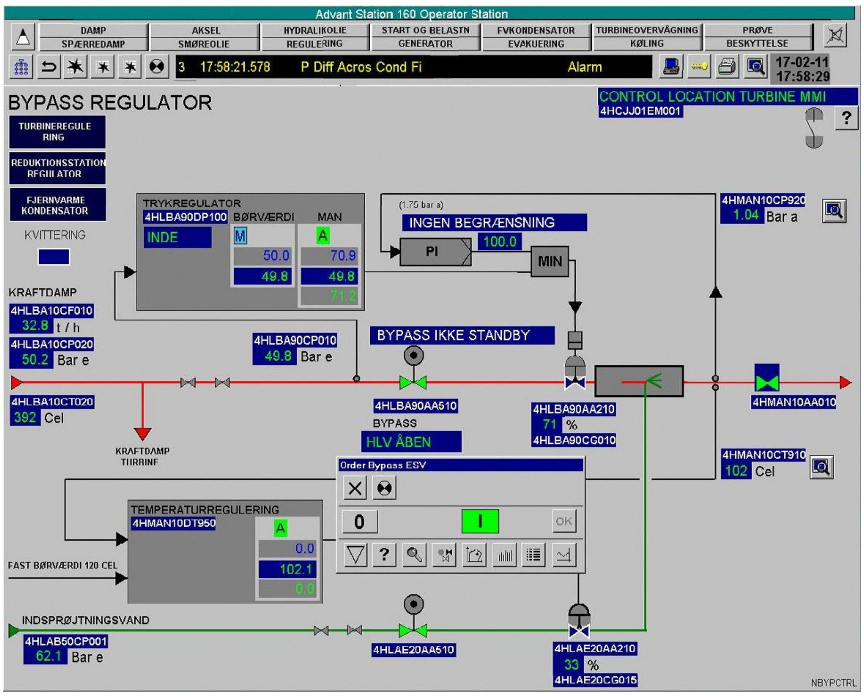

Figure 8. Bypass system (screen dump from ABB control-system).

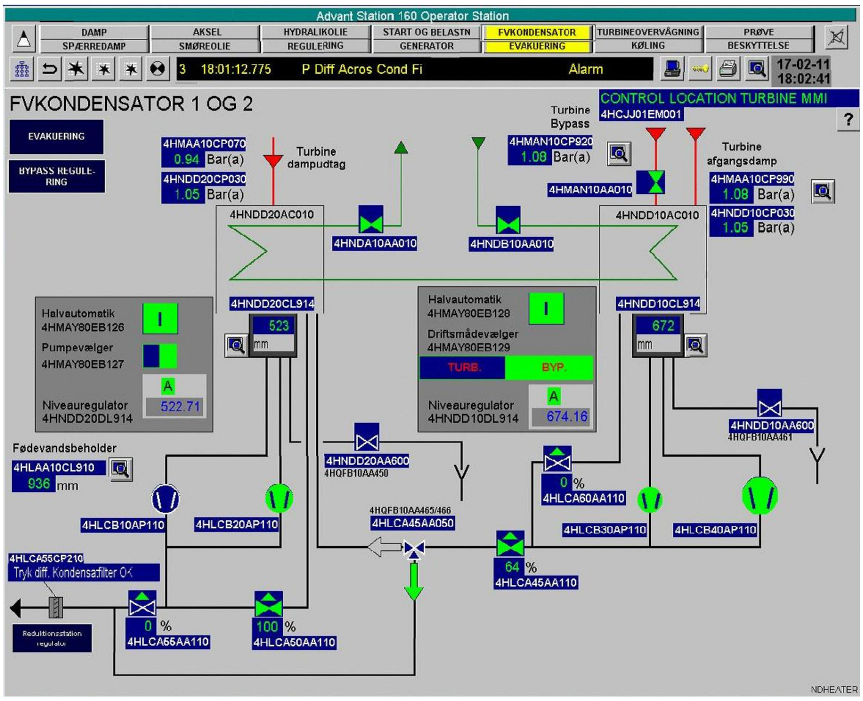

Figure 9. "FVKONDENSATOR 1 og 2" (Condenser 1 and 2) in the district heating system (screen dump from ABB-control system): Bypass-steam and turbine exit steam enter "FV KONDENSATOR 1" while extraction steam enters "FV KONDENSATOR 2".

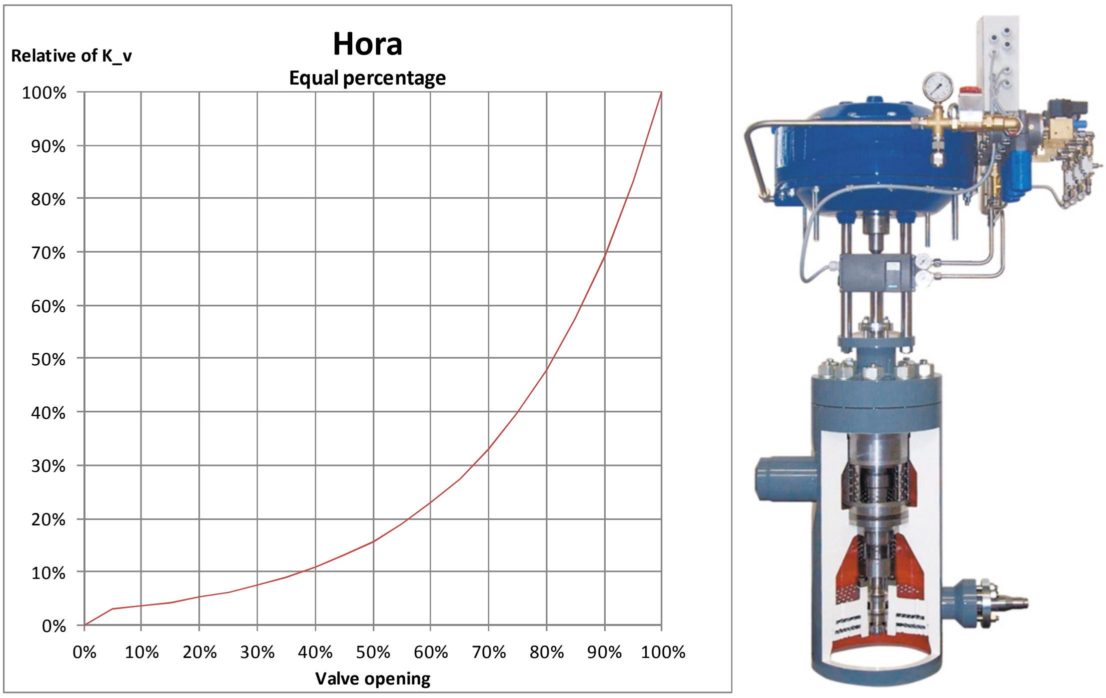

Figure 10. Characteristic of the HORA bypass valve (Equal percentage, Rangebility:40).

1.3.6 Plant analyses

Analyses of steady state as well as the dynamic behavior of the plant has been conducted by use of a dynamic simulator (WS.WtE-simulator) developed by Weel & Sandvig primarily for waste-to-energy plants but also for detailed analyses of steam turbine systems.

Having constant flow of steam from the boiler, increasing the amount of bypass, the turbine back pressure will increase as well.
In the case at Nordforbrænding, the bypass steam (live steam with a higher specific enthalpy than turbine exhaust steam) is directed to the first condenser and will imply a pressure rise according to a higher temperature difference over the condenser in order to balance the heat transfer conditions.
In Figure 11 and Figure 12 pressures in the turbine parts are shown during slow variation (reduction) of steam flow through the turbine by use of bypass (Figure 11) and by reduction of steam generation in boiler (Figure 12) respectively.

Note the turbine back pressure is highest when bypass is applied.

Also, and perhaps more surprisingly, note that the back pressure rises (see Figure 12), when the boiler load is decreased and consequently also the total heat transferred in the two condensers. This can be explained as follows: The district heating flow is controlled to maintain a fixed forward temperature, which will determine the pressure in the turbine at the extraction level for this condenser. The lower steam flow in the turbine will now cause a lower pressure drop in the low-pressure part of the turbine compared to a situation with higher flow rate, meaning that the back pressure must rise. This implies a higher temperature difference for exchanging heat in the first condenser, and consequently more steam will now be condensed here. Thereby, much less heat (remember that total load is decreased and condenser 1 is transferring more heat) is transferred in the second heat exchanger, implying less temperature difference and consequently lower pressure (see Figure 12).

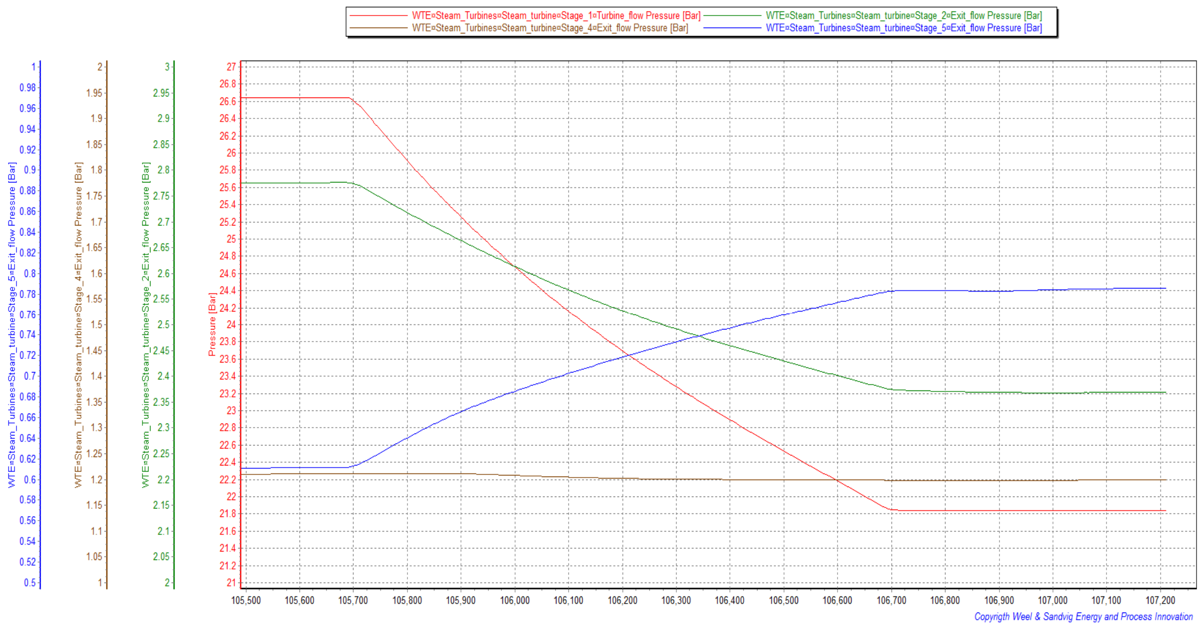

Figure 11 Pressures in the turbine stages during a slow (during 1000 seconds) opening of the bypass valve (0 - 25 % corresponding to a bypass flow from 0 to 5.7 ton/h) at a constant boiler steam flow of 36 ton/h. The pressure stages are: wheel chamber (red), extraction steam for deaerator (green), extraction steam for condenser 2 (brown) and exit pressure to condenser 1 (blue).

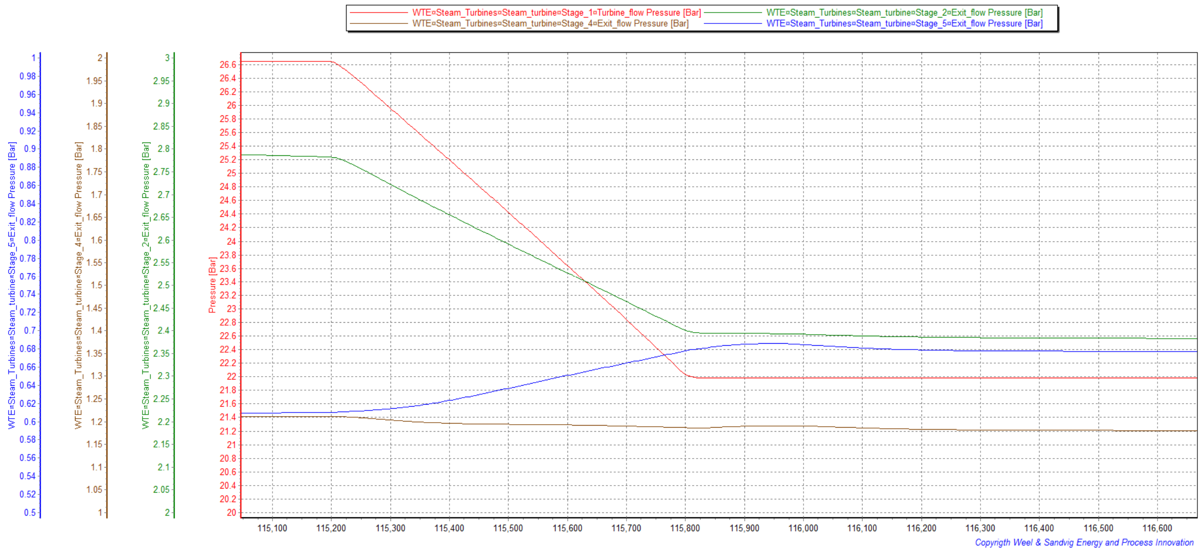

Figure 12 Pressures in the turbine stages during a slow (during 600 seconds) down regulation of boiler load from 36 ton/h to 30 t/h. The pressure stages are: wheel chamber (red), extraction steam for deaerator (green), extraction steam for condenser 2 (brown) and exit pressure to condenser 1 (blue).

The turbine performance curve (see Figure 6) gives for design conditions the expected power as function of steam flow through the turbine and no bypass flow, meaning that the turbine mass flow is the same as the mass steam flow from boiler.

When bypassing some of the steam, the mass flow through the turbine of cause decreases with the same amount, but the turbine power will decrease to a level slightly below the power produced in a situation with the same turbine mass flow but without bypass (less boiler load). The reasons are: all bypass steam is directed to Condenser 1 and more steam needs to be condensed meaning higher turbine back pressure. This was illustrated in the two scenarios investigated before (see Figure 11 and Figure 12).

In Figure 13 power production as function of bypass flow for five boiler loads is presented. The results are from the WS.WTE-Simulator. The horizontal lines (drawn) are meant as guidance to illustrate the difference in power production between reduced boiler load and bypass.

For instance the power production at a boiler load of 25 t/h (with no bypass) is 4.3 MW. The same turbine mass flow can be achieved with a boiler load of 35 t/h and a bypass of 10 t/h. This is illustrated with one of the red horizontal lines. The power production with this amount of bypass is approximately 4.1 MW, meaning that in this case a bypass flow of 10 t/h influences the performance curve (Figure 6) with approximately 200 kW.

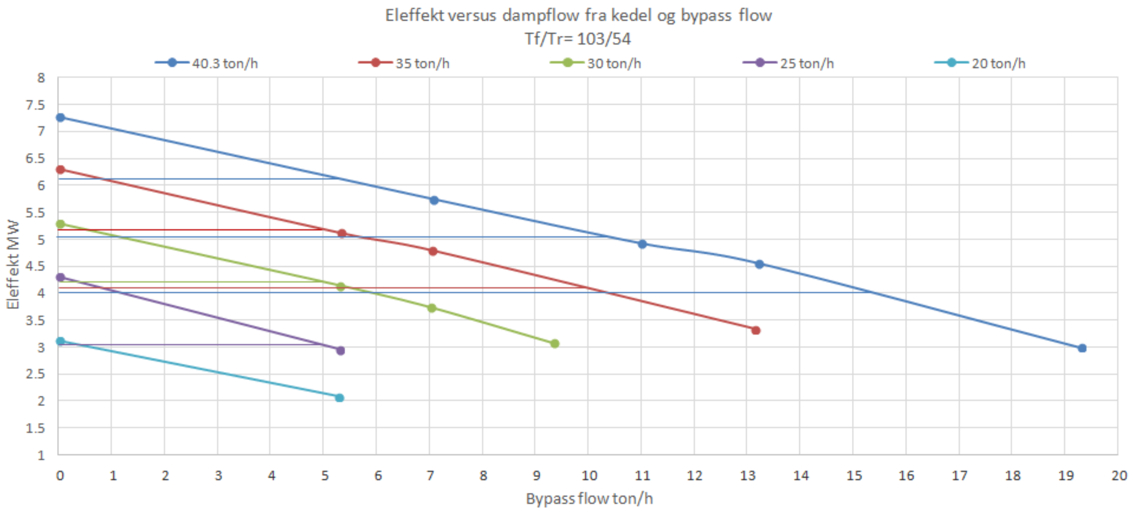

Figure 13. Calculated power as function of amount of bypass flow for 5 fixed boiler loads.

1.3.7 Turbine thermal stress from regulation

During regulation of the bypass valve the turbine main governor valve will response to control the inlet pressure to a set point value equal to 51 bara. During a maximum control range of ± 1.2 MW electricity within 100 seconds (the requirements for FNR is 150 seconds) the steam temperature in the wheel chamber will change from 328 C to 318 C. The change of steam temperature will follow the power regulation closely.
The rather thick casing made of cast iron having limited thermal heat transfer rate and rather large mass and heat capacity will respond with much slower dynamic. This means that during transients larger temperature difference will occur across the casing material implying thermal stress. For preventing thermal fatigue of the casing certain limits of temperature gradients should not be exceeded.

A simulation of a down regulation of 1.2 MWe has been simulated (See Figure 14). From a steady state condition the temperature difference across the casing (inside temperature minus outside temperature) cannot exceed the temperature difference of the steam during a transient.
The simulation shows a maximum difference between the average temperature of the casing and the steam of approximately 5 K. The maximum gradient on steam temperature is approximately -0.068 K/second or approximately 4.0 K/min.

From the OEM operating book the allowable steam temperature gradient during transient operation is limited to 10 K/min.
Consequently, bypassing the turbine for power regulation of ± 1.2 MW in 100 seconds should be well within the safe limits of the turbine.

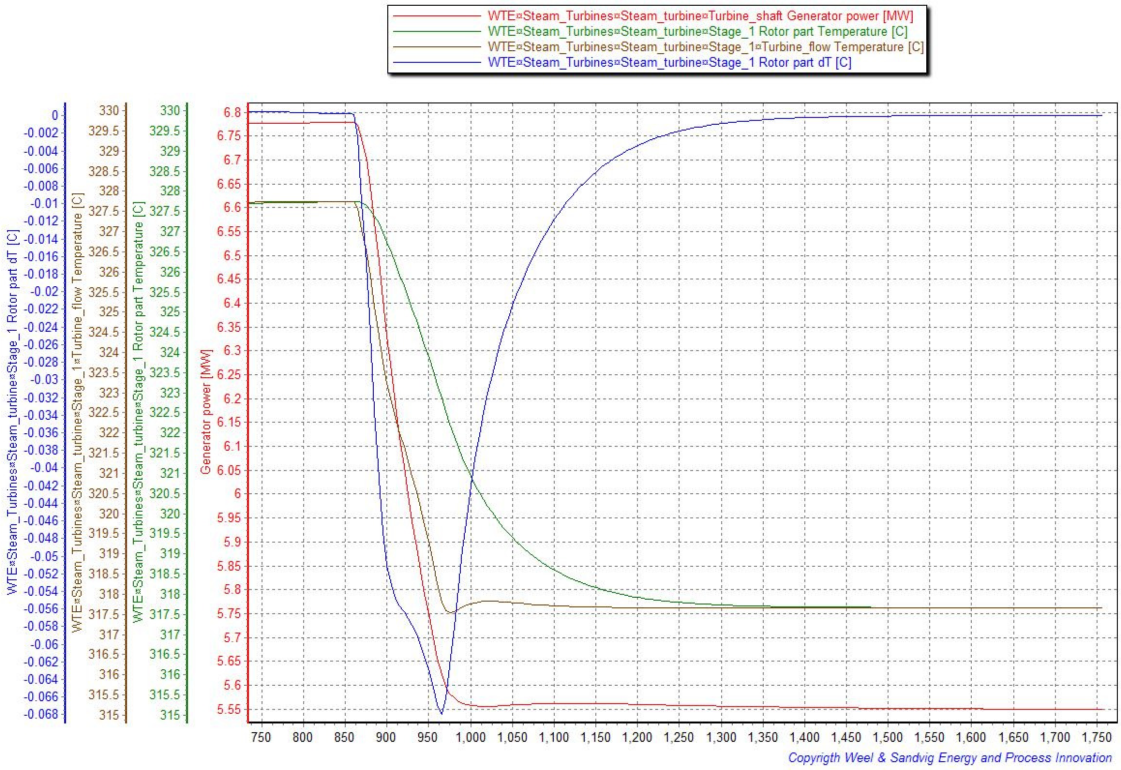

Figure 14 Simulated wheel chamber steam temperature and average casing temperature ("Stage_1 Rotor part Temperature") and its gradient ("Stage_1 Rotor part dT") and generator power during a down regulation of 1.2 MW within 100 seconds.

1.3.8 Initial plant test

A first test run at the site with down regulation of power with normal boiler load was conducted the 2.nd of March 2012.
Unfortunately, after the test run it turned out that Nordforbrænding was not able to extract time series of relevant operating parameters from the test run.

A new test run was then conducted the 12.th of April 2012. At that time, the boiler was running at rather low load (approximately 60-65% of normal load), due to a cleaning procedure of the super heater.
The bypass valve was operated up to 39% open. A higher opening degree was not applied as a power production of 2 MW from the turbine was considered as minimum safe limit in order to avoid possible trip of the turbine/generator.
The low load condition during the test run is not optimal considering a precise determination of power reduction as function of bypass degree, in normal full load operation.
In Figure 15 and Figure 16, some results from the test run of down regulation are presented. It is noticed that the steam production from the boiler varies quite a lot during this test.

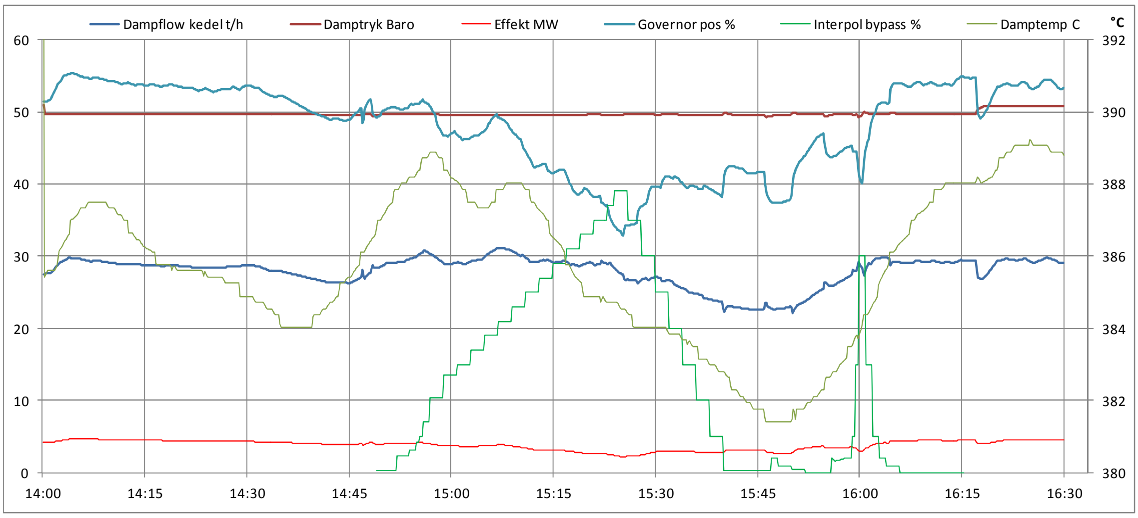

Figure 15. Test run (boiler load approx. 65%) with down regulation 12.th of April 2012.

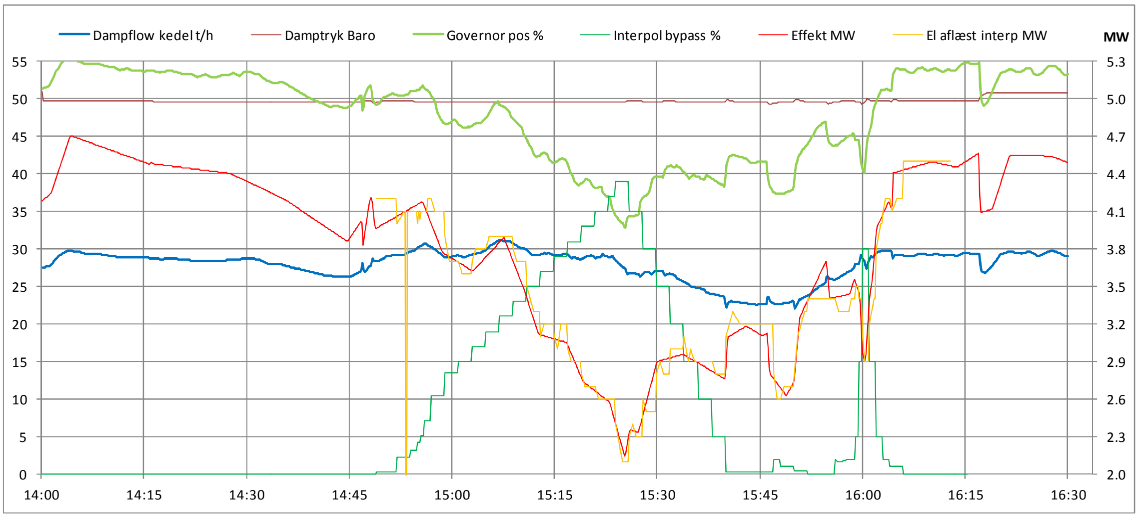

Figure 16. Test run (boiler load approx. 65%) with down regulation 12.th of April 2012.

A comparison of measured power and expected power (calculated in two ways) from the turbine during the test run can be made from Figure 17. The expected power in the one case is calculated based on a performance curve of the turbine (from Siemens documentation, see Figure 6) and not taking into consideration slightly different operating conditions (temperature and pressure before and after the turbine) than the ones valid for the performance curve.

In the other case, the expected power was calculated based on an estimated constant isentropic efficiency of the turbine assumed constant in the vicinity of the actual load level.

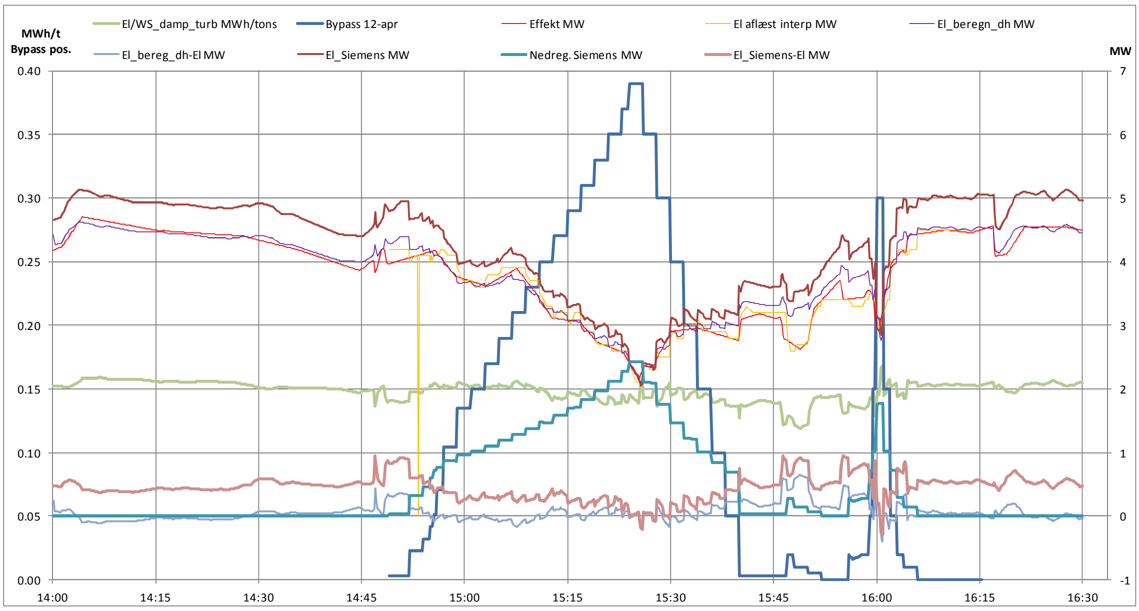

Figure 17. Test run 12. th. of April with calculated expected power based on either Siemens performance curve (W&S El_Siemens MW) or on an assumed constant isentropic efficiency of turbine (W&S El_beregn_dH MW) and calculated bypass regulation (W&Snedreg. Siemens 12 apr MW).

Deviations between calculated (expected) and observed power are identified mainly at times where the bypass valve is almost closed. Comparison with changes in governor position at these times indicates that the actual bypass cannot be as calculated based on valve position.

When doing high degree of bypass when the boiler load is low, the steam for deaerator might change from extraction steam to live steam. In case this transition occurs, a reduction of turbine power of approximately 200 kW is expected. There is no indication that this occurs in this test at low boiler load.

Another test run was conducted the 6.th of June 2012, in order to have a test run when the boiler was in normal load (boiler load was this time approximately 90% of full load).

Again a deviation between calculated (expected) and observed power is identified (see Figure 18). Apparently the deviation is almost zero when the bypass valve position is more than 5% open.
In Figure 19 the calculated and observed down regulation from the test applied the 6.th of June 2012 is presented as function of the valve position. It is clear that the regulation does not work as expected at very low valve openings.
On the opposite, there is a good accordance between expected (calculated) power and observed power for valve openings above 5%.

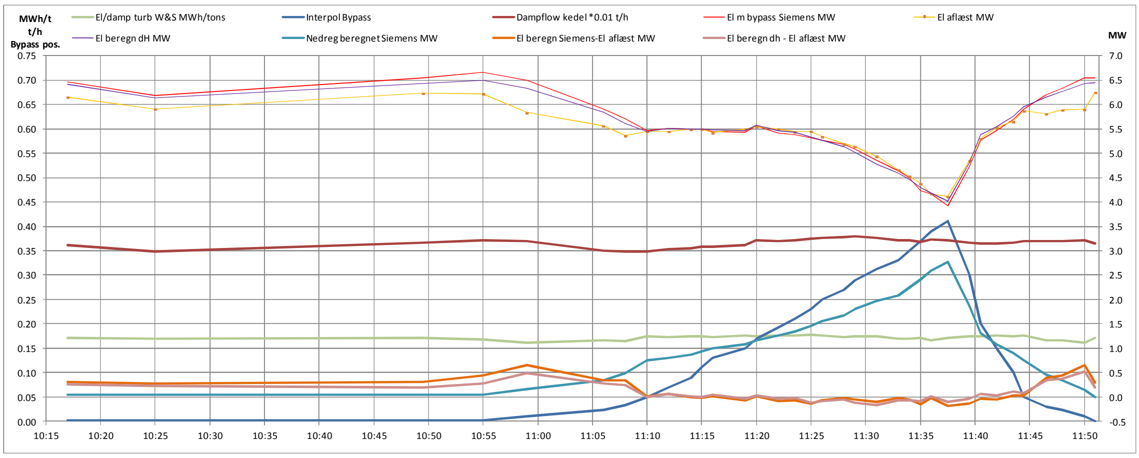

Figure 18. Results from test run the 6.th of June 2012.

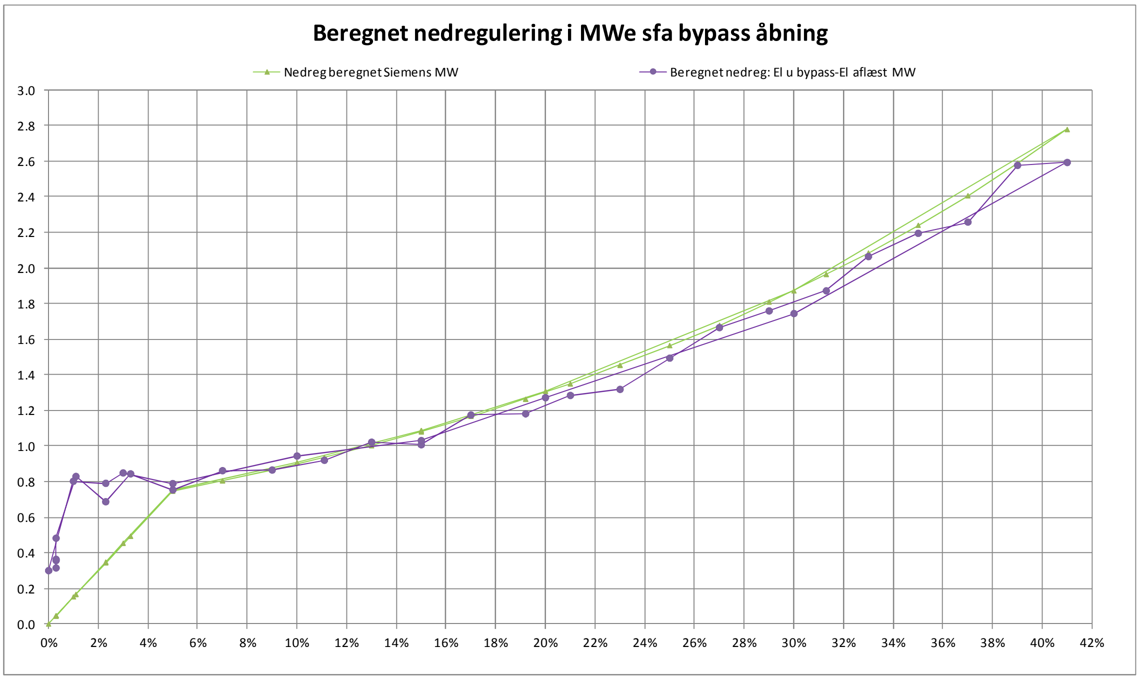

Figure 19. Comparison of calculated and observed down regulation the 6.th of June 2012 as function of bypass valve position.

1.3.9 Program logic

Based on the system analysis, the program logic, for conducting the primary control according to the specific terms and conditions, has been developed.

1.3.10 Tool for handling bids in the FNR-market

For the demonstration phase of 3 month, a tool (as spreadsheet) has been developed for calculating optimal bid price and amount in the FNR market. This tool needs information for the next day in terms of electricity prices (available from Nord Pool), heat demand in the district heating system, and planned production on the WtE-plant.
The spreadsheet then optimises (by the solver tool) the bids (amounts and prices) for the following day (consisting of six 4-hours periods) based on the electricity prices, heat demand

and marginal price in the district heating system. The spreadsheet takes into consideration relevant characteristics and bottlenecks associated with the WtE plant and connected systems. Limitations in operation, e.g. planed stop, abnormal bottlenecks etc. need of course also to be taking into consideration when the amount of regulated power is offered via bids to the market. Such abnormal conditions, however is not included in this demonstration tool.

At Nordforbrænding heat is distributed to its own district heating system and heat can be sold to or bought from two external systems (DTU, situated in Lyngby and HØK in Helsingør). Nordforbrænding does not have a heat accumulator, whereas DTU and HØK each have their own heat accumulator.
In addition, heat can be rejected to the surroundings (air) via dry coolers, when heat demand in the connected district heating systems is less than the heat production.
The WtE plant consists of one combined heat and power incineration line and three incineration lines, producing district heat only. In addition, natural gas fired boilers are distributed in the district heating system, for backup and peak load conditions.

The spreadsheet consists of an input area (see Figure 20), where day ahead electricity prices, production plan (tons of waste incinerated), heat demand are to be specified.

Time i døgnet	1	2	3	4	5	6	7	8	9	10	11	12
Elpriser (fra arket: "Elspot pris input")	118.5	113.9	110.9	110.6	113.6	118.3	130	356	321.8	334.1	334.9	366.2
Evt. justering af elpris	0	0	0	0	0	0	0	0	0	0	0	0
Elpris med garanteret mindste pris	370	370	370	370	370	370	370	370	370	370	370	370
Elpris justeret og med garanteret mindste pris	370	370	370	370	370	370	370	370	370	370	370	370

Time i døgnet	13	14	15	16	17	18	19	20	21	22	23	24	
Elpriser (fra arket: "Elspot pris input")	366.4	366.6	366.2	334.6	300.9	350.8	350.6	334.4	356.6	335	321.4	130.8	Kr./MWh
Evt. justering af elpris	0	0	0	0	0	0	0	0	0	0	0	0	Kr./MWh
Elpris med garanteret mindste pris	370	370	370	370	370	370	370	370	370	370	370	370	Kr./MWh
Elpris justeret og med garanteret mindste pris	370	370	370	370	370	370	370	370	370	370	370	370	Kr./MWh

FNR Blok	1	2	3	4	5	6	
Tidsperioder FNR 4-timers blokke	0-4	4-8	8-12	12-16	16-20	20-24	Klokkeslet
Vægtet elprisprognose	370	370	370	370	370	370	Kr./MWh
Vægtet realiseret elpris	370	370	370	370	370	370	Kr./MWh
Prognose og plan for varmebehov og varmeproduktion:							
Nordforbrændings fj.v. net	10	30	30	10	11	10	MW
DTU aftalt	4.3	0	0	2	2	2	MW
Helsingør aftalt	10	0	0	10	10	10	MW
Mulighed for ekstra varmeaftag til HØK + DTU	2.0	2.0	1.0	2.0	2.0	2.0	MW
Nødvendig indfyring for varmebehov	12.8	15.8	15.8	11.6	12.1	11.6	Tons/h
Forventet indfyring/affaldsmængde	15.0	15.0	15.0	12.5	13.0	12.0	Tons/h
Varmeproduktion forventet	28.4	28.4	28.4	23.7	24.6	22.8	MW
Varmeoverskud ift planlagt aftag	4.1	-1.6	-1.6	1.7	1.6	0.8	MW
Beregnet behov for gasfyring	0.0	1.6	1.6	0.0	0.0	0.0	MW
Udnyttet ekstra varmeaftag uden FNR (HØK+DTU)	2.0	0.0	0.0	1.7	1.6	0.8	MW
Uudnyttet ekstra varmeaftag HØK+DTU	0.0	2.0	1.0	0.3	0.4	1.3	MW
Estimeret bortkøling uden bypass	2.1	0.0	0.0	0.0	0.0	0.0	MW
Estimeret bortkølingskapacitet (beregnes evt.)	10.0	10.0	10.0	10.0	10.0	10.0	MW

Anlægsdata:			
Maksimal samlet op- og nedregulering	1.5	MW	(maksimal samlet budstørrelse)
Antaget brændværdi	10.5	GJ/tons	2.92 MWh/tons
Anlægsvirkningsgrad varme	0.65		
Pris varme eget net (Nordforbr)	350	Kr/MWh	(bruges pt. ikke)
Helsingør	275	Kr/MWh	(evt. med beregnet formel)
DTU	275	Kr/MWh	(evt. med beregnet formel)
Varmekostpris gasfyr	750	Kr/MWh	
Garanteret minimumspris for El	370	Kr/MWh	
FNR data m.m.			
Gennemsnitlig nedregulering pr MW opregul.	86.0%	(antaget symmetrisk frekvensafvigelse)	
Gennemsnitlig nedregulering pr MW nedreg.	14.0%		
Maks (pris_op/ pris_ned) ift budvalg	1.5		(bruges pt. ikke)
Konservativ prisfaktor	1.5		(bruges pt. ikke)
Mindste bud FNR	0.3	MW	

Figure 20. Inputs for electricity prices, production and heating plan, plant characteristics and heating prices and data associated with the FNR market.

The bid tool calculates bids (cost price) in four scenarios (see Figure 21):

a. ”Symmetrical up and down”
b. “Individual up and down”
c. ”Only up”
d. “Only down”.

De fire underscenarier er beregnet uafhængigt af hinanden. Derfor må kun et scenarium indmeldes på FNR markedet. Budpris er for den anføte effekt på det pågældende FNR marked i den aktuelle 4-timers periode.
Ved samtidigt bud i både op- og nedregulering, forudsætter de beregnede bud at begge bud vindes.

Symmetrisk op- og nedregulering

FNR Blok:	1	2	3	4	5	6	
Aktuel maks. till. symmetrisk budstørrelse	0.8	0.8	0.8	0.8	0.8	0.8	MWe
Symmetrisk bud op/ned	0.647	0.750	0.750	0.750	0.750	0.750	MWe (Solver)
Bud (offeromkostning) pr time	239	-285	-285	194	180	71	Kr/h for budstørrelse
Specifik budpris pr time	185	-190	-190	130	120	48	Kr/MWe/h bud
Fortrængt gasvarme	0.00	0.75	0.75	0.00	0.00	0.00	MW
Rest efter gas substitution	0.65	0.00	0.00	0.75	0.75	0.75	MW
Ekstra varmesalg ved FNR	0.00	0.00	0.00	0.30	0.35	0.75	MW
Mistet elproduktion gennemsnit	0.647	0.75	0.75	0.75	0.75	0.75	MWe
Uudnyttet budmulighed	0.1	0.0	0.0	0.0	0.0	0.0	MWe

Kun opregulering

FNR Blok:	1	2	3	4	5	6	
Aktuel maks. tilladelig budstørrelse	1.5	1.5	1.5	1.5	1.5	1.5	MWe
Kun opregulering	0.300	1.500	1.500	1.500	0.412	1.453	MWe (Solver)
Bud (offeromkostning) pr time	95	-490	-490	394	34	119	Kr/h for budstørrelse
Specifik budpris pr time	318	-327	-327	263	82	82	Kr/MWe/h bud
Fortrængt gasvarme	0.00	1.29	1.29	0.00	0.00	0.00	MW
Rest efter gas substitution	0.26	0.00	0.00	1.29	0.35	1.25	MW
Ekstra varmesalg ved FNR	0.00	0.00	0.00	0.30	0.35	1.25	MW
Mistet elproduktion gennemsnit	0.26	1.29	1.29	1.29	0.35	1.25	MWe
Uudnyttet budmulighed	1.2	0.0	0.0	0.0	1.1	0.0	MWe

Individuel op- og nedregulering

FNR Blok:	1	2	3	4	5	6	
Aktuel maks. tillad. samlet budst.	1.5	1.5	1.5	1.5	1.5	1.5	MWe
Samlet bud op + ned	1.5	1.5	1.5	1.5	1.5	1.5	MWe
Opregulering	0.300	1.200	1.200	0.300	0.300	0.331	MWe (Solver)
Nedregulering	1.200	0.300	0.300	1.200	1.200	1.169	MWe (Solver)
Bud (offeromkostning) pr time	158	-408	-408	75	60	43	Kr/h for budstørrelse
Specifik budpris pr time	105	-272	-272	50	40	28	Kr/MWe/h bud
Fortrængt gasvarme	0.00	1.07	1.07	0.00	0.00	0.00	MW
Rest efter gas substitution	0.43	0.00	0.00	0.43	0.43	0.45	MW
Ekstra varmesalg ved FNR	0.00	0.00	0.00	0.30	0.35	0.45	MW
Mistet elproduktion gennemsnit	0.43	1.07	1.07	0.43	0.43	0.45	MWe
Uudnyttet budmulighed	0.0	0.0	0.0	0.0	0.0	0.0	MWe

Kun nedregulering

FNR Blok:	1	2	3	4	5	6	
Aktuel maks. tilladelig budstørrelse	1.5	1.5	1.5	1.5	1.5	1.5	MWe
Kun nedregulering	1.500	1.500	1.500	1.500	1.500	1.500	MWe (Solver)
Bud (offeromkostning) pr time	78	-80	-80	20	20	20	Kr/h for budstørrelse
Specifik budpris pr time	52	-53	-53	13	13	13	Kr/MWe/h bud
Fortrængt gasvarme	0.00	0.21	0.21	0.00	0.00	0.00	MW
Rest efter gas substitution	0.21	0.00	0.00	0.21	0.21	0.21	MW
Ekstra varmesalg ved FNR	0.00	0.00	0.00	0.21	0.21	0.21	MW
Mistet elproduktion gennemsnit	0.21	0.21	0.21	0.21	0.21	0.21	MWe
Uudnyttet budmulighed	0.0	0.0	0.0	0.0	0.0	0.0	MWe

Figure 21. Calculation of bids in 4 scenarios: Top left corner:”Symmetrical up and down”, “Individual up and down”, ”Only up” and (bottom right corner) “Only down”.

"Symmetrical up and down" means that a pair of bids of the same sizes and prices is applied to the FNR market for up and down regulation. The calculation assumes that both bids are accepted, which cannot be guaranteed.

"Individual up and down" means that a pair of bids of individual (differently) sizes but of same prices is applied to the FNR market for up and down regulation. The calculation assumes that both bids are accepted, which cannot be guaranteed.

"Only up" means that only a bid in the FNR up regulation market is applied for the actual 4-hour block period.

"Only down" means that only a bid in the FNR down regulation market is applied for the actual 4-hour block period.

The spreadsheet provides two ways of calculating bids:

1. Manual (user specified) bid size.
2. Optimization of bid size (by use of solver functionality in spreadsheet) for maximizing estimated profit. This feature relies on expected (prognostics) for FNR prices.

In the manual calculation, the user can specify the bid size for each 4-hour block in each scenario. However it is assumed that mostly the bid size will be kept at a fixed value.
For each 4-hour block, the optimal bid is selected among the four scenarios having the lowest cost (penalty cost).

In the method where bid size can be optimized, the estimated profit is sought maximized with the build-in spreadsheet solver.
As mentioned, this optimization assumes known (or prognostic) prices of FNR. How to make prognoses for prices in the FNR market will not be addressed here. A simple and conservative price estimate might be used.
The feature is among others intended as an automatic procedure for avoiding a too large power bid or no bid at all, when a limited power bid is optimal, as for instance in a situation where heat demand (heat drain) becomes a limiting factor for production rate (incineration of waste and power production). In such case the marginal cost price (penalty) of FNR regulation changes in discrete steps.

FNR Blok:	1	2	3	4	5	6		
Indmeld bud op	0.00	1.50	1.50	0.00	0.00	0.00	MWe	
Budpris specifik	0	-327	-327	0	0	0	kr/MW/h	
Aktiveret pris FNR op (udfyldes efterfølgende)	200	250	200	350	300	200	kr/MW/h	
Vundet (1: Ja; 0: Nej)	0	1	1	0	0	0		
Omkostningstillæg ift. justeret elpris	0.0	0.0	0.0	0.0	0.0	0.0	Gevinst døgn FNR op	
Gevinst pr 4-timers blok	0	3461	3161	0	0	0	6622	Kr.
Indmeld bud ned	1.50	0.00	0.00	1.50	1.50	1.50	MWe	
Budpris specifik	52	0	0	13	13	13	kr/MW/h	
Aktiveret pris FNR ned (udfyldes efterfølgende)	200	225	175	300	200	150	kr/MW/h	
Vundet (1: Ja; 0: Nej)	1	0	0	1	1	1		
Omkostningstillæg ift. justeret elpris	0.0	0.0	0.0	0.0	0.0	0.0	Gevinst døgn FNR ned	
Gevinst pr 4-timers blok	889	0	0	1720	1120	820	4550	Kr.
Samlet gevinst (ved realiseret varmeplan)	889	3461	3161	1720	1120	820	11171	Kr.

Figure 22.Calculated bids in terms of type of bid (up and down) sizes and prices. The days profit based on won bid prices (or estimated FNR prices), is summed up.

1.3.11 The FNR market after 3.rd of October 2012

After the 3.rd of October 2012, the terms and conditions for FNR in DK2 have changed. Among others this means that only symmetrical up-dawn bids are now accepted, and bids now longer need to be in predefined 4-hour blocks, but can be defined by the bid provider. A bid period cannot include more than one date. Also the market is split into a 1-day ahead and a 2-day ahead market.
Another important change is that the FNR operators now being paid individually "paid as bid" instead as formerly a common price for all activated bids for each time block, defined as highest marginal activated bid price. Finally, the (by energinet.dk) published historical FNR market prices, now is an average market price and not the marginal price. This makes the FNR market less transparent for the operators.

The above changes mean that the cost price for FNR, calculated in the spreadsheet for optimizing bid size and price, should no longer be the bid price, if the operator should gain any profit for the FNR operation.
In that sense, the new condition "paid as bid" favors the operators having the most precise prediction of the market situation and marginal bid price in the market. Typically, the small operator will lack market information, resulting in a lower price for the same product (FNR).

One can argue that this implies reduced likelihood that the technically most suitable plants (lowest marginal costs) are being activated in the FNR market, and overall, the consequences of "paid as bid" instead of a common price for the same product is more resources (fuels, lifetime etc) being allocated for controlling the grid frequency.

1.3.12 FNR control unit (software)

From a local PC, a program is continuously calculating an output signal (set point) to the steam bypass valve in order to fulfil the demanded regulating power on the steam turbine. As input signal the FNR control unit has the measured frequency and amount (MW) of accepted (won bids) of FNR_{up} and FNR_{down}.

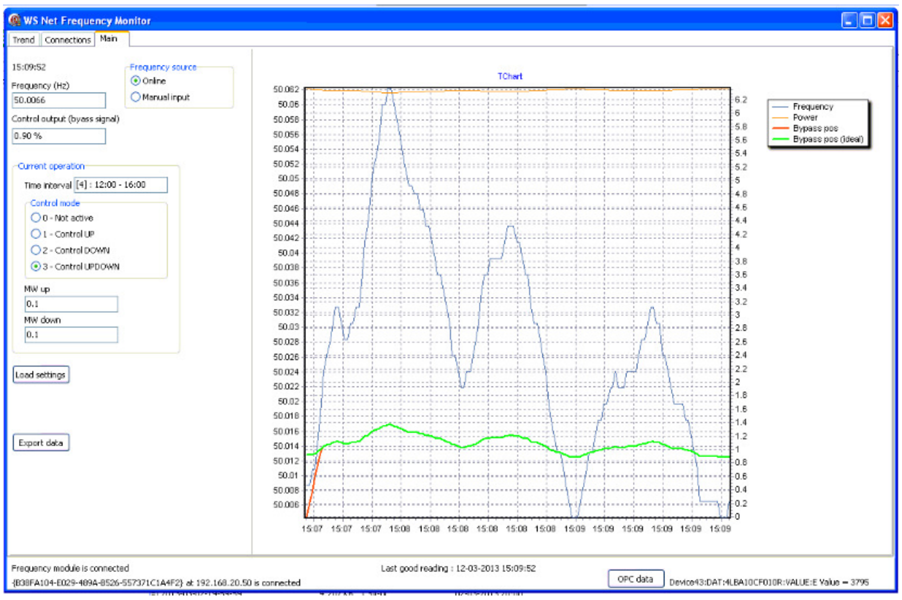

Figure 23. The WS.Frequency monitor screen from the FNR controller.

1.3.13 Test run 28.th of August 2012

The 28.th of August a FNR test run with bypass regulation according to grid frequency was conducted at the plant. The test simulated a FNR up regulation of 300 kW and 500 kW down regulation.
Process data in terms of steam flow, turbine power, steam pressure and steam temperature could now be extracted from the system. The test run was applied for approximately 2 hours. The data extracted from the system showed that the resolution of the turbine power is insufficient for documentation of the FNR regulation (see Figure 24).

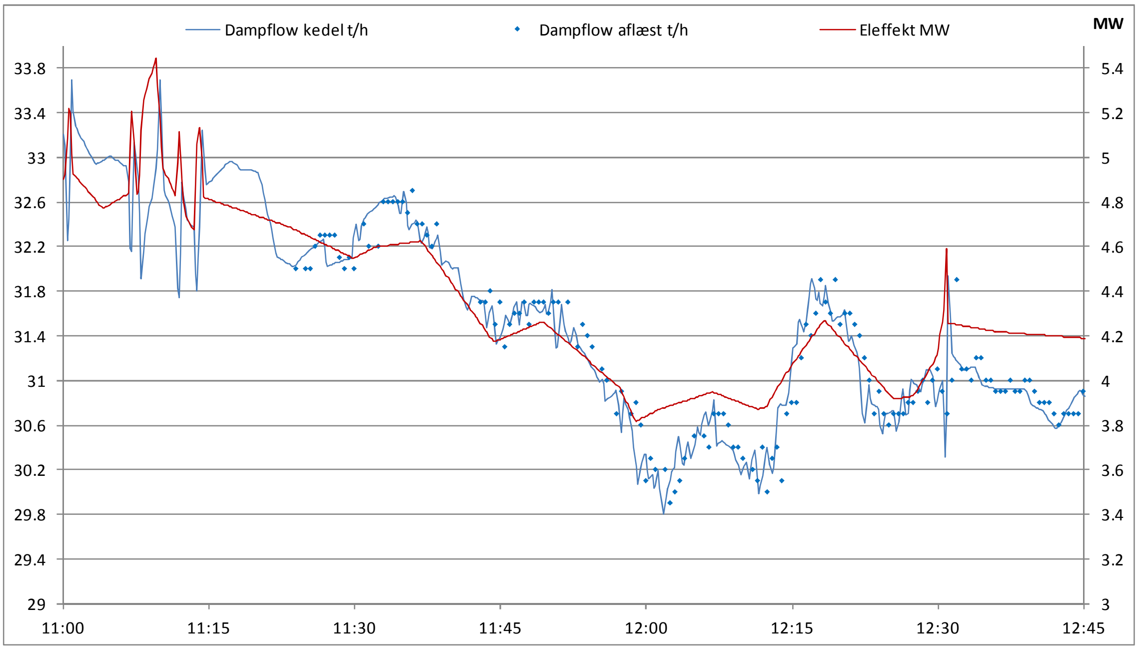

Figure 24. Steam flow and power.

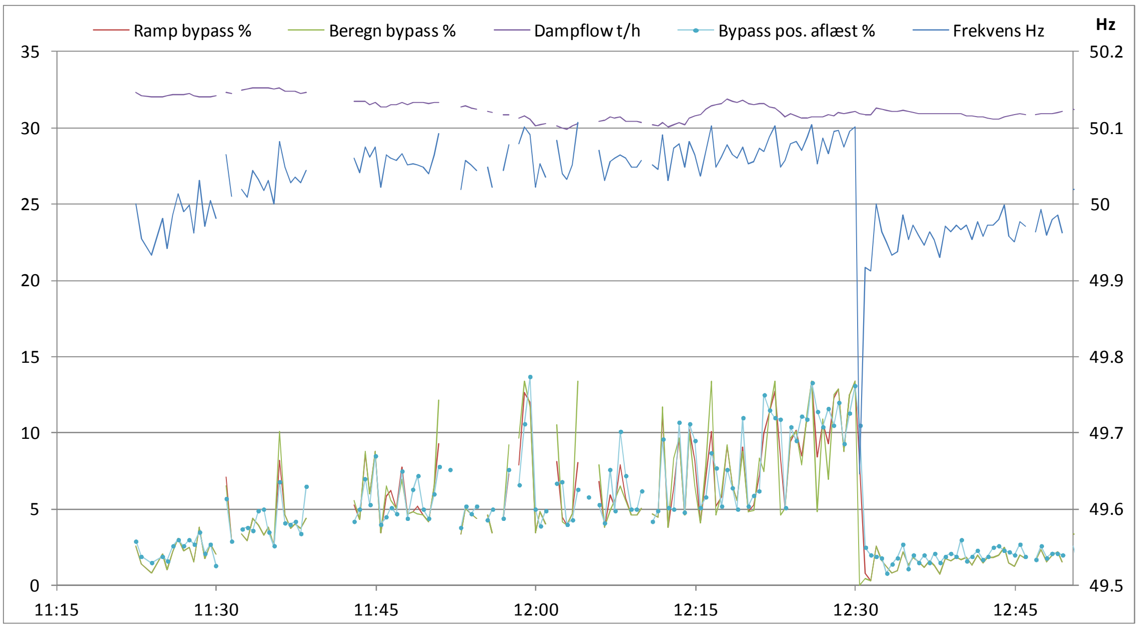

Figure 25. Observed bypass position together with calculated and ramped output bypass signal. Grid frequency (note the large frequency change at 12:30) and steam production rate are also included.

The bypass position (according to the installed valve positioner) was during the test read manually, as no logging is applied in the system. The bypass position follows the ramped output signal from the FNR controller closely (see Figure 25).

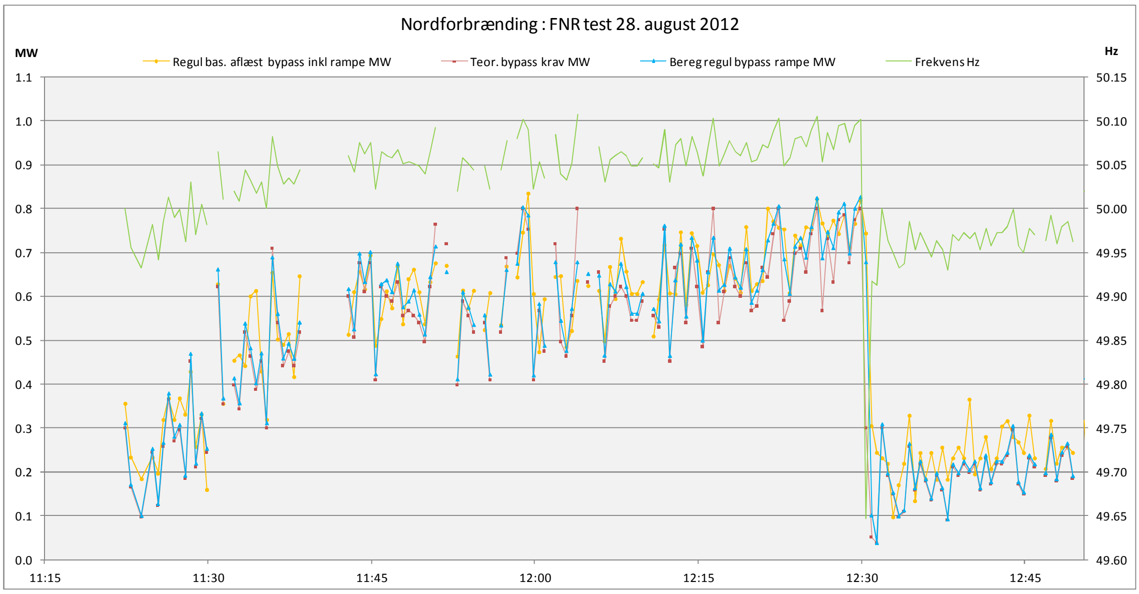

Figure 26. Calculated FNR regulation (yellow), based on observed bypass position. The calculated FNR regulation according to signal (limited with a maximum ramping speed) to bypass valve (blue) and the required FNR (red) according to the immediate grid frequency (green).

1.3.14 Test run 13.th of February 2013

In autumn 2012 during planned revision of the plant, damages to the labyrinth seals in the steam turbine was discovered. The turbine was sent to Nürnberg to be repaired.

Meanwhile the bypass regulator was programmed and installed on a PC at Nordforbrænding extracting data from the turbine control system and the grid frequency. An online simulation test of the FNR-control system was conducted the 13.th of February 2013. The WTE plant was in normal load but the steam flow varied quite a bit (see Figure 27).

The test was started with stepwise (0.02 Hz at a time) increase of frequency as fixed input to the FNR controller. The frequency was varied from 50 Hz up to 50.1 Hz and down to 49.9 Hz and for each value kept constant for about 3-4 minutes. Larger stepwise changes in frequency were then applied and also a test running with online measurement of grid frequency was conducted (see Figure 28).

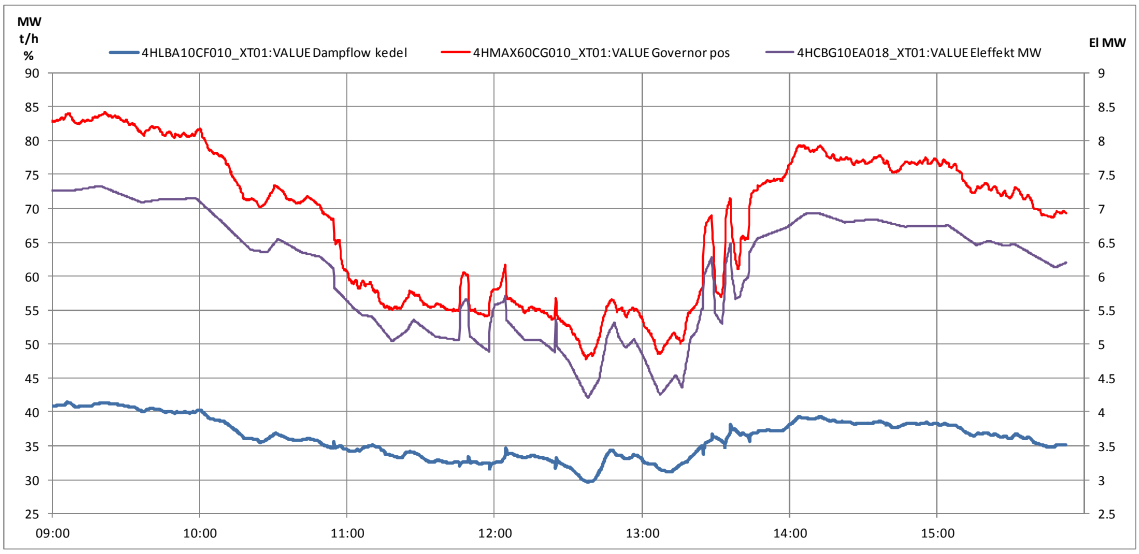

Figure 27. Steam flow from boiler and turbine governor position and power (right axis).

The data extracted from the system still indicate problems of controlling the power regulation at low valve openings. At 11:30 (see Figure 28) when the bypass valve opening is stepwise reduced, it appears that the bypass flow is not reduced accordingly from a certain time. This could indicate that the valve was stuck in a fixed position, and not moving according to the bypass signal. Such phenomenon is called "Stiction" (portmanteau of static or stick and friction), meaning that the static friction of the valve is much higher than the dynamic friction (during motion). This can lead to abruptly movements when the stocked valve suddenly releases, and consequently a limited accuracy of valve position and regulated power (see Figure 28 for example at 11:45 and 11:57).
However, when comparing the valve signal from the FNR-control system "BYPASSPLUS" with the observed readings of actual valve position, measured by a valve positioner and transferred to a monitor screen in the control room there is no such indication. The readings of valve positions are in fact in close accordance with the signal from the FNR-controller, which is also what should be expected when having a positioner.

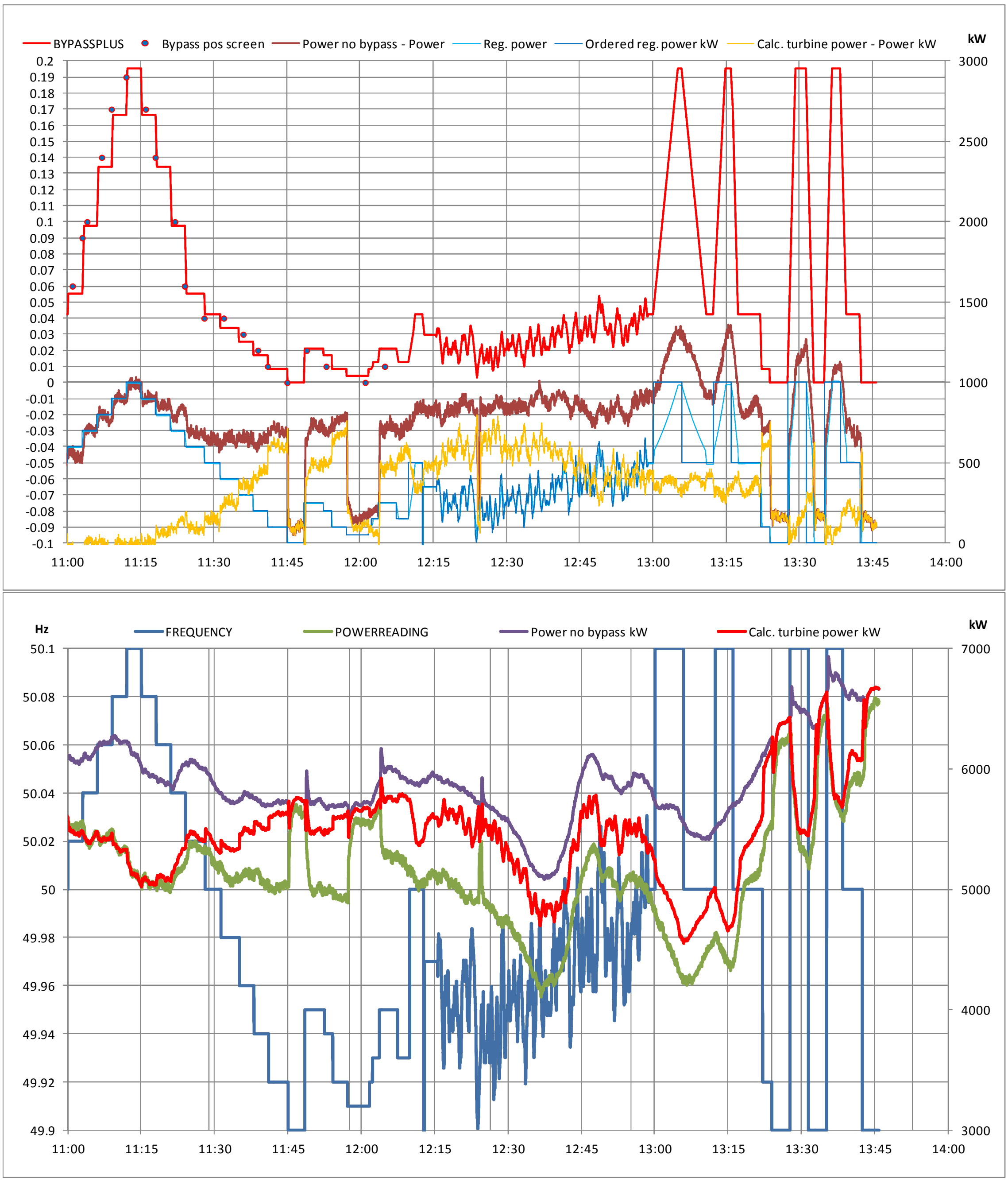

Figure 28. Results from test the 13.th of February with irregularities of the bypass valve.

It was observed, however, that the valve positioning was not maintaining exactly a fixed correct position of the valve, but tended to adjust the position typically within a band of ± 0.5% points. By more investigation it seemed like the pneumatic actuator was leaking air and consequently the actuator position slowly moved until suddenly, probably when the off-set dead band was exceeded, the positioner adjusted the valve position to the correct position.

At nearly closed conditions this means a relatively large deviation (as the equal percentage characteristic is not valid below 5% opening. At high opening degree the inaccurate position of the valve might also imply some inaccuracy in the regulated power. The valve position is only observed from screen and not logged in the system.

Comparison of the turbine governor valve position and the registered power (see Figure 29) show a consistent relation, indicating that the irregularities are to be addressed in the bypass system. Also there is a tight correlation between steam flow through the turbine and the governor position (see *Figure 30*).

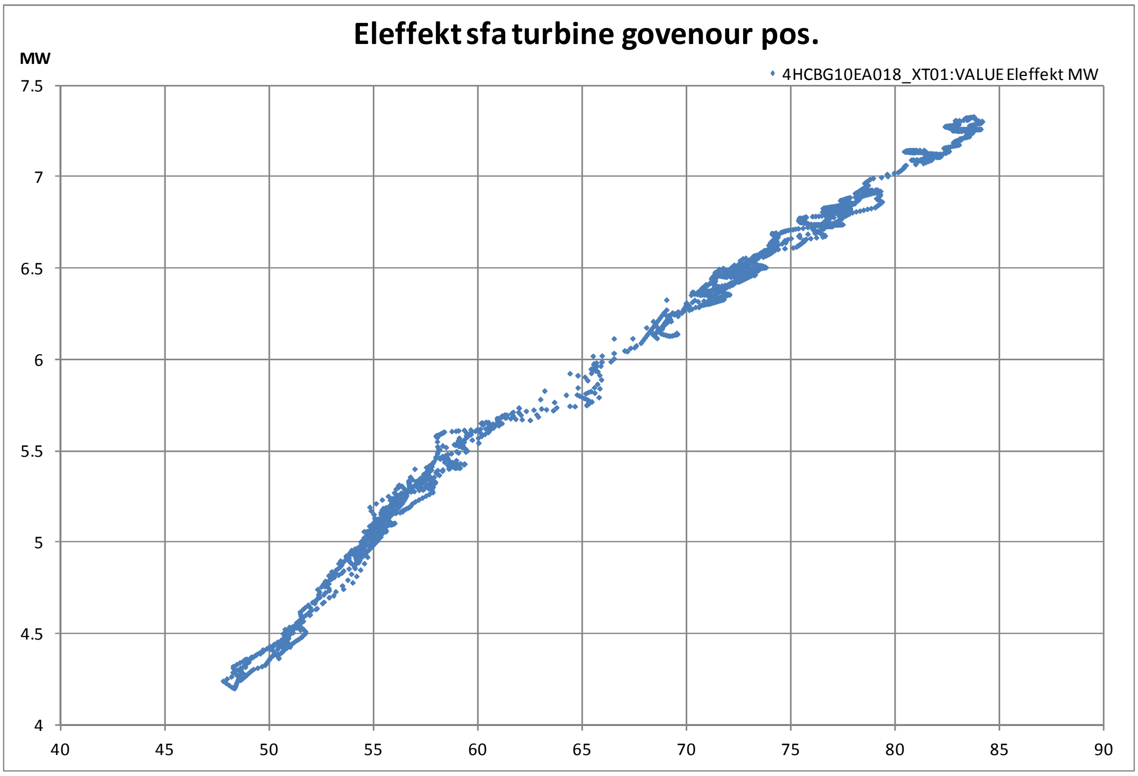

Figure 29. Governor valve position during test 13.th of February (8:52 – 15:49) 2013.

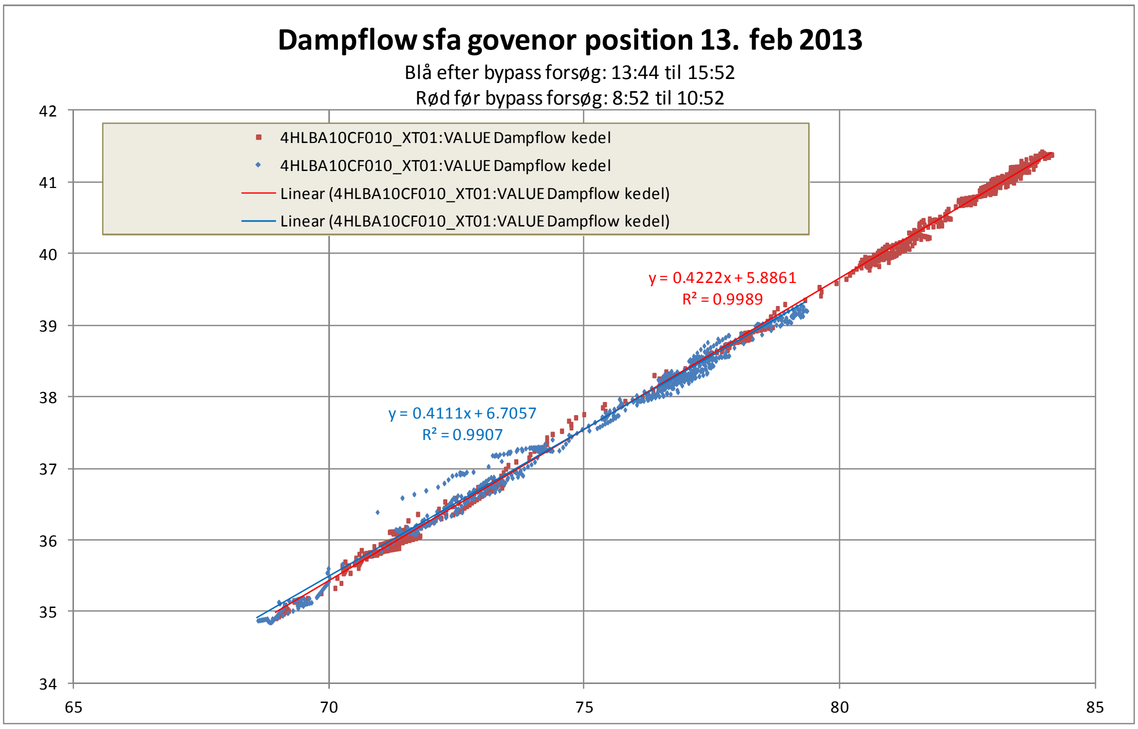

Figure 30. Steam flow as function of governor valve position during test 13.th of February. the red is before bypass test and the blue is after the bypass test.

Analysis by use of simulation

To evaluate the actual flow of steam through the turbine system we have compared actual manual pressure readings in the turbine with results from a turbine model simulating the same running conditions.

We have assumed a return temperature of the district heating constant at 54 C and the set point of forward temperature of the district heat constant at 103.5 C. The readings are actual time point readings which may represent neither an average value nor a fully balanced value. This can have some influence on the results.

At one certain time, the results show that even though the positioner of the bypass valve reads 1% (11:41 am) apparently the bypass flow corresponds to a valve opening degree of as much as 9%. We can only explain this by something must be wrong inside the valve. Perhaps some parts are not fixed as they should be and consequently might not always be in the correct place according to the valve rod position. The implication is that the Cv-value of the valve is not always unambiguous compared to a given position, which is an essential assumption for the FNR control strategy.

In Table 3, results from analysis of some observations picked out for closer analyses are presented. The table shows both the measured and the calculated (by use of WS.WtE-simulator) values. In the three columns far to the right design data is compared with the simulated values and the error is presented far to the right.

The two main indicators used for estimating the steam flow through the turbine are the pressure in the wheel chamber and the governor valve position. Other, less important however, indicators are the turbine back pressure and the pressure at the steam extracted to "Condenser 2".

Målinger fra den 13 /2 2012		OPC tid 11:41		11:45		13:26		13:32		Design point		error %
		Målt	Beregnet	Målt	Beregnet	Målt	Beregnet	Målt	Beregnet	Design	Beregnet	
M_damp_målt	t/h	32.5	32.5	32.3	32.3	35.8	35.8	35.8	35.8	40.3	40.3	0.00
påtrykt frekens	HZ	49.92		49.9		49.9						
P_hjulkammer	bara	21.8	21.56	23.7	23.83	26.1	26.5	22.8	22.45		30.23	
GOV pos	%	55	64.9	60	67.4	68	71.76	57	65.96		87.09	
P_udtag 2-målt	bara	2.2	2.35	2.3	2.54	2.6	2.77	2.3	2.42	2.84	3.05	-6.89
P_udtag 1	bara	1.12	1.19	1.18	1.19	1.19	1.21	1.19	1.2	1.17	1.16	0.86
P_ udløb	bara	0.74	0.737	0.62	0.648	0.61	0.612	0.78	0.76	0.624	0.615	1.46
Bypass pos	%	1	9%	0	0	0	0	19.5	19.5	0	0	
Bypass flow til cond	ton/h		3.01									
flow til Dearator	ton/h		1.63		1.69		1.75		1.77	2.02	1.98	2.02
Bypass flow til dearator	ton/h	0	0	0	0		0					
eleffekt	MW	5.05	5.14	5.61	5.73	6.26	6.44	5.3	5.23	7.405	7.212	2.68
Kondensretur temp	C	93	93	93.5	93.5	93	93	95.7	95.7		94.2	
Temp fjernvarnme f/r	C	103.5/54	103.5/54	103.5/54	103.5/54	103.5/54	103.5/54	103.5/54	103.5/54	100/65	100/65	

Table 3. Measured and calculated (WS.WtE-simulator) parameters at selected times.

From this test run and analysis we conclude that given the present condition of the bypass and turbine system it is not possible to operate the bypass regulation sufficiently accurately when the bypass valve is almost closed. It was also concluded that the bypass valve did not show a reversible characteristic which might be caused of internal loose parts in the valve. It should be noted here that the valve has recently (September 2013) been repaired and the original reversible valve characteristic has probably been recovered.

1.3.15 Test run 26.th of February 2013

A new test run was conducted the 26.th of February 2013 now adding an offset to the FNR-controller in order to avoid that the bypass valve will be operated in almost closed position.

This action, however, implies that a constant amount of power potential now is lost by bypassing the turbine disregarding the demand for FNR-regulation.

At 10:09 this offset was set to a constant value of 625 kW and a simulation of 625 kW FNR (symmetrical up and down) was then initiated. After a short period of regulating according to the grid frequency, manual input of frequency began 10:30 at a frequency of 50.4 Hz and was for each 3 to 4 minutes stepwise increased with 0.02 Hz up to 50.1 Hz and then with the same procedure stepwise decreasing down to 49.9 Hz and back again to 50 Hz.
Then at 10:55 larger steps of increment or decrement of frequency was applied from 50.0 Hz to 50.1 Hz in one step and back again to 50 Hz, and similarly the other way from 50 Hz to 49.9 Hz in one step and back again finishing approximately at 12:15.

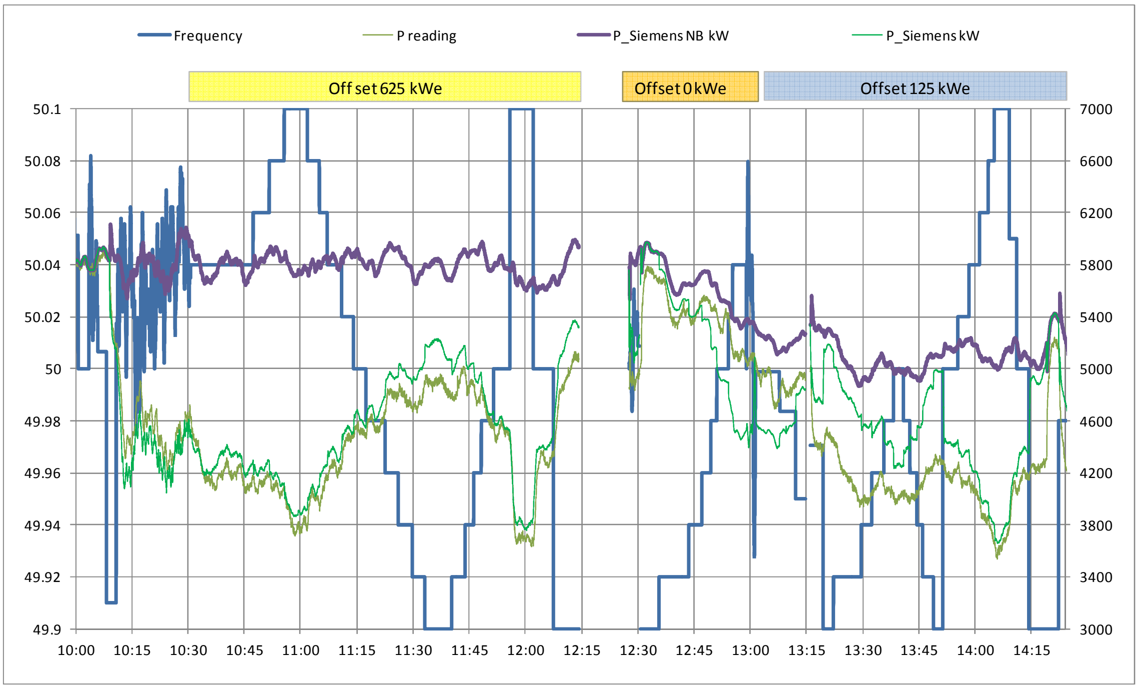

Figure 31. Results from test run 26.th of February 2013 with 625 kW FNR symmetrical.

The strategy with a rather large offset of bypass, has demonstrated much better performance. Still, when the valve is close to its minimum opening degree (in this case approximately 5%) there is some divergence between expected and observed power. The "applied" FNR regulation is here interpreted as the difference between "expected calculated power" of the turbine and actual measured power. Where "expected calculated power" is calculated power of the turbine if no bypass took place, and assuming certain design specifications present of inlet steam and in the steam condensers. This indicates that a slightly increased bypass offset corresponding to approximately 800 kW might be appropriate and sufficient.

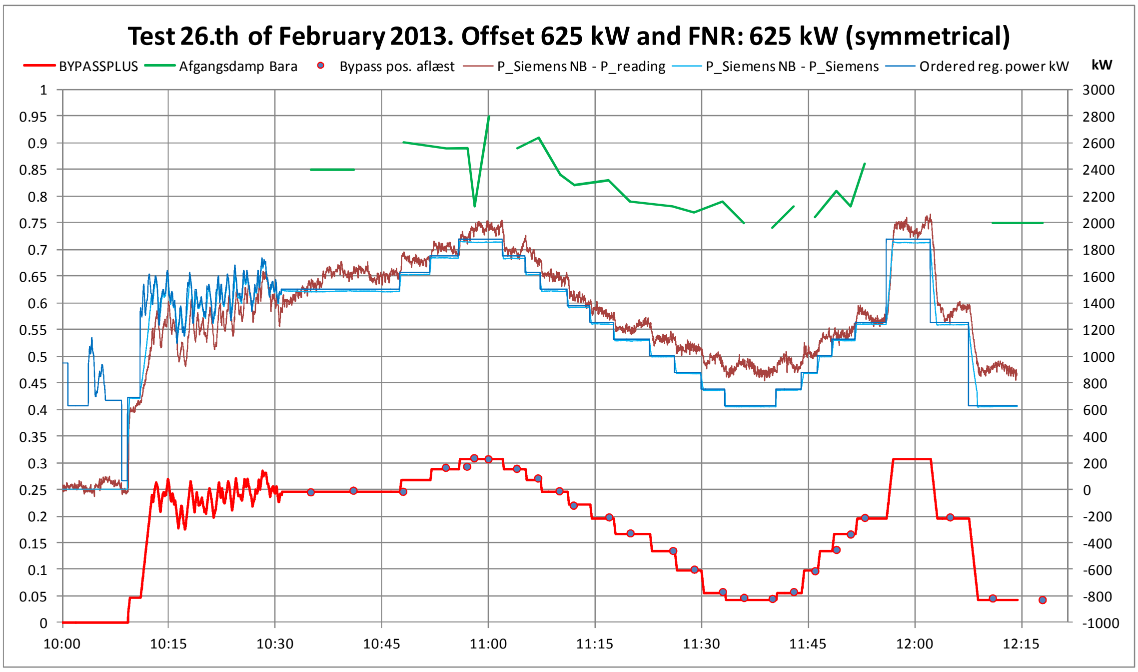

Figure 32. Ordered and "applied" (P_Siemens NB – P_reading) FNR regulation as observed 26.th of February 2013 when using an offset of 625 kW down regulation.

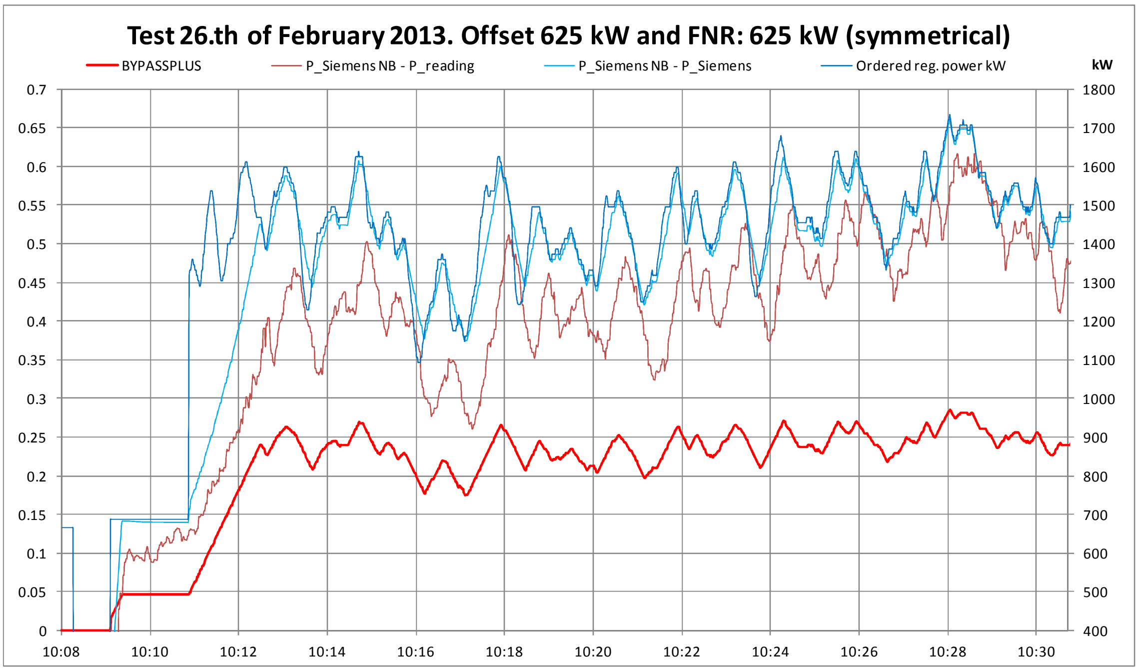

Figure 33. Close-up of the period when the FNR-regulator operates on the grid frequency.

Design conditions are not exactly present during the test. The expected calculated power assuming no bypass is consequently not a "true value", even when assuming that the calculated power corresponds to the actual performance of the turbine. In addition, bypassing steam to the first condenser will affect the condenser balance and pressures in the two condensers. Such second order effects on power are considered as acceptable when the amount of FNR-power is below 1MW.

1.4 Utilization of project results

During the demonstration phase the market conditions for the electricity area DK2 (East Denmark) were changed the 3.rd of October 2012. After this date significant lower prices are observed in the FNR-market (see Table 4 and Figure 34).

It should be mentioned that the prices in DK2 before and after the 3.rd of October cannot be compared directly. The prices before the 3.rd of October are marginal bid price activated, and are the price paid to all activated bids. Whereas the prices informed after the 3.rd of October are average prices activated in the two markets present (1-day ahead and 2-day ahead).

After the 3.rd of October 2012 the data are incomplete (only one week back download are available at Energinet.dk) and for some periods the data have not been downloaded.
The changed conditions, e.g. only symmetric bids (up and down) applicable, mean less incentive for the WtE plants to operate in the market, as mainly down regulation was intended and normally could be applied at a much lower price than up regulation.
Before October 2012 high prices for FNR down regulation (DK2) was observed and was the main driver for this project.

	2012 until October 3.rd	From Oct. 2012 to Sep. 2013		
Average FNR up**	357.1		DKK/MW/h	(DK2)
Average FNR down**	239.3		DKK/MW/h	(DK2)
Sum up and down **	596.4		DKK/MW/h	(DK2)
Average FNR (symmetrical up and down)*		169.4	DKK/MW/h	(DK2)
Average Primær opregulering **	241.6	237.5	DKK/MW/h	(DK1)
Average Primær nedregulering **	25.4	11.5	DKK/MW/h	(DK1)

*) Average price level of activated bids in the 1-day ahead and 2-day ahead market.
The average is based on incomplete data (not all days are included).
**) All activated bids are paid the same specific price (highest activated bid price).

Table 4. Average prices in the frequency control markets from 1st of January 2012 until 3rd of October 2012 and after this date (not complete data for FNR after 3.rd of October).

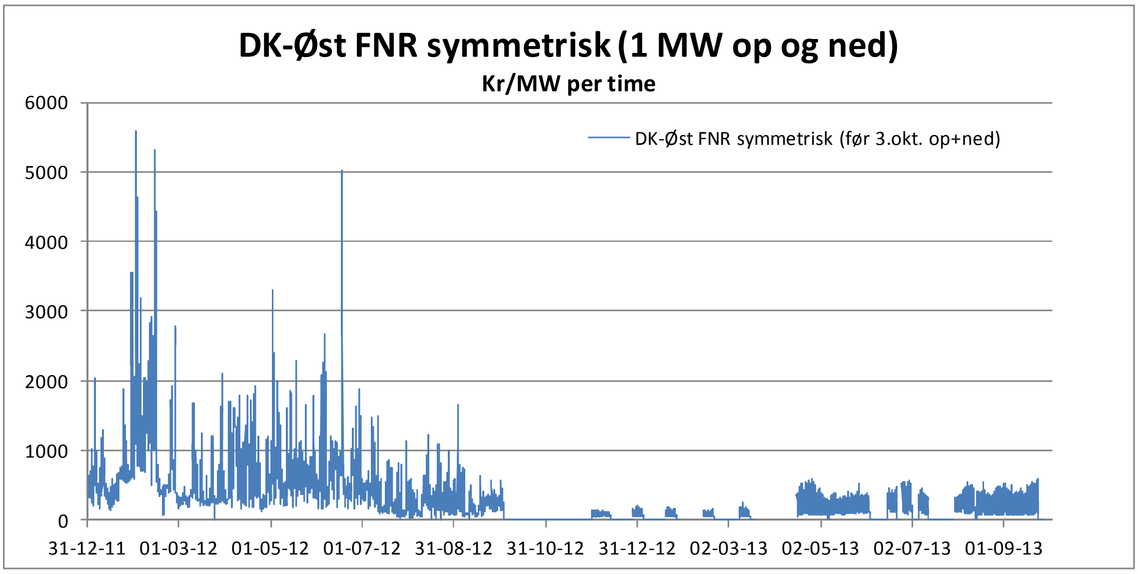

Figure 34. Market prices frequency control for DK2 (FNR). Data are not complete.

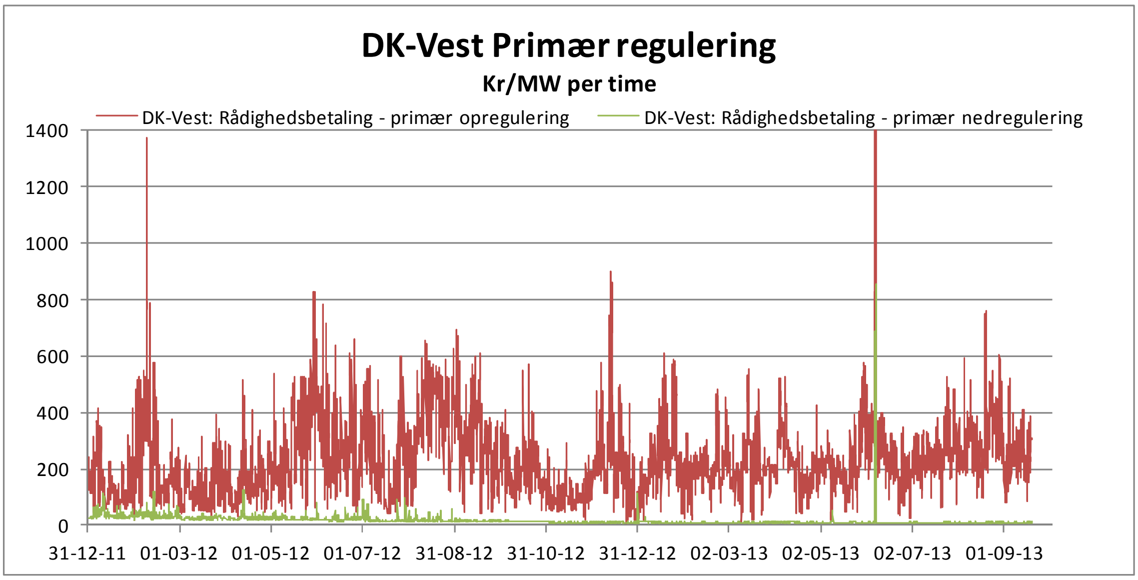

Figure 35. Market prices frequency control for DK1 (Primær regulering).

In the western part of the Danish electricity grid (DK1) the terms and conditions are unchanged during the period. However, in this part very low prices on down regulation have been observed even with a downward trend.

From the market prices observed since January 2012 we conclude that the incentive for bypass regulation to support grid frequency now seems largest in the western part of Denmark (DK1), and probably now involves both down and up regulation

1.5 Project conclusion and perspective

The project has demonstrated that a typical WtE plant is capable of doing bypass regulation of the steam turbine and by that either increase or decrease the power production from the turbine fast enough to fulfil the demand for response time that applies to either FNR or primary control.

Concerning the linearity of the regulated power according to the required regulation corresponding to a frequency deviation, the demonstration project have revealed that the chosen strategy of direct bypass regulation can be rather complex.
First the characteristic of the bypass valve is important. An equal percentage characteristic is not ideal for this situation – rather a linear valve characteristic seems appropriate. Certainly when operating an equal percentage also below its rangeability, the valve might be inappropriate.
In addition, at the demonstration facility the bypass valve showed inconsistencies in capacity versus observed position at low opening degrees.
As a consequence, we did a FNR test run with an offset on bypass regulation, eliminating the need for operating the bypass valve at small opening degrees. In this test the system worked well.

We did not find any proof of malfunction in the bypass valve. The valve was renovated in autumn 2013, and we decided to do another test for investigating whether or not the bypass valve after the renovation has become more consistent at low openings. In September 2013 however, damages to the labyrinth sealing was discovered and the turbine was sent to Nürnberg once again for reparation. We then decided to skip another test run.

The direct bypass control strategy, proposed in this project, has during technical feasibility tests identified some complexities regarding bypass valve characteristic, general valve condition and repeatability of the valve.
In that perspective, in some cases it might be more recommendable to apply another control strategy using the direct power controller, which typically is installed on a turbine.
The demanded power (input to the power controller) should then be calculated based on an estimated power potential and the required power regulation. To make this principle work in all conditions, the estimated power without regulation, needs being considered somewhat conservative, depending on how precise and how much effort is put into this estimator. In that sense, this alternative strategy still involves a model based power prediction in order to avoid unnecessary high amounts of bypass.

1.6 Annual export of electricity (only ForskVE)

1.7 Updating Appendix P and submitting the final report