Quantitative Valuation of Demand Response in Power Markets

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This paper presents results of an assessment of a Monte Carlo approach for determining the value of demand response in the Nordic power market. The analysis is based on the partial equilibrium model Balmorel, covering the Nordic power market, combined with a Monte Carlo framework. The result represents an analysis of changes in costs in the power market associated with Monte Carlo scenarios with or without different demand response alternatives. The results show the necessity of demand response in the power market in order to ensure the most comprehensive distribution of resources and thereby the largest welfare economic gain to society.

Overall, this case study shows that a Monte Carlo approach, coupled with a partial equilibrium model, can address the value of demand response undertaking the uncertainty in key variables. The paper presents results of a Nordic case study with large variation in benefit going from zero in most cases to very large numbers in a few percent of the cases. Large benefit is associated with extreme events such as high demand. Overall, demand response reduces net present value of total system costs.

Keywords: Demand Response, Monte Carlo, Partial Equilibrium Models, Power Markets

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1. INTRODUCTION

An efficiently operating electricity market depends upon well designed systems to balance demand and supply. Reality, in most electricity markets, is that demand does not play an active role in clearing of demand and supply in the short term market[1], nor in the determination of the power price. Recent years have caused growing concern whether the markets will function efficiently in the future. Evidence of abuse of market power (e.g., decision by the Danish Competition Authority from 30 November 2005), and a general fear that the markets will not attract the necessary investments in new capacity are some of the reasons. For many, it has become clear that demand response plays a key role in solving these issues, e.g., Borenstein and Bushnell (2000), Nordel (2002) and IEA (2003).

Demand response (DR) includes enabling the consumers to vary demand for electricity with the changes of supply, having a price determination that expresses scarce production resources efficiently. As a result, we choose to focus on welfare values generated from short-term reactions on day-ahead prices at the Nordic power market (Elspot at Nord Pool). Using a model of the Nordic power system (Balmorel, www.balmorel.com), we will analyze the economical consequences of adding two different demand response resources with either disconnection at a given price, or load shifting compared with a reference case with no additional consumer activity, or to building generation assets in form of a single cycle gas turbine.

The structure of the paper is as follows. After this introduction, section 2 describes the term demand response. After this, in section 3, we turn to the quantitative valuation of demand response with the use of the Nordic Power market as case study. Within this section, the model framework is presented including a short introduction to the Balmorel model and its adaptation for allowing demand response to be modeled. Then the methodology of using Monte Carlo simulations in combination with the Balmorel model is

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[1] The assumption that demand does not play an active role in clearing of demand and supply is valid on "very short term". Many empirical studies, e.g. Pindyck's book from 1979 "The structure of World Demand (MIT)", give support that short-run price elasticities for electricity are significant different from zero.

explained, and in the last part of the section, the results of the analyses are presented and discussed. Finally, in Section 4 we will draw the conclusions from the analyses.

2. DESCRIPTION OF DEMAND RESPONSE

As electricity is not economically storable, in real time, supply and demand must be balanced at system level. An imbalance in the system can generate blackouts over a very large area within seconds. In this perspective demand response aims at increasing the security of supply by using the given resources more efficiently. This is enabled through the reaction from consumers in a critical period via price signals.

Demand Response is here defined as a voluntary, temporary adjustment of electricity demand as a response to a price signal. Similar definitions can be found in U.S. Department of Energy (2006) and Nordel (2005). And reactions from the consumers may be categorized in three main categories (illustrated in Figure 1):

- Load shifting: Consumption that could be moved to another period with a lower price.
- Peak clipping: Reduction of consumption in periods where the marginal benefit of energy use is lower than the price, e.g., by substitution to another energy source.
- Valley filling: Strategic load growth when the marginal benefit of energy use is higher than the price, e.g., by substituting another source of energy (e.g. electrical heaters replacing heaters fuelled by oil or gas).

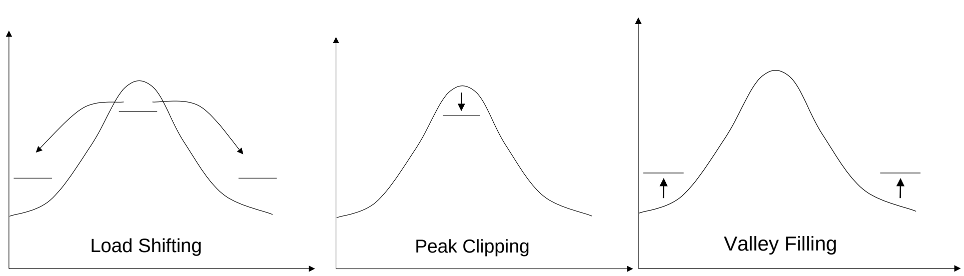

Figure 1: Three different kinds of Demand Response with respect to a given load profile (adapted from Gellings and Chamberlin, 1993, page 451).

Benefit from demand response include *participant financial benefits* (bill savings earned by customers that adjust their electricity demand in response to prices), *market-wide financial benefits* (lower wholesale market prices), *reliability benefits* (operational security and adequacy savings) and *market performance benefits* (mitigating suppliers' ability to exercise market power by raising power prices significantly above production costs) (U.S. Department of Energy, 2006).

From our findings, the most important benefits from increased demand response are:

- Increased resource efficiency and welfare gains from consumer reactions to market prices.
- Reduced volatility in market prices and consumption reducing the electricity bill for individual consumers (increased consumption at low prices (production costs) and reduced consumption at high prices).
- Increased security of supply.
- Reduced incentive for exercising market power; depending on the size and change in demand flexibility, the welfare gain may be positive, negative or zero, while electricity prices will decrease.
- Reduced investments in peak capacity decreasing the general price level.

With focus on welfare effects, consumers will, if it is possible to have flexible consumption, be able to obtain a better economy, and thereby also have an incentive to respond to fluctuations in the prices. Compared to the day-ahead power prices, consumers will in certain cases be able to obtain an even higher economic benefit, if they deliver regulation services, for example if they are able to decrease their consumption at short notice. However, this will only happen if the costs of reacting (e.g., costs of control equipment, communication of prices and consumption, etc.) are sufficiently low for them to react. Described in micro economic terms some of the welfare benefits are achieved when marginal costs of generation and willingness to pay for consumption are expressed in the market.

In this paper, the benefit of demand response will be calculated as a welfare benefit constituted by benefits from the consumers in form of voluntarily disconnections and reduction in production costs as results of the demand response reaction. That is why we choose to concentrate on the part of demand response that is short term, i.e., where the price signals, e.g. on an hourly basis, are generated from day-ahead or intraday markets, or from tariffs.

3. QUANTITATIVE VALUATION OF DEMAND RESPONSE

In recent years, a limited number of quantitative studies have been conducted within the area of demand response. Yusta et al., 2000 estimates the influence of the price elasticity in a technical-economic model of an electric energy service provider, and shows that the more elastic the behavior of the customer demand, the lower the profit obtained by retailers. Sezgen et al., 2007 values three demand response strategies; load shifting, peak clipping, and fuel substitution from an option value argument, i.e., finds values that include the uncertainties in the valuation of the different demand response investments. The results do not touch upon the social welfare gains as the focus is on investment possibilities. Only a few studies address the problem using the same overall framework as this study. Violette, 2005 assesses the benefits of demand response with a resource planning model with a Monte Carlo approach. This study mainly illustrates the method of using Monte Carlo simulations to evaluate demand response activities, and shows that the method is very suitable for addressing demand response under given uncertainties in future key variables.

The chosen analytical setup in this case study is the meta-modeling approach presented in Violette (2005). This is a methodology of how to combine existing modeling tools with Monte Carlo analysis to valuate different demand response products. This method has been chosen due to its sampling method to randomly vary parameters over a range of values from a specified frequency distribution and generate corresponding sets of model predictions. The argument behind this is that demand response may not be profitable in normal or average situations, but considering weighted cases, including more extreme events, may change the whole picture. Indeed, it is expected that the value of demand response in an average situation will be relatively small, compared to the average over a more representative distribution of situations. In this particular case, the method is used in order to include extreme events such as extreme hydrological situations, wind power situations or demand levels, and with the right probability, as demand response seems to give the highest benefit in extreme situations.

The Monte Carlo framework is combined with a partial equilibrium model named Balmorel (www.balmorel.com). The Balmorel model is here used with the adaptations needed to model demand response products. The analysis covers the Nordic region with Denmark, Finland, Norway and Sweden in the representative year 2010. The model will, in this setup, give hourly prices for one winter week.

The results are analyzed through changes in total system costs compared to a reference situation. Consequently, the results show the benefit to society of implementing demand response, as the only change between the compared situations is demand response actions. The changes in social welfare are given from the changes in total system costs. There are also some welfare distributional effects as a consequence of the demand response activity, but as we wish to analyze changes in total welfare this is not included in the study.

The interaction between the partial equilibrium model Balmorel and the Monte Carlo varied parameters are illustrated in Figure 2.

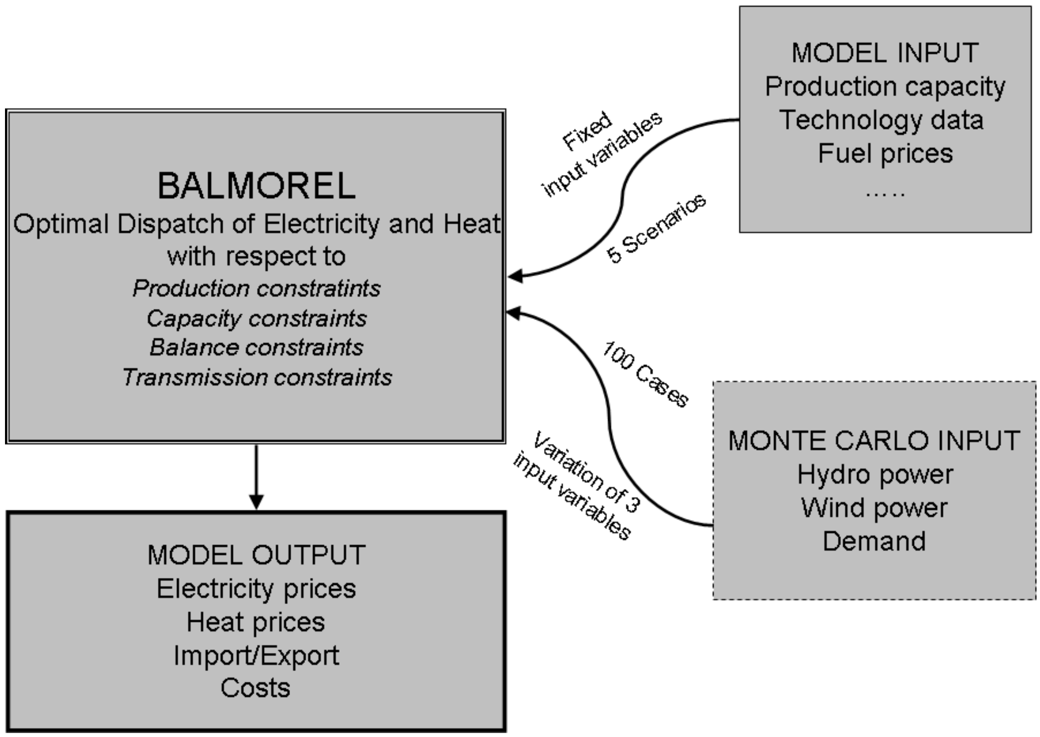

Figure 2: Interaction between the Monte Carlo framework and the Balmorel model.

The Balmorel Model uses some input parameters to define the power system which is modeled. The data are estimated beforehand and include information on, e.g., technologies, fuel prices, capacities and initial demand level. Additionally, we choose to vary three parameters that represent some of the main uncertainties in the system using Monte Carlo techniques. With these Monte Carlo variations, we obtain model outputs for each set of input variables (5 scenarios and 100 cases), i.e., 5x100 sets of output parameters.

3.1 Balmorel Model Framework

The Balmorel model is formulated as a partial equilibrium model covering the electricity and combined heat and power (CHP) sectors in the four Nordic countries Denmark, Finland, Norway and Sweden (Ravn, 2004). The objective function used for the optimization minimizes the production costs for the whole region under several restrictions.

The model estimates the production that is socially beneficial under the assumption of perfect competition. Optimal values for decision variables include:

- Prices on electricity and heat within each region, and thereby
- Production of electricity and heat each hour
- Imports and exports between the regions

The model structure is illustrated in Figure 3. For a more detailed description of the Balmorel Model see Hindsberger et al., 2003, Ravn, 2004 or Dittmar, 2006.

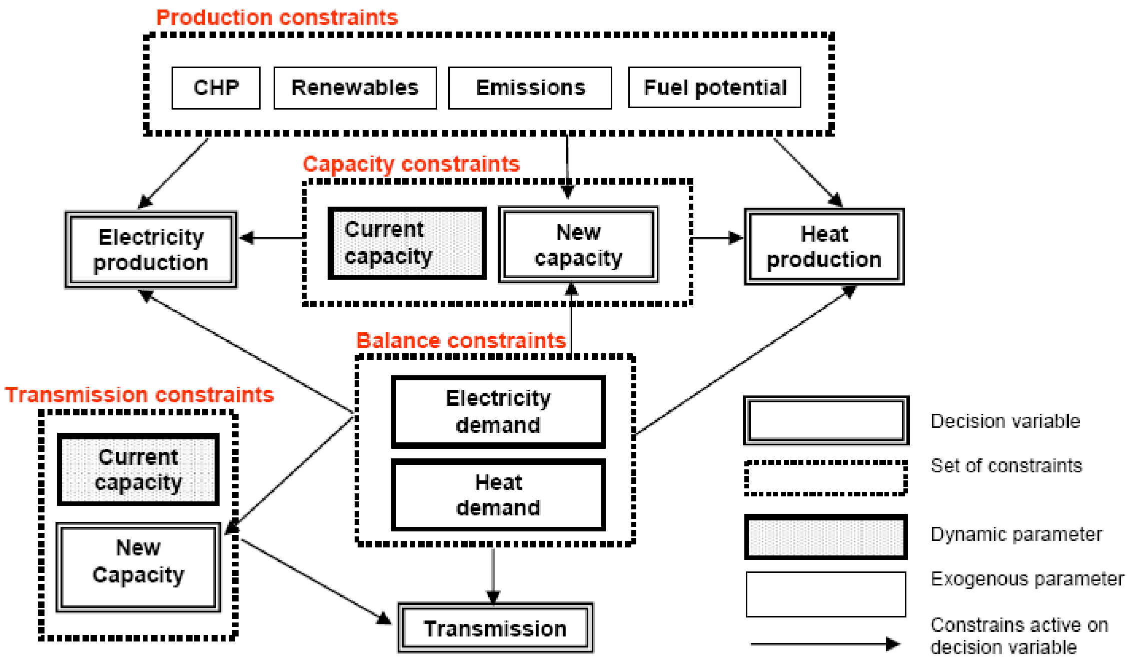

Figure 3: Balmorel model structure (Based on Hindsberger, 2003). In the present study, however, the two decision variables on new transmission capacity and new production capacity have not been used.

Pricing in the model is divided into four price areas in Norway, two in Denmark, three in Sweden and one in Finland. This is a bit more detailed than present practice in the Nordic power market where e.g. Sweden is only one price area. The model is linear (LP) and assumes full information including full foresight, e.g., the electricity demand and the available wind and water resources are fully known for the whole analysed period.

By computing optimal solutions it is easy to make comparative analyses, since we have two optimal solutions that can be compared. This feature is seldom found in e.g., simulation studies.

Data in the applied model combine historical data (for electricity and heat demand, wind power production and others) with scenarios for the future development in heat and power demand and installed capacity. In the present version one week is simulated with the time step of one hour.

The large share of hydro power with storage capacity makes it necessary to introduce boundary conditions when simulating a week. This is done by specifying a boundary condition where the possible production level from hydro power (available amount of water) for each week and each region is specified based on input from a version of Balmorel optimizing the use of hydro power over a yearly horizon.

The exchange between the countries modeled is determined endogenously, according to relative prices and transmission capacities. The exchange between the modeled Nordic countries and Germany/Poland is represented using a price interface calibrated with the use of the long-term version of Balmorel. The price interface is calibrated by assuming that the annual net exchange between the Continent and the Nordic countries is zero in a normal year with respect to hydro inflow. In dry years a net import is allowed, and in wet years a net export is allowed. Typically, the annual net exchange between the Continent and the Nordic countries is between 0 and 10 TWh (compared to the total Nordic consumption/generation of app. 400 TWh). The exchange between Finland and Russia is specified with fixed values giving a yearly net import to Finland from Russia of 11 TWh.

3.2 Monte Carlo Framework

A Monte Carlo analysis is based on performing hundreds or even thousands of simulations with probabilistically selected model input, and using the results of these evaluations to determine both the uncertainty in model predictions and the input variables that give rise to this uncertainty. It initially starts with the following four steps (uncertainty analysis):

- Range and distribution are selected for each input parameter. See description below.

- Sample the required number of outcomes of each input parameter from the given distributions. The program Crystal Ball is used for the sampling with the sampling method Latin Hypercube, whereas each case has equal probability.
- Produce simulation results with the inputs generated in the step above. The Balmorel model is used in this part.
- Calculation of mean, variance, and distribution functions of the results such as total costs in the Nordic region.

The uncertainty analysis should be followed up by a sensitivity analysis that investigates the impact of individual variables on model calculations. These measures include, e.g., correlation measures, regression analyses, Sobol measures, etc.

Latin Hypercube sampling (Iman and Helton, 1991), which is used as sampling method within the simulation, has been selected for the analyses, as it has shown to require fewer model iterations to approximate the desired variable distribution than the simple Monte Carlo method. The Latin Hypercube technique ensures that the entire range of each variable is sampled. A statistical summary of the model results will produce indices of sensitivity and uncertainty that relate to the effects of heterogeneity of input variables to model predictions. In addition, frequency distributions of model state variables can be compiled to determine the relative frequencies of the most frequent and maximum classes resulting from the model simulations.

3.3 Analysis of Demand Response in the Nordic Power Market

This analysis covers the four Scandinavian countries; Denmark, Finland, Norway and Sweden. In this area, a power exchange exists, Nord Pool, (www.nordpool.com) covering all four countries. In the Nord Pool price area zonal pricing is used with 6-8 price areas. This regime ensures a local signal, as prices will differ if transmission bottlenecks are hindering the most economical dispatch of power.

In the region, where the population is 25 million, the total annual electricity demand in just under 400 TWh. Large differences in both size of consumption and electricity generation sources exist between the countries as showh in Table 1. Historically, low power prices in Norway and Sweden have led to large power intensive industry sectors in those countries, and for Norway especially, also a tradition for using electricity for space heating has led to a relatively high electricity demand.

TWh	Denmark	Finland	Norway	Sweden	Total
Nuclear	-	22	-	69	92
Condensing power		6	-	1	6
CHP, district heating	26	14	0	6	47
CHP, industry	2	12	1	5	19
Hydro power	0	14	136	72	222
Wind power	7	0	1	1	8
Total	34	68	138	155	395

Table 1: Electricity Generation in the Nordic Countries 2005 (www.nordel.org).

Normal demand variation is between 29.000 MW and 69.000 MW with all four national systems being winter peaking (Nordel, 2006a). The highest simultaneous peak has been 69 GW (Nordel, 2006b).

Figure 4 shows a rather narrow power balance. As a consequence, the Nordic countries will soon need new means of supplying the peak demand, either through building new capacity or reducing the demand during peak load hours.

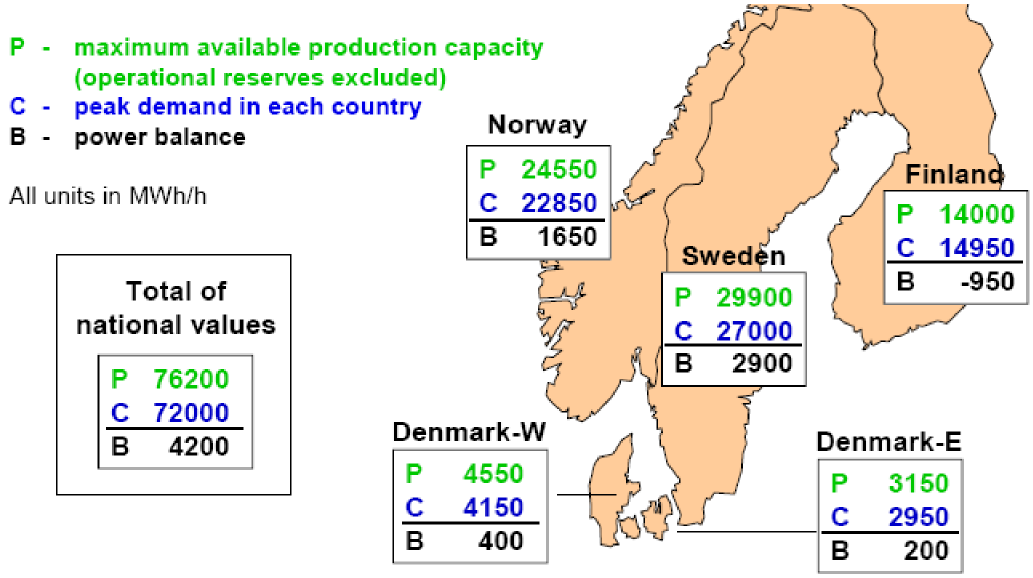

Figure 4: Estimated Average Power Balance for each country in 2009/10 in the Nord Pool area with average winter temperatures (Nordel, 2006).

Even though Figure 4 shows a positive capacity balance in the Nord Pool area, for average winter temperatures, the situation in a 10 years winter shows a balance for the whole area with a lack of capacity of -1,950 MW, and the area is dependent on import from the continent.

3.3.1 Reference Scenario

Capacity and technology data for the units in the present power system are taken from the data set described in Elkraft (2003). These data have been supplemented with a few other units to secure the best possible correspondence with aggregated capacity data distributed on main technology and fuel types published by Nordel (www.nordel.org). This is further described in Meibom et al. (2005).

The focus of the analyses is the year 2010. The development of installed capacity in the period 2005-2010 has been constructed, so that, in the whole period, 1% per year of the installed capacity of thermal power plants except nuclear power plants is decommissioned. We have used the investments in the period 2005-2010 that are already planned today, and to our judgment likely to be realized. The development in the yearly power consumption in the period 2004-2010 is based on Nordel (2002).

Caused by some new investments in the period 2005-2010, like the new 1,600 MW nuclear power plant in Finland, the year in focus is not a year with a very tight capacity balance, as the capacity excluding wind power is still higher than peak load demand in the winter period. At the same time, the balance is tighter than today, as decommissioning and increase in demand amount to more than the new investments.

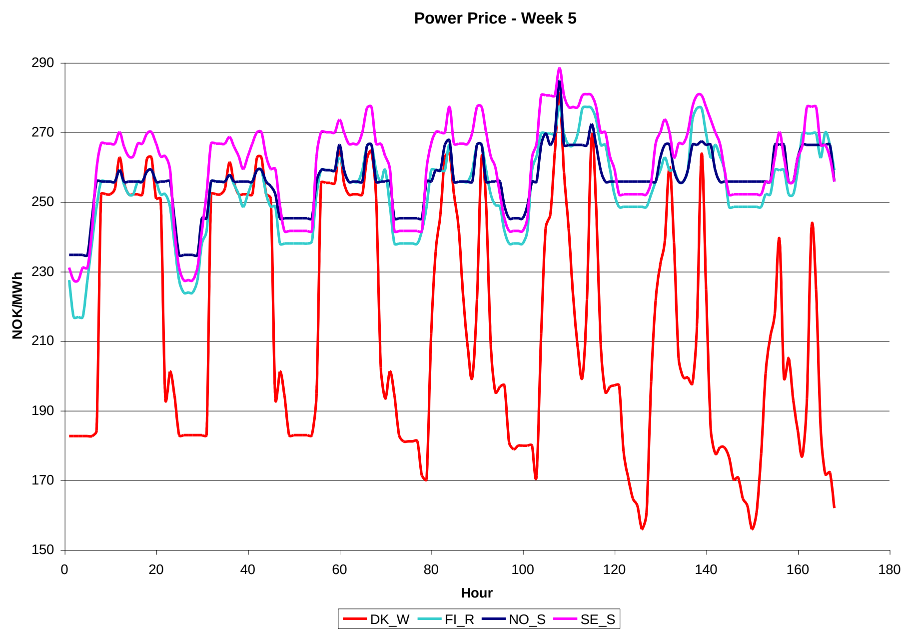

Figure 5: Power price example from the reference scenario simulated for week 5.

The reference scenario results in prices illustrated in Figure 5 for four of the price areas. None of the illustrated prices reaches level above 300 NOK/MWh which shows that production always meets demand in the given period assuming expected values for all input parameters. The larger variation in prices in Western Denmark is a result of the large share of wind power.

With respect to modeling of the demand response activity, the reference scenario does not include a possibility for consumers to decrease consumption, i.e., the demand curve is vertical. In the model this creates situations where demand and supply do not initially meet. In order for this to happen, we model a decrease in demand (disconnection from voluntarily agreements with large power consumers) at a price at 5000 NOK/MWh[2], i.e., total demand in the Nordic region can be reduced in peak load periods in order to meet supply.

The modeling of the reference scenario illustrates no welfare losses, as all units of disconnection result in the same voluntarily payment for all consumers corresponding to their marginal willingness to pay. It corresponds to pay all consumers the same amount for the disconnection. This can be illustrated in Figure 6 with a marginal willingness to pay that equals the consumer price when demand exceeds supply ($q_{load} > q^{max}$). The marked area is the payment to the consumers corresponding to their welfare loss, as the consumers in the model do not have decreasing marginal willingness pay with increasing supply.

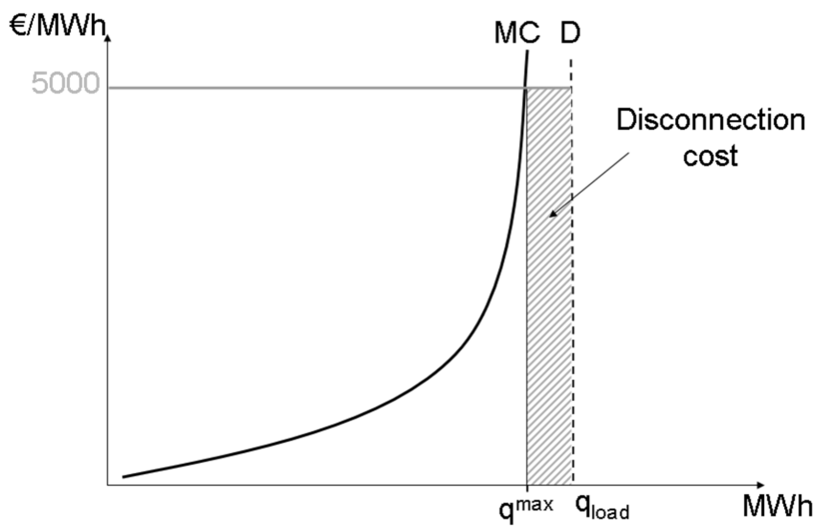

Figure 6: Illustration of costs in case of voluntarily disconnection (DR) from q_{load} to q^{max} at 5000 NOK/MWh.

[2] 1 NOK = 0.12 Euro = 0.17 USD (31.05.2005, Oanda.com)

3.3.2 Parameter variations

To capture the effect of demand response in a probabilistic manner, we include variation of three important parameters:

- Hydro power
- Wind power
- Temperature (resulting in demand changes)

The three included parameters all focus on situations that can be corrected within a relatively long time horizon, i.e., they focus on energy problems in the system, and not on sudden break downs caused by, e.g., sudden drop in transmission capacity.

The determination of the distributions can be based on statistical and/or subjective measures, but in this paper all the distributions are based on statistical data from relatively long time horizons in the Nordic region.

For **hydro power**, the figure below shows the variation in annual generation in Finland, Norway and Sweden. Each color represents one of the three countries and each color sums up to 100 %. The minimum level is typically reached in April. The total reservoir capacity in the three countries is 120 TWh, corresponding to 32% of the total yearly demand (2001).

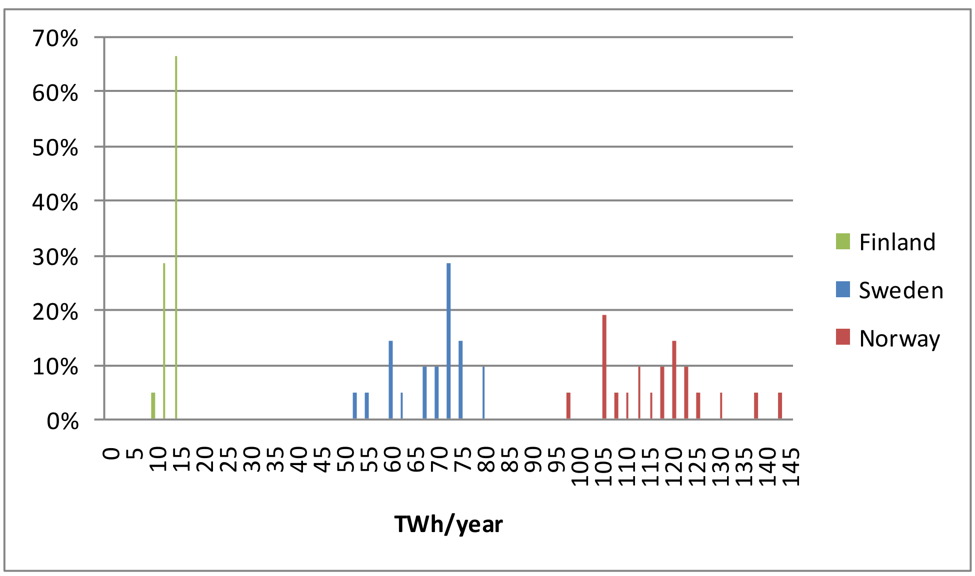

Figure 7: Variation of yearly hydro power generation 1950-2000. Note that the left hand side of the figure (green color) regards Finland, the middle part (blue color) Sweden, and the right hand part (red color) Norway.

The data in Figure 7 reflect the actual yearly hydro power production per country from 1950 to 2000. These variations are used to establish input values for the Balmorel simulations when considering the correlation between water inflows in the different countries.[3]

For **wind power**, the distributions are based on Danish data. The same hourly wind profile is used, but adjusted to the total weekly wind energy production to give the total energy production according to the weekly variation. This simplified method may in some periods lead to higher wind power production than the installed capacity.

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[3] Modelling in Balmorel, it is important to understand the meaning of availability of hydro power in the simulations. This treatment of hydro power generation is made because the model focuses on weekly optimisation, and hydro power generation optimised over longer time periods. A two step approach is applied:

1. In a simulation for a whole year the available hydro power is allocated to each week to maximize the total value. That is, each week is assigned an optimal amount of water for electricity generation.
2. Then the same procedure is repeated for each hour in a single week, i.e., the total value of the water is maximised.

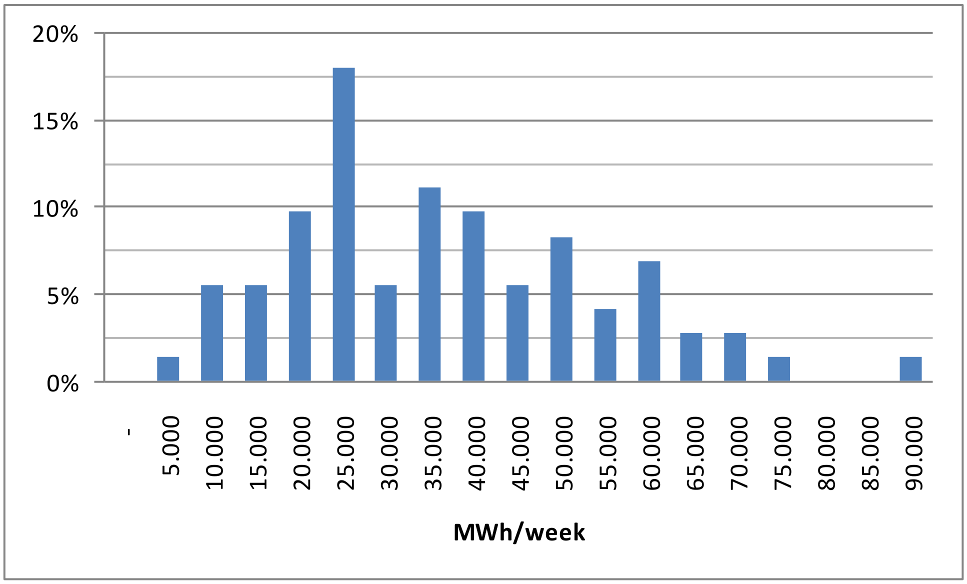


Figure 8: Probability of different weekly wind power production during January and February, 2000-2005. Data covers Denmark East and are normalized to the installed effect in the end of the period (743 MW). Average weekly wind power generation is 27 MW or 21% of installed capacity.

Finally, **demand** variation is found by using the daily temperature during 40 years, which forms the foundation for the variation in demand.

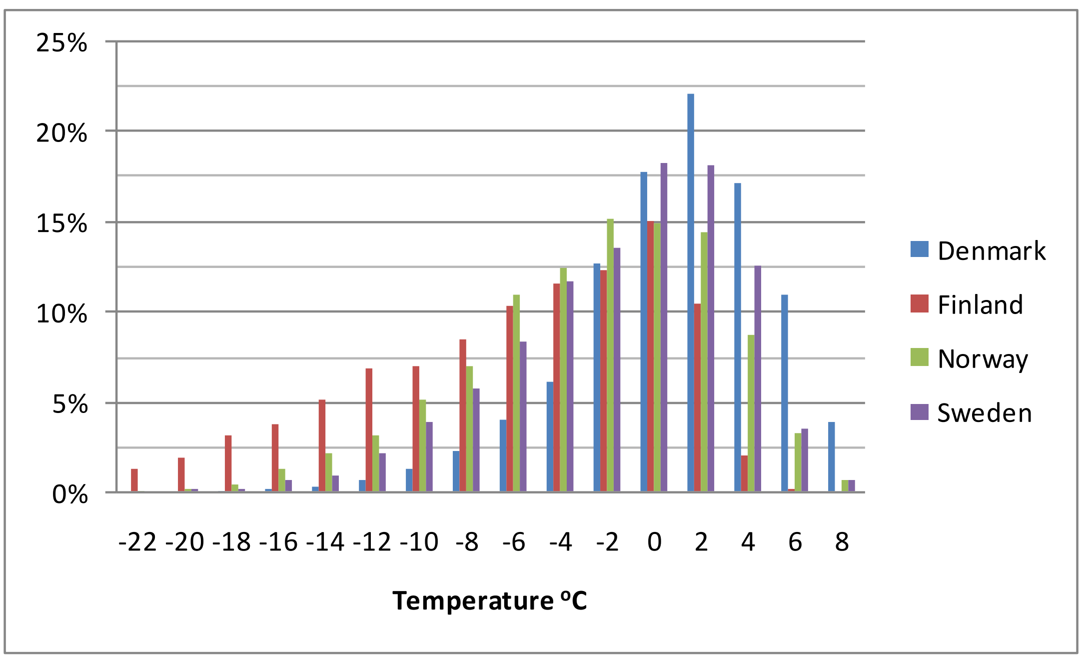


Figure 8: Variation in the daily temperatures in the four Nordic countries. January and February 1961-2004.

These variations are translated into demand increases given by Table 2 based on a regression model on hourly data for 2000-2005. This gives a rough estimation on changes in demand arising from changes in temperature.

Demand increase with 1°C decrease in temperature	Denmark	Finland	Norway	Sweden
MW	22	86	220	269
Relative to average demand	0.5%	0.9%	1.7%	1.6%

Table 2: Temperature dependence of electricity demand - based on regression model on hourly data for 2000-2005.

Furthermore, we need to find the correlation between demands in the different Nordic countries in order to represent plausible cases in each Monte Carlo run. These correlations are found by using the temperature data given in Figure 8.

Pearson Correlation	Denmark	Finland	Norway	Sweden
Denmark	1	0.68	0.83	0.89
Finland	0.68	1	0.77	086
Norway	0.83	0.77	1	0.94
Sweden	0.89	0.86	0.94	1

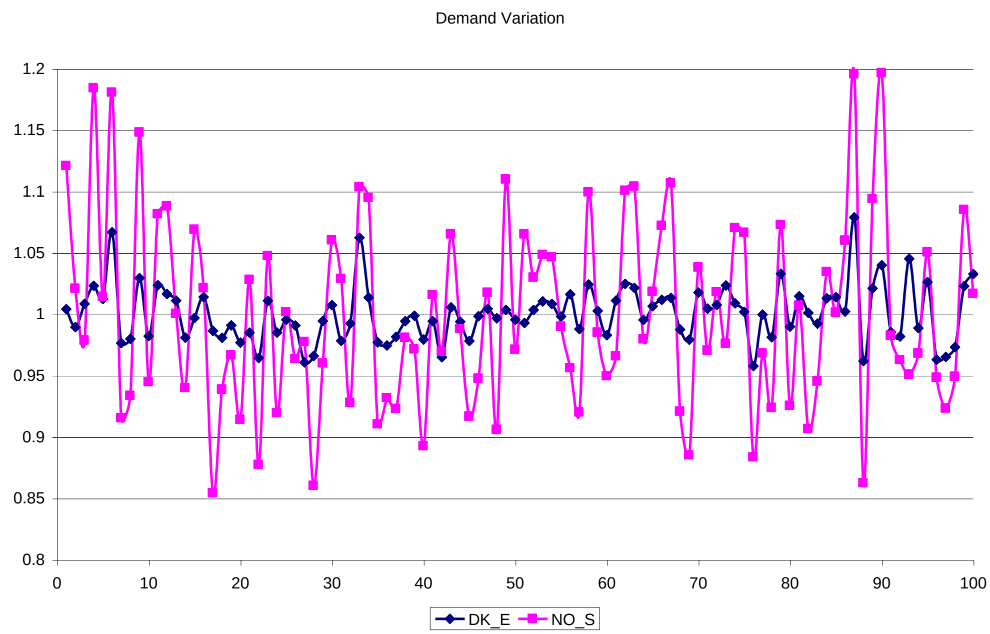
Table 3: Correlations between temperatures in the Denmark, Finland, Norway, and Sweden, 1965-2005.

The result on the parameter variation for demand is calculated based on temperature variation (Figure 8), the temperature dependency (Table 3), and the correlation between temperatures (Table 3).

Using the Crystal Ball® program (www.crystalball.com) for determination of 100 simulations, we obtain a sample by Latin Hypercube sampling. This method is a stratified sampling technique, where the random variable distributions are divided into equal probability intervals. A probability is randomly selected within each interval for each basic event. The advantage of this approach is that the random samples are generated from all the ranges of possible values, thus giving insight into the tails of the probability distributions. Furthermore, the method leads to output values that all represent equal probabilities.

The success of the technique depends on the number of simulations. In this case we conduct 100 simulations, which could be argued to be a bit low. With traditional Monte Carlo simulation, we could expect to run 10x10x10 simulations, caused by the three input parameters. A rule of thumb is then that Latin Hypercube sampling often only requires 1/5 of this, i.e., 200 simulations[4].

The number of the sample size in this analysis at 100 is generated due to computer time restraints. The 500 simulations (5 cases x 100) used in the paper have a computer run time of 16 hours. The 100 different samplings are illustrated for the input parameter demand in Figure 9.



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[4] One way to determine the right sampling size, in Latin Hypercube sampling, is to use the bootstrapping technique, e.g., as implemented in the Crystal Ball programme. With this technique you randomly select different samples of a given sample size, and the compute the sample mean for each sample. Following you compute the standard deviation of these sample means, and if this value is below one percent the sample size is large enough.

Figure 9: Change in values for demand for each of the 100 Monte Carlo simulations for Eastern Denmark and Southern Norway (The value 1 indicates no change in relation to base case).

3.3.3 Demand Response Scenarios

In order to evaluate the value of different types of demand response including also a comparison with traditional capacity oriented solutions (gas turbine versus demand response), we have to calculate the different output parameters for different alternatives. As point of departure, we have chosen to study the following four scenarios compared to the reference scenario:

1) *Reference.* If the market does not clear, consumers are disconnected at a price at 5000 NOK/MWh
2) Demand Response in form of *peak clipping (NO)*. As reference, but with 1,000 MW peak clipping in Southern Norway at 1,000 NOK/MWh (disconnecting)
3) Demand Response in form of *load shifting (NO)*. As reference, but with 1,000 MW with 6 hours flat payback (return energy) in Southern Norway
4) Demand Response in form of *load shifting (DK)*. As reference, but with 1,000 MW with 6 hours flat payback (return energy) in Western Denmark
5) *Gas turbine (NO)*. As reference, but with 1,000 MW power capacity in form of a single cycle gas turbine in Southern Norway.

The idea is to compare the impacts of implementing demand response with those of doing nothing or establish generation capacity instead. For each scenario, 100 simulations will be performed where outcomes of three random variables are sampled. The prices of 5,000 NOK/MWh and 1,000 NOK/MWh are rough assumptions used as an example only. If the price of 5,000 NOK/MWh in the reference situation were higher, the value of demand response would also be higher.

In the **peak clipping scenario**, it is possible for consumers to decrease consumption in periods with peak prices. This is modeled by having 1,000 MW capacity of demand response in Southern Norway at a price at 1,000 NOK/MWh, i.e., total demand in the

Nordic region can be reduced by 1,000 MWh in peak load periods. This demand response scenario illustrates the case, where there is a need to remove consumption and not just move to other time periods.

Also we gain welfare by activation of this demand response resource. In this case the price for disconnection is lowered from 5,000 NOK/MWh to 1,000 NOK/MWh. This could, e.g., illustrate the DR activity where a group of consumers (1000 MW in total) gets a common contract at 1,000 NOK/MWh, i.e., the marginal price for the 1,000 MW is 1,000 NOK/MWh. As a result we obtain a welfare gain by introducing this agreement at 1,000 NOK/MW compared to the situation illustrated in Figure 6. That is, if the marginal willingness to pay in Figure 6 is not the correct one, there is a welfare loss in the reference case, which is gain by the introduction of the activities in the peak clipping scenario.

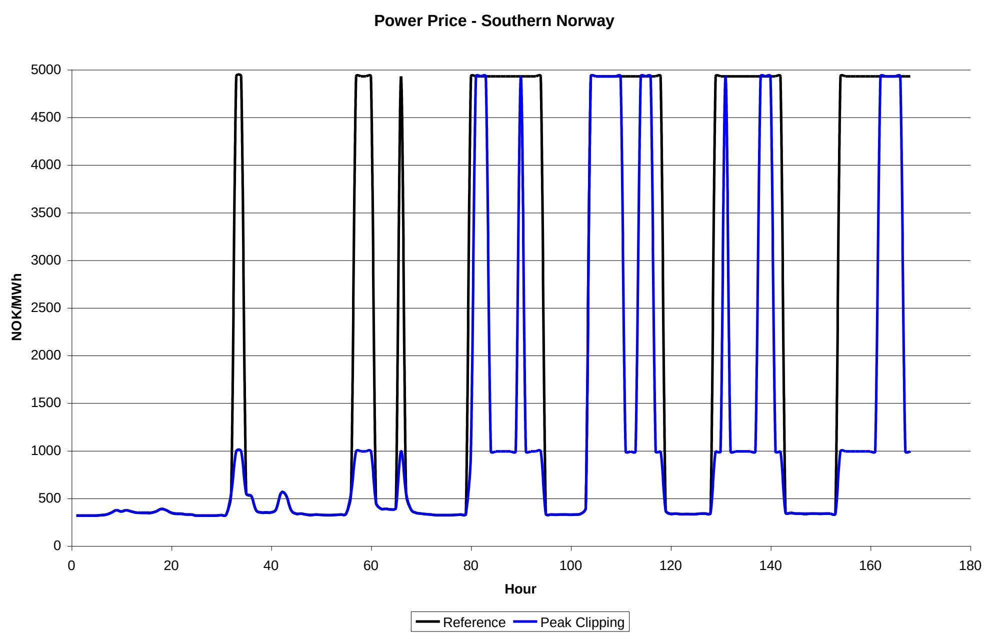

Figure 10: Example, peak clipping scenario, high demand: Electricity prices in Southern Norway for in week 5.

Changes in prices during week 5 in 2010 (Figure 5 compared to Figure 10) caused by the introduction of peak clipping, result in several hours where the prices have been reduced from 5,000 NOK/MWh in the reference scenario to 1,000 NOK/MWh in the peak clipping scenario. When 1000 MW peak clipping is not enough the price stays at 5,000 NOK/MWh.

In the **load shifting scenario**, it is possible for consumers to decrease consumption in periods with peak prices, but they are then forced to pay back the energy during the following six hours. This is modeled by having 1,000 MW capacity of demand response in Southern Norway or Western Denmark that function as energy storage with no loss of energy with the basis profile illustrated in Figure 11 (left). With these parameters a maximum of 3,500 MWh electricity demand can be removed from the market in one seven hour period and added to the market in the following six hour period (sum of net flows in right hand side of Figure 11).

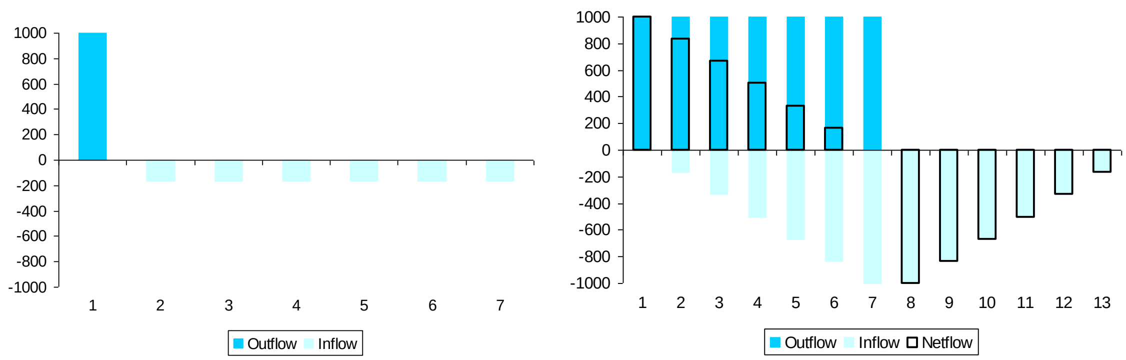

Figure 11: Profile for the demand response resource in the load shifting scenario with, e.g., use for one hour (left), and for seven hours (right). Many other patterns of use can take place dependent on system conditions.

This demand response capability is situated in Southern Norway (where capacity constraints take place in some cases) in one scenario and in Western Denmark (where a high share of fluctuating wind power exists) in another. The introduction of such a demand response resource has relatively large price effects, as illustrated in Figure 12. The added resource is active for almost all hours of the week caused by zero costs and no loss of energy. This results in lowering prices at daytime and increasing prices at night, i.e., equalizing prices during the week. The amount of price changes is also relatively large illustrated by the curves in Figure 12. This large effect is partly caused by the fact that there are not costs or losses combined with the use of the storage.

As expected the demand response results in lowering the high prices and increasing the low prices.

Figure 12: Example, load shifting scenario, high demand and low wind: Electricity prices in Western Denmark simulated for week 5.

In the **gas turbine scenario**, we install a 1,000 MW gas turbine in Southern Norway. This turbine produces electricity at marginal costs and is able to reduce peak prices by producing extra electricity instead of disconnecting consumers. The effect of introducing such an alternative is therefore very similar to the introduction of demand response peak clipping. The main difference is that the gas turbine produces energy at a lower variable cost: 310 NOK/MWh compared to 1,000 NOK/MWh for the peak clipping.

Investment costs and fixed O&M costs are not included in the model runs. Calculation of the profitability of such a turbine will require a longer simulation period (at least a year) and is not included in the current analyses.

The price effect of introducing a gas turbine is very limited if existing capacity can already meet demand, as the gas turbine is a peak load production capacity. But in cases with disconnection in the reference case the gas turbine can avoid disconnection by producing more power in order to meet demand.

3.3.4 Results and Sensitivity

The purpose of the analysis is to estimate the value of demand response taking extreme situations into account. In order to do so we gather information from the Balmorel model simulations from the following variables:

- Electricity prices
- Total costs

Electricity prices are mainly listed as output value in order to evaluate the impacts on power prices from the different scenarios. Also, it can help to indicate how strained the power system is.

Total costs are considered to be the main focus of this study in order to evaluate welfare changes in each of the three alternatives to the reference scenario. The total costs are divided into the following three groups:

- Production costs
- Costs of power exchange
- Cost of disconnecting consumers

The production costs include fuel costs, variable O&M costs and CO_2-emission costs. Fixed O&M costs as well as capital costs are not included as they only differ from one scenario to another with respect to the costs of implementing DR or establishing the gas turbine. Therefore, the estimated benefit in each alternative scenario should be compared to the expected additional costs. The CO_2-emission costs can be treated as a real cost as the Nordic countries have the opportunity to sell surplus quotas, or the obligation to buy additional quotas depending on the emitted amount of CO_2. Opposite, national taxes, e.g., SO_2 taxes, are not treated as a real system cost, as they are only an emission reduction instrument going from one economic group (the producers) to another economic group (the State).

The costs of power exchange only vary from one simulation to another with respect to the power exchange with the Continent. The costs differ from two reasons; different prices and different amounts. In each simulation, the electricity price at the Continent is calibrated in such a way that the annual net exchange is zero in a normal hydro year.

However, the net exchange in week 5 may very likely differ from zero, as this is not an average year.

The costs of disconnecting consumers (decreased consumer benefit) are estimated as the amount of disconnection in MWh multiplied by the consumers' willingness to pay in NOK/MWh. So therefore, in one simulation the production costs might be relatively low compared to another simulation due to some additional disconnecting, but this should be counterbalanced by an increase in the disconnecting costs.

Transmission costs have not been taken into consideration as they only differ very little from one simulation to another.

Normally, costs are not enough to estimate the total welfare gain of introducing different scenarios, as alternative plans yields different power prices, hence changing both demand and supply (Hobbs et al., 1993). But since the model we operate with assigns equal willingness to pay for all consumers the change between scenarios can be found by consideration of changes in production costs, power exchange costs, and disconnections costs.

The figure below shows the total costs in all 100 simulations and for all analyzed scenarios. The cases are ordered after decreasing costs in the reference situation.

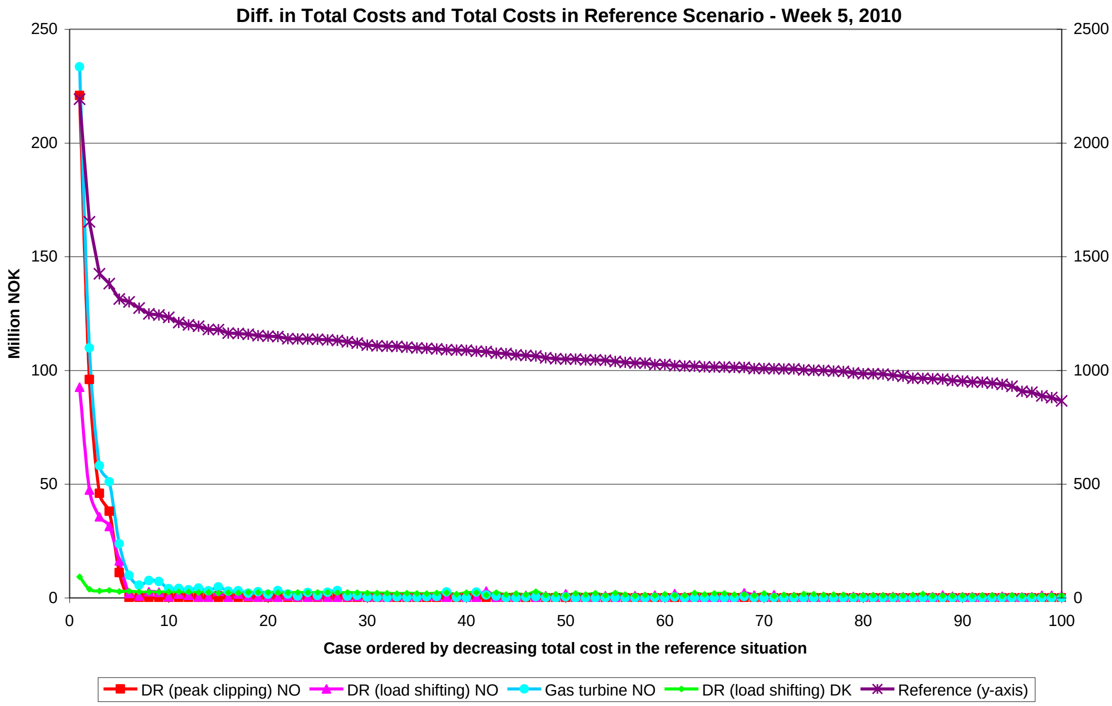

Figure 13: Total costs in the reference scenario (right hand side vertical axis) and difference in total cost for the alternative scenarios for all analyzed cases (left hand side vertical axis). Notice, that the production cost of water is not included in the figure, wherefore, the different cases are difficult to compare across cases, caused by change in available hydro power between each Monte Carlo scenario.

It appears from Figure 13 that the total costs in the reference scenario vary from 860 million NOK in the cheapest case (low demand, high hydro and high wind) to 2,190 million NOK in the most expensive case. In most of the cases the costs do not differ much between the five analyzed scenarios. The highest costs reduction compared to the reference situation is 230 million NOK, or 10% of total costs.

As mentioned earlier, the total costs are divided into three different cost groups; production costs, exchange costs and disconnecting costs. It can be mentioned that the production costs vary from 835 million NOK to 1,430 million NOK between the scenarios, the exchange costs between 30 million NOK and 110 million NOK, and the disconnecting costs between 0 million NOK and 706 million NOK. The reason why the exchange costs are positive in all analyzed cases and scenarios is the net import from the Continent (even though the net exchange on an annual basis was zero in normal hydro years).

The decrease in production costs compared to the reference situation is between -7 and 10 million NOK, the decrease in exchange costs is between -2 and 5 million NOK, and the decrease in disconnecting costs is between 0 and 230 million NOK.

The table below shows the total costs in the reference situation, and for the three alternative scenarios it shows the change in costs compared to the reference situation.

Million NOK	50% percentile	90% percentile	95% percentile	100% percentile	Average
Reference	1,050	1,213	1,302	2193	**1,084**
DR (peak clipping)	0.0	0.0	-0.6	-220.9	**-4.1**
DR (load shifting) NO	-0.5	-1.9	-3.6	-92.6	**-2.9**
DR (load shifting) DK	-1.8	-2.6	-2.8	-9.2	**-1.8**
Gas turbine	-0.1	-4.4	-10.6	-233.5	**-5.7**

Table 4: Total costs compared to the reference situation, million NOK

It appears how, in particular for the DR peak clipping scenario, even the 95% percentile of -0.6 million NOK is much lower than the average of -4.1 million NOK. The reason for this is that the benefit is zero in most analyzed cases (5 out of 100 in the peak clipping scenario), but relatively high in these five cases. Consequently we reach an average at approximately 4 million NOK.

Furthermore, it appears that the benefit from the gas turbine is higher than the benefit from DR. The reason why the benefit from the gas turbine is higher than the benefit from DR with peak clipping is that the variable generation costs of using the gas turbine are lower than the disconnecting costs. The reason why the benefit from DR with load shifting is relatively low may be that it can be interpreted as a kind of additional electricity storage in the system, with quite heavy restrictions, and that the value of such an additional storage in a system with lots of hydro power is quite limited. However, load shifting has an even lower value in Denmark West.

In addition, comparing the benefits of the two disconnecting scenarios placed in Denmark and Norway, we find that the flexibility in Western Denmark gains from better use of the transmission line to Germany to export wind power, counter wise, the case in Southern Norway where the benefit is mainly caused by decrease in disconnections.

The benefit in each alternative scenario should be compared to the costs of implementing DR and establishing the gas turbines. Assuming that the investment costs for gas turbines are around 3 million NOK/MW and assuming an economic lifetime of 20 years and an interest rate of 6%, the annual capital costs (found by an annuity) for 1,000 MW gas turbine capacity can be estimated to approx. 260 million NOK per year, i.e., in average 5 million NOK per week. If the average benefit of 5.7 million NOK in week 5 could be maintained for the whole year the gas turbine would be profitable. Assuming the year 2010 is representative for the lifetime of the gas turbine, the gas turbine would not be profitable, since week 5 is typically cold and with high electricity prices.

The costs of implementing DR have not been estimated. The average reduction in total cost in week 5 corresponds to 4.100 NOK/MW/week, while the load shifting corresponds to 2.900 NOK/MW/week in Southern Norway and 1.800 NOK/MW/week in Western Denmark.

For almost all cases the main benefit comes from the saved disconnection costs, except in the load shifting scenario in Denmark, which gains most from exchange costs. Therefore the result is extremely sensitive towards the levels of the disconnections costs, which is set at 5,000 NOK/MWh and 1,000 NOK/MWh. As a result we conduct a small sensitivity analysis with focus on these levels.

Disconnection costs NOK/MW	Peak clipping	Load shifting Norway	Load shifting Denmark	Gas turbine
7500	6.7	4.1	1.9	7.9
6000	5.2	3.4	1.9	6.6
5000	4.1	2.9	1.8	5.7
4000	3.1	2.5	1.8	4.9
2500	1.6	1.8	1.8	3.5

Table 5: Sensitivity analysis on total costs compared to the reference situation for the four scenarios at different levels of disconnection costs, million NOK.

In the case of the peak clipping the variation between differences in costs are between 1.6 and 6.7 million NOK, which is a very high variation. The value is highly dependent on the disconnection costs. The same is the case for load shifting (in Norway) and the gas turbine scenario.

In the case of the load shifting scenario in Denmark the variation is very small, as this alternative is placed in a price area where the main cost reduction is reached through export.

From this small sensitivity analysis on the disconnection costs parameter, we find that average benefits from demand response resources exist, but the determination of disconnection costs are important in the estimation of total benefits.

3.3.5 Discussion

Estimating the value of demand response is difficult using only one limited model. There are several limitations to the conclusions presented above. In general, the value of demand response is expected to have a lower value in this study than in real life. Firstly, we focus on the day-ahead market, which is why problems arising at a short notice are not included.

Secondly, the assumption of full information creates an ideal situation. Therefore the simulated results can be seen as optimal solutions, e.g., with the best use of the hydro power and transmission lines. Likewise, hard-to-predict wind power and individual market actors will give grounds for more price spikes, and a higher value for demand response.

Thirdly, the assumption of full competition between market actors leaves out the value of, .e.g., limitation of market power. Especially when the capacity balance is tight, the market is vulnerable for misuse of market power. This will produce more price spikes.

Finally, only three parameters are included in the Monte Carlo analysis, leaving several more to further studies only adding to the value of demand response. Of parameters left out in this analysis can be mentioned: Reduced capacities of transmission lines, reduced generation capacities (more tight capacity balances), and dynamics of prices outside the Nordic area.

4. CONCLUSION

The present paper has presented the results of a Nordic case study in which some of the benefits of implementing DR have been estimated by use of a Monte Carlo analysis approach. By this approach, 100 cases with equal probability of 1% have been analyzed for different scenarios. The cases differ with respect to hydro power generation, wind power generation and electricity demand. The analyses have been carried out for a winter week in 2010 (a week with a relatively tight supply/demand balance). Each alternative scenario with demand response or additional production capacity has been compared to the reference scenario with respect to electricity prices and total costs including production costs, costs of power exchange (with countries outside the Nordic area), and cost of disconnecting consumers.

The analyses indicate large price impact by demand response, by modest reduction in total costs. A considerable redistribution takes place. The model does calculate impact per area for both producers and consumers, but this has not been reported in this article.

The results show the largest differences in disconnecting costs; they decrease by 0 to 230 million NOK compared to the reference scenario. The change in production costs is between -7 and 10 million NOK, and the change in exchange costs is between -2 and 5 million NOK.

The average benefit from each alternative scenario, without taking the necessary investment costs into consideration, is 4.1 million NOK in the DR scenario with peak clipping, 2.9 million NOK in the DR scenario with load shifting in Norway, 1.8 million NOK in the DR scenario with load shifting in Denmark, and 5.7 million NOK in the gas turbine scenario. The reason why the benefit from DR with load shifting is relatively low may be that it can be interpreted as a kind of additional electricity storage in the system, with quite heavy restrictions, and that the value of such an additional storage in a system with lots of hydro power is quite limited.

The results have mainly focused on the differences in total costs compared to the reference scenario, and the benefit to society of implementing DR. It has been illustrated how electricity prices are influenced depending on the type of DR, and this may very well have some distribution consequences. For instance, if the average electricity price is lowered, the producers will lose from a lower producer surplus (depending on the production costs), whereas the consumers will gain from a higher consumer surplus. Furthermore the bottleneck incomes to the Transmission System Operators will be influenced from changes in electricity prices.

The results also show that in most of the analyzed cases the benefit from the peak load technologies is zero, but in some cases the benefit is quite high. For instance, in the scenario with DR peak clipping the 95% percentile is only a benefit of 0.6 million NOK, even though, the average benefit is 4.1 million NOK. Since the value is low in the majority of the cases, some market actors might not see the importance of DR. The rare occurring cases with a high benefit may be overlooked - especially as long as the high electricity prices as a consequence of lacking peak load technologies in the system have not yet been met in practice.

Comparing the benefits in each scenario it is doubtful whether the gas turbine is profitable. The annual capital costs of 1,000 MW gas turbine capacity are approximately 300 million NOK corresponding to 5.7 million NOK per week. The benefit in week 5 has been estimated 5.7 million NOK, but this week is also one of the weeks that are expected to benefit most from peak load technologies due to a low supply/demand balance. The costs of implementing DR (peak clipping and load shifting) have not been estimated.

It should be mentioned that the DR technologies may also have an additional value in the system because it levels out the demand variation, and thereby decreases the need for peak capacity in the system. The value of this (lower investment costs) has not been estimated (only short term marginal costs have been taken into consideration). The implementing of DR may also have an additional value with respect to market power as it may decrease the producers' possibilities of abusing market power and finally, DR may have a positive influence on the security of supply, which has not been estimated.

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