A massive introduction of wind power

Changed market conditions?

Elforsk report 08:41

Fredrik Carlsson
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Preword

The purpose of this project was to investigate the imbalance volume due to wind power forecast errors for the system as well as for different actors and the costs associated to the imbalances. The reduction of imbalance costs by trading at the adjustment market Elbas for different actors is also investigated.

The work was carried out by Fredrik Carlsson and Viktoria Neimane, Vattenfall Research and Development, as a part of the Swedish wind energy research programme “Vindforsk - II". The research programme was funded by ABB, the Norwegian based EBL-Kompetense, E.ON Sverige AB, Falkenberg Energi AB, Göteborg Energi, Jämtkraft AB, Karlstad Energi AB, Luleå Energi AB, Lunds Energi AB, Skellefteå Kraft AB, Svenska Kraftnät, Swedish Energy Agency, Tekniska Verken i Linköping AB, Umeå Energi AB, Varberg Energi, Vattenfall AB and Öresundskraft AB.

Comments on the work and the final report has been given by a reference group with the following members: Joakim Allenmark, Vattenfall Nordic Generation, Peter Fritz, EME Analys, Elforsk Market Design and Sara Hallert, Vindforsk, Elforsk.

Stockholm June 2008

Sara Hallert

Electricity and Power Production

Sammanfattning

Sverige har ett ambitiöst mål som syftar till att öka andelen förnybar energiproduktion. Energimyndighetens befintliga planeringsmål är att Sverige skall producera 10 TWh årligen från vindkraft år 2015. Nyligen har Energimyndigheten föreslagit ytterligare ett planeringsmål om en produktion av 30 TWh år 2020. Svårigheten med vindkraft ligger i dess oregelbundna produktion och att produktion är svår att förutsäga. Energin som vindkraften producerar säljs precis som alla annan producerad elektrisk energi på den nordiska elmarknaden – Nord Pool. För att göra det så måste produktionen prognostiseras på grund av att energin säljs dygnvis kl 12.00, det vill säga 12 – 36 timmar innan aktuell produktionstimme. Vindkraftproducenterna gör prognoser av sin elproduktion med hjälp av väderprognoser av vindhastigheter. Om tillverkarens produktion skiljer sig från sin planerade produktion som sålts på elmarknaden, så kommer producenten att få betala för avvikelsen. Eftersom elkraftsystemet måste vara i balans, måste den som ansvarar för balansen i elkraftsystemet be någon annan elkraftproducent kompensera för obalansen när det finns en obalans (under- eller överproduktion). Detta kallas för reglering och kostar pengar för den kompenserande aktören. De aktörer som orsakar obalans får betala för sina obalanser. Kostnaderna är i enlighet med det reglerpris som råder och fördelas mellan aktörer som orsakade obalanser. Processen kallas balansavräkning och äger rum dagen efter produktionsdagen.

Om en aktör vet att planen inte kommer att följas, till exempel om aktören har en uppdaterad vindprognos som visar en annan produktionsnivå, finns det en alternativ väg att gå. Den vägen är att köpa eller sälja obalansen vid intradagmarknaden Elbas, vilket kan göras så nära som en timme innan produktionstimmen. Nackdelen med handeln vid intradagmarknaden Elbas är att handeln i sig kostar pengar och att den nya prognosen fortfarande inte är exakt, det vill säga det nya prognosfelet kommer att kosta pengar på reglermarknaden.

I denna rapport har åtta olika aktörer skapats, som alla har balansansvar för sin produktion, vilket innebär att om de orsakar en obalans, så måste de betala upp- eller nedregleringspriser. Dessa aktörer är olika i den bemärkelsen att vissa är små och några är stora, vissa har koncentrerade vindkraftverk och några har vindkraftverk som är geografiskt utspridda. Dessa aktörers vindkraft har en samlad märkeffekt på 4 000 MW, och summan av deras årliga produktion uppgår till nästan 12 TWh. Den geografiska spridningen har valts så att 50% av energiproduktionen är förlagd till norr och 50% till söder. En aktör som kallas "en aktör" har också skapats, som består av samtliga åtta aktörer tillsammans. Denna aktör, har två syften: a) dels att tala om hur mycket obalans vindkraften tillsammans orsakar samt dess kostnader, och b) dels om alla vindkraftsaktörer skulle förena sig, vad har de då för möjligheter till minskade kostnader.

De obalanser som dessa aktörer skapar i systemet har modellerats med hjälp av studier av prognosfel från vindkraftsverken vid Horns Rev och andra

publicerade resultat av prognosfel. Det är välkänt att det prognostiserade felet minskas om lokaliseringen av vindkraften sprids ut, vilket har beaktats i modellen. Modellen ger svar på den obalans som aktörerna skapar samt elkraftsystemets totala obalans. För att beräkna kostnaden för det prognostiserade felet, har en utvecklad prismodell av Klaus Skytte vid Risö-laboratoriet i Danmark använts. Denna modell innehåller parametrar som har uppskattats för marknadsläget under 2006. Genom att skapa prognosfel för alla aktörer genom slumptalsgenerering som är normalfördelade i Excel för ett helt år, har det varit möjligt att beräkna aktörernas kostnader för deras prognosfel.

Det finns en möjlighet att uppdatera prognosen och placera (sälja eller köpa) det prognostiserade felet på intradagmarknaden Elbas, detta fall har också utvärderats. Men att uppdatera en prognos kommer också att generera ett nytt prognosfel, som naturligtvis i allmänhet är mindre än det ursprungliga prognosfelet. Detta har också tagits med vid kostnadsberäkningen av att agera på intradagmarknaden Elbas.

Kostnaderna för prognosfelen (obalansen) för dessa strategier presenteras i tabell A och visualiseras i figur A och B. Som referens har kostnaden beräknats med reglerpriserna under år 2006. Det kan konstateras att systemets årliga obalans kommer att öka med 70% från omkring 1,0 TWh till 1,7 TWh med 4 000 MW vindkraft i Sverige. Vindkraftverken genererar cirka 1,3 TWh obalanser per år, vilket innebär att vindkraften kommer att vara den dominerande källan till obalanser. Men, aktörerna kommer att tillsammans handla med så mycket som 1,6 TWh obalanser per år trots att de endast bidrar med 0,7 TWh per år, vilket innebär att aktörerna kommer att handla med mer än dubbla mängden obalanser än vad de tillför system. Så, den mesta handeln (55%) kommer att vara en onödig handel som skulle kunna kallas för nonsenshandel.

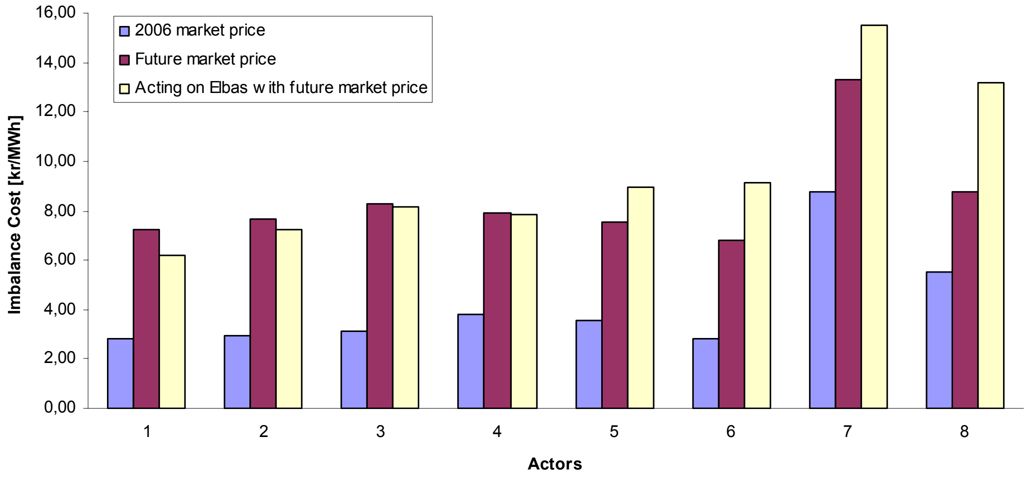
Den ökade obalansen leder till höjda reglerpriser, som till följd av att mer reglerkraft måste köpas. Dessutom leder en ökad obalans också till att det blir färre timmar utan reglering, vilket innebär att aktören måste betala för fler timmar. När vindkraften är den dominerande bidragaren av obalanser till systemet, innebär det att sannolikheten att vindkraftens aktörer har en obalans i samma riktning som systemet ökar, vilket resulterar i ett högre antal timmar som aktörerna måste betala för reglering. Dessa tre faktorer, resultera i cirka tre gånger högre kostnader för aktörerna, jämfört med dagens (2006) priser på marknaden.

I tabell A visas tydligt att aktörerna kommer att få betydligt högre kostnader för obalanser som mer vindkraft genererar. Kostnaden per producerad energi ökar från ca 3 kr/MWh idag till ca 7 kr/MWh för större aktörer. För små aktörer, är ökningen från cirka 6 kr/MWh till ca 13 kr/MWh. Då de stora aktörerna har vindkraftverken utspridda i landet, minskar prognosfelen, vilket förklarar varför de relativa kostnaderna är lägre för de stora aktörerna.

Table A: Visar den årliga kostnaden för aktörerna.

Aktör	1	2	3	4	5	6	7	8	En aktör
Allmänt									
Installerad effekt [MW]	1 905	660	415	445	200	170	125	100	4 020
Årlig produktion [GWh]	5 708	1 889	1 218	1 239	640	520	350	300	11 800
Årlig inkomst [Mkr]	2 545	842	543	552	285	232	156	134	5 300
Årlig obalans [GWh]	647	229	183	179	93	69	114	64	1 280
Referensfall: Kostnader på marknaden 2006									
Kostnad: pris 2006 [Mkr/år]	16,0	5,5	3,8	4,7	2,3	1,5	3,1	1,7	29,9
Kostnad/Produktion [kr/MWh]	2,80	2,91	3,10	3,81	3,54	2,85	8,80	5,50	2,52
Kostnad jämfört med inkomsten	0,6%	0,7%	0,7%	0,9%	0,8%	0,6%	2,0%	1,2%	0,6%
Kostnader med framtida priser									
Kostnad i framtiden [Mkr/år]	41,1	14,4	10,1	9,8	4,8	3,5	4,7	2,6	83,2
Kostnad/Produktion [kr/MWh]	7,20	7,65	8,26	7,93	7,51	6,81	13,31	8,76	7,01
Kostnad jämfört med inkomsten	1,6%	1,7%	1,9%	1,8%	1,7%	1,5%	3,0%	2,0%	1,6%
Kostnader med framtida priser vid handel på Elbas									
Kostnad Elbas [Mkr/år]	35,2	13,7	9,9	9,7	5,7	4,7	5,4	3,9	70,0
Kostnad/Produktion [kr/MWh]	6,18	7,25	8,17	7,84	8,97	9,13	15,51	13,19	5,87
Kostnad jämfört med inkomsten	1,4%	1,6%	1,8%	1,8%	2,0%	2,0%	3,5%	3,0%	1,3%
Sparmöjlighet genom att agera på Elbas	15%	5%	1%	1%	-	-	-	-	16%

Dock är kostnaderna relativt inkomsterna fortfarande låga (även om de stigit tre gånger), cirka 1% - 3%. Jämfört med systempriset (ca 450 kr/MWh) är reglerkostnaden också i denna låga storleksordning.



Figur A: Jämförelse mellan kostnaden för prognosfel för a) prisläget 2006, b) ett framtida prisläge och c) genom att handla på Elbas.

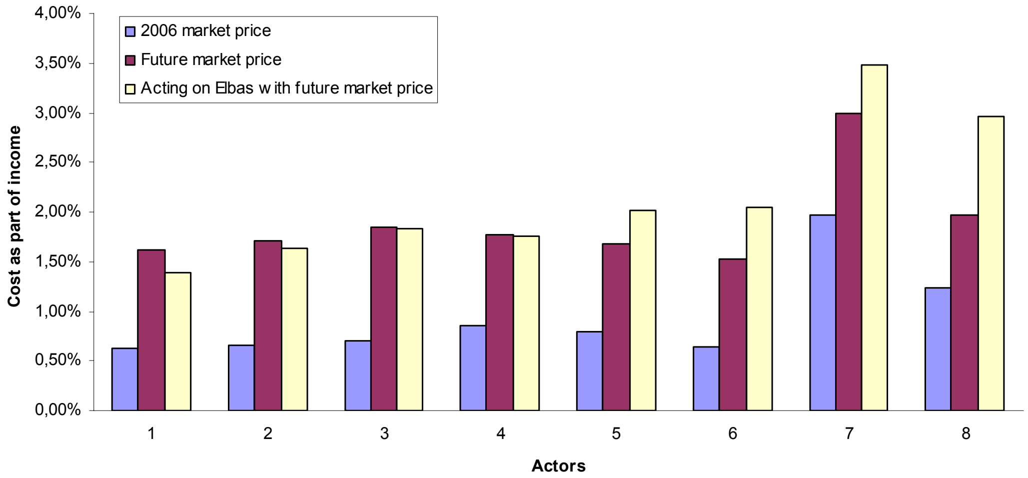


Figure B: Årliga kostnader jämfört med årlig inkomst.

Möjligheten att handla på intradagmarknaden Elbas är också med i tabell A. Eftersom det finns kostnader förknippade med handeln på Elbas, till exempel personal, köp av uppdaterade prognoser, handel, och så vidare, så måste obalansens volym vara tillräckligt stor för att det ska vara lönsamt med handeln.

Tabellen visar att det endast är aktör 1 och "en aktör" som har möjlighet att minska kostnaderna avsevärt (cirka 15%) genom att köpa eller sälja sina obalanser på Elbas.

Fyra andra scenarier har också utvärderats. Dessa scenarier är a) ännu mera vindkraft i Sverige, b) lokaliseringen/koncentrationen av vindkraften, c) förbättrade prognoser och d) flera prisområden. En allmän slutsats från dessa scenarier är att mer vindkraft leder till ökade obalanser och kostnader, ökad koncentration av vindkraft leder till ökade obalanser och kostnader, förbättrade prognoser leder förstås till minskade obalanser och minskade kostnader, och slutligen leder en indelning av Sverige i olika prisområden till ökade obalanser och kostnader.

Marknadsstrukturen och dess regler diskuteras i rapporten, där dagens tvåprissystem har fördelen med goda incitament för att minska obalanserna i systemet. Dock finns nackdelen att de små vindkraftsägarna drabbas hårt av detta, då de får höga kostnader för sina prognosfel och inte heller har reella möjligheter att minska dessa genom att handla på intradagmarknaden Elbas. Det är viktigt att marknadslösningarna stödjer en vindkraftsutbyggnad, samtidigt som det är viktigt att hela elmarknaden tas med i bilden. Fördelar och nackdelar finns med alla lösningar och förändringar bör analyseras noga innan de genomförs.

Slutligen kan man sammanfatta rapporten med att en ökad vindkraft ökar obalanserna i elkraftsystemet och på grund av detta ökar också reglerpriserna. Aktörer med geografiskt utspridd vindkraft (vilka också är stora aktörer) får lägst kostnad. Stora aktörer har dessutom möjlighet att minska sina kostnader ytterligare genom att sälja sina obalanser på intradagmarknaden elbas. Dock är kostnaden för obalanser tämligen små, och utgör endast några procent av inkomsterna.

Summary

In Sweden there is an ambitious target to increase the renewable part of the power production. The Swedish Energy Agency has a planning goal of 10 TWh wind energy produced annually by 2015. The newest suggested planning goal extends the plans to 30 TWh wind energy by 2020. The well-known concerns about wind power are related to its intermittent nature and difficulty to make exact forecasts. Energy from wind power is as all other electrical energy sources sold at the Nordic Power Exchange – Nord Pool. To do that, it is necessary to forecast the production, as the energy for a whole day is sold at 12.00, which means 12 – 36 hours ahead the production hour. Wind power producers do forecasts of their production, by using weather forecasts of wind speeds, and by that estimating their future production. If the producer’s production differs from its planned production, the producer will have to pay for the deviation. Since the electric power system needs to be in balance, the balance responsible for the electric power system needs to order someone (another electric power producer) when there is an imbalance (under- or overproduction) to compensate the imbalance. This is called regulation and costs money for the compensating (regulating) actor. The actors causing the imbalances must pay for their imbalances. The costs are settled according to the regulating prices and distributed among the actors who caused imbalances. The process is called balance settlement and takes place the day after the production day.

If an actor knows that his plan will not be followed, for instance if the actor has an updated wind forecast that tells otherwise, there is an alternative way to go. That way is to buy or sell the imbalance at the adjustment market Elbas, which could be done as near as one hour before the production hour. The drawback of trading at the adjustment market Elbas is that the trade itself costs money and that the new forecast might still not be perfect.

In this report eight different actors have been created, that all have balance responsibility for their production, which means that if they cause an imbalance they have to pay up or down regulating prices. These actors are different in the sense that some are small and some are big, some have concentrated wind farms and some have wind farms that are geographically spread-out. These actors’ wind power sums up to 4 000 MW, and their annual production sum up to almost 12 TWh. The geographical spread-out of the wind power is 50% to the northern part of Sweden and 50% to the southern part of Sweden. An actor called “one actor” has also been created, who consists of all eight actors together. This actor, has two purposes: a) telling how much the wind power together cause imbalance and its costs, and b) if all wind power actors would unite, what could they gain in cost reduction.

The imbalances that these actors cause the system have been modelled using forecast error data from the wind power farm Horns Rev and other publication results of forecast errors. It is well known that the forecast error is reduced if the location of the wind power is spread-out, which has been taken into account in the model. The model gives the answer on the imbalance volume

for the actors as well as on the system. To calculate the cost of the forecast errors, a developed price model by Klaus Skytte at Risö Laboratory in Denmark has been used. This model has parameters that have been estimated for the market situation during 2006. By generating the forecast errors for all actors as random numbers with normal distribution in Excel for a whole year, it has been possible to calculate the actors' cost for their forecast errors.

Since there is a possibility, to update forecast and placing the forecast error on the intraday market Elbas, this case has been evaluated as well. However updating a forecast will also generate a new forecast error, which of course is in general smaller than the original forecast error. This has also been taken into account, when calculating the cost for acting on the intraday market.

The costs for the forecast errors by using these two strategies are presented in Table A and visualised in Figure A and B. As a reference, the cost has been calculated by using the regulating prices during the year 2006. It is found that the system's annual imbalance will increase by 70% from about 1,0 TWh to 1,7 TWh with 4 000 MW wind power in Sweden. The wind power it self generate about 1,3 TWh of imbalances, which means that the wind power will be the dominating source for imbalances. But, the actors will together trade as much as 1,6 TWh/year, although the wind power increase the imbalance with just 0,7 TWh/year, which means that the wind power actors will trade more than twice the amount of imbalances on the regulating market than the wind power will contribute to the system's imbalance. So most of the trade will be a nonsense trade (55%).

The increased imbalance in the system leads to increased regulating prices, since the regulating prices gets higher as more power need to be bought. Furthermore, an increased imbalance also leads to fewer hours where there is no regulation, which means that the actors have to pay for more hours. When the wind power contributes to the system as such, it also means that the probability that the wind power actor has an imbalance in the same direction as the system increases, which results in an higher amount of hours that the actor have to pay for regulation. These three factors, result in about three times higher costs for the actors, compared to the market today (2006).

The Table A shows clearly, that the actors will have significantly higher costs of imbalances as more wind power installs. The cost per produced energy increases from about 3 kr/MWh to about 7 kr/MWh for larger actors. For small actors, the increase is from about 6 kr/MWh to about 13 kr/MWh. Large actors have the wind power spread out, which reduces the forecast error, which explains why the cost is lower for large actors. However, the cost related to the income is still low, just in the order of 1% - 3%. Relating the cost to the spot price (ca 450 kr/MWh) also gives a fairly low number.

Table A: Shows the annual cost for the actors.

Actor	1	2	3	4	5	6	7	8	One actor
General									
Installed power [MW]	1 905	660	415	445	200	170	125	100	4 020
Annual production [GWh]	5 708	1 889	1 218	1 239	640	520	350	300	11 800
Annual income [Mkr]	2 545	842	543	552	285	232	156	134	5 300
Annual imbalance [GWh]	647	229	183	179	93	69	114	64	1 280
Reference case: Cost on market 2006									
Cost 2006 price [Mkr/year]	16,0	5,5	3,8	4,7	2,3	1,5	3,1	1,7	29,9
Cost/Production [kr/MWh]	2,80	2,91	3,10	3,81	3,54	2,85	8,80	5,50	2,52
Part of income	0,6%	0,7%	0,7%	0,9%	0,8%	0,6%	2,0%	1,2%	0,6%
Cost on future market price									
Cost future market [Mkr/year]	41,1	14,4	10,1	9,8	4,8	3,5	4,7	2,6	83,2
Cost/Production [kr/MWh]	7,20	7,65	8,26	7,93	7,51	6,81	13,31	8,76	7,01
Part of income	1,6%	1,7%	1,9%	1,8%	1,7%	1,5%	3,0%	2,0%	1,6%
Cost on future market price when acting on Elbas									
Cost Elbas [Mkr/year]	35,2	13,7	9,9	9,7	5,7	4,7	5,4	3,9	70,0
Cost/Production [kr/MWh]	6,18	7,25	8,17	7,84	8,97	9,13	15,51	13,19	5,87
Part of income	1,4%	1,6%	1,8%	1,8%	2,0%	2,0%	3,5%	3,0%	1,3%
Savings by acting on Elbas	15%	5%	1%	1%	-	-	-	-	16%

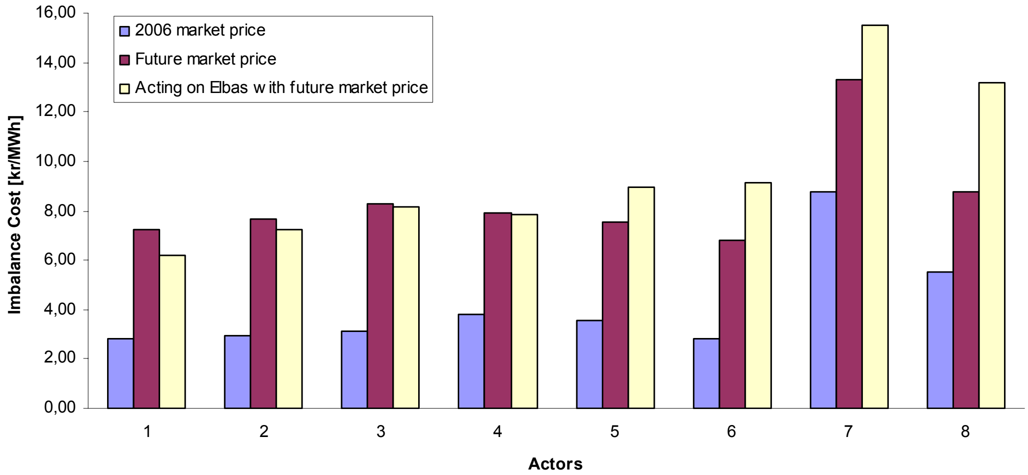


Figure A: Comparison on the cost of forecast errors on a) the 2006 market, b) the future market and c) future market and acting on Elbas.

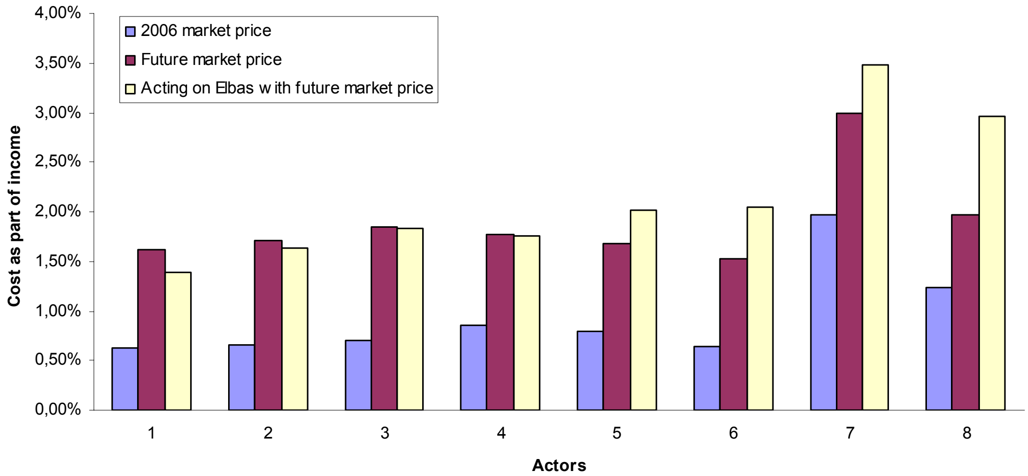


Figure B: Cost in relation to yearly income for the actors.

The possibility to act on the intraday market Elbas is also calculated in Table A. As there are costs associated with acting on Elbas, for instance personnel, buying updated forecasts, trading, etc, the amount of imbalance has to be large enough to make it profitable. The table shows that only actor one and the "one actor" can benefit enough (about 15%) on trading on the intraday market Elbas, compared to leave the imbalance to the regulating market.

Four other scenarios have also been investigated, where a) the wind power has been increased further, b) the spread-out of the wind power in north south direction, c) improved forecasts and d) different price areas. A general conclusion from these are that increased wind power will increase imbalance and costs, concentrated wind power to either north or south will also increase imbalance and cost, improved forecast will of course reduce imbalance and costs, and finally, different price areas will increase imbalance and cost.

The adequacy of the present market structure and alternative solutions for wind power balance settlement in the system with large amounts of wind power is discussed. The present two-price balance settlement system provides good incentives for planning and developing of forecasts. However, assuming large-scale expansion of wind power the system discriminates the smaller actors in a sense that they may face higher imbalance costs and don not have the possibility to reduce the costs by acting on adjustment market. It is important that market-based solutions still supporting the expansion of wind power are applied. It is also important to point out that alternative market solutions will induce both advantages and disadvantages, therefore the consequences for different affected parties must be analysed carefully.

Finally, it can be concluded that increased wind power will increase the imbalance of the system and therefore increase the regulating costs for wind power actors. Actors with its wind power spread-out (which are mainly large actors) will have lowest prices. Large actors can also benefit from acting on the intraday market Elbas. However, the costs for imbalances are quite small, compared to the income, only in the order of a couple of a percent.

Content

1 Introduction

1.1 Background

The modern society requires energy to produce welfare such as heat, transportation and electricity. As it has been evident, that some energy production might harm our planet by its pollution, the society has put large effort in finding energy sources less harmful to the environment. One of these sources is wind power, which converts the kinetic energy in the wind to electric energy. The use of wind energy is nothing new; farmers have used it to grind grain for thousands of years in windmills. The kinetic energy in wind originates from the sun, in a series of energy conversions on earth. The wind energy is therefore called a renewable energy source.

The wind power is growing very fast in Sweden both as in number of installations and installed power. Wind power is in many cases installed as large wind farms, and one of the latest large installations is the wind farm at Lillgrund, see Figure 1, which started to produce electric power in early 2008. The wind power production has increased almost linear since the beginning of the 1990, with a yearly increase of about 0,1 TWh, see Figure 2 [1]. The wind power in Sweden produced in 2007 almost 1,5 TWh by about 850 wind turbines. The installed wind power capacity is about 700 MW. However, wind power is still very small compared to other electric power producers, such as hydropower and nuclear power, which produced 65 TWh respectively 64 TWh in 2007 [1].

Figure 1: Wind Power at Lillgrund, Sweden.

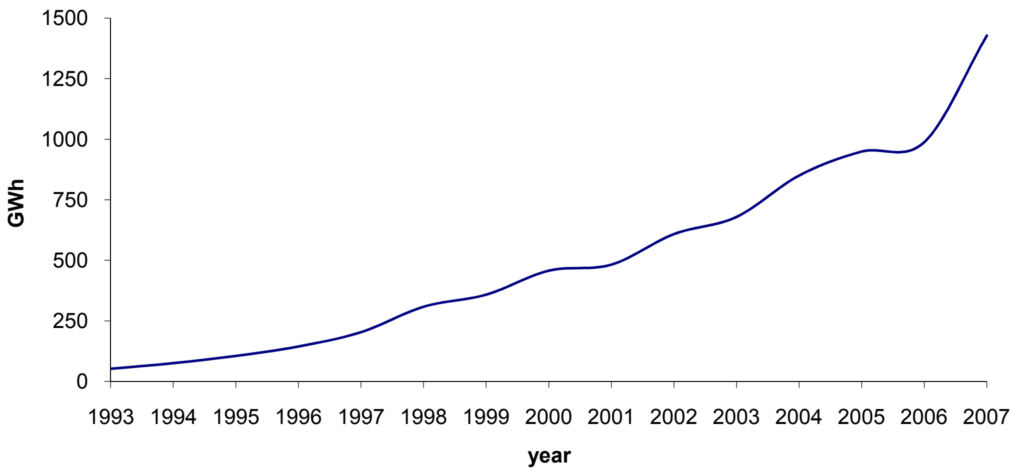


Figure 2: Wind Power production in Sweden 1993 – 2007.

To give some perspective of the energy consumption, it is worth mentioning that about 400 TWh was consumed in Sweden 2007 [1]. Of that about one third came from electric power, one third from oil, and one third from other sources. The total amount of carbon dioxide produced in Sweden is about 60 Mton/year, which is about 6 ton/capita.

In the beginning of 2008, the European Union (EU) has been targeted that the countries within the European Union should increase their energy from renewable sources[1] and to decrease their CO_2 emissions by the year 2020 [2]. This is often referred to as "20-20-20"-package. The package includes a reduction of CO_2 by 20%, an increase of renewable energy sources by 20% and a trade with emissions of CO_2. Swedish part in this decision, is to increase Sweden's renewable energy production by the year 2020 to 49% from today's 40%. Sweden has already a planning goal since 2006, which involve an increase of renewable energy to 17 TWh by 2015 [3]. Of 17 TWh, wind power is supposed to contribute by about 10 TWh, which gives about 4 000 MW[2] installed wind power. The Swedish Energy Agency[3] has now developed this planning goal further; the suggested new planning goal is to have 20 TWh wind power on land and 10 TWh wind power offshore by the year 2020 [4]. As 10 TWh of energy is about five times this year's forecasted production of wind power (2 TWh), we may say that this is a massive introduction of wind power.

[1] "Energy from renewable sources" means renewable non-fossil energy sources: wind, solar, geothermal, wave, tidal, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases [EU]

[2] If we assume 2 500 full load hours as a mean value for Sweden. The term "full load hours" is defined as the energy production divided by the installed power.

[3] Energimyndigheten

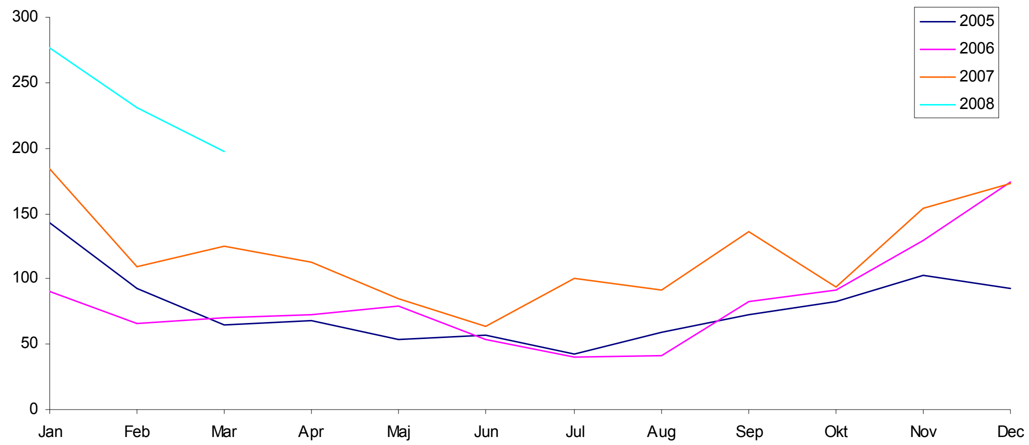


Figure 3: Monthly wind power production during 2005 – 2008 [SCB].

Wind power behaves differently compared to most other power production sources; in the sense that electric energy can only be produced when the wind is blowing, in other words, there is no built in energy storage in the power source. Most other power sources have energy storages which they convert their energy from to electricity, for instance hydropower usually have water reservoirs, nuclear power have nuclear fuel, and fossil fuel power have coal, fuel oil, or natural gas. A power producer that has energy storage can choose whether to produce electric power or not, depending on the current and expected future market price and the producer's costs of producing electric power, etc. The wind power producer do not have this choice of waiting for the best time to sell electric power, the wind power producer must sell when the wind blows. It is not only wind power that has this problem, solar power and some very small water power producers have it as well. These producers have so to say no control over their energy production. It is of course possible to reduce production, by capturing less energy, but that is only done when there is not enough consumers on the market, it is difficult to reduce production from other production sources or if the weather conditions do not allow electric power production.

Energy from wind power is as all other electrical energy sources sold at the Nordic Power Exchange – Nord Pool. To do that, it is necessary to forecast the production, as the energy is sold 12 – 36 hours ahead. Wind power producers do forecasts of their production, by using weather forecasts of wind speeds, and by that estimating their future production. If the producer's production differs from its planned production, the producer will have to pay for the deviation. Since the electric power system needs to be in balance, the balance responsible for the electric power system needs to order someone (another electric power producer) when there is an imbalance (under- or overproduction) to compensate the imbalance. This is called regulation and costs money for the compensating (regulating) actor. The actors causing the imbalances must pay for their imbalances. The costs are settled according to the regulating prices and distributed among the actors who caused imbalances. The process is called balance settlement and takes place the day after the production day.

If an actor knows that the plan will not be followed, for instance if the actor has a newer wind forecast that tells otherwise, there is an alternative way to go. That way is to buy or sell the imbalance at the adjustment market Elbas, which could be done as near as one hour before the production hour. The drawback of trading at the adjustment market Elbas is that the trade itself costs money and that the new forecast might still not be perfect.

However, a producer who has other controllable production sources besides its wind production may control that production in order to keep the production plan. That control, may not be totally free of costs, due to that

- the efficiency of the regulating production may go down, and
- the production must consider the forecast error from the wind power and reserve space in the production to handle the forecast error, such as having larger margins in the water reservoirs, etc. It may also have the consequence that it will not be possible to produce maximum at the hours with highest prices.

So, the conclusion of this is that internal control of forecast errors, may lead to a sub-optimisation that is not beneficial.

1.2 Investigation

As has been discussed in the previous section, one drawback of wind power is that it is not possible to make totally correct production plans. Since there are political ambitions for massive introduction of wind power, there is a need to know how the new energy source will integrate into the system and if some institutional and regulatory changes are required. This investigation focuses on future costs wind power producers will suffer, due to difficulty to deliver correct plans to Nord Pool 12-36 hours before the hour of operation.

In a scenario with 4000 MW wind power in Sweden, this report investigates:

- The imbalance volume due to wind power forecast errors for the system as well as for different actors
- The costs associated to the imbalances
- The reduction of imbalance costs by trading at the adjustment market Elbas for different actors.

1.3 Literature review

A number of investigations in adjacent areas have been made. A some of these publications including brief summary and how it relates to this report are listed below.

- The report "Effektvariationer av Vindkraft" investigates a scenario with 4000 MW wind power in Sweden. The size and location of possible future wind power farms are suggested.
- The report "4 000 MW wind power in Sweden" evaluates the increased need for regulating power, due to increased wind power production, based on the calculated production data.
- The possibility to profit from providing the regulating power is investigated in the report Future Trading with Regulating Power. [6].
- In the PhD thesis The Impact of Large Scale Wind Power Production on the Nordic Electricity System [8] the influence of a large amount of wind power on the Nordic power system is investigated, proving that if wind power is installed over a large area the influence of a sudden change in the power supply is decreasing due to the smoothing effect. This smoothing effect is of important concern for the wind power producer and for this investigation as well.

1.4 Outline of the report

This report is divided into nine chapters and a brief outline of these chapters is listed below.

Chapter 1 introduces the reader to the subject and the reason why a massive introduction of wind power is studied. Furthermore the reader is introduced to the obstacles and necessity with forecasting wind power production.

Chapter 2 visualises the future plans of new wind power in Sweden and in Europe. Based on that, a 4 000 MW scenario in Sweden with eight wind power actors with balance responsibility is presented, which will be the target to be studied in this report.

Chapter 3 explains how the electricity market works in the Nordic countries, and how power-producing actors can handle the forecast errors in different ways to minimise their costs.

Chapter 4 gives an insight into the work of forecasting wind power, and how the forecasting error can be modelled for single sites, whole areas with many sites and spread-out sites and areas.

Chapter 5 shows how the electricity markets can be modelled, as it aims to be used in calculating future costs of forecast errors on a market with increased forecast errors.

Chapter 6 shows the results of costs calculations for the forecast errors for the eight actors as well as the actors' yearly forecasting errors (imbalances).

Chapter 7 introduces one alternative way of handling the forecast errors on the adjustment market Elbas. The costs are compared to when the forecast errors are not handled actively, that is the cost on the regulating market.

Chapter 8 investigates changes of imbalance costs in four different scenarios; these are increased wind power, improved forecasts, changed location, and different price areas.

Chapter 9 discusses alternative solutions for balance settlement in the system with large amounts of wind power.

Chapter 10 makes conclusions from the investigation and also gives some suggestions on how the forecast errors should be handled. Some ideas on future work are also suggested.

1.5 Reference group

Vindforsk finances this project and the members of the reference group are:

- Sara Hallert, Vindforsk
- Peter Fritz, EME Analys, Elforsk Market Design
- Joakim Allenmark, Vattenfall Nordic Generation.

1.6 Acknowledgements

The reference group are thanked for valuable comments on the report as well as good suggestions during the work. Johan Gustafsson (Vattenfall Elproduktion) is thanked for many good discussions on the topic during the work.

2 Electricity markets in the Nordic countries

2.1 Background

The Nordic countries deregulated the market for electric power trading and Nord Pool was created in 1993 as the market place for handling power trading. Norway was the first country trading on this market, and Sweden started trading 1996. Denmark and Finland joined some years later.

The forecasted total energy consumption in the Nordic countries for 2008 is 415 TWh (average power is 47 GW), and the annual increase is in the order of 1,5%/year [10]. That gives about 6 TWh increased consumption every year in the Nordic countries, which will be partly met by new wind power installations. The consumption and production is shown in Figure 4 for the Nordic countries. It is seen that Sweden is the largest energy producer and consumer, which is logical since Sweden has the largest population (9 million people). Since the sum of generation is 16 TWh larger than the consumption, that part is exported to other countries outside the Nordic countries.

2.2 Electric Power Balance

Electric power production should be equal to the consumption in an electric power system. If the generation is higher or lower than the consumption, the power difference will be stored in or discharged from the rotating masses in the system. The energy *E* in the rotating masses can be expresses as

$$E = \frac{J\omega^2}{2} = \int (P_{in} - P_{out}) \cdot dt \,, \qquad (1)$$

where *J* is the total inertia in the electric power system, ω is the angular frequency of the rotating masses, and *P* is the power. As a consequence of that, the frequency will increase when the generation is higher than the output power, and vice verse. The frequency in the Nordic countries should be 50 Hz ± 0,1 Hz and it is the Transmission System Operator (TSO) in each country who is responsibility for keeping the frequency. In Sweden, the TSO is Svenska Kraftnät (SvK). Keeping the frequency is done by primary and secondary regulation. Computers controlling water flow in hydropower stations do primary regulation automatically. The primary regulation is proportional to the frequency deviation from 50 Hz, and the activated primary regulation is 600 MW at 0,1 Hz deviation. Secondary regulation is done by telephone calls from the TSO to electric power producers, who activate electric power production, which could be a anything from just a part to several electric power stations.

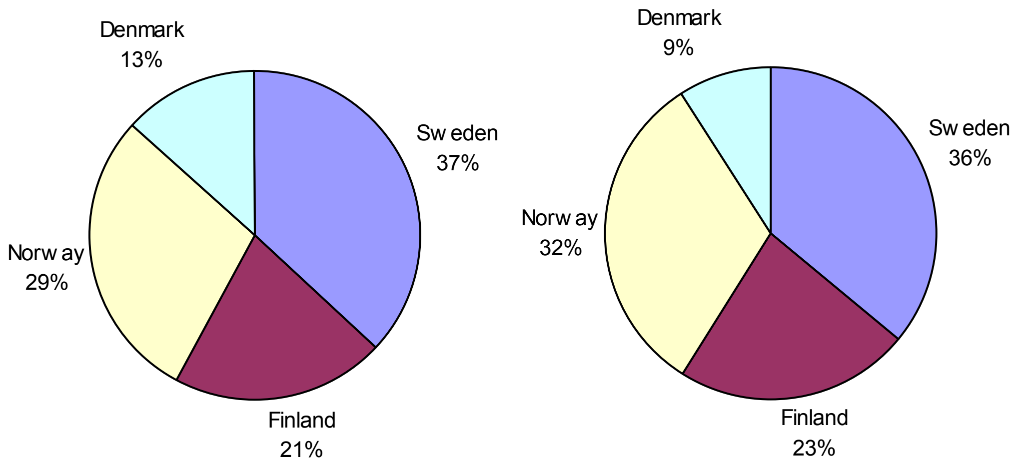


Figure 4: Forecasted generation (left) and consumption (right) for the Nordic countries 2008 [Nordel].

Table 1: Forecasted production and consumption for the Nordic countries 2008 [Nordel].

	Sweden	Finland	Norway	Denmark	Sum
Generation	159 TWh	90 TWh	124 TWh	58 TWh	431 TWh
Consumption	150 TWh	94 TWh	133 TWh	38 TWh	415 TWh
Population	9,0 M	5,2 M	4,6 M	5,4 M	24,9 M

2.3 Balance responsibility and imbalance costs

As it was mentioned in the previous section in Sweden the TSO Svenska Kraftnät is responsible for maintaining the country's spinning power balance. This responsibility is executed through, for instance, entering into agreements with companies who want to become balance responsible actor. The balance responsible actor undertakes to plan, on an hourly basis, in such a way that the production and purchasing of power correspond to the anticipated consumption and sales of the consumers/suppliers that the company has the balance responsibility for, and subsequently to financially regulate balance discrepancies vis-à-vis Svenska Kraftnät. A balance responsible has several possibilities of creating a balance between the supply and consumption of power; for example, through bilateral deals with other balance responsible actors, trading on the power exchange and planning own production resources. A power trading company can either assume the balance responsibility itself or engage a company, which has an agreement with Svenska Kraftnät regarding balance responsibility. Normally there is a fee associated with buying balance responsibility services from somebody else. Presently there are about 30 balance responsible actors in Sweden.

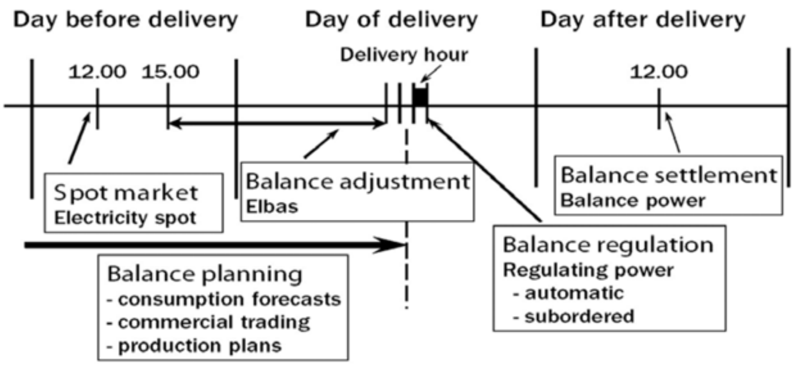


Figure 5 Sequence of events on the Nordic power market Nord Pool.

2.4 Trading at Nord Pool

Trading electric power differs in some ways compared to trading stocks, raw materials, etc. The main difference is that electric power is traded for future actions. Trading for future actions implies that forecast about the future electric power consumption and production has to be made. At Nord Pool, the trade is performed at spot market, the production plans can be adjusted at adjustment market Elbas and the balance service is supported by means of regulating market. System imbalances are settled the day after delivery (Figure 5). The market actors send bids to Nord Pool no later than 12.00 the day prior to the day of production (Figure 5). One bid is made for each hour of the day. Two hours before the spot market closure, the TSO informs the market of the existing transfer capacities at every existing price area border. This is important information because transfer capacity limitations have a severe impact on the spot price.

The time between the gate closing and delivering the bids, 36 hours at most, and the consumption and production situation might change during that period. The Nordic intraday market, named *Elbas,* provides that possibility to adjust the production plans after the gate is closed (Figure 5). The regulating market provides the secondary regulation for the balance service maintained by the TSO. Balance providers willing within 10 minutes to increase or decrease the level of production or consumption have the possibility to add regulating bids at the regulating market.

2.5 Spot market

The spot market at Nord Pool is the first market place. The producers sell electric energy and the consumers buy electric energy by placing bids at latest 12.00 for all 24 hours the next coming day, which starts at the clock hour 00.00. That means that the trade is about production and consumption 12 – 36 hours ahead. The actors put bids for each hour (including a volume of energy) and a computer program calculates the cheapest possible price for the sum of all energy volumes that has been bought. This way everybody gets the same price. The spot price is presented at 14.00. The spot market had a turnover of 250 TWh during 2006, which correspond to about $100 \cdot 10^9$ kr.

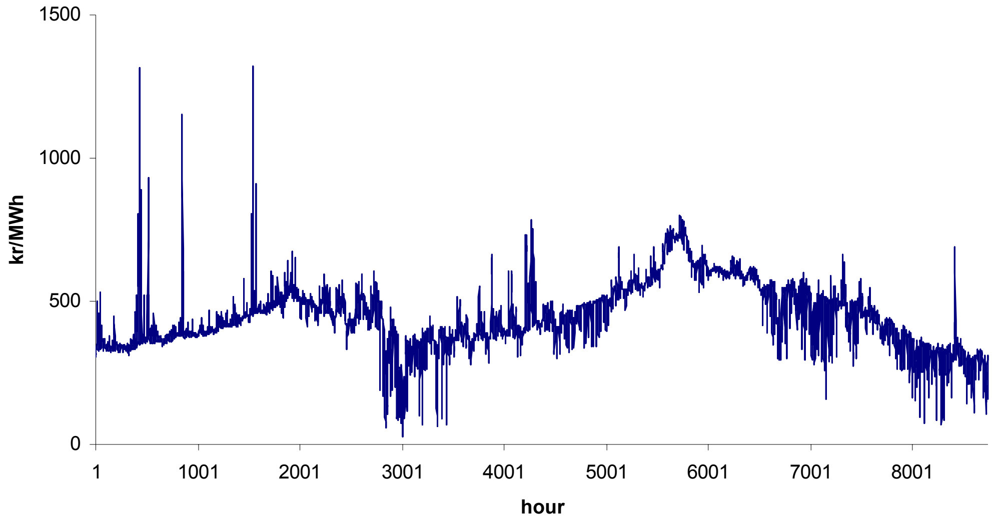


Figure 6: Spot market hourly price during 2006.

Figure 6 shows the hourly price at the spot market during 2006. It can be seen from the figure that the prices sometime get very high and during 2006 the prices was almost three doubled during some few hours. However, most of the time, the prices on the spot market are quite steady.

2.6 Adjustment market

The intraday adjustment market Elbas was launched as a separate market for power balance adjustment in Finland and Sweden 1999 [Nord Pool]. Sometimes the intraday adjustment market is just called the intraday market or just the adjustment market. At the intraday market power is continuously traded 24 hours a day, 7 days a week, covering individual hours, up to one hour prior to the hour of operation.

In June 2007 the Elbas covered Sweden, Finland, Denmark and Germany, meaning that it creates a market coupling between the Nordic market and the German market. Norway will enter the adjustment market during 2008.

The adjustment market makes it possible for actors to adjust their balance according to their reported production to the spot market. In Figure 7, the adjustment market (Elbas) hourly mean value price during 2006 is shown. Maximum and minimum prices at the adjustment market are reported as well, but in this report, only the mean value is used.

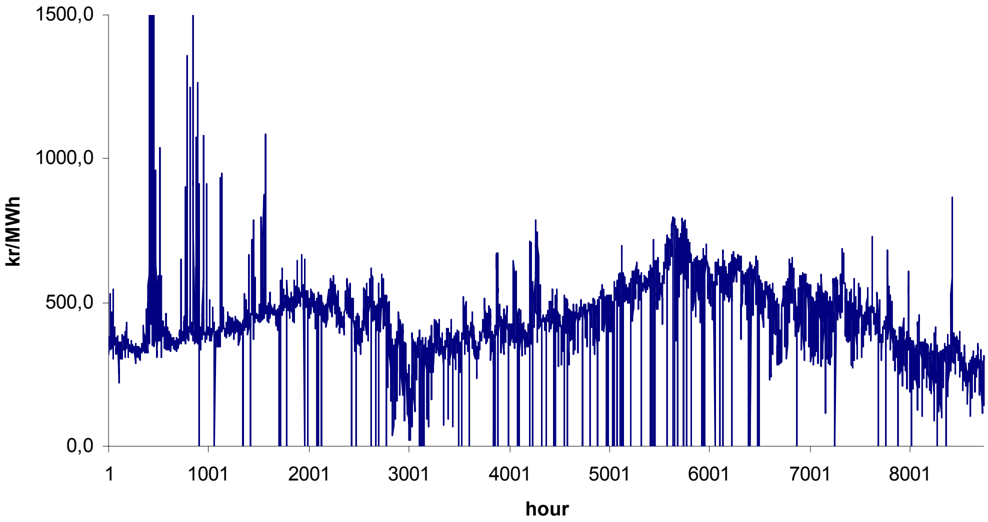


Figure 7: The adjustment market (Elbas) hourly mean price during 2006.

At the adjustment market, the actors do not get the same price, as on the spot market, where the price is the same for everyone. Comparing Figure 7 with Figure 6, clearly shows that the prices are connected, however the prices at the adjustment market Elbas has a more noisier behaviour, due to that the trade is more urgent, which makes the market actors more willing to pay extra high prices or willing to sell at low price when there are high imbalances. However, most of the imbalances are traded at the regulating market (87%) compared to the adjustment market (13%).

2.7 Regulating market

The regulating market is only open the hour of operation. Its purpose is to keep the electric power system stable, so that the production equals the consumption. It is only the TSO who can buy regulating power, which is done when needed. The regulating market contains two prices for each hour, one for up regulating and one for down regulation. If upward regulating is done the TSO must take the cheapest bid. If that is not enough, the TSO takes the next cheapest and so on. However if more than one trade has been made it is the most expensive of the bids the TSO has taken that makes the price for everyone. During down-regulation, it is the opposite, meaning it is the cheapest bid bought that will hold for everyone. So, as on the spot market, everyone gets the same price.

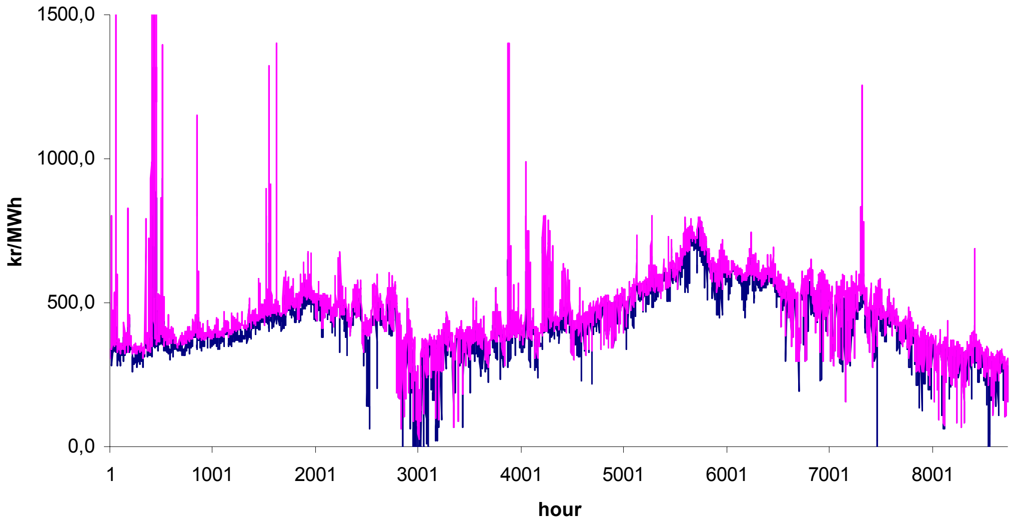


Figure 8: The regulating market hourly price during 2006. Includes both upwards (red line) and downwards (blue line) regulating prices.

2.8 Balance settlement

Balance settled the day after delivery. This is needed since there may be over- or underproduction according to the sold power at the Nord Pool market. This production error is called imbalance and is calculated as

$$\Delta E = E_p - E_s , \qquad (2)$$

where E_p is the energy production during the hour and E_s is the predicted energy sold at the Nord Pool spot market and the adjustment market Elbas. The TSO in Sweden has a balance service function, which has the task to distribute the costs of maintaining the balance between the actors on the market via balance settlement. The actors will get paid according to rules, which say that if an actor has an imbalance that helps the system's imbalance the actor will get paid by the spot price P_s. In the opposite case, the actor will pay the down or up regulation price for the imbalance, K_d respectively K_u. This is illustrated in Figure 9. In the case where no regulation is needed, all actors get the spot price. For some few hours during the year there is both up- and down regulation. For these hours the largest volume determines the direction for the whole hour.

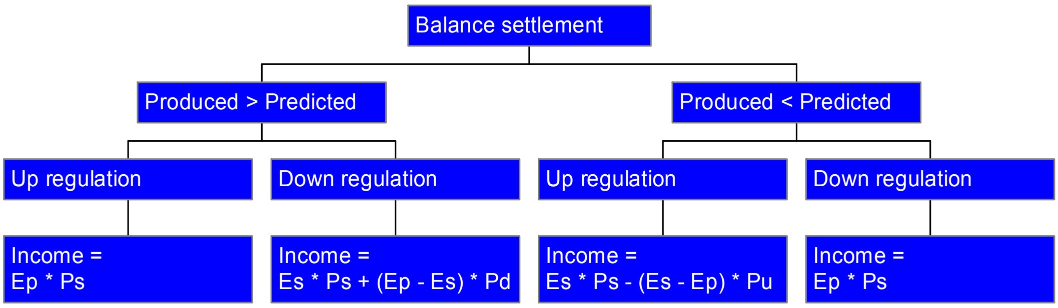


Figure 9: Price calculation for actors at Nord Pool.

The price rules make it expensive with high forecast errors (imbalances), and are therefore a driving force for the actors to keep their balances. This is good for the electric power system since it works as an economic regulator, which makes the electric power system stable. For a small actor, whose imbalance is small compared to the system's (all other actors) imbalance will statistically have to pay regulating prices 50% of the time. As an actor's imbalance grows compared to the system imbalance, and thereby affects the system, will have to pay more than 50% of the hours. If the correlation between the system imbalance and an actor's imbalance is 100%, then the actor has to pay regulating price 100% of the hours (with regulation). In other word it means that the probability to be on the right side decreases with increased correlation. Mathematically, the amount of hours an actor has to pay the regulating price can calculated by

$$\mathrm{P}(P_p \cdot P_s > 0) = \frac{1}{2} + \frac{\arcsin \rho}{\pi}. \tag{3}$$

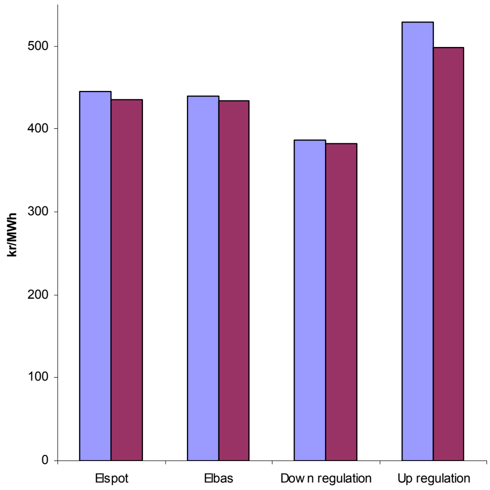
2.9 Jiggling

Since infinitely small forecast errors (imbalances) are impossible in reality, there is a so-called "jiggle allowance[4]" at the regulating market today. This "jiggle allowance", means that an actor's deviation from the planned power production P_p without any cost is limited to

$$\Delta P = 5\,\mathrm{MW} + 0{,}5\% \cdot P_p, \tag{4}$$

in other words, a wind power actor (or any other power actor) may deviate at least 5 MW[5] from the production plan without cost. A small producer, who has a lower power than 5 MW, does not need to keep his balance due to that. It has been suggested that the jiggle allowance will be removed in the future, and therefore it has been neglected in this report for the studies of the future market.

[4] In Swedish this is referred to as "vingelmån".
[5] The mean power during an hour. It could also be expressed as 5 MWh/h.



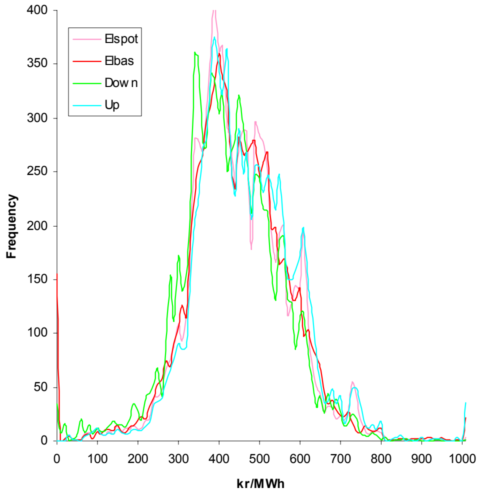


Figure 10: Left: Mean and median prices at the spot, adjustment and regulating markets 2006. Right: Price distribution at the spot, adjustment and regulating markets 2006.

Table 2: Mean, median and standard deviation prices at the spot, adjustment and regulating markets 2006. Prices are in kr/MWh.

	Elspot	Elbas	Down regulation	Up regulation
Mean	446	440	386	529
Median	436	434	382	499
Standard deviation	116	144	125	325

2.10 Concluding remarks about the markets

The prices at Nord Pool markets are closely related. The mean value and median value of the prices during 2006 for the different markets are shown in Table 2, and by a graph in the left part of Figure 10. It is clear that the mean value and median value of the price difference is only in the order of 20%. For the up and down regulation prices, the values have been calculated for the hours with regulation in their respective direction, which is up (3 034 h) and down (3 320 h) direction. The standard deviation of the prices is also shown in the Table 2, as well as the distributions of the prices in the figure. The distributions of the prices are also very similar. The up regulating price has a very high standard deviation (325 kr/MWh), the reason for that is that there are some hours (about 60 h) with very high prices (up to 16 794 kr/MWh), which affects the standard deviation very much. If these hours are removed, the standard deviation is only 108 MWh and the mean value is only 495 kr/MWh.

3 Wind power plans in Sweden and other countries in Nordic Europe

3.1 Ambitions

Wind power is a growing market, due to political and environmental ambitions as stated in the previous chapter. Plans on building small and large wind farms are made by a number of electric power producers, companies and even by associations, since wind power is becoming a safe and good investment. The trend is the same in most other countries. Electric wind power is a safer investment nowadays, due to the introduction of the trade with electricity certificates in Sweden and higher energy prices on electric power. As wind power installations are becoming a larger market, the prices on wind power installations are falling, making investment safer.

3.2 Plans in Sweden

The future plans for large (> 20 MW) wind farms in Sweden are compiled in a map and published monthly by Svensk Vindkraft at its homepage www.svenskvindkraft.se [9]. Svensk Vindkraft is an organisation consisting of two associations, VIP[6] and ViS[7]. The map is shown in Figure 11 and all these projects are compiled in Table 3. The sum of all wind power projects is above 10 TWh and the sum of the power is almost 4 000 MW. The previous chapter stated that the Swedish Energy Agency planned 4 000 MW wind power, and as we see, these plans are supported by concrete projects.

Most of the wind farm projects on this map are located in the South (about 75%) of Sweden. It can also be said that most of the wind farms in the northern part of Sweden are located on-shore, while most of the projects located in the south are located to offshore locations. However, due to recent problems with gearboxes in offshore wind farms and the high costs of building and maintaining offshore wind farms, new projects in the southern part of Sweden will most likely be placed on land. The process of planning wind power is very long and takes many years. One of the main reasons that the process takes many years is that it takes long time to get the permissions. Once the permissions have been approved, these can be appealed to court, which delays the wind power project even further.

[6] VIP = Intresseföreningarna Vindkraftens Investerare och Projektörer

[7] ViS = Vindkraftsleverantörerna i Sverige

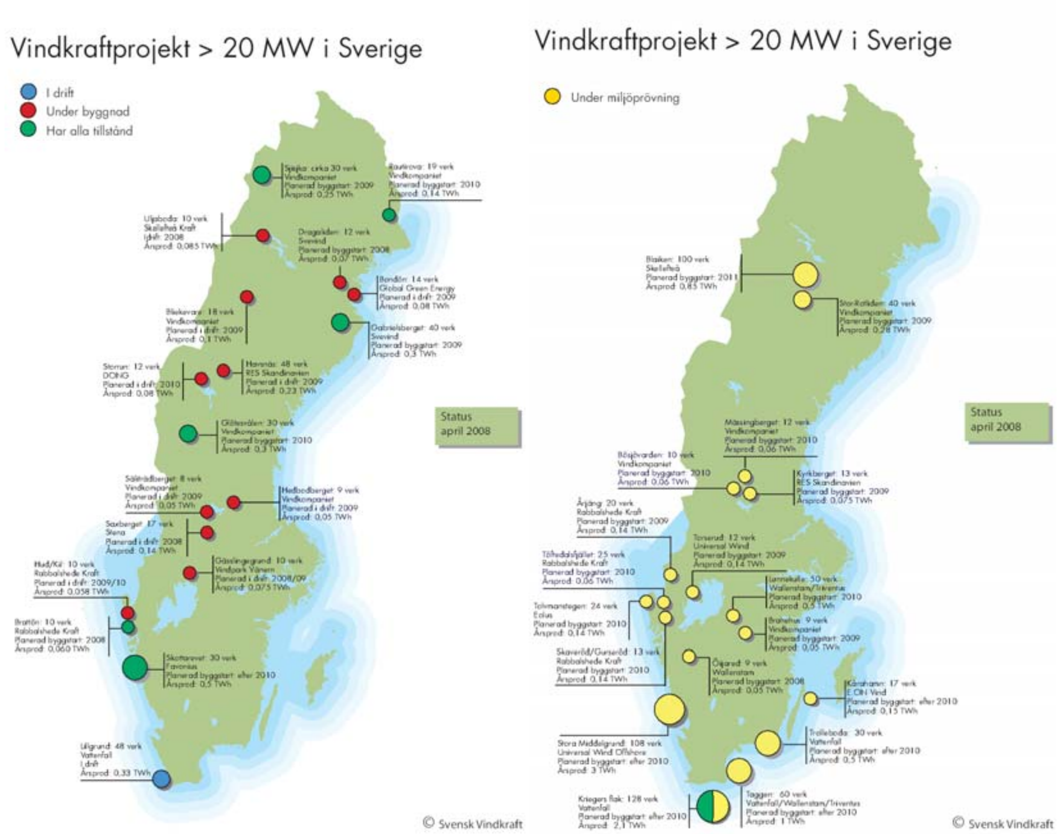


Figure 11: Planned wind farms in Sweden with installed power at least 20 MW [9].

The map can be seen in Figure 11, and shows projects that:

- (light blue dot) just have been built and are producing electric power,
- (red dot) are under construction,
- (green dot) have all permissions to start the construction process,
- (yellow dot) and are under environmental trial.

Table 3: Project plans in Sweden

Project	Place	Company	#	Power MW	Yearly GWh	Full load hours	Start
Mässingsberget	Mora	Vindkompaniet	12		60		2010
Bondön	Piteå	NordanVind	14	35	80	2286	2008
Dragaliden	Piteå	Svevind	12		70		2008
Storrun	Krokom	Dong Energy	12	30	80	2667	2008
Uuljaboda	Arjeplog	Skellefteå Kraft	12	36	100	2778	2008
Gässlingegrund	Vänern	Vindpark Väners	10	30	75	2500	2009
Bliekevare	Dorotea	Vindkompaniet	20	60	200	3333	2009
Brattön	Falkenberg	Rabbalshede kraft	10	25	60	2400	2008
Hud/Kil	Tanums	Rabbalshede kraft	10	25	58	2400	2010
Skottarevet	Falkenberg	Favonius	30	135	500	3704	2010
Hedbodberget	Rättvik	Vindkompaniet	15	45	150	3333	2009
Torserud		Universal Vind	12		140		2009
Årjäng		Rabbalshede kraft	20	50	140	2800	2009
Töftedalsfjället		Rabbalshede kraft	25	65	140	2800	2010
Öjared	Lerum	Wallenstam	9	27	65	2407	2009
Havsnäs	Strömsund	RES Skandinavien	48	96	235	2448	2010
Gabrielsberget	Nordmaling	Svevind	40	120	250	2083	2010
Sjisjka	Gällivare	Vindkompaniet	30	90	250	2778	2010
Glötesvålen	Härjedalen	Vindkompaniet	30	90	300	3333	2010
Kyrkberget	Mora	RES Skandinavien	11	33	80	2424	2010
Rautiorova	Övertorneå	Vindkompaniet	19		140	3000	2009
Stor-Rotliden	Storuman	Vindkompaniet	40		280		2009
Blaiken	Storuman	Skellefteå	100	300	850	2833	2011
Säliträdberget	Mora	Vindkompaniet	8	24	50	2083	2009
Saxberget	Ludvika	Stena	18	54	140	2593	2008
Tolvmanstegen	Strömstad	Eolus Wind	24	48	140	2917	2010
Stora Middelgrun	Laholm	Universal Wind	108	864	3000	3472	2011
Kårahamn	Öland	E.ON Vind	17		150		2010
Trolleboda	Karlskrona	Vattenfall	30	150	500	3333	2011
Taggen	Kristianstad	Vattenfall	60	300	1000	3333	2011
Kriegers flak	Trelleborg	Vattenfall	128	640	2100	3281	2011
Lunnekullen	Karlsborg	Wallenstam	50	150	500	3333	2011
Gunnarby	Uddevalla	Wallenstam	11	18	61	3389	2011
Total/Mean			**995**	**3900**	**11864**	**2800**	**2010**

3.3 Plans in Nordic Europe

Since the target for the European Union is to increase the renewable energy sources by the year 2020, all countries within the EU are planning for new wind power projects. According to the European Wind Energy Association (EWEA) forecasts, 180 GW can be installed in the European Union by 2020, capable of meeting approximately 13% of EU electricity demand. Figure 12 shows the forecasted wind power installations.

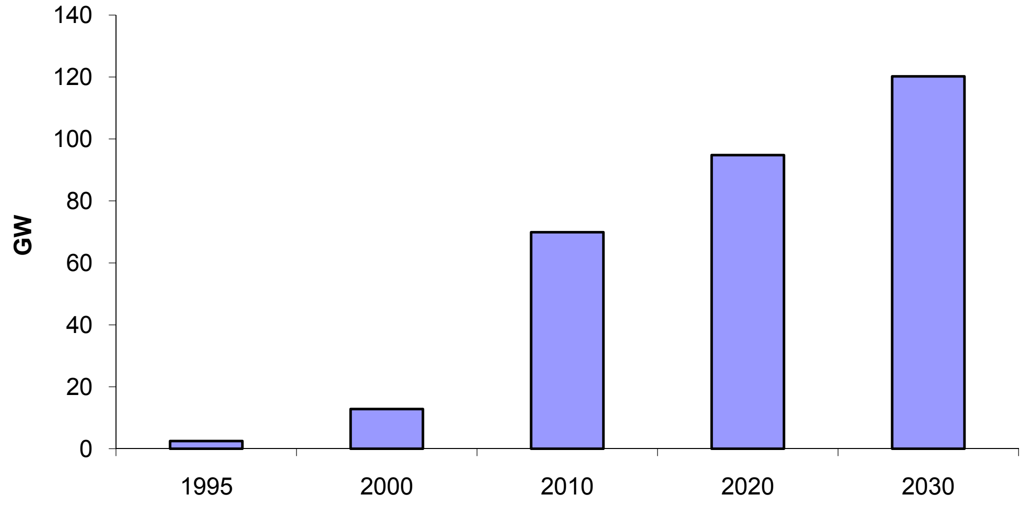


Figure 12: Estimated capacity development of wind power in Europe[26].

3.4 Actors

The map in Figure 11 shows that of the 4 000 MW projects in Sweden, about 75% is located in the South of Sweden. The report [*7*] also points out a scenario of possible wind power locations, with 75% located south of Gävle. However, the report [19] points out a scenario with 50% wind power to the South and 50% to the North. Since the latest trend seems to be more land based wind power, it is also likely that because of that more wind power will be located in the North, as there is more space in the North (less occupied with people) and wind speed on land is not much less in northern parts (6 m/s) of Sweden as on the southern part (8 m/s) of Sweden. Reduced wind speed, reduces the amount of produced energy, however as we see from the planned projects, the full load hours in the northern part of Sweden is just slightly less. Therefore, this report has put the wind power evenly distributed (energy vice) between the southern part and the northern part of Sweden. Since the full load hours are higher in the South, the installed wind power is distributed as 47% South and 53% North.

As the aim of this report is to study imbalances resulted from the forecast error and the costs associated to that for different actors. Eight different types of wind power actors has been created within the 4 000 MW scenario with 50% of the wind power located to the southern part of Sweden and 50% located to the northern part of Sweden. The actor's location of wind power is shown in Figure 13 and compiled in Table 5. The actors have different amount of wind power in their portfolio, and the geographical spread-out is also different for the actors. Table 4 shows typical full load hours in each area, which is based on the wind power projects in Table 3. The electric power production from the wind farms as well as the energy production per year is also shown in the table.

Table 4: Full load hours in each area in Figure 13

Area	1	2	3	4	5	6
Full load hours [h]	3200	3300	3000	2700	2800	2800
Rated power [MW]	900	400	580	680	515	945
Energy production [TWh]	2,9	1,3	1,7	1,8	1,4	2,6

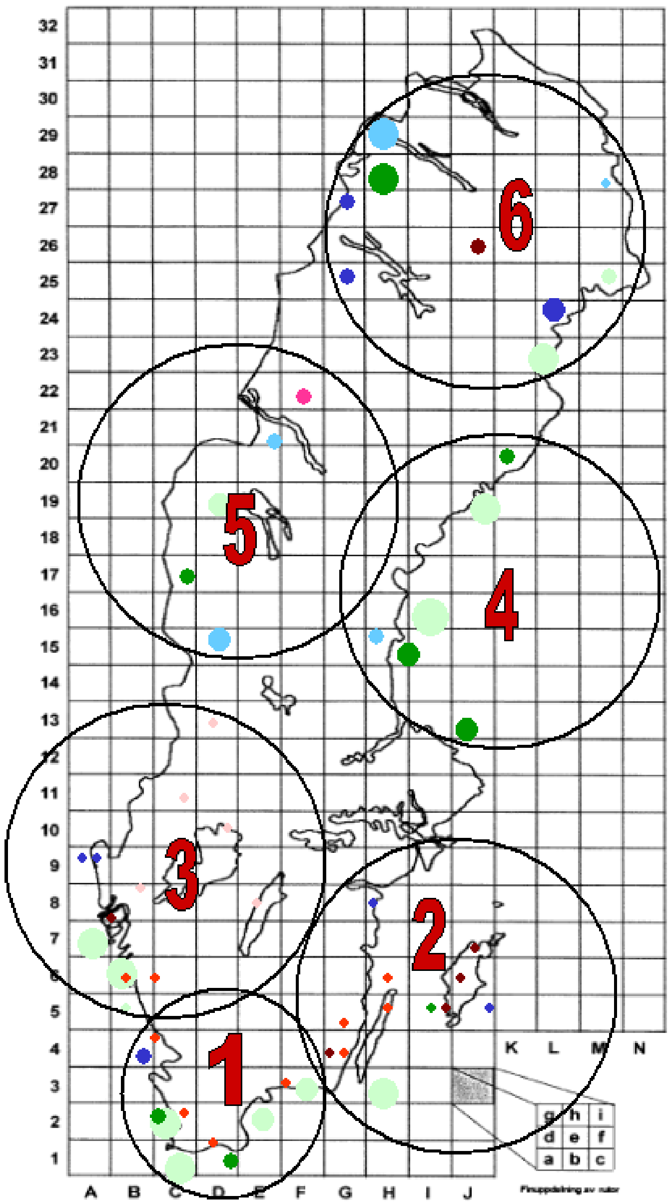
Table 5: The scenario includes eight balance responsible actors with different distances between their production sites

Actor	1	2	3	4	5	6	7	8	Total
Capacity [MW]	1 905	660	415	445	200	170	125	100	4 020
Annual production [GWh]	5 708	1 889	1 218	1 239	640	520	350	300	11 864
Full load hours [h]	3 000	2 900	2 900	2 800	3 200	3 100	2 800	3 000	3 000
Distance between sites	Large	Large	Large	Medium	Small	Large	One site	Medium	

The eight actors created in this report represent eight different scenarios and the ambition is that every wind power investor would find one of the scenarios corresponding well with its investment plans. Since only the forecast errors are modeled, an investor in the southern part of Sweden, who just wants to invest in one site, can look upon actor 7, since the forecast error is not dependent on location; it is only the full load hours that depend on location. A compilation of the portfolio for the wind power actors is shown in Table 5.

Following from the market structure described in Chapter 2 the balance responsible actors face some costs associated with day-ahead forecast errors. One can adjust the mismatch by acting on the intra-day market, but normally this is a worse deal compared to placing the right bid directly to the spot market. Balance settlement according to the regulating market prices leads to imbalance costs, which arise when the direction of the actor’s imbalance coincides with the direction of markets imbalance, and can be assessed as the difference between the spot price and regulating price for the given hour multiplied by the imbalance volume.

The well-known concerns about wind power compared to other production types are related to its intermittent nature and difficulty to make exact forecasts especially on the day-ahead time perspective. This lead to concerns related to high imbalance costs, which may influence profitability of the projects.



Type	Actor	Power	Colour
Large	1	1905	
	2	660	
Middle	3	415	
	4	445	
	5	200	
	6	170	
Small	7	125	
	8	100	

Size	Power
	180 MW
	125 MW
	70 MW
	20 MW

Figure 13: The investigation in this report consists of 8 actors with a total capacity of 4000 MW located as presented in the map. Sweden is divided into six areas, each area having its own full load hours.

This report makes an attempt to assess imbalance costs of balance responsible wind power producers of different sizes. It is assumed that the actors own only wind power and have at the same time balance responsibility. In reality it does not have to be so. Large actors probably will own other production sources besides wind power and small actors probably will leave balance responsibility to someone else. However the assumptions in this report allow us to estimate the future imbalance costs associated just with wind power and separate them from other costs.

4 Forecasting wind power

4.1 Background

It is necessary to have good production plans day-ahead since the spot market requires its actors to place sell bids at 12.00 for the next 24 operating hours starting at midnight (00.00). This means that the wind power producers will have to make forecast for 12 – 36 hours ahead. It is important to make as good forecasts as possible, since otherwise there will be imbalances associated to the forecast errors. The actor's forecast error will lead to imbalance costs. The balance responsible actor has two choices; either to handle the imbalances at the adjustment market Elbas or to leave the imbalances to balance settlement and take the corresponding costs. In the adjustment market (Elbas) case the imbalance is most likely to be bought/sold at worse prices compared to the spot price and trading itself also costs money (personnel, updated forecasts, trading taxes). In the second case there may be high costs associated with high regulating prices. Both cases are costly, however making improved forecasts are costly as well, which means that the actor has to optimise the costs of these three items (improved forecasts, Elbas trading, leave to regulating market).

4.2 Forecasts of wind power

Production forecasts are based on weather forecasts of wind speeds. Weather forecasts are bought from forecasting institutes like the Swedish SMHI[8]. The wind speed is then used to calculate the production. The relation between wind speed and production is well known and is provided by the manufacturer of the wind power plant.

The wind speed may vary fast, and can in the most extreme situations change from very low wind speed to storm in just a few hours. The wind speed is often modelled as a Weibull distribution or in some cases approximated to a normal distribution; the latter is often used since it is very easy to use mathematically. The wind speed is not only varying daily, but it has also a quite big seasonal variation and yearly variation. A typical yearly variation is shown in Figure 14. A reduced or increased yearly wind speed reduces or increases the energy production quite much, since the relation between wind speed and output power is far from linear.

[8] SMHI = The Swedish Metrology and Hydrology Institute (Sveriges Meteorologiska och Hydrologiska Institutet).

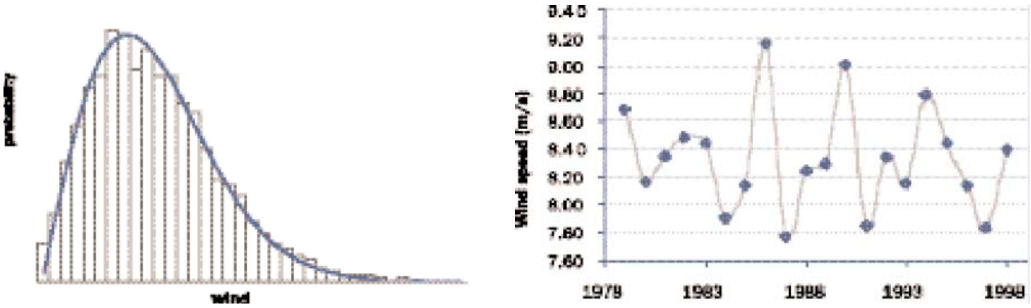


Figure 14: Wind speed variations as distribution and time series.

Figure 15 shows the hourly variations of wind power during one month and the forecasts of wind power for 12 – 36 hours ahead. The quality of wind power forecast increases with decreased forecast time. The publication [12] by Holtinen has showed this, where the expected prediction error is about 20% for 1 hour ahead and 50% for 40 hours ahead (and in between almost a linear relationship).

4.3 Making a model of forecast errors

One way of making a model for the forecast errors is to analyse the statistical data. Such data was available for the wind farm Horns Rev[9], which is partly owned by Vattenfall. The wind farm Horns Rev has the installed power 160 MW and data from 11 September 2006 to 31 mars 2007 has been made available for this study. The yearly mean production is about 95 MW, which equals 5200 full load hours. Figure 15 shows the wind power production for Horns Rev during September 2006, together with the forecasted production. Most of the time the forecasted production is near the real production, however during some hours the difference is very high. The time series contain hourly discrete values. The values contain the mean power during an hour in MW. From now on the production is denoted $P_p(t)$ and the forecasted production is denoted $P_f(t)$. The difference between them is then the forecast error and is denoted $P_e(t) = P_p(t) - P_f(t)$. The imbalance (forecast error) has a mean value (mathematical expectation) that is

$$\mathrm{E}(P_e(t)) = 2\,\mathrm{MW}\,. \tag{5}$$

The mean value of the forecast error is almost zero (2 MW / 160 MW = 1%), which makes it likely that it is zero for infinitely long time series. So we use μ = 0 MW as the mean value for our model of the forecast error. The relative standard deviation[10] of the forecast error for Horns Rev is calculated to

$$\sigma_{rel} = \frac{\sqrt{\mathrm{var}(P_e(t))}}{160\,\mathrm{MW}} = \frac{33\,\mathrm{MW}}{160\,\mathrm{MW}} = 21\%\,. \tag{6}$$

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[9] Horns Rev is an offshore wind power farm in southwest Denmark.
[10] With the relative standard deviation for the forecast error, the standard deviation is related to the installed power (and not the forecast error).

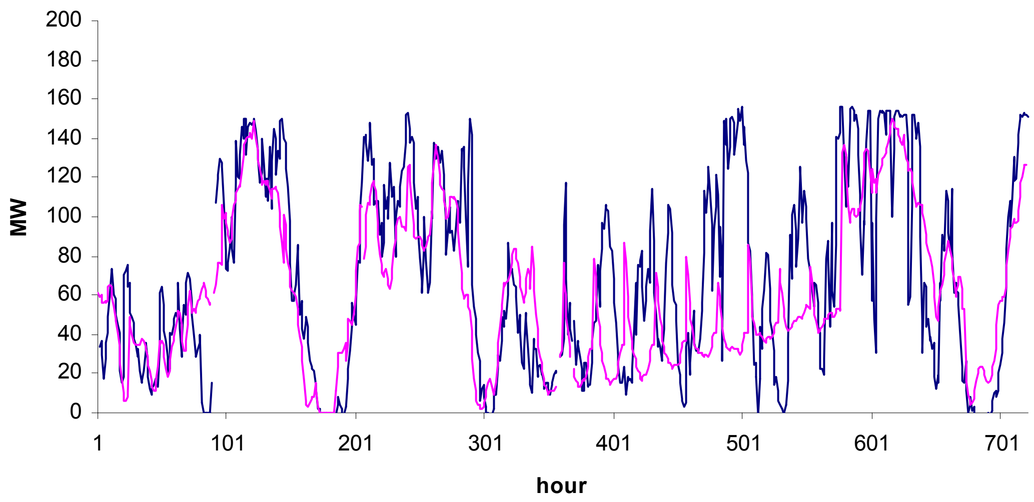

Figure 15: Horns Rev hourly production and forecast during September 2006.

This is a quite high value, other studies such as [14] has found lower value. There is a number of commercial tools for wind power forecasting used in different countries, such as Prediktor (RISØ, Denmark), WPPT (Denmark), Previento (Germany), HIRPOM (Ireland), WPMS (Germany) to mention a few. Together with high ambitions for wind power introduction the intensive work is going on development and improvement of forecast tools. In [15] the comprehensive analysis of wind power forecast tool performance for German wind power farms was done. In this investigation the standard deviation for the forecast error for wind farms varied between 8% and 18%. For most of the farms the value stayed between 10 and 13%. It is also likely that the forecast is going to be even better in the future as the weather models are improving, and hopefully wind power actors will drive the market on wind speed forecasts.

Based on reasoning above the standard deviation for wind power forecast error is set to 13% in our models.

A good number to have is the correlation coefficient ρ, which says how correlated the forecasted production is with the actual production. The correlation coefficient for Horns Rev is

$$\rho = \frac{\mathrm{cov}(P_p(t), P_f(t))}{\sigma_p \sigma_f} = 80\%, \tag{7}$$

which is a fairly good value and is in parity with [14].

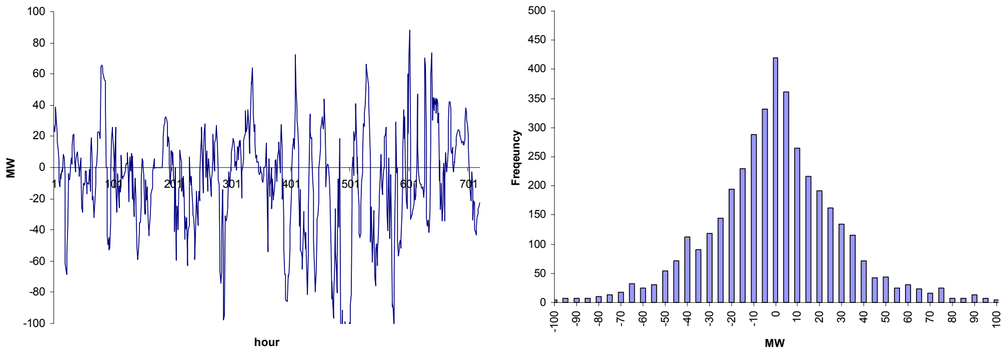

Figure 16: The forecast error at Horns Rev during September 2006. Left: time series and right distribution.

The yearly imbalance at Horns Rev is calculated to

$$E_e = \frac{24 \cdot 365}{n} \sum_{t=1}^{n} P_e(t) = 8760\,\text{h} \cdot 23{,}9\,\text{MW} = 210\,\text{GWh}\,, \quad (8)$$

which related to the yearly production for Horns Rev is

$$\frac{E_e}{E_p} = \frac{210\,\text{GWh}}{833\,\text{GWh}} = 25\%\,. \quad (9)$$

The forecast error shown in Figure 16 has a distribution that is similar to a normal distribution in the sense of being an even function and decreasing for larger deviations. As the normal distribution is also very easy to use, this investigation will use the normal distribution for the model of the forecast error. A compilation of the calculated values for the forecast error at Horns Rev during 2006 is shown in Table 6.

Table 6: Forecast error analysis for Horns Rev.

	Mean value	Correlation	Standard deviation	Mean deviation	Forecast error
Absolute	2 MW	2100 $(MW)^2$	33 MW	24 MW	210 GWh
Relative	1%	80%	21%	15%	25%

4.4 Models for larger areas

Wind power actors may have different wind farms with different distances between the sites. The balance responsible for the wind farm owner has then to do forecast on each of the farms within his balance responsibility. It is well known that the total forecast error for several wind farms is reduced, in mathematical terms that could be expressed as a reduced standard deviation (relatively, absolutely it increases) for sums of forecast errors. One way of proving that is to look on two forecast errors expressed as the normal distributed stochastic processes $X(t) \in N(\mu_x, \sigma)$ and $Y(t) \in N(\mu_y, \sigma)$. Then the sum of the stochastic processes is also a normal distribution that is expressed as

$$X + Y \in N(\mu_x + \mu_y, \sqrt{\sigma_x^2 + \sigma_y^2 + 2\,\mathrm{cov}(X,Y)}) . \tag{10}$$

If the stochastic processes are independent then Cramér's theorem may be used, and the stochastic process is reduced to

$$X + Y \in N(\mu_x + \mu_y, \sqrt{\sigma_x^2 + \sigma_y^2}) . \tag{11}$$

It is now clear that if we add two independent stochastic processes, the expected value is the sum (in our case it is zero as we assume that the mean value for forecast errors is zero) and standard deviation increases only with the square root. This is also referred to spatial smoothing effect.

For example, if an actor has two independent forecast errors for two 100 MW wind farms with the same relative standard deviation, lets say 13%, then the standard deviation for the forecast error is

$$\sigma_{rel} = \frac{1}{200}\sqrt{13^2 + 13^2} = 9\% . \tag{12}$$

However, since there is often a correlation between wind forecast errors for nearby farms, the forecast error cannot always be assumed to be uncorrelated to other forecast errors. U. Focken, et al has done such a study in [14], where they has found relationships between the standard deviation for forecast errors for both large areas and for long distances between wind farm areas. For large areas, the relation between the standard deviation of a single wind farm is shown in Table 7. Table 8 shows then the correlation of forecast errors for different distances between ensembles of wind farms. The same information is depicted graphically in Figure 17. One can see that correlation decreases almost exponentially with increase distance.

The annual imbalances can easily be calculated, since the forecast error is modelled as a normal distribution. Using the relation between the standard deviation and the mean absolute deviation for a normal distribution

$$\frac{P_e}{\sigma} = \frac{\sum |P_e|}{\sum P_e^2} = \sqrt{\frac{2}{\pi}} = 80\% , \tag{13}$$

gives the annual accumulated imbalance as

$$E_e = 24 \cdot 365 \cdot \sigma \cdot \sqrt{\frac{2}{\pi}} = 8760 \cdot \sigma \cdot 80\% = 7000 \cdot \sigma_{rel} \cdot P . \tag{14}$$

Table 7: The ratio between the standard deviation of ensemble and single forecast error time series for various region sizes and time horizon [14]

Diameter	Equation	36 hours Time-horizon
0 km		100%
140 km	$\frac{\sigma_{ensemble}}{\sigma_{\sin gle}}$	82%
350 km		71%

Table 8: The correlation of forecast errors for different distances between ensemble [14]

Distance	Equation	36 hours Time-horizon
0 km		100%
300 km		20%
350 km	$\frac{\text{cov}(X(t),Y(t))}{\sigma_x \sigma_y}$	14%
400 km		12%
500 km		11%
>600 km		0%

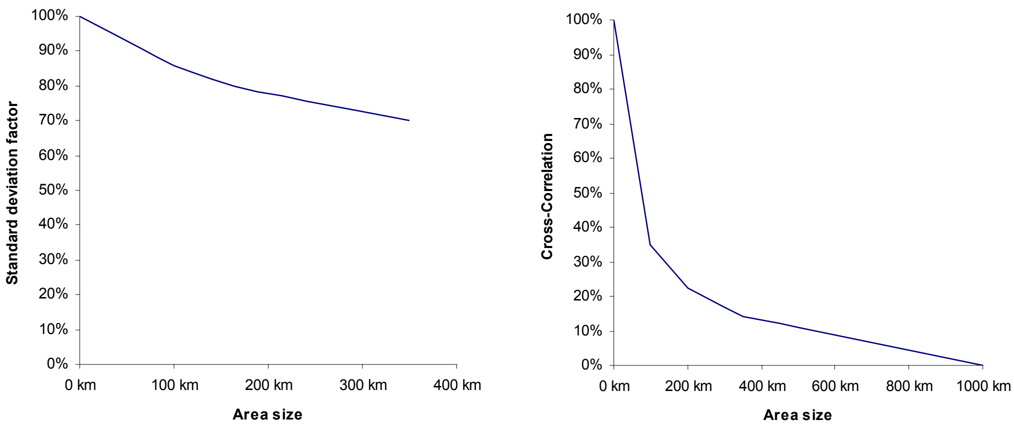

Figure 17: Left: The ratio between the standard deviation of ensemble and single forecast error time series for various region sizes and time horizon [14]. Right: The correlation of forecast errors for different distances between ensemble [14].

4.5 Actors

In chapter 3.4, eight actors were presented with different wind farm ownership. To be able to calculate the annual imbalances resulted from forecast errors for the actors, six circular areas has been created with different diameters. Area 1 has the diameter 140 km and the other seven areas have the diameter 350 km. We assume that all actors are buying forecasts from the same weather institute. So actors that have wind power on the same locations have the same forecast error. It is now possible to calculate the standard deviation of the forecast error for each actor in each area, by using Table 7. By using the data from Table 8, it is possible to sum up the standard deviation for each actor by using a more general form of equation (12), that is

$$\sigma_{all} = \sqrt{\mathrm{var}(\sum_{i=1}^{n} X_i)} = \sqrt{\sum_{i=1}^{n}\sum_{j=1}^{n}\mathrm{cov}(X_i, X_j)} \ . \qquad (15)$$

Table 9 shows the annual forecast error (imbalances) for the eight actors. For the actors, with wind farms located in all areas, particularly actor 1, the forecast error (and therefore imbalances) is very low compared to actors with just one site (actor 7) or just one area (actor 8).

Table 9: Annual imbalances for the eight actors

Actor	1	2	3	4	5	6	7	8	Total
Capacity [MW]	1 905	660	415	445	200	170	125	100	4 020
Annual production [GWh]	5 708	1 889	1 218	1 239	640	520	350	300	11 864
Imbalances [GWh]	647	229	183	179	93	69	114	64	1 215
Standard deviation [MW]	93	33	26	26	13	10	16	9	174
Standard deviation	4,9%	5,0%	6,3%	5,8%	6,6%	5,8%	13,0%	9,1%	4,3%
Imbalances related to annual production [%]	11%	12%	15%	14%	14%	13%	32%	21%	10%

Another important observation, which can be made from the table, is that on the system level (column named "total" in the table), the relative imbalances are much smaller (only 10%) than for any on the actors.

5 Model and assumptions for estimation of future regulating and adjustment market prices

5.1 Making a model for markets

Making a model of the future market prices is essential to be able to calculate the costs associated with forecast errors after the massive introduction of 4000 MW wind power. The forecast errors will be handled on the regulating market or if the actor has an updated forecast the actor may choose to buy or sell the forecast error on the adjustment market Elbas. Therefore, a model of the regulating market and a model of the adjustment market is needed. Klaus Skytte at the Risö Laboratory in Denmark has developed a market model for the prices [17], which was further developed in [6]. That developed price model for the regulating market and the adjustment market Elbas is described by equations (16) and (17). The values of symbols k_1, k_2, and k_3, are of course different for the different markets and different for up or down regulating hours.

$$P_{up} = k_1 \cdot P_{spot} + k_2 \cdot E_e + k_3 \tag{16}$$

$$P_{down} = k_1 \cdot P_{spot} + k_2 \cdot E_e + k_3 \tag{17}$$

The equations relate to the spot price P_{spot}, the hourly forecasted error E_e on the Swedish market and a bias term k_3. The model assumes that there is a correlation between the prices on the spot market and the regulation respectively adjustment markets, and to verify that that is a valid assumption the correlation between the prices has been calculated in Table 10. There is a close relation between the down regulation price and the Elspot market price; the up regulation price is also correlated to the spot market price, but not so close as the down regulating price. The adjustment market Elbas has a good correlation, however not perfect. One reason to that the correlation is not very high is of course that the market prices also relate to the forecasted errors and that the actors on the markets want to earn money on trading, but have different strategies, which are difficult to consider in a simplified models. Beyond that, there are other factors beyond our ability to model, such as changed weather conditions, unplanned shutdown of power stations, force major etc.

Table 10: Correlation coefficient between the market prices 2006.

	Elspot	Elbas	Down regulation	Up regulation
Elspot	1,00	0,74	0,93	0,44
Elbas	0,74	1,00	0,71	0,40
Down regulation	0,93	0,71	1,00	0,42
Up regulation	0,44	0,40	0,42	1,00

5.2 Adjustment market prices

The correlation coefficient for the spot market and the adjustment market Elbas is 74% according to Table 10. As the equations (16) and (17) state that the markets should be linearly related by a factor k_1, it is important to verify that, to be able to make a model based on prices during the year 2006. The easiest way to verify that is to plot the market prices versus each other as in Figure 18. It is clear from the figure that the relation is linear, and also that the price spread is almost the same at all price levels. The forecast error volumes and the bias term could explain that price spread. The price spread is either positive or negative, depending on if there has been up or down regulation during the hour. The right part of Figure 18 shows the adjustment market Elbas deviation price, which is the Elbas price minus the spot price, versus the forecast error. The correlation is clearly quite week in the figure, as it is almost impossible from the figure to find out a relation. A calculation of the correlation of the Elbas deviation price and the forecast error gives the value of correlation coefficient to 10%.

The coefficients k_1, k_2 and k_3 in equations (16) and (17), can be calculated by using the least square method. Then the median price for the model was studied and by optimising on that value as well, the parameters came out in Table 11. To verify the model, the correlation coefficient was calculated as well for the model and the adjustment market, which turned out to be 74%. That is fairly good, since the correlation coefficient for the Elbas and the spot price is also 74%.

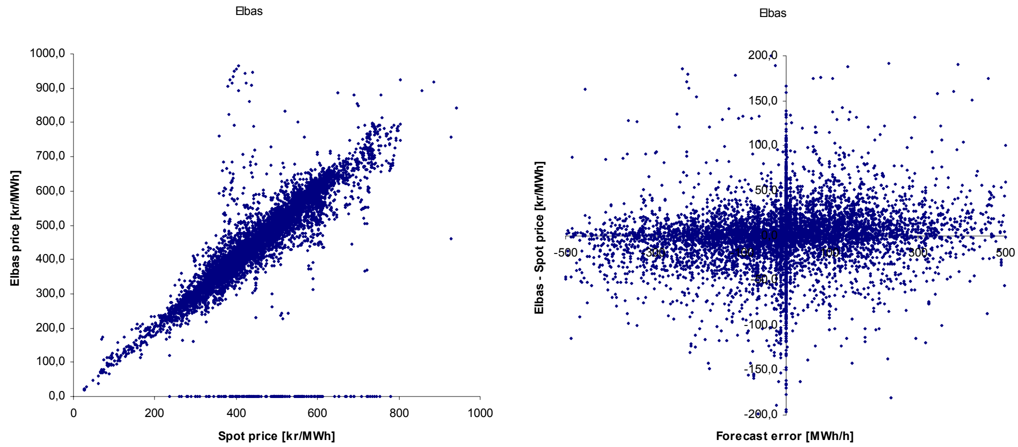

Figure 18: Left: The adjustment market (Elbas) price 2006 versus the Elspot price 2006. Right: Elbas – Spot price versus forecast error (imbalance).

Table 11: The coefficients in the model of the adjustment market Elbas

Symbol	Down	Up	None
k_1	0,98	1,02	1
k_2	0,02	0,05	0
k_3	-5	2	-2

5.3 Regulating market prices

The correlation coefficient for the spot market and the regulating market is 93% (down) and 44% (up) according to Table 10. As mentioned earlier, there are some very high price hours (60 h) for the up regulating market. If these 60 hours are removed, then the correlation coefficient for the markets is also 93%. The mean price for these 60 hours is about 2000 kr/MWh. The regulating prices are plotted versus the spot price and the forecast error versus the regulating deviation prices, that is the regulating price minus the spot price. There is a linear relationship between the prices and the price spread is almost the same for all price levels, and also almost the same for up and down regulating prices. The forecast error has a correlation coefficient to the regulation deviation price by 30%. The correlation to the forecast error is much stronger compared to the adjustment market Elbas.

The coefficients in equations (16) and (17) was found by using the same method as with the adjustment market Elbas. The results are shown in Table 12. The coefficient k_2 is about ten times higher for the regulating market compared to the adjustment market. That means that it is likely that it is beneficial to sell forecast errors on the adjustment market compared to pay regulating prices.

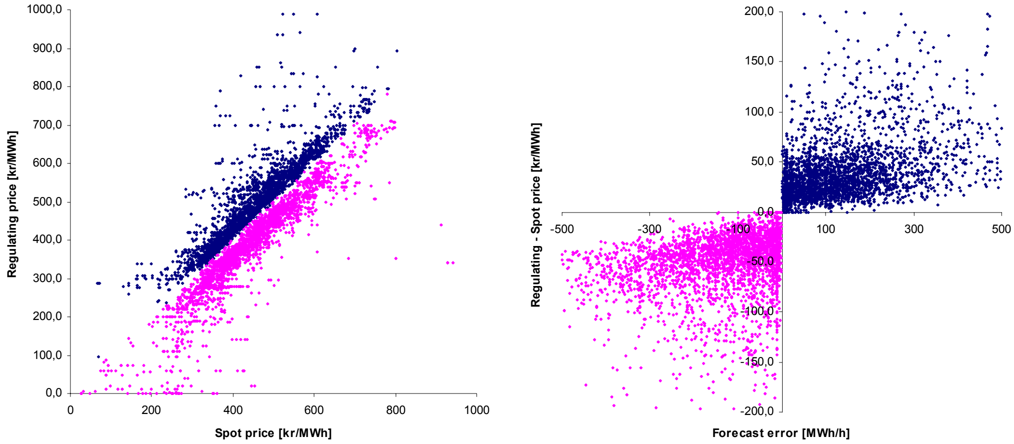

Figure 19: Left: The regulating market price 2006 versus the Elspot price 2006. The graph clearly shows how correlated the two prices are. Right: Regulating – spot price 2006 versus forecast error (imbalance).

Table 12: The coefficients in the model of the regulating markets.

Symbol	Down	Up	None
k_1	1	1	1
k_2	0,12	0,15	0
k_3	-40	37	0

A graphical comparison for 500 hours of the regulating prices during 2006 and the price model is shown in Figure 20. The price model follows the real prices quite well and the correlation coefficient during these hours is 92%. For the whole year the correlation coefficient is only 50%, however that is due to some very expensive hours, where the high prices is due to other circumstances that is not part in the model.

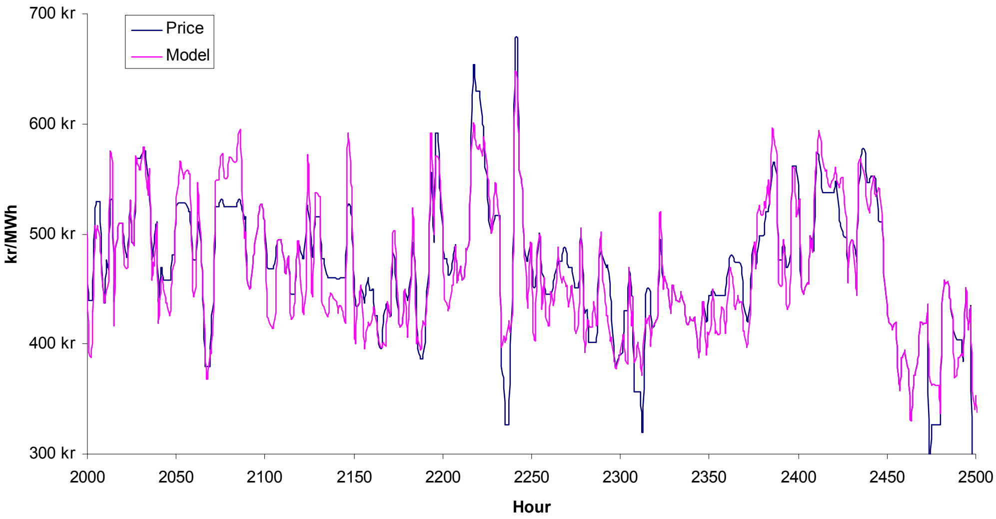

Figure 20: Comparison of regulating price 2006 and the price model. The correlation is 92% for the shown hours.

6 Calculations of imbalance costs for wind power owners

6.1 Forecast errors and corresponding imbalances

The annual imbalance today (2006) at the regulating market is 0,95 TWh/year. Related to the electric power production in Sweden, which is about 150 TWh, the imbalance is not even a percent. The introduction of 4000 MW wind power in the electric power system will generate additional imbalances.

If we sum up the yearly imbalance for each actor in Table 9, there is 1,6 TWh for all actors together that has to be handled on the regulating market. However, as the forecast errors are normal distributed, the hourly sum of each actor partly cancels out, and therefore gives only 1,2 TWh for the wind power. (If the actors' forecast errors would be uncorrelated to each other the total imbalance is reduces to 1,0 TWh). These imbalances should then be added to the imbalances on the current market to get the total imbalance.

6.2 Distribution of forecast errors

The forecast errors for all eight actors have been generated in a Microsoft Excel sheet by the random number generation function in the Analysis Toolpak. As it was discussed earlier (see section 4.3) the standard deviation of the forecast error is assumed to be 13% and the forecast errors between the areas are correlated as described in section 4.4.

The sum of the hourly imbalances during 2006 and the 4 000 MW wind power results in 1,7 TWh/year. The mean hourly imbalance is about 200 MW. For 2006 the mean hourly imbalance was 150 MW for the regulating hours. So the net contribution to the imbalances in power system is about 80% per year but only 33% per regulating hour, when introducing 4 000 MW wind power in the Swedish power system. This is due to the fact that the amount of hours with regulation is becomes much higher. Since primary regulation exists, secondary regulation is only called when the imbalance is above some level and if the frequency deviation is too high. Therefore, to include this in the model, up and down regulating is called when the system imbalance is higher than 50 MW.

The forecast error distribution for 2006 is shown in Figure 21. The figure shows that about one third (2 400 h) of all hours during the year 2006, there was no regulation. Figure 22 shows the generated forecast error and the sum of the generated forecast errors and the year 2006 forecast errors. Clearly, the amount of hours with no regulation is dramatically reduced.

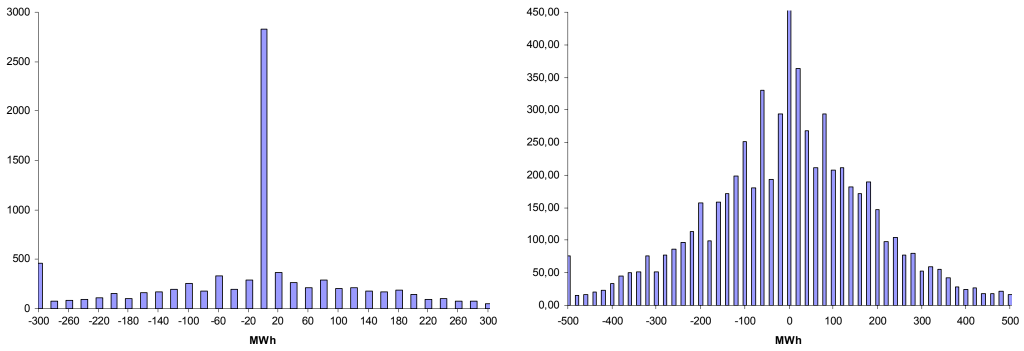

Figure 21: Forecast error distributions of the year 2006. Right is zoomed.

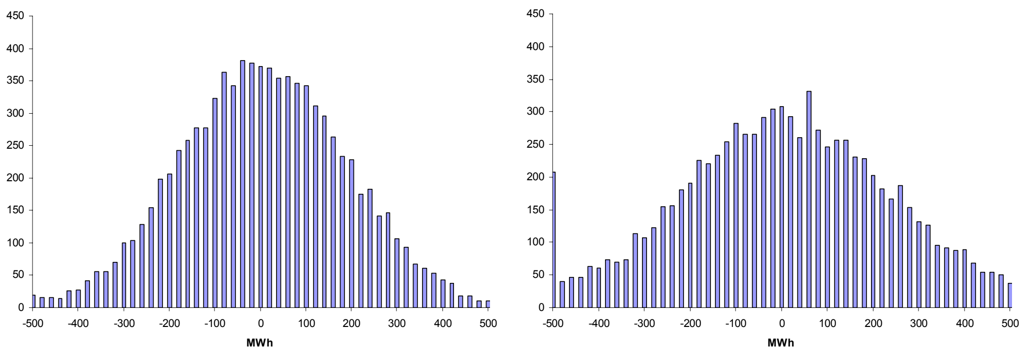

Figure 22: Left: Generated forecast errors for the wind power. Right: The sum with the forecast error 2006.

6.3 Simplified estimation of the cost

Using the model for the regulating market and assuming that all distributions are normal distributions, the cost can roughly be calculated for the imbalances associated with forecast errors. The price model tells us that the price is related to the forecast error with the constant k_2 and there is a bias term k_3. Since k_1 = 1, the spot price do not influence the cost (only the price). It is then possible to calculate in which range the price will be, depending on the actor's forecast error correlation to the system's forecast error, see chapter 4. The mean price for up and down regulation can be calculated by assuming a mean deviation of the system's forecast error, which is 1,7 TWh / 8760 h = 200 MW. That gives the mean deviation of up and down regulating price P_{down} = 0,12·(-200) - 40 = -64 kr/MWh and P_{up} = 0,15·200 + 37 = 66 kr/MWh. The up and down regulating price deviation during 2006 is if we recall from chapter 3.9, -58 kr/MWh respectively 73 kr/MWh. The reason for the very high mean up regulating prices 2006 is some very high price hours.

For an uncorrelated forecast error with the system's imbalance, the actor will pay up regulating prices 25% of the hours and down regulating prices 25% of the hours, and 50% of hours nothing (since in this case the actor helps the system). For an actor who has a correlation coefficient that is 100% between the actor's forecast error and the systems forecast error, the actor will pay up regulating prices 50% of the time and down regulating prices 50% of the time. The cost for an actor can be calculated by multiplying the actor's yearly imbalance (forecast error) with the mean value of the modelled up and down regulation price, that is (64 + 66)/2 = 65 kr/MWh. This value has then to be adjusted with the amount of hours that the actor has to pay regulating price, see equation (3). The cost can then be expressed as

$$K = \frac{K_{up} - K_{down}}{2} \cdot E_e \cdot \frac{t_{regulation}}{t_{year}}. \qquad (18)$$

A compilation of the analytical calculations of the cost for each actor is shown in Table 13. For the large actor the amount of hours that the actor has to pay is very high, since the actor influences the system so much, which can be seen from the correlation with the system imbalance. The actor 7, with wind power at just one site has a very low correlation with system imbalance, only 29%.

Table 13: Rough estimation of imbalance costs for the actors settled according to the modelled regulating prices

Actor	1	2	3	4	5	6	7	8
Income [Mkr/year]	2 545	842	543	552	285	232	156	134
Imbalance [GWh]	647	229	183	179	93	69	114	64
Annual production [GWh]	5 708	1 889	1 218	1 239	640	520	350	300
Correlation with system imbalance	69%	64%	56%	49%	49%	48%	29%	30%
No pay hours [h]	2 242	2 421	2 730	2 941	2 931	2 973	3 555	3 525
No pay hours [h]	26%	28%	31%	34%	34%	34%	41%	40%
Estimated cost [kr/MWh]	5,48	5,70	6,70	6,23	6,25	5,72	12,51	8,22

The analysis presented in this section allows estimating the imbalance cost fast and very rough. Still it gives the idea about the imbalance costs without going into detailed calculations.

In the next section more detailed calculations of the imbalance costs will be presented.

6.4 Results

For more detailed calculation of the imbalance costs the forecast error for each hour was multiplied with the hourly price. This has been done for both with and without jiggling, for the following two cases:

- Balance settlement according to today's (2006) regulating market prices
- Modelled future (higher) prices for the system with 4 000 MW wind power.

One big difference between the two cases is the number of hour with no regulation. In the case today, there are 8736 h – 3320 h – 3034 h = 2382 h with no regulation. The hours that an actor does not have to pay regulation prices are both the hours with no regulation and the hours that the actor has a balance that help the system to be in balance. That number of hours is about 5550 h on today's market, which is almost 2/3 of the hours (8736 h).

When 4 000 MW wind power is introduced, the number of hours with no regulation in the simulation is about 1 500 h, which is a reduction by 40%. These hours are as mentioned before in section 6.2, hours with a system imbalance less than 50 MW.

The results from the simulation are presented in Table 14 - Table 16. There is a huge difference in yearly imbalance cost; if we compare the cost on the 2006-year market and the future market, it is almost three times. For actor 1, who has much wind power, the cost is increased from 2,80 kr/MWh to 7,20 kr/MWh, which is 2,6 times. Actor 7, who just own one site, has increased the cost from 5,50 kr/MWh to 8,76 kr/MWh, which is 1,6 times. The main difference between actor 1 and actor 7, is that actor 1 is so large that its imbalance will influence the system imbalance, consequently the actor 1 much more often have its imbalance in the in the same direction as the system imbalance. To sum up the main reasons to the higher cost; they can be explained by three main points, which are:

1. There are fewer hours with error in the right direction, 50% has moved to up to 70%.
2. The prices are higher, due to higher imbalances. However, the prices for up regulation could be even higher if the high price hours had been taken into account. That would have increased the price further with about 10%.
3. There are fewer hours with no up or down regulations, so 2382 h no regulation hours is now reduced to 1 500 h.

Two of the three explanations are about paying hours. We see that it is almost three times as many hours that the actor has to pay. So, the main reason for higher cost is that the amount of hours to pay is so much higher.

Finally, the cost should be related to income, and Figure 25 shows that the cost is increasing much, however, it is still a relatively small part of the income, just in the order of 1% - 3%.

Table 14: Imbalance costs for the actors settled according to the 2006 regulating prices, including jiggling.

Actor	1	2	3	4	5	6	7	8	One actor
Cost [Mkr/year]	14,0	4,3	2,7	3,5	1,3	0,6	2,0	0,7	21,0
Cost/Production [kr/MWh]	2,46	2,26	2,23	2,80	1,98	1,17	5,78	2,48	1,77
No pay hours [h]]	5 778	6 070	6 191	6 152	6 550	6 892	6 365	6 925	6 212
Part of income	0,6%	0,5%	0,5%	0,6%	0,4%	0,3%	1,3%	0,6%	0,4%

Table 15: Imbalance costs for the actors settled according to the 2006 regulating prices

Actor	1	2	3	4	5	6	7	8	One actor
Cost [Mkr/year]	16,0	5,5	3,8	4,7	2,3	1,5	3,1	1,7	29,9
Cost/Production [kr/MWh]	2,80	2,91	3,10	3,81	3,54	2,85	8,80	5,50	2,52
No pay hours [h]	5 543	5 570	5 604	5 560	5 536	5 569	5 565	5 465	5 553
Part of income	0,6%	0,7%	0,7%	0,9%	0,8%	0,6%	2,0%	1,2%	0,6%

Table 16: Imbalance costs for the actors settled according to the modelled future regulating prices

Actor	1	2	3	4	5	6	7	8	One actor
Cost [Mkr/year]	41,1	14,4	10,1	9,8	4,8	3,5	4,7	2,6	83,2
Cost/Production [kr/MWh]	7,20	7,65	8,26	7,93	7,51	6,81	13,31	8,76	7,01
No pay hours [h]	2 790	2 989	3 371	3 547	3 559	3 620	4 250	4 212	2 579
Part of income	1,6%	1,7%	1,9%	1,8%	1,7%	1,5%	3,0%	2,0%	1,6%

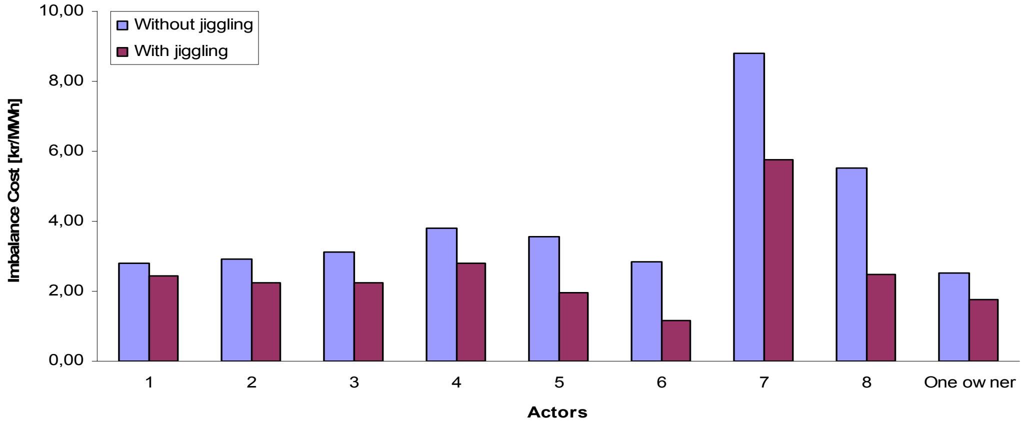

Figure 23: Imbalance costs in relation to the energy production settled according to the 2006 regulating prices, including jiggling.

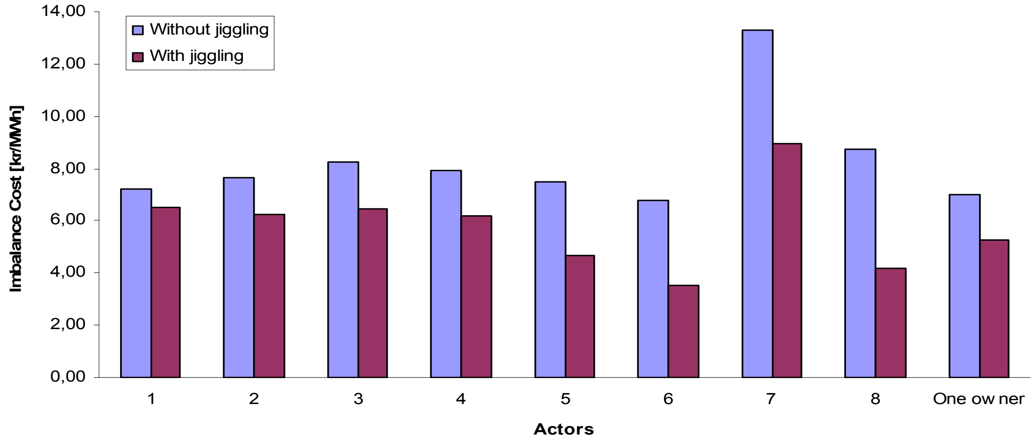

Figure 24: Imbalance costs in relation to the energy production settled according to the future regulating prices.

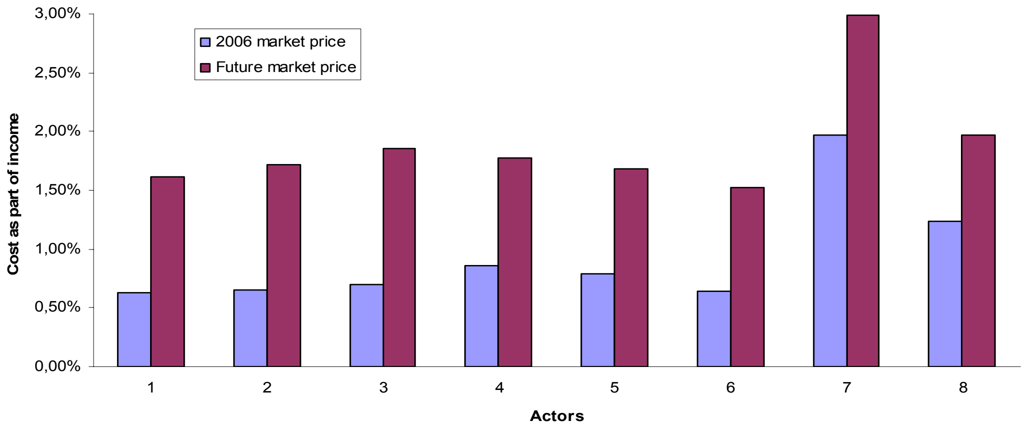

Figure 25: imbalance costs in relation to income.

7 Acting on the adjustment market – possibility to reduce costs?

7.1 Background

As mentioned in the earlier chapters, the adjustment market Elbas can be used to update the production plan, by buying or selling forecasted under- or overproduction. This may be a good option to reduce the costs on the regulating market. However, the new forecast must be significantly better (much lower forecast error), as there is a cost associated with trading at the adjustment market. Updating the forecast can be done in several ways, for instance buying additional forecasts from a weather forecast institute. Another option is to use the persistence method, which does not require the actor to buy a service.

7.2 Persistence method

One method to estimate a production forecast of the future production is to use the current production value as a forecast for the future – the persistence method. It requires that the actors have access to the instantaneous power production. For this method to be successful, there must be a high correlation in time. The correlation in time of a stochastic process, often called the auto correlation function (AKF) or covariance function (kernel) *r*(t), can be used to evaluate this method in comparison to forecast of wind speed (which gives power). If we recall from chapter 4.3, the correlation coefficient for the production and forecasted production made 12 - 36 ahead at Horns rev is ρ = 80%. The correlation coefficient is expressed as

$$\rho(\tau) = \frac{r(\tau)}{\sigma^2} = \frac{\mathrm{cov}(P_p(t), P_p(t+\tau))}{\sigma^2}, \tag{18}$$

and Figure 26 shows the plot of the function. When τ > 4 h, the correlation coefficient is $\rho(\tau)$ < 80%, thus less than correlation coefficient is for 12 – 36 h ahead forecasts at Horns Rev. It implies, that if this method is going to be used as an updated forecast, it must be used less than four hours ahead the production hour. Since the adjustment market Elbas closes one hour before the production hour, and the highest correlation coefficient exists for one hour, this chapter will study a case where the updated error is sold on the adjustment market Elbas. It means that there is a new forecast error that has to be handled at the regulation market. It is worth mentioning, that for some hours, statistically the forecast error may be higher with this method compared to the original forecast error, and it is especially costly when the forecast errors have different signs. However, a reduced forecast error in general is of course good, but adding the costs of trading is important to decide whether it is economically.

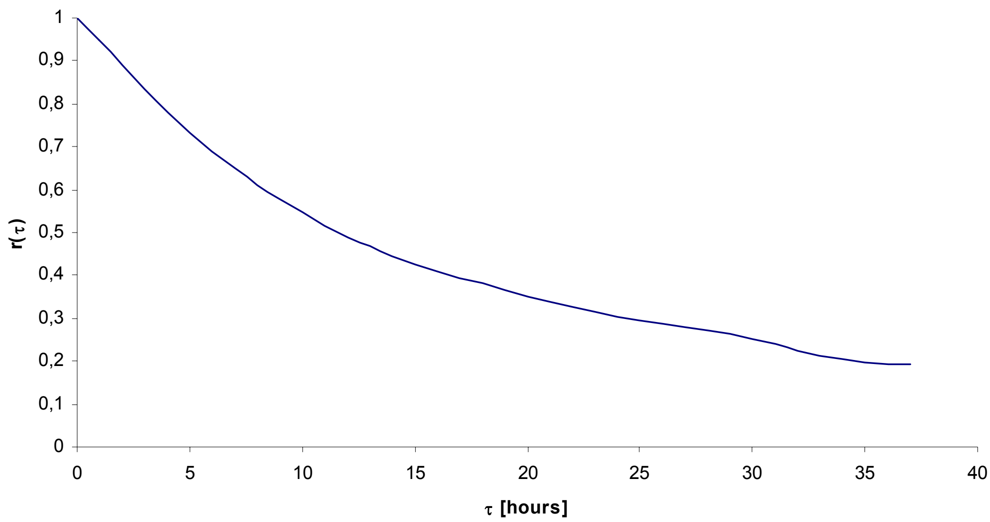

Figure 26: Correlation coefficient of the production at Hornsrev.

The correlation coefficient for τ = 1 h, is $\rho(\tau)$ = 95%. The imbalances for Horns Rev with the persistence method reduce the imbalances to 44% of the imbalances with the 12 – 36 hours ahead forecast. As the standard deviation is proportional to the imbalances, the relative standard deviation with the persistence method is 44% · 21% = 9%. The forecast error with the persistence method will then be modelled as a normal distribution with the relative standard deviation 9%. By using this strategy, we will place a forecast error with the standard deviation $(0{,}09^2 + 0{,}13^2)^{0{,}5}$ = 16% on the adjustment market Elbas and a forecast error with standard deviation 9% on the regulating market. Is this really economical? Well, the results in the next chapter will tell, however we know from the previous chapter that the price model for the adjustment market Elbas and the regulating market punishes the forecast error with a factor of 2% - 5% respectively 12 - 15%. This is a huge difference!

7.3 Results

The results have been calculated in Microsoft Excel by generating additional normal distributions with the standard deviation 9%. Then the cost on Elbas is calculated by putting the forecast error minus the persistence error on Elbas. Then the cost on the regulating market is calculated for the persistence error. All actors have the same strategy. If just one actor would have this strategy, the prices on Elbas would be lower, and the prices on the regulating market would be higher. Even though, it is likely that this case would be beneficial for that actor, since the price is lower at Elbas. However, the cost for trading must be taken into account to get the right picture.

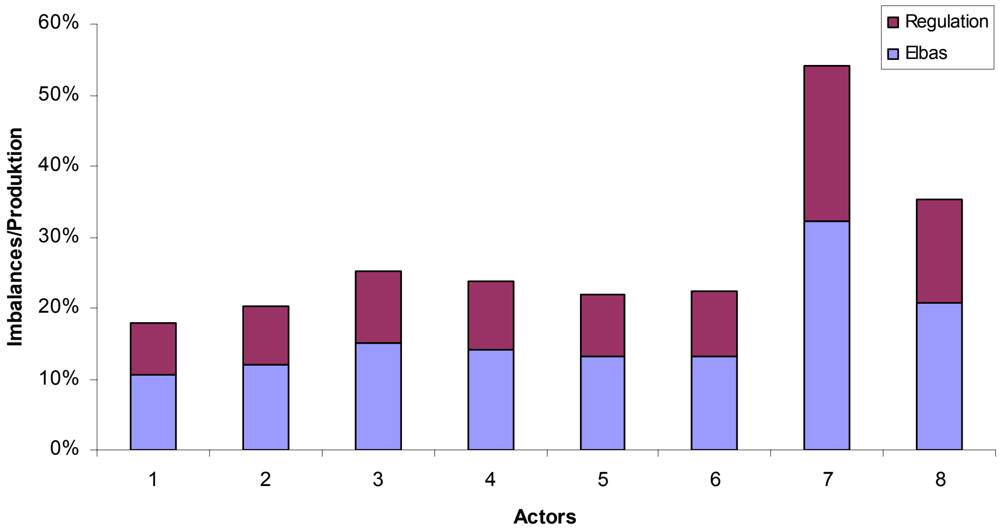

Figure 27: Forecast error volume in relation to produced energy when acting on the adjustment market Elbas.

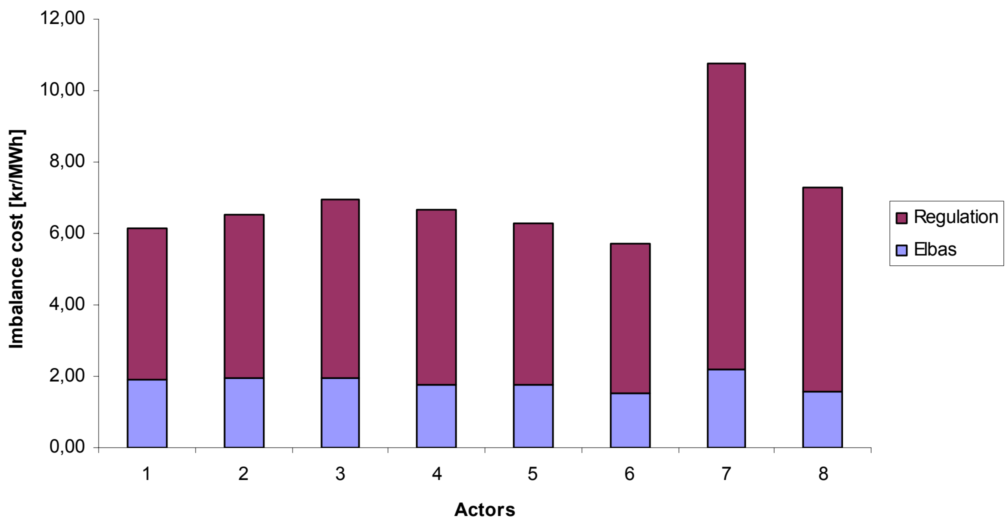

Figure 28: Imbalance costs in relation to produced energy when acting on the adjustment market Elbas.

To make an easy comparison, a compilation of the costs for a) 2006 market prices (reference) b) the future market price, and c) acting on the adjustment market Elbas with future market price has been done in Table 17, which is visualised in Figure 29. All actors can save money by trading at the adjustment market Elbas, for instance actor 1 may reduce his cost from 41 Mkr/year (see Table 16) to 33 Mkr/year. That reduces the cost per produced energy from 7,20 kr/MWh to 5,82 kr/MWh.

Table 17: Annual costs for the actors associated with forecast errors

Actor	1	2	3	4	5	6	7	8	One actor
General									
Annual production [GWh]	5 708	1 889	1 218	1 239	640	520	350	300	11 800
Annual income [Mkr]	2 545	842	543	552	285	232	156	134	5 300
Annual imbalance [GWh]	647	229	183	179	93	69	114	64	1 280
Costs associated with trading on Elbas (compared to right forecasts and trading on the spot market)									
Traded on Elbas [GWh]	794	293	220	229	113	84	135	75	1 541
Cost on Elbas [Mkr]	10,9	3,6	2,49	2,2	1,1	0,8	0,8	0,5	22,3
Cost on Elbas [kr/MWh]	1,91	1,95	1,97	1,77	1,75	1,54	2,18	1,58	1,88
Imbalance costs (after trading on Elbas)									
Imbalance [GWh]	442	164	123	129	62	46	75	42	862
Imbalance cost [Mkr]	22,4	8,0	5,5	5,5	2,6	1,9	2,6	1,4	45,3
Imbalance cost [kr/MWh]	3,92	4,25	4,56	4,45	4,10	3,75	7,61	4,94	3,82
Total costs associated with forecast errors									
Total cost [Mkr]	33,2	11,7	7,9	7,7	3,7	2,7	3,4	1,9	33,2
Total cost [kr/MWh]	5,82	6,20	6,53	6,22	5,84	5,28	9,79	6,52	5,82
Part of income	1,3%	1,4%	1,5%	1,4%	1,3%	1,2%	2,2%	1,5%	1,3%
Total costs including administration costs for acting on Elbas (2 Mkr)									
Total cost inc adm [Mkr]	35,2	13,7	9,9	9,7	5,7	4,7	5,4	3,9	35,2
Total cost inc adm [kr/MWh]	6,18	7,25	8,17	7,84	8,97	9,13	15,51	13,19	5,87
Part of income	1,4%	1,6%	1,8%	1,8%	2,0%	2,0%	3,5%	3,0%	1,3%
Savings compared to not act on Elbas	15%	5%	1%	1%	-	-	-	-	15%

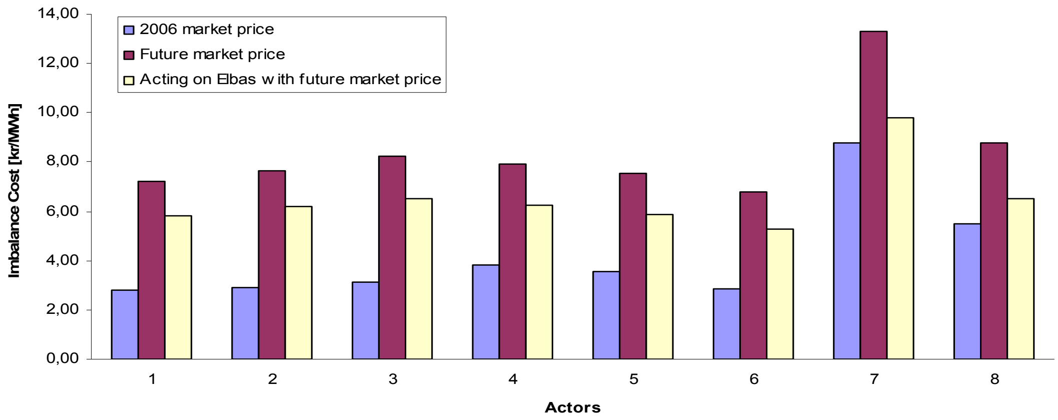

Figure 29: Comparison on the cost of forecast errors on a) the 2006 market, b) the future market and c) future market and acting on Elbas.

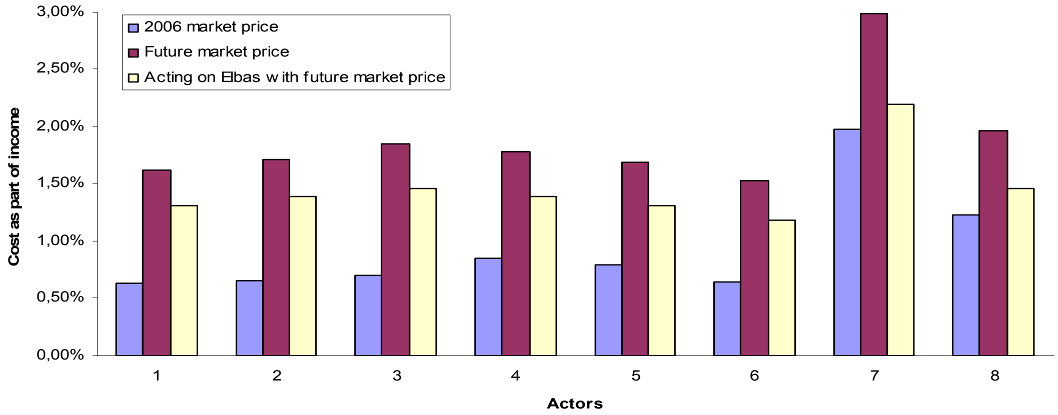

Figure 30: Cost in relation to yearly income for the actors.

However, since there are costs associated with trading at Elbas, it may not be beneficial for everybody. If we assume that updated forecast requires an extra cost of 2 Mkr for having people working all 24 hours a day and buying updated forecast, this will be too high price for some of the actors. This has been calculated in the last part of Table 17, and is illustrated in Figure 31, where it is seen that only actor 1 – 4 may earn from trading at the adjustment market Elbas.

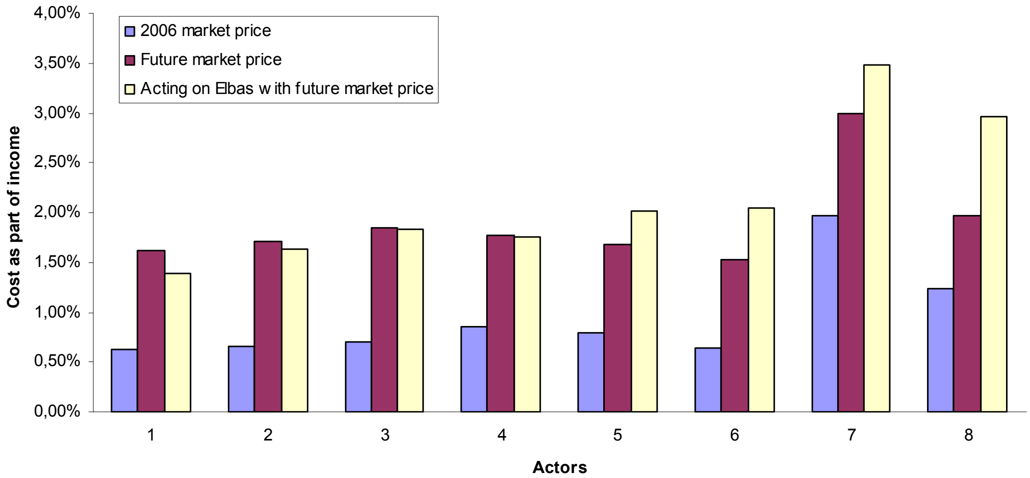

Figure 31: Comparison on the cost of forecast errors on a) the 2006 market, b) the future market price and c) future market price and acting on Elbas including administration costs

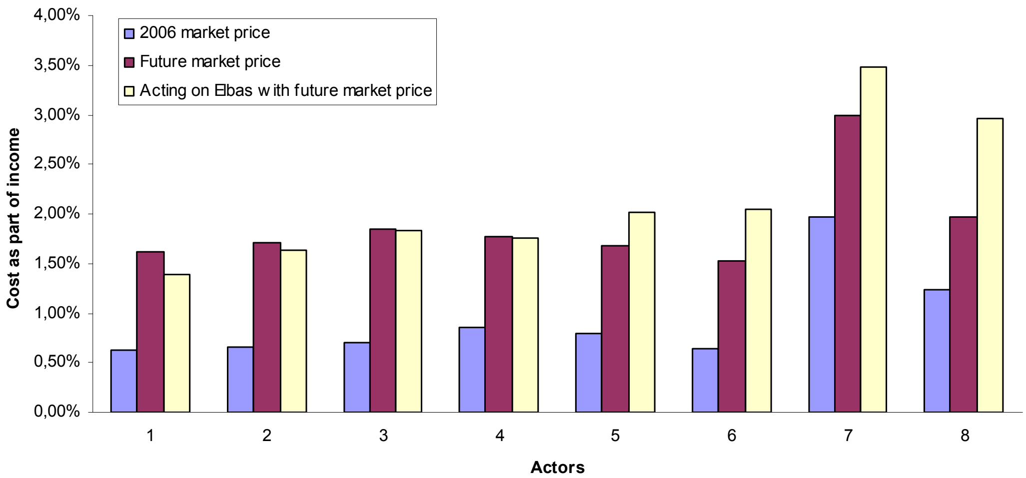

Figure 32: Cost in relation to yearly income for the actors.

8 Scenarios for future energy supply system affecting the results

8.1 Introduction

In this report the imbalance cost have been calculated for an installation of 4000 MW wind power in Sweden. The wind power has been located with 50% of the energy production to the northern part of Sweden and 50% located to the southern part of Sweden. Furthermore we have assumed that the relative standard deviation of forecast errors is 13%. Sweden has also been treated as a one-price area system, which Sweden is today. All these four assumptions could of course be changed. Especially, the first one, that there will be 4000 MW wind power, will of course just exist in a very little time window, since we can expect wind power to grow continuously. Therefore four scenarios have been evaluated where these parameters are changed, and the costs for handling the imbalances are calculated.

8.2 More wind power

The installation of wind power will not stop at 4000 MW, as studied in this report. Beyond 2015 and looking at 2030, it is likely that there is wind power installed with something in between 8000 MW – 15000 MW. That amount will of course affect the forecast errors in the system. To study such scenarios, six simulations have been run, where the earlier suggested wind power installations have been scaled to 0,5 GW, 1 GW, 2 GW, 4 GW, 8 GW, and 16 GW. The results are shown in Figure 33 and Figure 34. Figure 33 shows how the yearly imbalances are related to the installed wind power. It is clearly a linear relationship for larger values. So is also the case for the costs related to imbalances. However, as the cost per installed power increases, it means that the absolute cost increases to the power of two with installed power. In other words, if both an actor and the system doubles the installed wind power, the annual cost for the actor will increase four times, but the cost per installed power two times.

Table 18: Forecast error cost on future market price.

Installation	Wind energy	Wind imbalance	System imbalance	Year
0,5 GW	1,5 TWh	159 GWh	1 000 GWh	2007
1 GW	3,0 TWh	319 GWh	1 078 GWh	2009
2 GW	5,9 TWh	639 GWh	1 256 GWh	2010
4 GW	11,8 TWh	1 279 GWh	1 713 GWh	2015
8 GW	23,8 TWh	2 558 GWh	2 822 GWh	2017
16 GW	47,4 TWh	5 116 GWh	5 270 GWh	2030

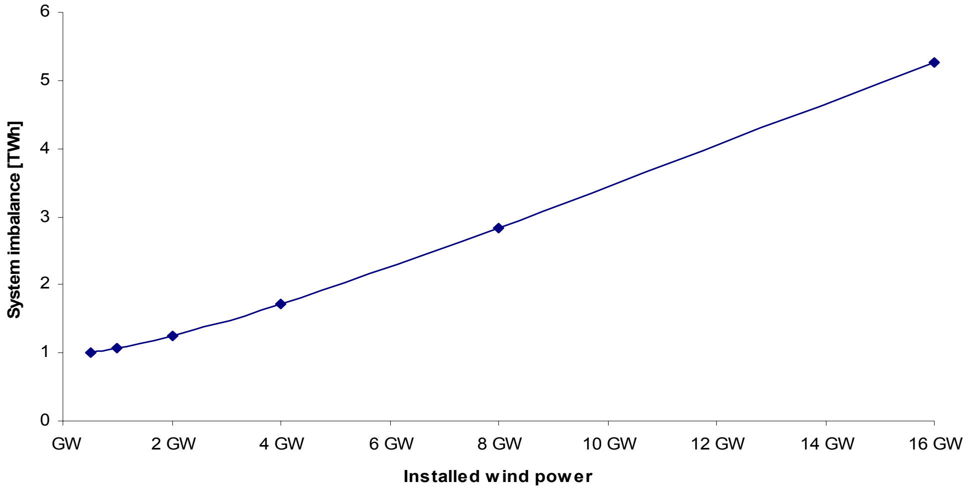

Figure 33: System imbalance when more wind power is installed.

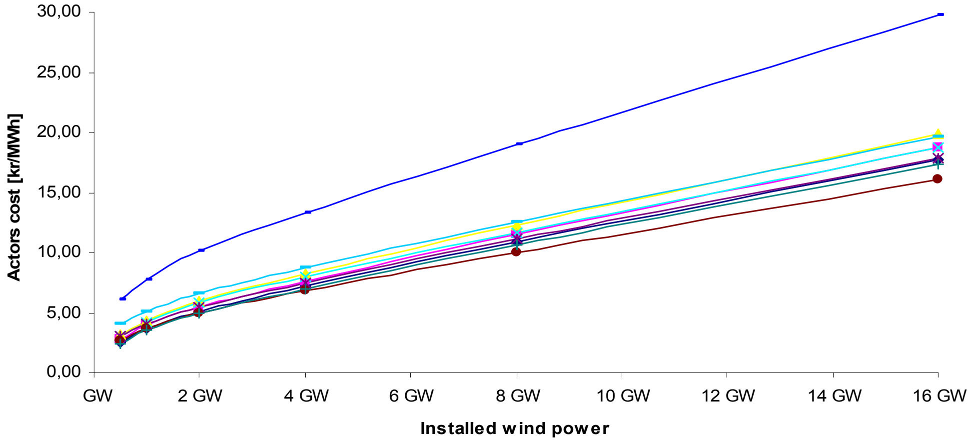

Figure 34: Actors imbalance costs, when more wind power is installed.

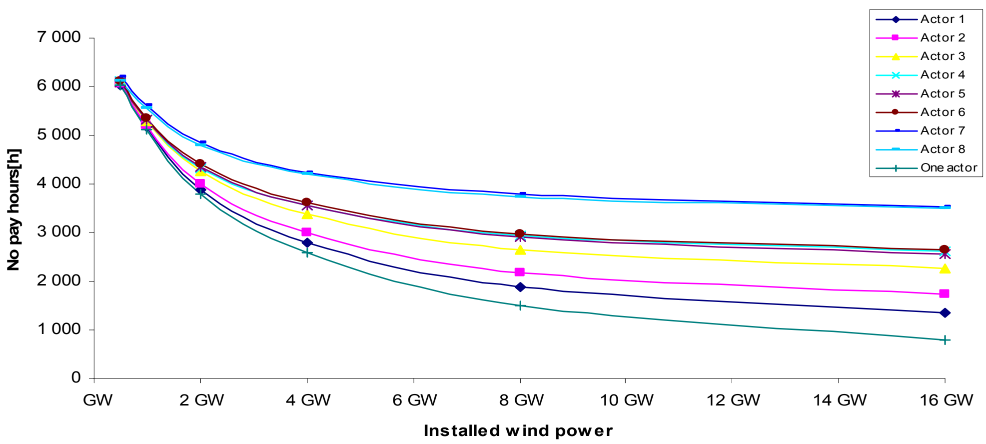

Figure 35: The number of hours that the actor has to pay regulating prices.

8.3 Improved forecasts

In this section 4.3 in this report we assumed that the relative standard deviation of the forecast error is 13%. However forecasts are improved as weather models gets more reliable, and there will be an increased demand on wind speed models as wind power is expanding all over the world. Improved forecasts result in lower forecast errors (imbalances) for the actors as well as on the system, which in its turn reduces the regulating price and cost for regulating. In Figure 36, the actors' costs have been calculated for different standard deviations, and it is very clear that the reduced forecast errors give lower costs.

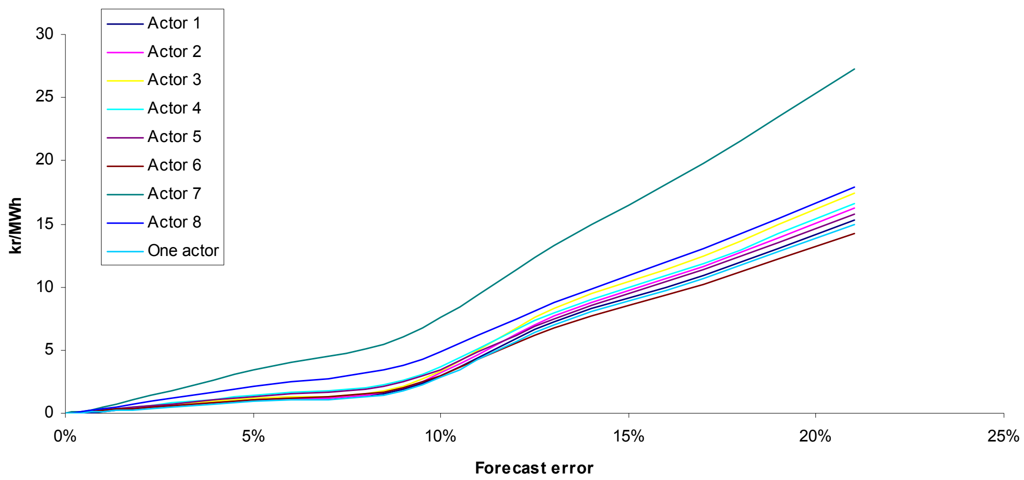

Figure 36: Imbalance costs depending the relative forecast error.

8.4 Geographically spread

In this report, the wind farms have been located with 50% of the installed wind power to the north and 50% of the installed wind power to the south of Sweden. Since, there might be other scenarios, as mentioned in Chapter 2, five simulation cases has been run in Excel with modified wind power distribution. The same wind farms and actor ownership has been used, but the ownership in the south and north has been scaled up and down like vice. The result is presented in Table 19, and also graphically for the actors 1, 2, 3 and 6 in Figure 37, since they have wind farms all over the country. As seen from the figure, an even distribution (50% north and 50% south) gives the least imbalance cost. This is due to lower imbalances, since the forecast error will have a normal distribution with a lower standard deviation. For instance, for actor 1, the standard deviation changed from 4,9% to 7,1% when all wind power placed in the south of Sweden. Figure 38 shows the system imbalance, which increases from 1,5 TWh/Year to 2,0 TWh/Year if all wind power is located to one part of Sweden.

Table 19: The installed wind power capacity in the case with 100% of the wind power located to the North.

Actor	1	2	3	4	5	6	7	8	One actor
Capacity 100% North	1 470	1 000	530	890	0	140	250	0	4 280
Annual production [GWh]	4 077	2 733	1 479	2 453	0	395	693	0	11 900
Imbalance [GWh]	583	404	336	357	0	89	227	0	1995
Standard deviation	5,7%	5,8%	9,1%	5,8%	-	9,1%	13,0%	-	5,5%
Cost [kr/MWh]	11,87	12,15	14,91	11,79	-	14,76	18,12	-	12,15
Capacity 50% N, 50% S	1 905	660	415	445	200	170	125	100	4 020
Annual production [GWh]	5 708	1 889	1 218	1 239	640	520	350	300	11 800
Imbalance [GWh]	647	229	183	179	93	69	114	64	1 280
Standard deviation	4,9%	5,0%	6,3%	5,8%	6,6%	5,8%	13,0%	9,1%	4,3%
Cost [kr/MWh]	7,20	7,65	8,26	7,93	7,51	6,81	13,31	8,76	7,01
Capacity 100% South	2 340	320	300	0	400	200	0	200	3 760
Annual production [GWh]	7 339	1 045	957	0	1 267	645	0	594	11 900
Imbalance [GWh]	1151	215	141	0	185	106	0	127	1925
Standard deviation	7,1%	9,6%	6,7%	-	6,6%	7,6%	-	9,1%	6,8%
Cost [kr/MWh]	12,50	15,01	11,76	-	11,32	9,59	-	11,94	12,02

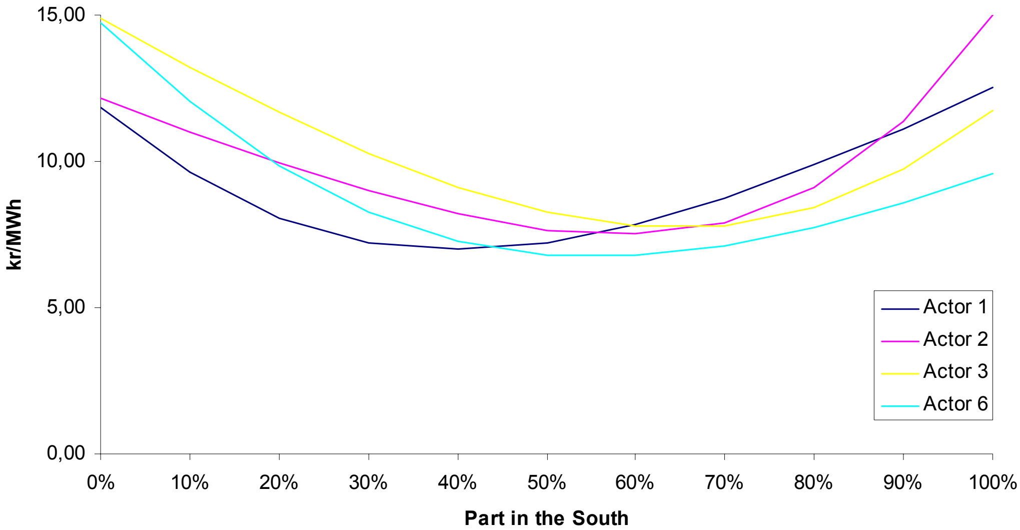

Figure 37: The cost for the forecast error, as the location of wind power is moved.

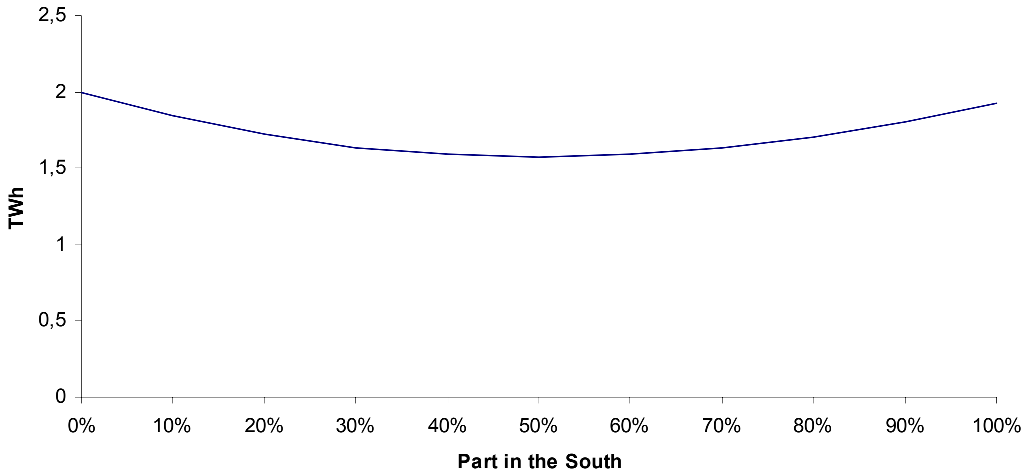

Figure 38: System imbalance when the wind power location is moved in north-south direction.

8.5 Different price areas

At the Nord Pool spot market, there are several price areas, which means that there are different prices in the different areas. As long as there are no bottlenecks (transfer limitations of electric power) in the electric power system, the price is the same in different parts. However, as bottlenecks occur, the cheapest power is not available any more in all price areas, which gives different prices. Sweden is kept as one price area, transmission limitations are handled by Svenska Kraftnät via limiting export capacities at the planning stage and counter trading during the operation stage. In this section, an investigation is made on the consequences of if Sweden was divided into two price areas for some hours. This investigation has been done in the following way:

- Sweden has been divided into two price areas, which are referred to as price area one and two. Price area one is above "Cut 2" and price area two is below "Cut 2", geographically that is a border located at Gävle.
- The number of hours that two price areas occur in Sweden has been set to 40%; see explanation below. These hours has been randomly selected for all 8760 hours during the year.
- During these hours, the southern part of Sweden gets up regulating prices that is based on a price model of the Denmark prices, since it is not possible to buy cheap regulating power from the northern part of Sweden. As down regulation always is available from the northern part of Sweden, bottlenecks are assumed to not influence the down regulating price.

The amount of hours that Sweden is divided into two price areas can be evaluated in the following way. Sweden's transfer capacity from the northern part of Sweden to the southern part of Sweden is about 7 000 MW. That means when this is fully utilised, the export capacity has to be limited to provide the southern part of Sweden with power. Furthermore, Sweden's export capacity is 3 130 MW (600 MW to Poland, 550 MW to Germany, 1 300 MW to Denmark, 680 MW to Denmark). Since limitation of the export does not always mean that a bottleneck occurs, it is assumed that the amount of power has to be reduced further, that amount has been assumed to 2000 MW. The number of hours when the export capacity is reduced to about 2 000 MW is about 40%.

To model the prices during up regulation in the southern part of Sweden, new coefficients has been calculated, that is based on the regulating prices in Sjælland (SJ) in Denmark, see Table 20.

Table 20: The coefficients in the model of the regulating markets.

Symbol	Down	Up SE	Up SJ	None
k_1	1	1	1	1
k_2	0,12	0,15	0,2	0
k_3	-40	37	65	0

During the hours with bottlenecks, the imbalances in the northern and southern part of Sweden are split into one area each. That also means that the imbalances in each part will be treated separately. For instance if an actor has an imbalance of +5 MW in the northern part and –10 MW in the southern part, the actor has to pay regulating prices for 15 MW. When Sweden is just one price area the actor will in this case pay only for 5 MW, which is a big difference. Since the areas are treated separately, the prices will be different in each area, and Table 21 shows how the prices are calculated.

Table 21: Choice of price model at different regulation directions.

South regulation	North regulation	South price	North price
Down	Down	$P_{down} = k_1 \cdot P_{spot} + k_2 \cdot E_e + k_3$	$P_{down} = k_1 \cdot P_{spot} + k_2 \cdot E_e + k_3$
Down	Up	If $E_e > 0$ => $P_{down} = k_1 \cdot P_{spot} + k_2 \cdot E_e + k_3$	If $E_e < 0$ => $P_{up} = k_1 \cdot P_{spot} + k_2 \cdot E_e + k_3$
Up	Down	$P_{up} = k_1 \cdot P_{spot} + k_{SJ2} \cdot E_{es} + k_{SJ3}$	$P_{down} = k_1 \cdot P_{spot} + k_2 \cdot E_{en} + k_3$
Up	Up	$P_{up} = k_1 \cdot P_{spot} + k_{SJ2} \cdot E_{es} + k_{SJ3}$	$P_{up} = k_1 \cdot P_{spot} + k_2 \cdot E_{en} + k_3$

Table 22: Forecast error cost if Sweden is divided into a two-price area system.

Actor	1	2	3	4	5	6	7	8
Sweden is a two price area system								
Cost [Mkr/year]	50,27	16,46	11,46	9,86	5,88	4,26	4,57	3,06
Cost/Production [kr/MWh]	8,81	8,72	9,41	7,95	9,18	8,19	13,07	10,20
No pay hours [h]	1 952	2 151	2 375	3 309	3 258	2 755	4 185	4 123
Sweden is a one price area system (reference)								
Reference Cost [Mkr/year]	41,1	14,4	10,1	9,8	4,8	3,5	4,7	2,6
Cost/Production [kr/MWh]	7,20	7,65	8,26	7,93	7,51	6,81	13,31	8,76
No pay hours [h]	2 790	2 989	3 371	3 547	3 559	3 620	4 250	4 212

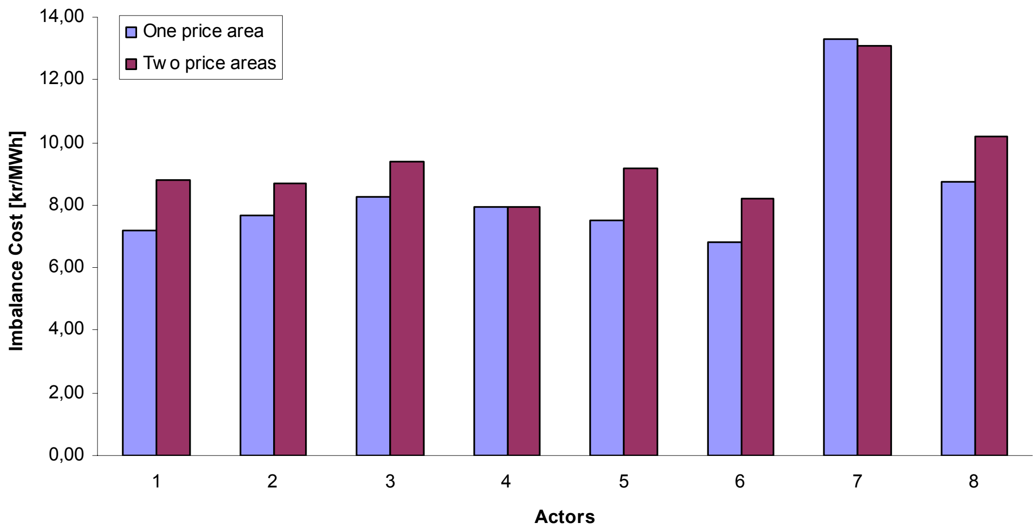

Figure 39: The cost for the forecast error, with one (current situation) and two price areas in Sweden.

The cost for the forecast error (imbalance) has been calculated by using the same method as before, and is presented in Table 22, where also the reference case (one price area) has been included for comparison. The cost is clearly going up for actors having wind power in the South of Sweden. On the other hand, these actors (with wind power in the South) would probably benefit from higher spot prices in the South as well during these hours, so the net contribution might not be so much.

9 Design of balancing markets for the system with large amounts wind power

In relation to the characteristics of wind power, (e.g. intermittent nature, geographically spread out, and large number of potential owners), together with the strong political support there is an ongoing debate on how wind power preferably should be integrated in the market in relation to the design of balancing markets.

It was shown that in terms of "spatial smoothing effects", large market players have an advantage compared to the smaller actors. Larger actors have even resources to participate in the intraday trading leading to possibility to reduce their imbalance costs. If the incentives for small wind power producers to handle imbalances are low, most balance responsibility may end up in larger companies. Some of the alternatives to the present market structure suitable for wind power integration are briefly discussed in this section and summarized in Table 23. There are other solutions that also may be possible, as suggested in [27].

Table 23: List of alternative methods for wind power balance settlement with the Nordel proposal as reference

Alternative	Pros	Cons
"Nordel" 2-price settlement	Good incentives for planning and development of forecasts	Relatively large economic risks for small balance responsible parties.
TSO as balance responsible for wind – socialized costs	Supports a fast growth of wind power with dispersed ownership	Requires additional regulations. Hard to forecast system – high balance cost Weak incentives to place balance bids. Currently phased out in Denmark
Cooperative balancing organization	Possible compromise of other alternatives	Requires a relatively large volume. Large actors are not expected to participate voluntarily.
Single price settlement for wind power	Reduced economic risk for balance responsibility for wind power	Neutrality - discriminating for other technologies Oppose Nordic harmonization proposal Small incentives to develop forecast tools

The Nordic TSO:s have published a proposal for a harmonized Nordic balance settlement mechanism, based on a two-price system for production imbalances and a single price system for consumption imbalances [20]. The advantage of the two-price settlement is that it creates clear incentives for good production plans. Apart from the single price system, there is no extra premium paid for unintended imbalances that counter the system's total imbalance. The most frequent argument for a single price settlement is that it implies a reduced economic risk related to balance responsibility, thereby supporting a large number of balance responsible parties.[11]

In Germany the TSO:s are responsible for the feed-in of wind power, thus the total imbalance is handled by the TSO and financed via a separate fee on consumers. The obvious advantage of this design is that it facilitates an expansion of wind power, but as a counter argument, the socialized cost may generate a system that is difficult to forecast and with relatively high cost of imbalances.

In Denmark a Cooperative balancing organization is used for approximately 70% of the wind power with market-based conditions for imbalances [22]. This practice enables an economic smoothing out of imbalances from wind power with dispersed ownership.

A third alternative could be to use single price settlement only for wind power. Reference [23] argues that since wind power producers do not have the choice of producing or not as for traditional technologies, there are not as strong arguments for traditional balancing incentives. The impact of single price settlement may be of greater importance for small actors as the probability of that a larger actors imbalance will counter the system's total balance is presumed to be lower.

The design for balance settlement may affect the speed of the wind power expansion. Historically the alternative TSO–responsibility has proved to be most efficient from this aspect, however this design is currently phased out in Denmark with respect to increased efficiency and security of supply [22]. For the Nordic market possible alternatives that support an expansion of wind power, while maintaining a market-based solution incentives are cooperative voluntary balancing organization[12] or single price settlement for wind power. Even TSO taking responsibility for making forecasts and balancing wind power is possible solution, the consequences of which however must be analyzed carefully.

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[11] Another frequently mentioned drawback is that it theoretically enables some speculation See [21]

[12] Given that the design maintain good conditions for a competitive market.

10 Closure

10.1 Conclusions

The effects of installing large amounts of wind power into the Nordic energy system have been investigated in several studies [8], [11], [12]. This report focuses on the balance responsible actor owning wind power and trying to minimise imbalance costs. Imbalance costs are the result of discrepancy between the production sold on the spot market and the actual production. For bidding at Nord Pool forecasts for at least 12 - 36 hours ahead are used.

Wind power is difficult to forecast and therefore forecast errors are unavoidable. This investigation makes an attempt to model future forecast errors based on statistical information about the wind power forecast errors. The real-life statistical data for wind power forecast error for Horns Rev was analysed and it was found that at the moment the error is very high. In the nearest future one can count on modern forecast tools allowing to make much more exact forecasts and this fact was taken into consideration in this report.

It is known [8] that total variability of wind power is reduced when considering a large interconnected system with geographically dispersed wind power production. A large expansion of wind power will therefore benefit from an accompanying expansion of the transmission grid. Wind power prediction errors are also reduced for larger areas as a result of the spatial smoothing effect. Statistical analysis from Germany [14] and [16] was used in order to model correlation of forecast errors associated with wind power production located in different regions of Sweden. The spatial smoothing effect has a large impact on the net forecast error. It was shown that the sum of the actor specific day-ahead forecast error is much larger compared to the net forecast error volume. As expected, the actors having wind power production spread within larger geographical areas have smaller total relative forecast errors compared to the actors having production within one smaller region. The 4 000 MW wind power increase the imbalance in the system by 70% to 1,7 TWh/year (1,0 TWh imbalance during 2006). Observe that the eight actors will be trading almost 1,6 TWh/year on the regulating market, which means that most (55%) of the trade is nonsense[13], since the wind contribution is only 0,7 TWh/year.

Correspondingly the imbalance costs differ considerably between the actors. The small actors can experience twice the cost of imbalance compared to the large actors (7,2 kr/MWh compared to 13,3 kr/MWh), due to that large actors have their wind power spread out. At the same time the imbalance costs on the system level are even lower, only 7 kr/MWh, see Figure 40.

[13] Nonsense trade is a term that means a trade of nothing, or the sum is nothing.

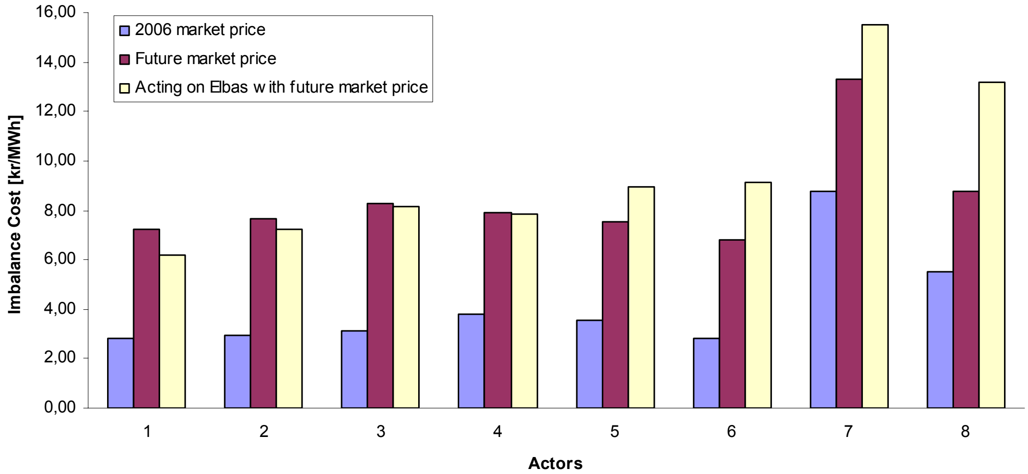

Figure 40: Comparison on the cost of forecast errors on a) the 2006 market, b) the future market and c) future market and acting on Elbas.

Actors responsible for balancing wind power have a possibility to update their day-ahead forecasts and correct the production plan by using the intra-day market. However, even if the precision of the forecast is improving when approaching the time of delivery there is a risk that the updated forecast would contain an error as well. In the worst case acting at the market according to the updated forecast may increase the total error experienced by the balance responsible actor.

Updated forecasts are associated with an operational cost, e.g. personal, intraday market access and extended weather forecast. Therefore the cost saving potential for the smaller actor by updating the forecast and acting at the intraday market is lower compared to the extra cost. This allows to assume that smaller wind power actor will not act at the intraday market and probably will not take own balance responsibility but instead will sign a balance agreement with a larger actor. This is probably the reasonable solution beneficial for all parties with the present market structure, assuming however that the fee for balancing is reasonable.

The adequacy of the present market structure and alternative solutions for wind power balance settlement in the system with large amounts of wind power was discussed. Present two-price balance settlement system provides good incentives for planning and developing of forecasts. However, assuming large-scale expansion of wind power the system discriminates the smaller actors in a sense that they may face higher imbalance costs and don not have the possibility to reduce the costs by acting on adjustment market. It is important that market-based solutions still supporting the expansion of wind power are applied. It is also important to point out that alternative market solutions will induce both advantages and disadvantages, therefore the consequences for different affected parties must be analysed carefully.

10.2 Future work

Since the Swedish Energy Agency has suggested that the installations of wind power will be 30 TWh at the year 2020, which corresponds to 12 000 MW wind power, this case would be of high interest to investigate.

This report has discussed imbalance costs for wind power actors, another important question related to wind power integration is regulating power. This issue was addressed in [11], however the study must be expanded to the new goals with 30 TWh wind in the system.

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Abbreviations

AC	Alternating Current
AKF	Auto correlation function
DC	Direct Current
EU	European Union
EWEA	European Wind Energy Association
HVDC	High Voltage Direct Current
INPS	Interconnected Nordic Power System
Nordel	Organisation for the Nordic Transmission System Operators
NPS	Nord Pool Spot
SvK	Affärsverket Svenska kraftnät
TSO	Transmission System Operator

List of Symbols

Symbols	Quantity	Unit
E	Energy	J, Wh
f	Frequency	Hz
I	Current	A
J	Inertia	kgm^2
K	Cost / price	kr
P	Power	W
Q	Reactive Power	VA, var
$r(\tau)$	Covariance function or AKF $r(\tau) = cov(X(t),X(t+\tau))$	
t	Time	s, h
U	Voltage	V
π	Pi = 3,14159265358	
ρ	Correlation coefficient $\rho = cov(X,Y)/(\sigma_x\sigma_y)$	
$\rho(\tau)$	Correlation coefficient $\rho(\tau) = r(\tau)/\sigma^2$	
σ	Standard deviation	MW=MWh/h
σ^2	Variance	
μ	Expected value, mean value	
τ	Time difference	s, h
ω	Angular frequency	rad/s

List of Operators

E(X)	Expected value
cov(X,Y)	Covariance
$N(m,\sigma)$	Normal distribution
$P(X>0)$	Probability
var(X)	Variance

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