THE VALUE OF WIND POWER FOR AN OWNER OF A LOCAL DISTRIBUTION NETWORK

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INTRODUCTION

The amount of wind power increases continously in Sweden. In December 1998 there were 421 wind power stations with a total installed capacity of 174 MW. The total production during 1998 was 300 GWh. There are several values connected to these wind power stations from the power system point of view. They include:

1. Decrease of operation cost of other power stations. This is the most important value of the four mentioned here.
2. Increased reliability of the power system, i.e., a decreased risk of power deficit and a decreased risk of energy deficit.
3. Decrease of distribution losses depending on that the production is closer to the consumers compared to more centralized located units.
4. Possible decrease of the connection charges for the points where the local networks are connected to the transmission network.

In Sweden the deregulation implies that legal entities involved in electricity generation or trading are not allowed to operate networks. Network operation must always be carried on as a separate business.

For the owner of a local distribution network with some wind power installed this implies that mainly the two last values above influence the economy of the company.

The Swedish island Gotland is fed from the mainland with an HVDC cable. On this island a substantial part of the Swedish wind power is located. An investigation has been performed concerning the value of this power production. The items that have been studied include:

- The decrease of grid losses depending on wind power at Gotland. The impact on the losses in the local grid as well as on the losses in the regional and transmission grids have been studied. The total production during the studied year was 90 GWh and the total decrease of energy losses was 4.6 GWh (5.1 %).
- The possible decrease of grid charges. On Gotland there was 43 MW of wind power in this study and depending on this production the charges to the grid owner, to which Gotland is connected, could be decreased with 0.3 MSEK/year.

In chapter 1 the study of reduced losses is treated and in chapter 2 the grid charges study is presented. The here presented result is a part of a larger report concerning the value of wind power [8].

1 REDUCED LOSSES DEPENDING ON WIND POWER ON GOTLAND

In this study the impact from wind power on Gotland, on the grid losses is studied. The changed losses are studied for the local grid, the regional grid and the transmission grid.

1.1 Loss reduction value on the Gotland grid

The impact from wind power on the local losses on the island Gotland have been studied by Gotlands Energiverk AB, GEAB, and the result has been presented in an internal report [1, 3]. A summary of the result is shown in table 1. The calculations were performed in

Wind power	Grid losses
0 GWh/year	37.2 GWh/year
90 GWh/year	40 GWh/year

Table 1: Grid losses on Gotland with and without wind power

such a way that the year was divided into 8 different load levels and 11 different wind power production levels. For all of these $8 \cdot 11 = 88$ different combinations, the grid losses were calculated with and without wind power. These $2 \cdot 88$ values were then weighted together to the values in table 1. For the calculations, some approximations were introduced. It was, e.g., not studied whether there are different wind power production levels at different load levels. If this had been considered, it is possible that the increase of losses caused by wind power had been slightly reduced since there are more often high wind speeds at higher load levels, seen on a yearly base. In Sweden there are higher wind speeds and load levels during the winter than in the summer. The principle problem on Gotland is that there is rather much wind power on southern Gotland and its production level is often significantly higher than the local consumption. It can be noted that alternative methods of calculating the changed losses are presented in [6, 7].

The conclusion from this report is that an installation of 43 MW of wind power, with an assumed production of 90 GWh/year in the Gotland grid, increases the losses with 2.8 GWh corresponding to 3 % of the yearly production. This implies that the loss reduction value for the Gotland grid is negative, since the losses increased.

1.2 Loss reduction value in the regional grid

Gotland is fed with a 100 km long HVDC cable from Västervik on the mainland, c.f. figure 1. In Västervik the cable is fed from the regional 130 kV grid. This 130 kV grid, including the cable to Gotland, is owned by Vattenfall Regional Grid AB. This regional grid is then fed from the national transmission grid close to Norrköping (Glan and Kimsta). The Vattenfall regional grid is also connected to another regional grid which is owned by Sydkraft. Below it is shown how wind power

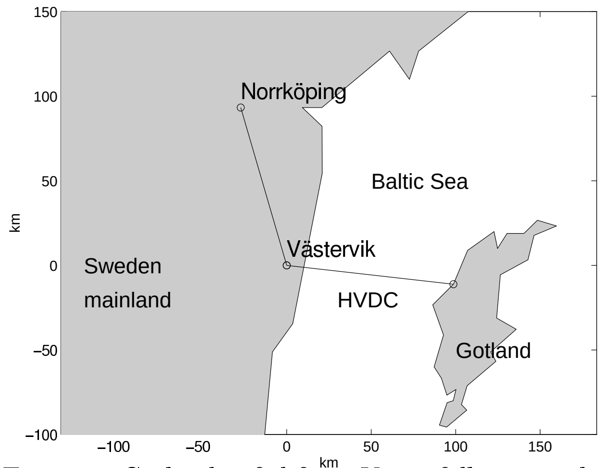

Figure 1: Gotland is fed from Vattenfalls regional grid on the mainland

on Gotland affects the losses in Vattenfall regional grid. First the losses on the HVDC cable are analyzed, and then the losses on the regional grid is treated.

Figure 2 shows the duration curve (straight line) of the electric consumption on Gotland for the year 1994 [3]. In addition to this an assumed net demand, i.e., consumption - wind power, has been drawn (dashed). This curve has been obtained by reducing the consumption with a constant level. The reduction level is determined by the fact that the yearly energy reduction must become 90 (=wind power production) - 2.8 (=increased losses on Gotland) = 87.2 GWh/year. This is an approximative calculation but better data have not been available for this project. The area below each curve corresponds to the yearly energy consumption for each case.

Under normal conditions all energy that is consumed on Gotland, except for the local wind energy production, is transmitted from the mainland on the HVDC-cable from Västervik. On Gotland there are also gas tubines but they are only used as reserve plants and produce only marginal amounts of energy/year.

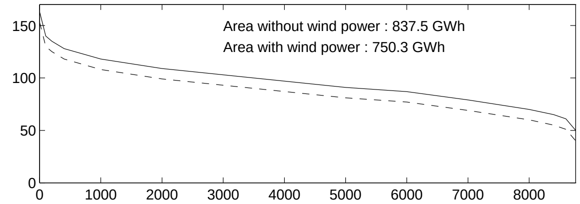

Figure 2: Load duration curve for Gotland : without wind power (–), with wind power (- - -)

This implies that the wind power on Gotland causes the transmission on the HVDC cable to be reduced from the straight line to the dashed line in figure 2. This also implies that the losses on the cable decrease. The losses on a cable can be approximated to be proportional to the square of transmitted power. At a transmission of 130 MW it is here assumed that the transmission losses are 2 MW [3]. This means that the cable losses, $P_{l-cable}$, approximatively can be estimated as a function of the transmission on the cable, P_{cable}:

$$P_{l-cable} = 2 \cdot \left(\frac{P_{cable}}{130}\right)^2 \text{ MW} \tag{1}$$

With this assumption the losses on the HVDC cable can be estimated with and without wind power. The result is shown in figure 3. As shown in the figure, the

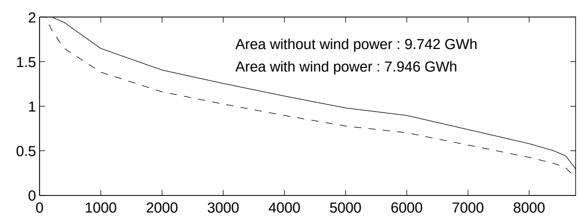

Figure 3: The duration curve of the cable losses: without wind power (–), with wind power (- - -)

cable losses decrease with 1.8 GWh when wind power is considered.

For Vattenfall's regional grid according to figure 1, no detailed calculations have been performed. But the marginal loss coefficients for the HVDC terminal in Västervik have been available [2]. In table 2 these coefficients are shown as well as how common the different load situations are. If the marginal losses are

Time period	Hours	Marginal losses	Relative Wind power
winter, high load	1680	4.1 %	120 %
winter, low load	1944	3.2 %	120 %
spring/autumn, high load	960	3.2 %	100 %
spring/autumn, low load	1224	2.6 %	100 %
summer, high load	1344	2.6 %	75 %
summer, low load	1608	2.4 %	75 %

Table 2: Marginal losses for Vattenfall's and the neighbouring company's regional grids excluding the HVDC cable

weighted together according to how many hours they are valid, and also considering the level of wind power production at the different occations, then the weighted value becomes 3.1 %. This corresponds to a loss reduction of $0.031 \cdot (90 - 2.8 + 1.8) = 2.8$ GWh. The losses in Vattenfall's regional grid (including the neighbouring Sydkraft grid, but not the HVDC cable) is consequently decreased with 2.8 GWh, depending on the studied amount of wind power on Gotland.

1.3 Loss reduction value in the transmission grid

As mentioned above the studied regional grid of Vattenfall is fed from Glan and Kimsta close to Norrköping. The marginal loss coefficients for these two sites are shown in table 3 [4]. It can be mentioned that in Sweden, the grid tariff for the transmission grid is based on marginal loss coefficients. The negative values for Glan

Time period	Hours	Glan	Kimstad	Wind power
High load, weekdays	1568	-4 %	-4 %	115 %
High load, other days	2056	-3 %	-3 %	115 %
Low load, weekdays	2352	-4 %	-3 %	89 %
Low load, other days	2784	-2 %	-2 %	89 %

Table 3: Marginal loss coefficients for Glan and Kimstad

and Kimstad in table 3 means that the losses in the national transmission grid decrease when power is produced in the nodes. The figures are calculated with a method that implies that production in one node is balanced with a reduced production in other nodes. The reduced production in other nodes is assumed to be distributed among all power stations in the Swedish power system.

A weighted mean is for Glan -3.2 % and for Kimstad -2.9 %. If one assumes that the power is distributed equally between the two nodes this implies that the weighted marginal losses become -3.0 %. This implies that wind power on Gotland reduces the losses in the national grid with $0.03 \cdot (90 - 2.8 + 1.8 + 2.8) = 2.8$ GWh. This is based on the assumption that the wind power production on Gotland is balanced with a reduced production in all other power stations in Sweden.

A perhaps more realistic alternative to wind power, is if the alternative to wind power is assumed to be the oil condensing unit in Karlshamn or an extension of hydro power. Here the marginal loss coefficients for Gardikforsen in Ume River in northern Sweden is assumed to be representative for new hydro power. Table 4 shows the marginal loss coefficients for these two alternativs [4].

Time period	Hours	Karlshamn	Gardikforsen
High load, weekdays	1568	-3 %	10 %
High load, other days	2056	-2 %	6 %
Low load, weekdays	2352	-3 %	8 %
Low load, other days	2784	-2 %	5 %

Table 4: Marginal loss coefficients for Karlshamn and Gardikforsen

As shown in the table the losses decrease with production in Karlshamn but they increase at production in Gardikforsen. With the assumption that the production is about the same the year around, the mean marginal loss coefficients become -2.4 % for Karlshamn and +6.9 % for Gardikforsen. This should now be compared with -3.0 % for Glan/Kimstad.

In table 5 the results concerning the loss reduction caused by 90 GWh of wind power on Gotland are summarized. The studied wind power installation is compared with the alternatives that the same amount of energy had been produced in Karlshamn or in Gardikforsen.

Losses for grid	Wind power Gotland	Oil unit Karlshamn	Hydro power Gardikforsen
Local grid	-2.8 GWh	-	-
Regional grid	1.8+2.8 = = 4.6 GWh	-	-
Transmission grid	2.8 GWh	$0.024 \cdot 90 =$ = 2.2 GWh	$-0.069 \cdot 90 =$ = -6.2 GWh
Total:	4.6 GWh	2.2 GWh	-6.2 GWh

Table 5: Loss reduction value for 90 GWh production located on three different sites

The table shows that the wind power alternative on Gotland is the alternative that most reduces the losses among the three studied alternatives. The difference compared to Karlshamn is 2.7 % of the production of 90 GWh. The difference to Gardikforsen corresponds to 12 % of the production.

On the electricity market, as it is defined in Sweden, the owner of the wind power plants do not have to pay for the increased losses of 2.8 GWh in the local grid. Concerning the feeding grid, the local grid owner have to pay the wind power plant owners for reduced tariff charges. Since less power is transmitted from the mainland, these charges, which include costs for losses, are reduced. According to the tariff the compensation during high load period should be 1.7 öre/kWh and 0.9 öre/kWh during other hours. By using the same prices as in the used transmission grid tariff for 1997 [4] (high load, weighted value 34.5 öre/kWh, low load weighted value 26.6 öre/kWh) this implies that Vattenfall regional grid assumes that one, during high load, pays for losses corresponding to $1.7/34.5 \Rightarrow 4.9$ % of the consumption. This implies that the wind power production on Gotland is paid for a loss reduction of 4.9 %. For low load periods the corresponding figure is $0.9/26.6 \Rightarrow 3.4$ %.

It should though be noted that these calculations also should include the losses on the national transmission grid. The real marginal losses during high and low load can be obtained as the weighted mean values in table 2 and 3 for each period. For high load periods the marginal losses are 6.9 %, and during low load periods they are 5.5 %. With the assumptions above this implies that the wind power owners are compensated for 2 % lower losses than the real marginal losses.

The conclusion with the actual Swedish situation is that the local grid owner is not paid for the extra losses in the local grid caused by the wind power plants on Gotland. On the other hand: the regional grid owner does not pay for the true loss reduction caused by wind power, since the tariffs are not based on marginal losses.

2 EXAMPLE OF GRID CHARGES REDUCTION CAUSED BY WIND POWER

In this example it is approximately studied how the power charges in the tariff for the feeding to Gotland could be reduced depending on the wind power installation on Gotland. This charge is paid by the grid division of Gotlands Energiverk AB (owned by Vattenfall) to Vattenfall Regionnät AB who owns the feeding regional grid. The tariff of the regional grid includes the charges that the regional grid has to pay to the national transmission grid, owned by Svenska Kraftnät.

The base for these calculations is therefore the tariff of Vattenfall Regionnät AB concerning Southern Sweden [9]. Table 6 shows the tariff for the node where Gotland is connected.

Charge	SEK/kW,year
Yearly power charge	31
High load power charge	72

Table 6: Subscription based charges concerning the connection to a regional 130-70 kV grid [9]

Yearly power is defined as the mean value of the two highest monthly demand values.

High load power is defined as the mean value of the two highest monthly demand values during high load. High load is during weekdays 06-22 in January–March and November-December.

Subscription Concerning these two power levels a subscription should be signed in advance. If real "yearly power" is higher than the subscribed value, then 100 % extra is paid for the excess power, i.e., a total of 62 SEK/kW. If real "high load power" exceeds the subscribed value, one have to pay 50 % more for the excess power, i.e., 108 SEK/kW.

Monthly demand value is the highest hourly mean value during the month.

As shown above, the subscribed values have to be defined in advance. The real power levels varies of course between different years. In the description below it is firstly shown how the optimal subscribed values are estimated. This is followed by an example of how this level is changed when wind power is considered.

Before a year starts one has to define the subscribed power levels for both the "yearly power" and the "high load power". Here I assume that both weeks with the dimensioning load have a weekly variation according to figure 4. The figure shows only one week but the other week in the other month has the same variation but

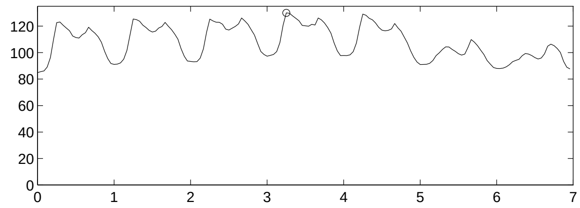

Figure 4: Hourly consumption during one week

another weekly mean level. The used load curve concerns a week from Monday 01.00 to Sunday 24.00. The load is here scaled so the peak load during week 1 is 130 MW and during week 2 123.5 MW, i.e., 5 % lower. The following calculations are based on that these two weeks contain the dimensioning hours for the two dimensioning months. The peak load is therefore during both weeks on the Thursday from 8.00-9.00. These two hours are during the high load period, so the dimensioning hours are the same for the "yearly power" as for the "high load power". The mean value for these two occasions is 0.5(130+123.5)=126.75 MW.

Statistics for several years have not been available for this study. Instead it has been assumed, that the mean value of the two highest monthly values varies with ±4 % (4 % standard deviation). The standard deviation implies that the level 126.75 MW varies with ±4 % between different years. The aim is now to select the subsribed levels in order to obtain a minimal expected power charge. If the subscribed level is too high then you always pay too much. If you, on the other hand, select a too low level, then it will be too expensive since you have to pay extra for excess capacity. The optimal level can be obtained in the following way:

Assume that the real measured power, which defines the charge, varies between different years with a mean value $= m$ and a standard deviation $= \sigma$. Assume also that the subscription level has been selected to be a, c.f. figure 5. This implies that at a year when

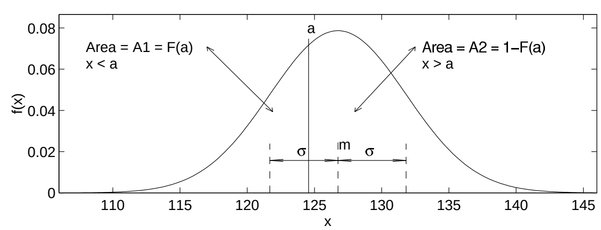

Figure 5: Gaussian approximation for the measured power which defines the power charge

the measured level x is lower than the subscribed level, i.e., when $x \leq a$, then the cost is $p(x) = T_1 a$, where T_1= cost for the subscription per kW,year. During a year when the measured power exceeds the subscribed level, i.e., when $x > a$, then the cost instead becomes $p(x) = T_1 a + T_2(x - a)$, where T_2= price for excess power per kW,year. The expected cost, E_p, where the probabilities for different years are weighted together, can be calculated as:

$$
\begin{aligned}
E_p &= \int_{-\infty}^{\infty} p(x)f(x) = \int_{-\infty}^{a} T_1 a f(x)dx + \\
&+ \int_{a}^{\infty} [T_1 a + T_2(x-a)]f(x)dx = \\
&= T_1 a \int_{-\infty}^{\infty} f(x)dx + \\
&+ T_2 \int_{a}^{\infty} xf(x)dx - T_2 a \int_{a}^{\infty} f(x)dx = \\
&= T_1 a + T_2 \int_{a}^{\infty} xf(x)dx - T_2 a[1-F(a)] = \\
&= T_1 a + T_2 \left[m[1-F(a)] + \sigma^2 f(a)\right] - \\
&- T_2 a[1-F(a)] = (T_1 - T_2)a + T_2 m + \\
&+ T_2 F(a)(a-m) + T_2 \sigma^2 f(a) \qquad (2)
\end{aligned}
$$

where

$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-m)^2}{2\sigma^2}}$ = Gaussian probability density function

$F(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} e^{-\frac{(y-m)^2}{2\sigma^2}} dy$ = Gaussian distribution function

In figure 6 it is shown how the expected cost E_p depends

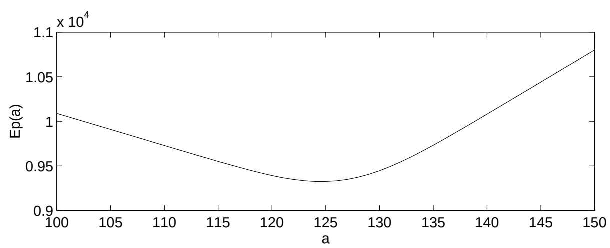

Figure 6: Expected cost E_p in kSEK as a function of selected subscription power level a

on the selected subscription level. As shown in the figure, a higher cost is obtained for too low or too high subscription level. The minimum level is obtained when:

$$
\begin{aligned}
\Delta a(T_2 - T_1)A_2 &= \Delta a T_1 A_1 \\
&\Rightarrow \\
(T_2 - T_1)[1-F(a)] &= T_1 F(a) \\
&\Rightarrow \\
F(a) &= (T_2 - T_1)/T_2. \qquad (3)
\end{aligned}
$$

This solution can be explained in the following way:.

1. Assume that the subscription level has been selected to a. If this level is slightly increased to $a + \Delta a$, then the cost, for the years when the dimensioning power is lower than a, will increase with $\Delta a T_1 A_1$. A_1 is the share of the years when the dimensioning power is lower than a, c.f. figure 5.
2. During years when the dimensioning power is higher than a, the cost will instead decrease with $\Delta a(T_2 - T_1)A_2$. A_2 is the share of the years when the dimensioning power is higher than a, c.f. figure 5.
3. The minimal cost is obtained when a small change of a does not change the cost, i.e., when a cost increase according the point 1 is the same as the cost decrease according to point 2, which is the same as equation 3.

With charges as in table 6, the subscription values can be optimized and the result is shown in table 7.

Tariff	yearly power	high load power
m	126.75 MW	126.75 MW
σ	5.1 MW	5.1 MW
T_1	31 SEK/kW	72 SEK/kW
T_2	62 SEK/kW	108 SEK/kW
min cost	4.1 MSEK	9.3 MSEK
a	126.7 MW	124.6 MW

Table 7: Optimal subscribed levels without wind power

Now assume that there is wind power in the system. The question is then whether there is a new optimal subscription level, and if the total expected cost will be reduced.

Figure 7 shows one example of how total wind power could vary during a week. In this study, one month real production data has been used. The available data is for 12 MW of wind power. In [5], where wind speeds at

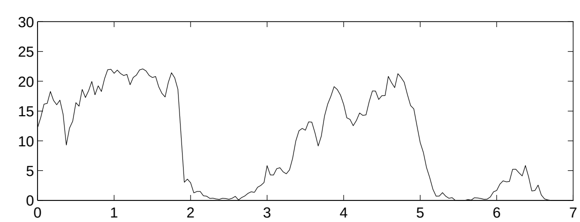

Figure 7: Wind power production during one week

8 load peaks have been studied, the conclusion is that "The result indicates that there is not a great difference between wind speed levels at load peaks and the yearly mean wind speed". Therefore the available data have been scaled to obtain a yearly production of 90 GWh, i.e., a mean production level of 10.3 MW. Here the whole available month will be used, which means that each studied week will not have this mean level.

Now assume that one has a power demand according to figure 4 and a wind power production level according to figure 7. The net load, i.e., the load that now has to be produced in other power sources, is shown in figure 8. As shown in this figure, wind power will cause the dimensioning power to decrease. At the same time the dimensioning hour is moved in the week. It could also be the case that the dimensioning hour is moved to another week with lower wind speeds.

In this study the wind speeds during one month is used. This implies that one week is constructed for day 1-7 one

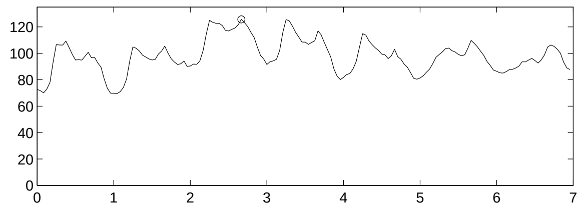

Figure 8: Power demand - wind power production for one week

for day 3-9 etc, i.e., from the whole month 12 different weeks have been obtained. By studying $12 \cdot 12 = 144$ combinations, (12 wind weeks in one month, and 12 wind weeks in the other month), a mean dimensioning power of 123.1 MW is obtained. This implies that 43 MW of wind power has reduced the dimensioning power with 3.65 MW. The different combinations of weeks gave different decreased levels, and this could be formulated as that the dimensioning power became 123.1± 3.1 MW where

$$\sigma_{load-w} = 3.1 \text{ MW} = \text{standard deviation} \tag{4}$$

In addition to this, one has to consider that the wind speeds differ between different years. Here wind data from Visby airport has been available and based on these data the year-to-year variation of the mean wind power can be estimated, c.f. figure 9.

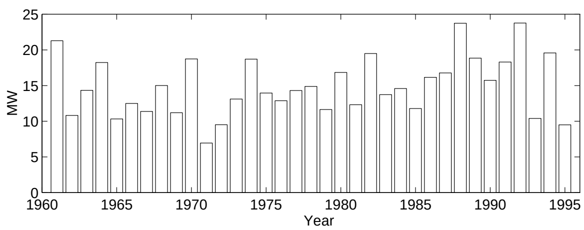

Figure 9: Mean power during January-February for 43 MW of wind power on Gotland, for the period 1961-95

As shown in the figure the wind power production during January-February differs a lot from year to year. The mean value, m_w, and standard deviation, σ_w, for the production in figure 9 is

$$\begin{aligned} m_w &= 14.9 \text{ MW} && (5) \\ \sigma_{w-data} &= 4.1 \text{ MW} && (6) \end{aligned}$$

It is here assumed that mean wind power production during the studied period is the same as the yearly mean (10.3 MW). Based on this assumption it is also assumed that the standard deviation for the year-to-year variation is reduced to:

$$\sigma_{w-\text{year}} = 4.1 \cdot \frac{10.3}{14.9} = 2.8 \text{ MW} \tag{7}$$

The net level (power demand - wind power production) for the measured power levels, that the charges are based on, can now be described with a Gaussian distribution according to figure 5. With the assumption of independence between load and wind generation, i.e., there is no statistical dependence between the load and wind generation in January-February, the parameters for the Gaussian distribution can be calculated as:

$$\begin{aligned} m_{net} &= m_{load} - m_w = 123.1 \text{ MW} && (8) \\ \sigma_{net} &= \sqrt{\sigma^2_{load} + \sigma^2_{load-w} + \sigma^2_{w-\text{year}}} = && (9) \\ &= \sqrt{5.07^2 + 3.1^2 + 2.8^2} = 6.6 \text{ MW} \end{aligned}$$

Optimal subscription can now be obtained according to eq. 3 and the expected cost can be estimated with eq. 2. The result is shown in table 8.

Tariff	yearly power	high load power
m_net	123.1 MW	123.1 MW
σ	6.6 MW	6.6 MW
T_1	31 SEK/kW	72 SEK/kW
T_2	62 SEK/kW	108 SEK/kW
min cost	4.0 MSEK	9.1 MSEK
a	123.1 MW	120.3 MW

Table 8: Optimal subscribed levels with wind power

By comparing table 8 with table 7, one can see that the subscription level as well as the expected costs decrease depending on the installed amount of wind power. The cost decreases with (4.1-4.0)+(9.3-9.1)=0.3 MSEK which corresponds to (300 kSEK)/(43000 kW) = 7 SEK/kW,year installed wind power capacity.

3 REFERENCES

[1] Castro Ana Díez, *Paper concerning wind power generation at Gotland*, Gotlands Energiverk AB, GEAB, 1997-04-06.

[2] Kellberg Jonas, Vattenfall Regionnät AB, communication summer-autumn 1997

[3] Liljegren Christer, Gotlands Energiverk AB, communication during October 1997

[4] *Grid charges 1997*, Håkan Nyberg, Svenska Kraftnät 1996-10-17

[5] Söder L., *Wind power availability at high load*, Electric power systems, KTH, Stockholm, (in Swedish) (1987)

[6] Söder, L., Renström, A.-K. : *Reduced electrical distribution losses depending on wind power production - A case study*, presenterat vid European Wind Energy Conference, EWEC'94, Thessaloniki, Grekland, oktober 10-14, (1994)

[7] Söder L., *Estimation of reduced electrical distribution losses depending on dispersed small scale energy production*, presenterat vid 12:th Power Systems Computation Conference, Dresden, Tyskland, augusti 19-23, (1996)

[8] Söder L. *Capacity credit of wind power* Elforsk report 97:27, Final report from Elforsk project 2061, (in Swedish), (1997)

[9] *Vattenfall Regionnät AB:s grid tariff 1997 for Southern Sweden*, Vattenfall oktober 1996.