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Cost savings by low-loss distribution transformers:

the influence of fluctuating loads and energy price on the economic optimum

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1 INTRODUCTION

1.1 Background

Studies carried out in 1999 and 2001 by the European Copper Institute have revealed that the scope for energy savings and CO_2 reduction through the use of energy-efficient distribution transformers in the EU is substantial. The savings potential is approximately 22 TWh/year for "public" electric utilities and approximately 5,5 TWh/year for industries and offices. This savings potential can be achieved by application of energy-efficient transformers, the extra investment cost of which is earned back by the energy savings.

For some industries and public utilities, energy-efficient transformers can save a lot of money during the lifetime of the transformer.

In order to select the transformer with the optimum balance between investment cost and the cost of no-load and load losses, loss evaluation during transformer purchasing is the usual and appropriate method. The cost of losses is represented through an A and B factor (A represents the loss evaluation for the no-load losses; B represents the loss evaluation for the load losses).

Surprisingly, many industries and public utilities are not familiar with energy-efficient transformers. Therefore, in earlier publications [1,3], the method of loss evaluation was given and a software tool for calculation was developed [4].

It may be difficult to determine the A and B loss evaluation factors, as these factors provide a capitalisation of future cost of losses and are depended on (expected) load patterns, load growth and changes of energy prices. Usually, due to a lack of clairvoyance and to reduce complexity, A and B are based just on average values. Little is known about the loss evaluation for transformers if e.g. the peak loading and/or the variation of electricity price is taken in account.

An example of the price variation in the year 2002 is given in figure 1 (source: APX spot market 2002). This figure shows that the average price for energy at the APX spot market was about 30 Euro/MW. However there is a peak above 200 Euro/MW. It is unknown whether these peaks can be neglected for the loss Evaluation.

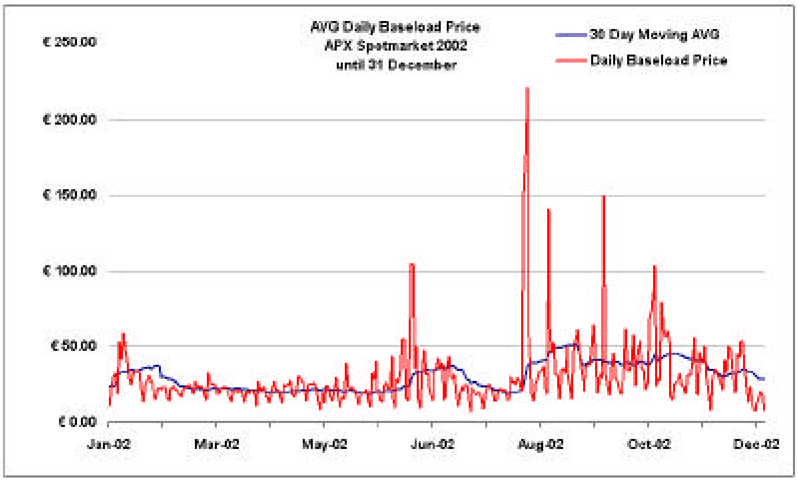


Figure 1: spot market prices

A similar question applies to (step-up) transformers of wind turbines: what is the effect of such a strongly fluctuating source on the loss capitalisation?

Figure 2 Wind turbines

1.2 Scope and purpose

The purpose of this report is to show the influence of fluctuating loads and energy price on the loss evaluation factors A and B and hence on the economic optimum for distribution transformers.

Two cases are considered: an economic study based on historical data from the forward market, and an economic study into the A and B factor for wind turbines based on historical data for wind-speed and a given wind turbine characteristic.

The target group for this report are industries, utilities, project developers of wind turbines and other customers of energy efficient transformers.

2 CONVENTIONAL LOSS EVALUATION METHOD

A power transformer normally consists of a pair of windings, primary (HV) and secondary (LV), linked by a magnetic circuit or core. When an alternating voltage is applied to one of these windings, generally the HV winding, a small current will flow which sets up an alternating magnetic flux in the core. This alternating flux, linked to both windings, induces a voltage in each of them. The current that is flowing in the situation that both windings are not loaded is the magnetising current. For further reading about transformer losses is referred to the J&P transformer book [11].

2.1 Types of losses in transformers

NO LOAD LOSSES

An unloaded transformer experiences losses. The magnetising current is required to take the core through the alternating cycles of flux at a rate determined by system frequency (50 Hz). In doing so energy is dissipated. This loss is known as the core loss, no load loss or iron loss. The core loss is present whenever the transformer is energised. Thus they represent a constant and therefore significant energy drain on any electrical system. In addition, the alternating fluxes generate also alternating forces in the iron core and hence noise.

The core loss is made up of two components: the first one, the hysteresis loss, is proportional to the frequency and dependent on the area of the hysteresis loop in the B-H diagram, and therefore characteristic of the material and a function of the peak flux density. The second component is the eddy current loss that is dependent on the square of the frequency, the square of the thickness of the material and the resistivity. Minimising hysteresis losses therefore implies application of a material having a minimum area of hysteresis loops, while minimising eddy current loss is achieved by building up the core from a laminate of thin strips and high resistivity.

LOAD LOSSES

The load loss of a transformer is that part of the losses generated by the load current and which varies with the square of the load current. This falls into three categories:

- Resistive loss within the winding conductors and leads
- Eddy current loss in the winding conductors
- Eddy current loss in the tanks and structural steelwork.

The latter two categories are also referred to as “extra losses”.

Resistive loss follows Ohm’s law and can be decreased by reducing the number of winding turns, by increasing the cross-sectional area of the turn conductor, or by a combination of both. However, reducing the number of turns requires an increase of the flux i.e. an increase in the core cross-section, which increases the iron weight and iron loss. So a trade-off has to between made between the load loss and the no-load loss.

Eddy currents arise from the fact that not all the flux produced by one winding links to the other winding. This flux leakage also leads to the short-circuit reactance or impedance of a transformer. In the past, this reactance was simply considered an imperfection arising from the unavoidable existence of leakage flux. Nowadays, the transformer impedance is a valuable tool for the system designer to determine system fault levels to meet economic limitations of the connected plant.

The path of eddy currents in winding conductors is complex. The magnitude of this leakage flux depends on the geometry and construction of the transformer. The effect of leakage flux within the transformer windings results in the presence of radial and axial flux changes at any given point in space and any moment in time. These induce voltages, which cause currents to flow perpendicular to the fluxes, which lead to losses. The magnitude of these currents can be reduced by increasing the resistance of the path through which they flow, and this can be effected by reducing the total cross-sectional area of the winding conductor, or by subdividing this conductor into a large number of strands insulated from each other (in the same way as laminating the core steel reduces eddy-current losses in the core). However, the former alternative increases the overall winding resistance and thereby the resistive losses. Conversely, if the overall conductor cross-section is increased with the object of reducing resistive losses, one of the results is an increase of the eddy current losses. This can only be offset by a reduction in strand cross-section and an increase in the total number of strands. It is costly to wind a large number of conductors in parallel and so a manufacturer will wish to limit the total number of strands in parallel. Also, the extra insulation resulting from the increased number of strands results into a poorer winding space factor. It will be evident that in a transformer having a low reactance, winding eddy currents are less of a problem than one with high reactance.

On very high currents (>1000 A) fluxes generated at the main leads can give rise of eddy current losses in the tank adjacent to these. Due to the leakage flux there are also eddy-current losses in tanks and internal structural steelwork.

2.2 Transformer loss evaluation – A and B factors

The total owning cost of a transformer consists of several components, including the purchase price, the value of energy losses, maintenance and repair costs over the lifetime, and decommissioning cost. The purchase price and the energy losses are the two key factors for comparison of different transformers.

In the industry it is very common that transformers are part of a turn key project. The contractor is often interested in a transformer with a low purchase price. However the user/owner of the transformer aims at buying the cheapest transformer, i.e. with the lowest total owning cost, which complies with the requirements for a given application. Losses, installation, maintenance, repair and decommissioning costs are seldom taken into account by the contractor when choosing between transformers.

The utilities are not encouraged by their government and/or regulators to buy a transformer with less losses. In most countries the energy savings of transformers with low losses are not assigned to the utilities. This means it is not in the interest of a utility to invest in a transformer with low losses (higher purchase price), since there is no pay back for the utility during the life time of the transformer! This is contradictory to the public interest. Nowadays some governments and regulators have realised this problem and want to change so the utilities are stimulated to buy energy saving transformers.

When comparing two transformers with different purchase prices and/or different losses, one must take into account that the purchase price is paid at the moment of purchase, while the cost of losses comes into effect during the lifetime of the transformer. Usually the costs are converted to the moment of purchase by assigning capital values. When transformers are compared with respect to energy losses, the process is called loss evaluation.

In the basic loss evaluation process, three transformer figures are needed:

- purchase price
- load loss
- no-load loss.

For the specified load loss of a transformer, the purchaser can assign a cost figure per kW of loss representing the capitalised value (net present value) of the load losses over the lifetime of the transformer or a shorter time scale e.g. 5 or 10 years. This cost figure is based on the expected transformer load over time and the average cost per kWh.
Similarly, for the no-load loss of a transformer, the purchaser can assign a cost figure per kW of no-load loss representing the capitalised value of the no-load losses. This cost figure is also based on the average cost per kWh and the interest rate chosen by the purchaser. As nearly all transformers are connected to the grid for 100% of the time, and the no-load losses

are independent on the load, the load curve is not relevant. The average cost per kWh will tend to be lower than for the load losses, as the latter will tend to coincide with peak loads, at which time energy is very expensive.

If high capitalisation values for losses are chosen, transformers with low losses but with higher investment cost tend to be favoured. If however capitalisation values are set to zero, a purchaser effectively eliminates energy loss evaluation from the purchase decision, which favours the cheapest transformer.

Thus, the capitalised cost (CC) of a transformer can be expressed as the sum of the purchase price (Ct), the cost of no-load bsses and the cost of the load losses, or as a formula:

CC = Ct + A x Po + B x Pk

where A represents the assigned cost of no-load losses per watt, Po the value of the no-load losses per watt, B the assigned cost of load losses per watt and Pk the value of the load losses per watt. This formula can also be found in HD428 and HD538.

Po and Pk are transformer properties. A and B are properties that depend on the expected loading of the transformer and energy prices. A and B are calculated as follows:

$$A = \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \times C_{kWh} \times 8760$$ **(no-load loss capitalisation)**

and

$$B = \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \times C_{kWh} \times 8760 \times \left(\frac{I_l}{I_r}\right)^2$$ **(load loss capitalisation)**

where:

i = interest rate [%/year]
n = lifetime [years]
C_{kWh} = kWh price [EUR/kWh]
8760 = number of hours in a year [h/year]
I_L = loading current [A]
I_r = rated current [A]

Usually, the loss evaluation figures A and B are submitted to the transformer manufacturers in the request for quotation. They can in turn start the complicated process of transformer design, to obtain a transformer design which performs best using the same formula. The result of this open process should be the cheapest transformer, i.e. with the lowest total owning cost, optimised for a given application.

For large transformers, above a few MVA, the costs of losses are so high, that transformers are custom-built, tailored to the loss evaluation figures specified in the request for quotation for a specific project.

For distribution transformers, often bought by large batches, the process is undertaken infrequently, e.g. once every 5 years. This yields an optimum transformer design, which is then kept for several years until energy prices or load profiles have changed dramatically. In fact the loss levels established in HD428, HD538 and national standards reflect established practice of preferred designs with respect to loss evaluation values.

2.3 Determination of A and B factors, limitations and uncertainties

In practice an ending up for A between less than 1 and 12 EUR/W and B ending up between 0,2 and 5 EUR/W is realistic.

The given formulae in chapter 2.2 assume that energy prices and the loading are constant over the transformer life. As often the future loading of the transformer is not known at the moment of buying the transformer. If the load grows over time, the growth rate must be known.

Also, the applicable kWh price over the lifetime must be forecast. A tricky task! Finally, the interest rate and the economic lifetime may be difficult to choose. In practice, therefore, there may be a lot of guesswork in determining A and B factors. The choice of the factors A and B is therefore difficult.

For this report, we provide a method based on historical data for determining the A and B factor when

- the load of the transformer is fluctuating very fast (wind turbine),
- the electricity price is fluctuating (forward market).

For the transformers at wind turbines it is common to use the same transformers as used for distribution. Since the direction of the loading is different (from LV to HV, where regular distribution transformers have a direction from HV to LV), there can be a small difference in the No-load losses, since the system voltage at the transformer is slightly higher. Appendix B gives more technical information about this aspect. Since the extra no-load losses are small, they are not taken in account in this study.

3 STATISTICAL LOSS EVALUATION METHOD

In [1] a definition of “to invest” is given. To invest means to employ general resources that are available, or were obtained for a definite purpose that is directed toward the future. The following characteristics are typical of investment:

- Multiperiod consideration: The benefits of an investment do not occur immediately, only at a later time. So investments require a multi-period, long-term method of consideration.
- Uncertainty: Because investments have an effect in the future, every investment project is encumbered with uncertainty. That means that the expected benefits are dependent upon different influencing factors.
- Irreversibility: The means of payments are specialised for an investment project, that is, they are tied up and are more or less irreversible, or otherwise reversibility is associated with high costs.

3.1 Dealing with uncertainty

The model described in chapter 2 uses input parameters, which are uncertain. This uncertainty rises from the following sources: The actual data are not available (of future load curves) or the value varies unpredictably (future electricity prices). This lack of knowledge about particular values, or the knowledge that some values may always vary contributes to the model's uncertainty.

Traditionally, there are three basic ways to deal with uncertainty: Point estimates, Range estimates, and What-if scenarios.

Point estimates are when you use what you think are the most likely values (technically referred to as the mode) for the uncertain variables. These estimates are the easiest, but can return very misleading results.

Range estimates typically calculate three scenarios: the best case, the worst case, and the most likely case. These types of estimates can show you the range of outcomes, but not the probability of any of these outcomes.

What-if scenarios as many scenarios as can be thought of are calculated. What is the worst case or average case? This form of analysis is extremely time consuming, and results in lots of data, but still doesn’t give you the probability of achieving different outcomes.

With the traditional loss evaluation method [4] the point estimate (average) was used to calculated the capitalized costs of different transformers. Range estimates and what-if scenarios can also be made with the deterministic version of Traloss[1].
Another way of capturing the uncertainty is to use the complete **distributions** of the input variables. The complete distribution of the output values will be calculated. With this method all possible outcomes are taking into account when making a decision. An easy to use method for making calculations with distributions is Monte Carlo simulation.

3.2 Monte Carlo simulation

Monte Carlo simulation was named for Monte Carlo, Monaco, where the primary attractions are casinos containing games of chance. The random behaviour in games of chance is similar to how Monte Carlo simulation selects variable values at random to simulate a model. For each uncertain variable (e.g. interest rates, energy prices, lifetime of the transformer, loading, possible values are defined with a probability distribution. A simulation calculates multiple scenarios of a model by repeatedly sampling values from the probability distributions for the uncertain variables and using those values for the outputs. For these calculations Crystal Ball 2000 has been used.

With Monte Carlo simulation a whole range of values for each uncertain variable can be calculated. By using distributions of the input variables, the output will not be a single number, but a distribution as well. This will be helpful for a better understanding of the problem and a better determination of the risk taken by a certain decision (in this case the risk taken by buying a certain transformer).

3.3 A probabilistic methodology to determine the loss evaluation factors

The uncertain parameters in the model described in §2.2 to determine the most efficient transformer are:

- interest rate
- kWh price
- lifetime of the transformer
- loading current
- CO2 prices
- price of the transformers.

[1] Software package developed at KEMA-TDC to evaluate the A and B factors for different situations.

Implementing these factors in the model results in a probabilistic model. To investigate the effects on the choice of the most efficient transformer of probabilistic analysis we performed two case studies. In these case studies we implemented the following parameters with uncertainty: the electricity price (chapter 4) and the loading current (chapter 5). These cases have been chosen for their practical applicability.

With this research the following questions can be answered:

- Is there a difference in the results using average prices or the distribution of the prices? (chapter 4)
- Should another type of transformer be used in combination with a wind turbine? (chapter 5).
- What is the influence of probabilistic calculations on the A and B factor?
- Is Traloss (a deterministic model) good enough to determine the A and B factor (and with these the optimal transformer for a certain user) or should a probabilistic model be used?
- Is it possible to find a rule of thumb between deterministic answers and probabilistic answers?

The following assumptions have been made:

- Influence of harmonics in the loading is not included in this research (set to 0).
- Different scenario's can be made for the CO2 prices. Therefore each case has been run with three different CO2 prices (0, 10, 33 Eur/Ton).
- The choice of the best transformer to choose in a specific situation is based on the capitalised cost.

3.4 Sensitivity Analysis

The outcomes of a sensitivity analysis on the probabilistic model (all uncertain input parameters modelled in a probabilistic way) are described in this paragraph. The following input parameters were tested for their influence on the different output values. The initial values of these parameters can be found in brackets next to the input names:

- Interest rate (7%)
- Economic lifetime (20 years)
- Energy price (100 Euro/MWh)
- CO2 emission price (33 Eur/ton
- Purchase prices (see Table 1)
- Load kVA (246 kVA).

Table 1: Purchase prices of the different 1000 kVA transformers

	Name	Price (Euro)
Base case	Oil CC’	8,007
Alternative 1	Oil DD’	10,353
Alternative 2	Dry HD 538	10,074
Alternative 3	Dry Low-Loss	11,108

3.4.1 INFLUENCIAL FACTORS ON THE A FACTOR

The parameters with the highest influence on A are (in order of highest appearance first):

- Energy price
- Interest
- Economic lifetime.

The other input parameters had no influence on A. Figure 3 illustrates these outcomes. In this figure it can be seen that a 20% rise in energy price induces the A factor to rise from 9.28 to 11.14. The interest rate and the A factor have a negative correlation. This means that a higher interest rate leads to a lower A factor.

The **spider chart** illustrates the differences between the minimum and maximum output values by graphing a curve through all the input values tested. Curves with steep slopes, positive or negative, indicate that those input variables have a large effect on the output, while curves that are almost horizontal have little or no effect on the output. The slopes of the lines also indicate whether a positive change in the variable has a positive or negative effect on the output.

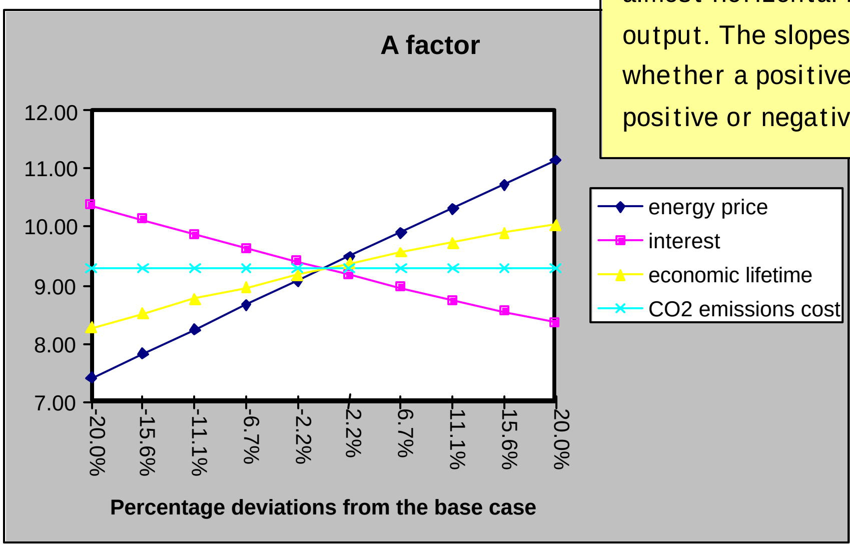


Figure 3: Spider chart A factor

3.4.2 INFLUENCIAL FACTORS ON THE B FACTOR

The parameters with the highest influence on B are:

- The load
- Energy price
- Interest rate
- Economic lifetime

The other factors do not have an effect on the B factor. This is shown in Figure 4.

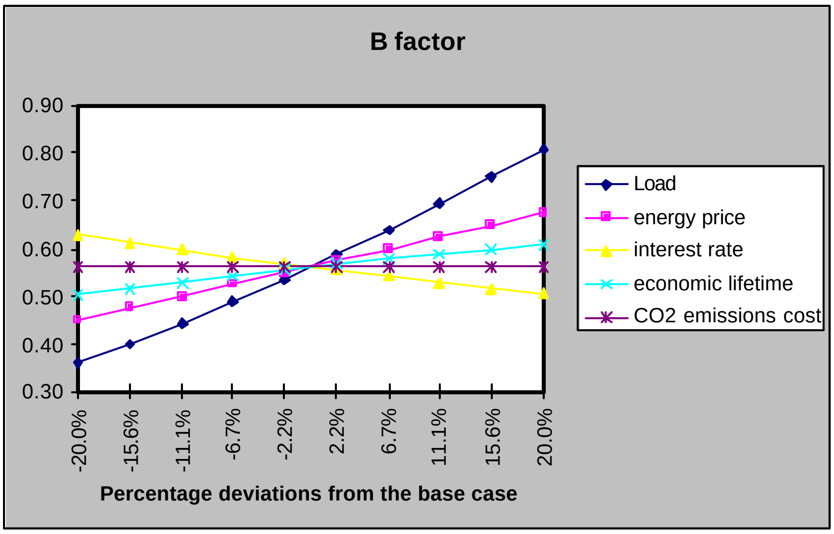


Figure 4: Spider chart B factor

3.4.3 INFLUENCIAL FACTORS ON THE CHOICE OF THE OPTIMAL TRANSFORMER

The same input parameters have been tested for their effect on the choice of a transformer. These results are summarised in Figure 5. A value of 5 on the y-axis represents the base case (Oil CC') as the optimal solution, a value of 1 stands for alternative 1 (Oil DD') being the optimal solution.

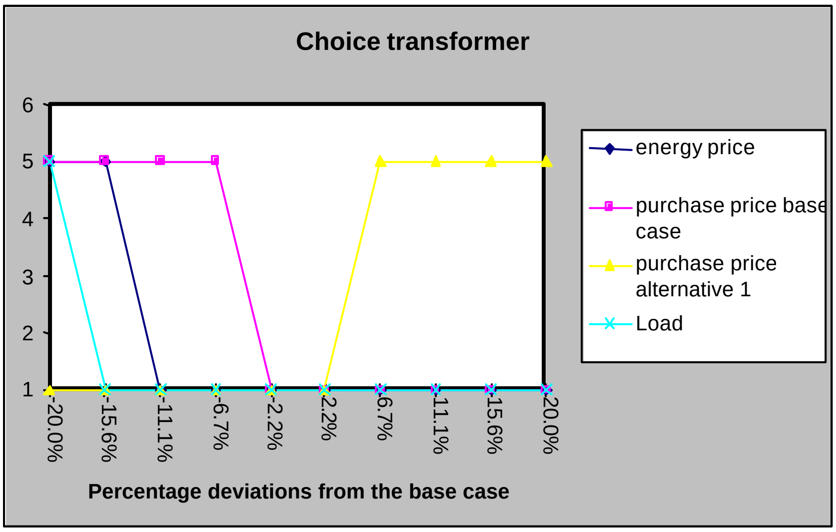


Figure 5: Spider chart optimal choice of transformer

Figure 5 shows that the higher the purchase price of alternative 1, the more likely that the base case will be chosen. A higher energy price leads to choosing a more energy efficient option: alternative 1. The same argumentation is valid for the Load.

This sensitivity analysis has shown that the most important input parameter for the A factor is the energy price and the most influencing parameter on the B factor is the load. Therefore two case studies have been chosen where the energy price and the load fluctuate respectively. To keep the case studies as practical as possible for the fluctuating load, a wind turbine has been simulated (chapter 4) and for the fluctuating prices, the prices on the forward market have been used for simulation (chapter 5).

3.5 Number of trials

To improve the accuracy of the simulations a certain number of trials have to be made. 1000 trials are sufficient to draw accurate conclusions of the data. Due to the way Traloss is made, a random drawing out of the distributions has to be made for each hour of the year. The average per year for the A and B factor was calculated afterwards. To get 1000 trials this way 8,760,000 different scenarios were calculated for each case. Variation in the CO_2 emission cost (discrete values of 0, 10 and 33) resulted in a total number of trials of: 2 (cases) * 3 (CO_2 scenario's) * 8760 (hours) * 1000 (trials) = 52,560,000 trials.

4 CASE STUDY 1: INFLUENCE OF ELECTRICITY PRICE VOLATILITY

Is there a difference in the results using average prices or the distribution of the prices? The answer to this question will be given in this chapter.

4.1 Case description

As given in §3.3 the most important and at the same time fluctuating input parameter on the A factor is the electricity price. The price that has to be paid depends on the type of customer. For example large industries have their own electricity purchase department and will trade on the long-term en short-term electricity markets to obtain the lowest price possible. Smaller industries have contracts with trading companies for a fixed price for a whole year. In this case two tariffs will be used: peak prices and base prices. Grid companies buy their energy losses with standard contracts (like smaller industries). But if a grid company uses more or less than the contracted amount of energy a clearance price has to be paid. The following figure illustrates this principle.

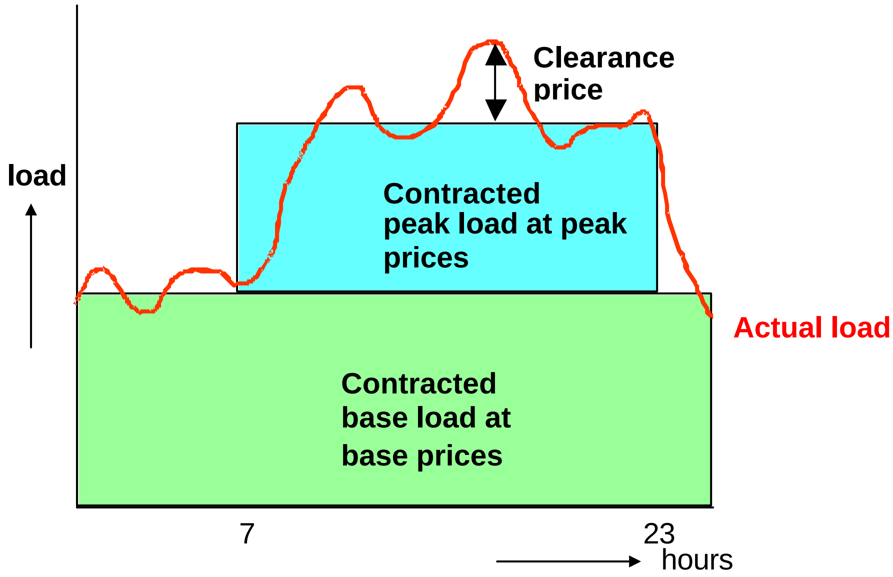


Figure 6 Contracted versus actual load of a grid company

The focus of this case study has been on the smaller industries. For such an industry only the base load and the peak load have to be bought. For simplicity the assumption has been made that the actual load follows the contracted load exactly. Also the no-load losses are included in the contracted peak and base load and evaluated against the peak and base prices respectively.

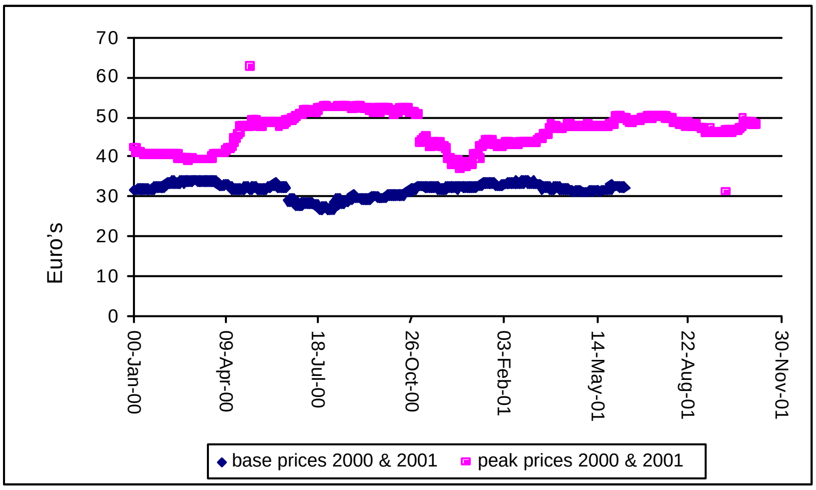


Figure 7 Base and peak prices of the forward market

Prices of the forward market of 2000 and 2001 have been used to make a distribution of the prices for the model. Figure 7 shows the base and peak prices of the historical data set. A yearly pattern can be seen in this figure.

To use these data as input numbers in a Monte Carlo simulation the data have to be fitted into a distribution. Figure 8 shows the fitted distributions of these data used for the Monte Carlo simulation.

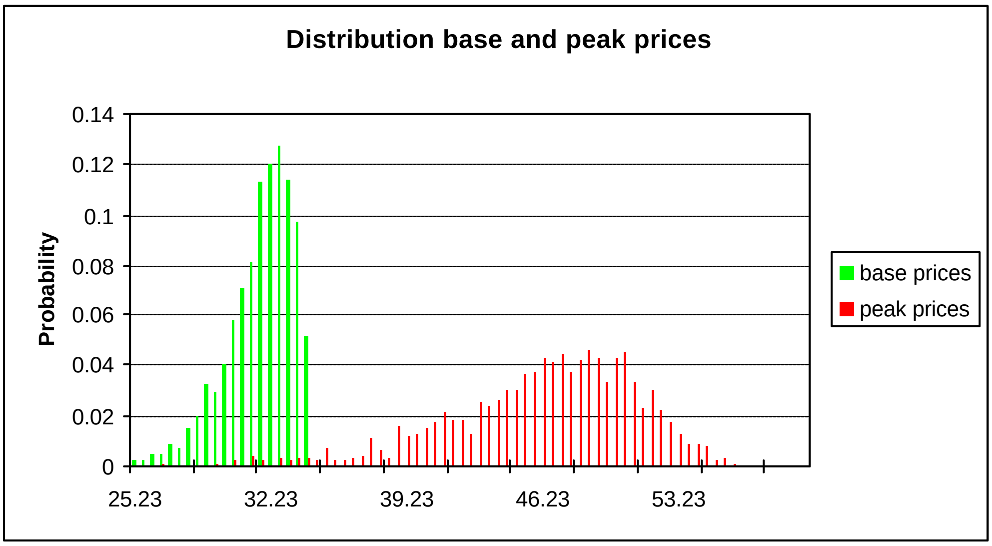


Figure 8 Fitted distributions of the base and peak prices

The base prices are beta distributed and the peak prices have an extreme value distribution. The continuous base load lasts 8760 hours per year and is set to 500 kVA. Two third of the year (5840 hours) a peak load is requested of 500 kVA on top of the base load.

The data of the four 1600 kVA transformers used in the simulations can be found in table 2, the other (fixed) input values can be found in table 3.

Table 2 1600 kVA transformers

	Name	**Price (Euro)**
Base case	Oil CC’	10,865
Alternative 1	Oil DD’	12,832
Alternative 2	Dry HD 538	14,451
Alternative 3	Dry Low-Loss	14,990

Table 3 Input values for the wind case

Variable	**Fixed value**
interest rate	10%
ECONOMIC LIFETIME	5 years
CO2 emissions cost	0, 10 en 33 Eur/ton
CO2 emissions per kWh	0.4 kg/kWh

4.2 Conventional A and B factors

The average base price is 31.67 Euro/MWh. The average peak price is 46.13 Euro/MWh. Three cases for the CO2 emission prices were calculated (CO2 emission prices of 0, 10 en 33 Eur/ton). The results of using these values to calculate the optimal transformer in the Traloss model can be found in table 4.

Column 1 gives a short case description. The next column displays the A factor, the third column the B factor. With a deterministic model standard deviations are not applicable (N/A). In all the cases the Oil CC’ transformer was the best option. This is displayed in the last two columns. A 1 stands for: “this transformer is optimal in this case”.

Table 4 Deterministic results price case

	A factor (Euro / W)	B factor (Euro / W)		Optimal transformer	
		Average	St. dev	Oil CC'	Oil DD'
Deterministic CO2 0	1.29	0.37	N/A	1	0
Deterministic CO2 10	1.42	0.41	N/A	1	0
Deterministic CO2 33	1.73	0.50	N/A	1	0

Other factors that can be determined are the total CO2 emissions per type transformer, capitalized costs, pay back time and the IRR (internal rate of return). The pay back time and the IRR are calculated for the 3 alternatives in comparison of the base case. Table x shows the results for the Oil C-C' and the Oil D-D' variants.

Table x Deterministic results of other outputs of Traloss

	Deterministic CO2 0	**Deterministic CO2 10**	**Deterministic CO2 33**
CO2 emissions Oil C-C'	20.3	20.3	20.3
CO2 emissions Oil D-D'	17.3	17.3	17.3
Capitalized costs Oil C-C'	18250	19020	20793
Capitalized costs Oil D-D'	19109	19764	21270
Pay back time Oil D-D'	7	6	5
IRR alternative Oil D-D'	N/A	N/A	N/A

4.3 Statistically determined A and B factors

Using the distribution of the peak and base prices (see Figure 8) the following results are obtained. (see table 5). In this case also the three values of the CO2 emission prices were used. With a probabilistic model the standard deviations of the A and B factor were calculated. Even in these cases the Oil CC' transformer was the optimal solution for all trials. Therefore this transformer scored a 100%.

Table 5 Probabilistic results price case

	A factor (Euro / W)		**B factor (Euro / W)**		**Optimal transformer**	
	Average	St. dev	Average	St. dev	Oil CC’	Oil DD’
Probabilistic CO2 0	1.29	9.5 e-4	0.37	2.5 e-4	100%	0%
Probabilistic CO2 10	1.42	9.5 e-4	0.41	2.5 e-4	100%	0%
Probabilistic CO2 33	1.73	9.6 e-4	0.50	2.6 e-4	100%	0%

Table x Probabilistic results of other outputs of Traloss

	Probabilistic CO2 0	**Probabilistic CO2 10**	**Probabilistic CO2 33**
CO2 emissions Oil C-C’	20.3	20.3	20.3
CO2 emissions Oil D-D’	17.3	17.3	17.3
Capitalized costs Oil C-C’	18250	19020	20793
Capitalized costs Oil D-D’	19109	19764	21270
Pay back time Oil D-D’	6.89	6.22	5.09
IRR Oil D-D’	N/A	N/A	0.8%

It should be noted that only the averages of these quantities are displayed in table x. But each quantity also has a probability distribution.

4.4 Discussion – selection of optimum transformers

For dealing with fluctuating prices it is not necessary to use a probabilistic version of Traloss, even at prices with a larger deviation than the prices used above. For example, if the prices of the spot market are inserted into the model (see Figure 1) then there still is no difference between the deterministically determined B factor and the average B factor of the Monte Carlo Simulations. Only the standard deviation of the B factor is much larger than the standard deviations in table 5.

The spread on the prices does not have an influence on the optimal transformer choice. This is due to the fact that the prices will fluctuate during the life of the transformer, but in the end positive values and negative values will compensate each other. If there were a growth in the prices or another trend, then this would have affected the optimal transformer choice. The authors wish to recommend to review these effects.

5 TRANSFORMERS AT WIND TURBINES

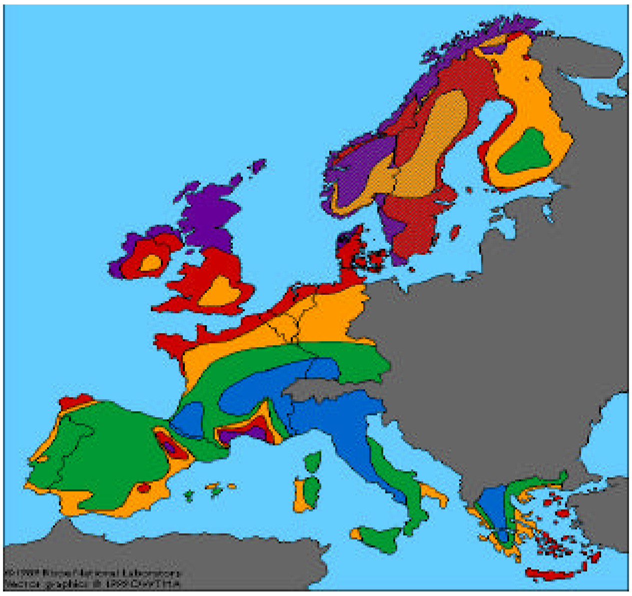
The wind power industry is the world's fastest growing energy technology; leading is Germany with an installed capacity of 12 GW, followed by Spain with 5 GW and Denmark 3 GW. According the 2003 European Wind Energy Conference (EWEC), the total installed capacity in the EU was 23.8 GW by the end of 2002 and will grow to 40 GW in 2010 [5] and according to [6] even to 60 GW in 2010.

A modern wind turbine usually has a step-up transformer (size and range equal to a distribution transformer) either at the base of the tower or in the nacelle. Electrical connections between wind turbines are usually at a voltage level of 10 kV or above. These transformers are bought based on the limited sizes inside the wind turbines. If energy efficient transformers can be used they should be placed next to the wind turbine.

To evaluate if an energy efficient transformer can be used at wind turbines, the deterministic method does not lead to the correct A and B factor of the transformer, since a variation in the load (wind turbine) influences the values of the B factor and therefore the optimal choice of transformer. The influence of load variations on the A and B factor will be answered in this chapter with a case example. Fixed values of all input factors have been used except the input factor *load.* In case of a wind turbine this factor depends on the wind speed.

5.1 The power of wind

The wind power density has a cubic relationship with wind speed. For example, the wind power density increases by a factor of 8 for a doubling of the wind speed. The wind velocity at a particular location varies in speed and direction. Figure 9 shows the wind map of Western Europe.



WIND RESOURCES AT 50 M ABOVE GROUND

	Sheltered terrain		Open plain		At a sea coast		Open sea		Hills and ridges	
	m/s	W/m²	m/s	W/m²	m/s	W/m²	m/s	W/m²	m/s	W/m²
	>6.0	>250	>7.5	>500	>8.5	>700	>9.0	>800	>11.5	>1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
	<3.5	<50	<4.5	<100	<5.0	<150	<5.5	<200	<7.0	<400
			>7.5							
			5.5-7.5							
			<5.5							

Figure 9 Wind map in Europe

The total energy produced by a wind turbine depends on the wind speed. The general pattern of the wind speed variation is distributed as a Weibull distribution as shown in figure 10 for the Northern European countries at sea coast.
The area under the curve is always exactly 1, since the probability that the wind will be blowing at some wind speed including zero is 100%. The average value of the wind speed is 8.24 m/s. The statistical distribution of wind speed varies form place to place around the globe. The Weibull distribution may thus vary, both in its shape, and in its mean value. The assumption has been made that the Weibull distribution shown below is valid for the Netherlands.

Figure 10 Weibull distribution

The power output of a wind turbine is a function of wind speed. The power curve (power output (P) versus wind speed (v) (P-v)) is produced by plotting turbine electrical power measurements, which have been averaged over a period of several minutes, against wind speed measurements. Figure 11 shows the power curve of a 750 kW wind turbine.
The discrete values of the

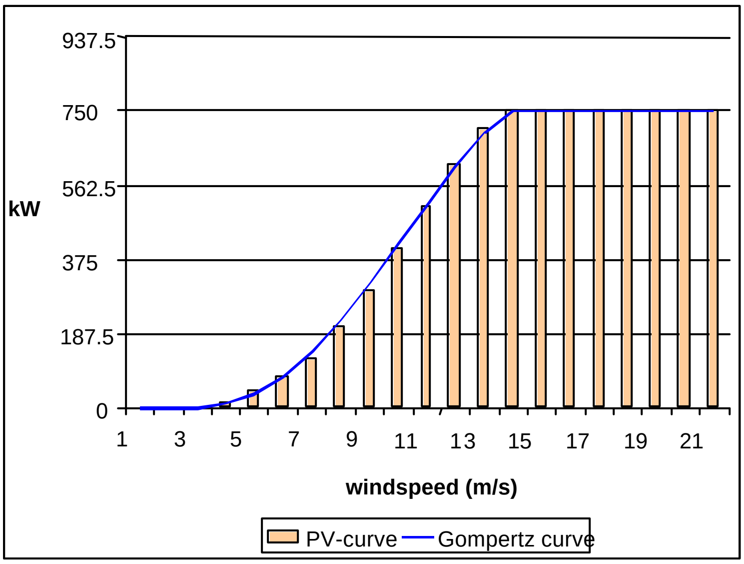


Figure 11 Discrete PV curve transformed into a continuous curve

power velocity (PV) curve have been transformed (by means of a Gompertz curve) to a continuous version.

The key features of the power curve are:

- Cut-in wind speed (typically at 3 m/s), at which the wind turbine commences operation
- Cut-out wind speed (typically at 23 m/s), at which the wind turbine is shut down to avoid damage.

Figure 12 shows the probability distribution of the transformer load. This is a combination of the Weibull distribution function and the power curve of the wind turbine. Based on 8760 hours a year, the average loading of the wind turbine is 291 kW (38,8% of the full capacity). The estimated energy production of the wind turbine is about 2550 MWh per year.

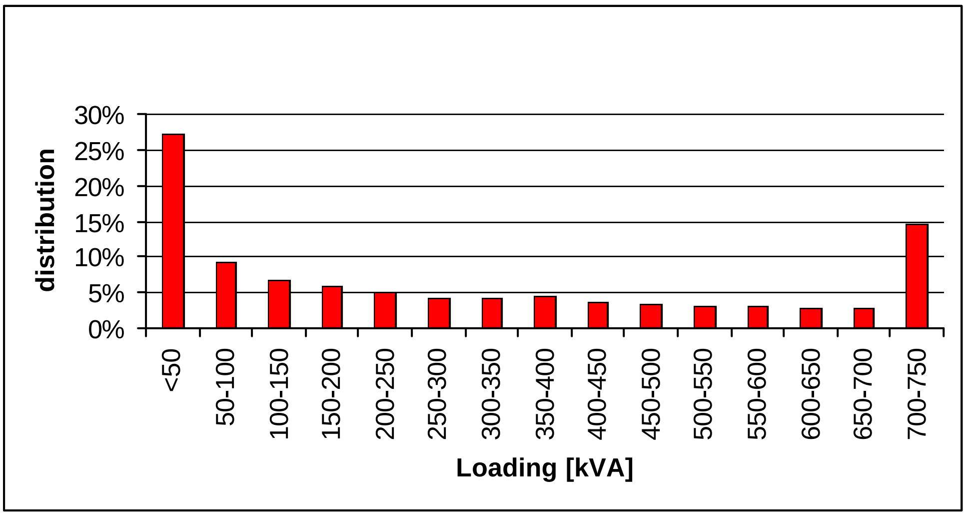


Figure 12 Frequency distribution load

5.2 Case study for energy-efficient transformers at wind turbines

The given 750 kW wind turbine is used for a case study to calculate if energy-efficient transformers can be used at wind turbines. For the connection to the grid a distribution transformer of 1000 kVA is taken (for data about the transformer see appendix A). To evaluate if an energy efficient transformer (Oil D-D') can be used compared to an Oil C-C' transformer the input values as given in table 6 are used in the Traloss model.

Table 6 Input values for the 750 kW wind turbine (case study)

Parameter	Value
interest rate	7%
economic lifetime	20 years
energy price	100 Euro/MWh
CO_2 emissions cost	0, 10 or 33 Eur/ton
CO_2 emissions per kWh	0.4 kg/kWh

The energy price is based on the market price. The market price for the kilowatt-hour produced can be established by the extent that the installation is used for the network power supply. The market price is approximately 0.10 Euro/kWh (according to the Renewable Energy Act in Germany[2]).
With the average load of the 750 kW wind turbine equal to 291 kW, the Traloss model with a 1000 kVA transformer gave the following results (table 7):

Table 7 Deterministic results wind case

	A factor (Euro / W)	B factor (Euro / W)
CO2 costs 0 euro/tonnes	9.28	0.79
CO2 costs 10 euro/tonnes	9.65	0.82
CO2 costs 33 euro/tonnes	10.51	0.89

Due to the long economic lifetime (20 years) the A factor is relatively high compared with other case studies [1,3]. The B-factor is rather small. This can be explained by the average loading of the transformer (just 29%). This means the average load losses are about 8.5% of a full operated transformer.

Other factors that can be determined are the total CO_2 emissions per type transformer, capitalized costs, pay back time and the IRR (internal rate of return). The pay back time and the IRR are calculated for the 3 alternatives in comparison of the base case. Table 8 shows the results for the oil C-C' and oil D-D' variants, the capitalised costs of the D-D' transformer being underlined.

Table 8 Results from the Traloss model

	CO2 costs 0 euro/tonnes	CO2 costs 10 euro/tonnes	CO2 costs 33 euro/tonnes
CO_2 emissions Oil C-C'	6.7 t/a	6.7 t/a	6.7 t/a
CO_2 emissions Oil D-D'	5.7 t/a	5.7 t/a	5.7 t/a
Capitalized costs Oil C-C'	25681 Euro	26388 Euro	28104 Euro
Capitalized costs Oil D-D'	25376 Euro	25977 Euro	27359 Euro
Pay back time D-D'	9 Years	9 Years	8 Years
IRR D-D'	9%	9%	10%

Although the differences are rather small, in all situations the D-D' energy-efficient transformer is the most economical, having a pay-back period of about 8-9 years.

The above given results with Traloss should be compared with a statistical method on which the A and B factors are statistically determined. Using the model with the load distributed as given in figure 5.4 the following results were acquired:

Table 9 Probabilistic results wind case

	A factor (Euro / W)	B factor (Euro / W)	
		Average	St. dev
CO2 costs at 0 euro/tonnes	9.28	1.43	0.02
CO2 costs at 10 euro/tonnes	9.65	1.48	0.02
CO2 costs at 33 euro/tonnes	10.51	1.62	0.02

The A factor is for all trials the same. This is due to the fact that the A factor is independent of the load. The B factor is a lot higher than calculated with the traloss model. In this case the changing of the B factor did not influence the choice of the transformer as can seen from table 10. Nevertheless it shows that taking the average loading of the wind turbine is not correct. By using the average load, the B factor will always be lower than using the loading distribution. However not everybody uses statistical tools to evaluate which transformer is the most economical.

Table 10 Probabilistic results of other outputs of Traloss

	CO2 costs 0 euro/tonnes	CO2 costs 10 euro/tonnes	CO2 costs 33 euro/tonnes
CO2 emissions oil C-C’	8.99	8.98	8.99
CO2 emissions oil D-D’	7.64	7.63	7.63
Capitalized costs oil C-C’	31784	32720	34919
Capitalized costs oil D-D’	30564	31359	33228
Pay back time oil D-D’[2]	10.57	10.29	9.24
IRR oil D-D”[2]	12%	13%	14%

It should be noted that only the averages of these quantities are displayed in table 10. But each quantity also has a probability distribution.

5.3 Discussion – selection of optimum transformers

There is a large difference between the B factor determined deterministically and the B factor determined probabilistically. This could result in a wrong transformer choice. The differences should therefore be clarified.

The load has an asymmetric spread with a so-called bathtub curve (see figure 12). If this load were fixed for the whole lifespan of a transformer only one B factor would have been necessary to select the optimal transformer. In the deterministic case this has been done. The load is assumed to be 291 (the average load). This resulted in a fixed B factor of 0.79. But the load is distributed and therefore the B factor is distributed (see figure 13).

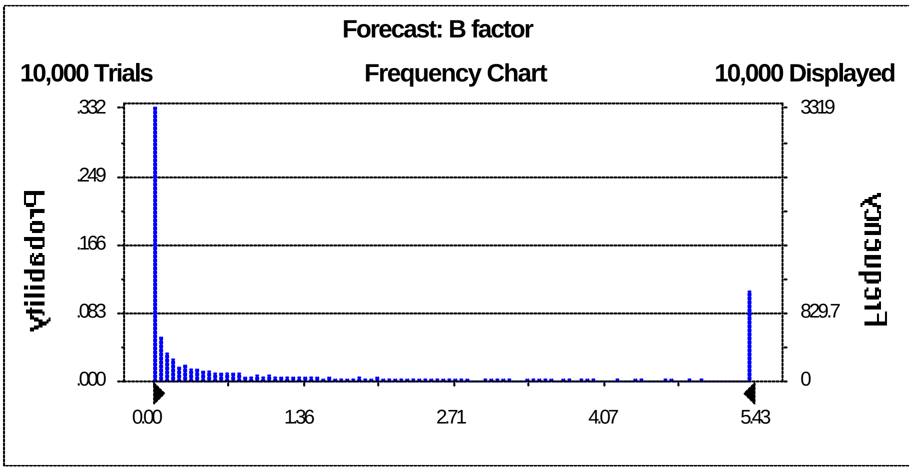


Figure 13 Distribution of the B factor

[2] The Pay Back time and the IRR cannot be calculated for all cases. Therefore the average has been taken over the trials were a positive pay back time and IRR have been found.

The transformer should be optimal for several different (fluctuating) loads and fluctuating B factors. Therefore the average B factor for the lifespan of the transformer has been calculated. This B factor has a spread that is much smaller (standard deviation is a factor $\sqrt{8760}$ smaller, to be exact). The distribution of this B factor can be found in figure 14.

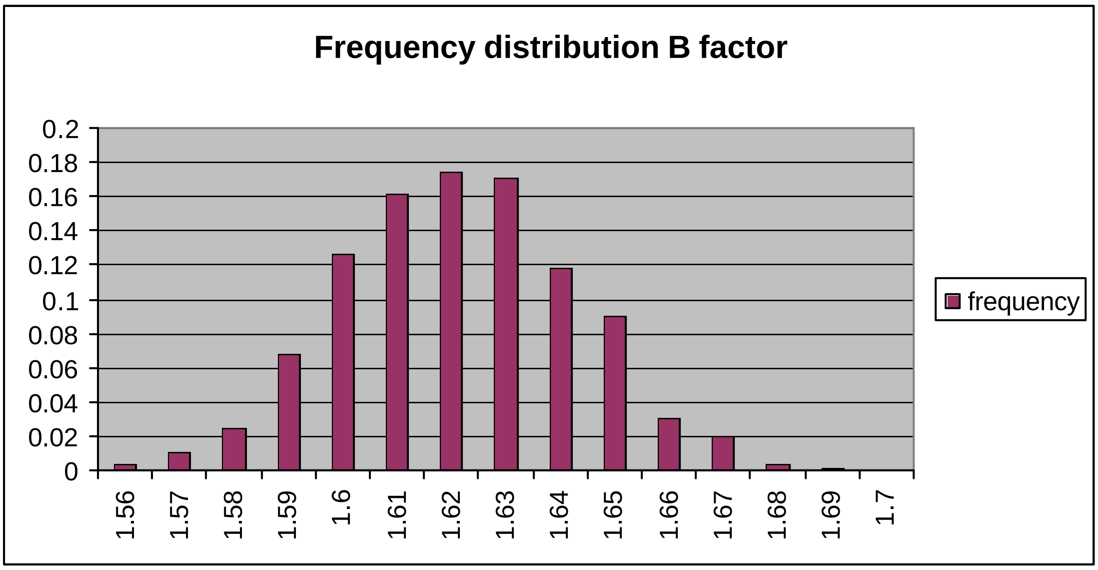


Figure 14 Frequency distribution of the B-factor with CO2 costs 33 euro/tonnes

So far, the B factor was calculated from the average loading, based on the energy production by the wind turbine during one year. If instead of the average load the average of the losses were taken, the probabilistic B factor would have been found.

The average of the losses can be taken from figure 12. Since the load losses are quadratic with the load, the average loss (based on the 750 kW wind turbine) equals 27% during a year. The transformer loading at which the load loss equals 27% of the rated load loss, equals 52% (390 kW). The average of the distribution of this quantity has to be used in Traloss to find the average probabilistically determined B factor. So by changing the loading of the transformer in the Traloss software to 390 kW, the following results are found:

Table 11 Deterministic results wind case

	A factor (Euro / W)	Loading = 390 kW	Loading = 291 kW
		B factor (Euro / W)	B factor (Euro / W)
CO_2 costs 0 euro/tonnes	9.28	1.41	0.79
CO_2 costs 10 euro/tonnes	9.65	1.47	0.82
CO_2 costs 33 euro/tonnes	10.51	1.60	0.89

As can seen from table 9, these B values met the values produced with the probabilistic method. So without using a probabilistic tool it is possible to make an estimation of the B factor if the loading changes. If the average losses are taken in account it is possible to use the Traloss model for evaluation of the transformers instead of using a probabilistic model.

5.4 Market opportunities for transformers at wind turbines

Figure 15 gives the power installed in the EU by the end of 2002. The expected growth in Europe of wind energy is according [6] from 23.8 GW by the end of 2002 up to between 40 and 60.0 GW in 2010. For this study we take the average 50 GW. According to [6] the average size of new wind turbines being installed is expected to grow over the next decade from today's figure of 1 MW to 1.3 MW in 2008 and 1.5 MW in 2013. If an average size of 1.5 MW is taken, the total number of wind turbines during 2003 – 2010 will be about 17500. It is expected that the electricity price will be lower in 2010.

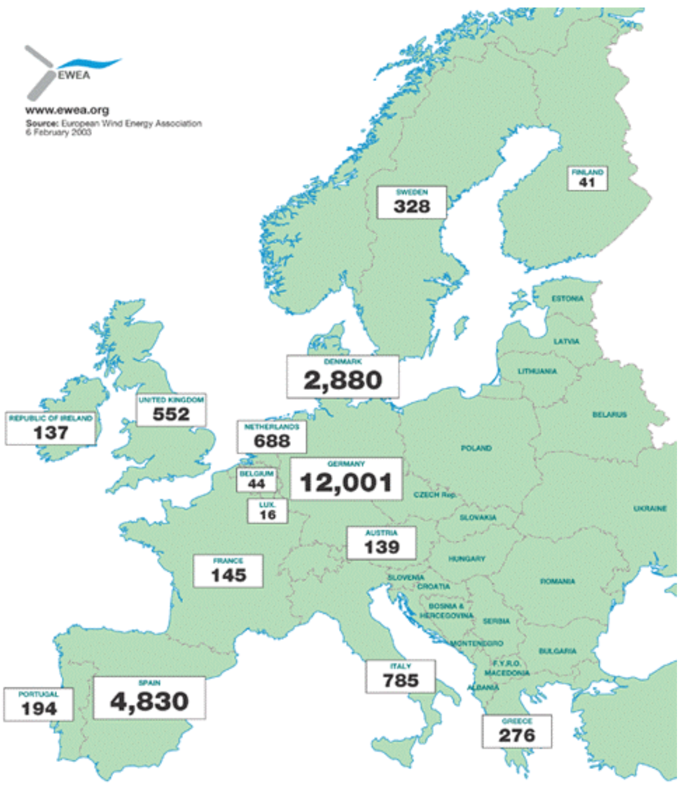


Figure 15 Installed wind power (MW) by the end of 2002 in EU

Presuming that a transformer of 1600 kVA will be used and the power curve is the same as given in figure 5.3 (scaled up to 1500 kW) the consequences can be calculated for the transformer market. Using the traloss model, the equivalent loading on which the same losses are produced equals 780 kVA. The consequences of the larger physical size of energy-efficient transformers have not been considered.

Table 12 shows the input data for the market situation in 2010. Also shown are the economic loss evaluation factors resulting from the input data. We presumed that the electricity price is 75 Euro/MWh.

Table 12 Input data 1600 kVA oil type transformer

Transformer load	**Depending on the wind speed, average load 48,8%**
Economic lifetime	20 year
Interest rate	7%
Energy price	EUR 75 /MWh
A (no-load loss evaluation)	EUR 6.96 /W
B (load loss evaluation)	EUR 1.65 /W

Based on these values, the key output data are given in table 13.

Table 13 Outcome 1600 kVA transformer

	Unit	**Oil C-C'**	**Oil D-D'**	**Difference**
Transformer rating	kVA	1600	1600	
Rated no-load loss	W	1700	1445	-225
Rated load loss	W	14000	11900	-2100
Total annual losses	kWh/a	44038	37432	-6606
CO_2 emission @ 0.4 kg/kWh	ton/a	17.6	15.0	-2.6
Purchase price	EUR	10865	12832	1967
Present value no-load loss	EUR	11832	10058	-1774
Present value load loss	EUR	23158	19685	-3473
Capitalised costs	EUR	45856	42574	-3282
Pay Back (years)				4
Internal rate of return				25%

Although the oil transformer with low losses (D-D') has a purchase price that is 18% higher than the oil transformer C-C', it is clear that the D-D' transformer is in fact the most economical transformer. Even without evaluation of the CO2 emission values, the D-D' transformer is the least expensive transformer during the lifetime (pay back period 3 years). At a CO2 evaluation of 10 Euro the difference in capitalised costs is 3562 Euro (A factor = 7.33 Euro/W; B = 1.74 Euro/W; at a CO2 evaluation of 33 Euro the difference is 4205 Euro (A = 8.19 Euro/W; B = 1.95 Euro/W).

Table 14 gives the potential annual energy and CO2 emission savings for wind energy, if with all 17500 new wind turbines, until 2010, a 1600 kVA energy efficient oil type transformers D-D' are placed instead of the C-C' transformer.

Table 14 Estimated annual electricity saving of transformers at wind energy in Europe by 2010

Economical sector	Electricity production (TWh)	Losses in distribution transformers (GWh)	Savings potential (GWh)
New wind energy	90	771	116

Application of transformers in all new wind turbines offers a savings potential of approximately 116 GWh/year at 2010. The associated CO_2 emission reduction would amount to 46,000 tonnes/year, or 0,014% of the 340 Mton emission reduction target of the European Union for 2012. It should be noted that the above given values can be even higher since:

- The expected 50 GW wind production capacity at 2010 may be higher
- More efficient transformer types could be employed, outside the range considered
- Replacement of existing wind turbines is not taken in account
- The transformers as given in study [3] are taken. These transformers are not optimised for wind energy but for industry. Since the A and B factor are different compared with industry, the optimised transformer for wind energy will have different losses.

Amorphous transformers at wind turbines

Since the A factor for wind turbine is relatively high, it was decided to perform a study with an amorphous transformer. Although the information about these transformers is based on a 400 kVA transformer (see [1]), the benefits of using these transformer at wind turbine can be found (in theory) by performing a study based on a 300 kW wind turbine with the adjusted PV curve from the 750 kW wind turbine. Based on the losses, the power of the wind turbine is equivalent to 156 kW.

If the lifetime is 20 years, the interest rate is 7% and the energy price is 100 Euro/MWh the A factor is 9,28 Euro/W and the B factor 1,41 Euro/W. The results as shown in table 15 are found when the amorphous transformer (Oil C-AMDT) is compared with a regular C-C' oil transformer:

Table 15:outcome 400 kVA transformer

	Unit	Oil C-C'	Oil C-AMDT	Difference
Transformer rating	kVA	400	400	
Rated no-load loss	W	610	160	-450
Rated load loss	W	3850	3850	0
Total annual losses	kWh/a	10473	6531	-3942
CO_2 emission @ 0.4 kg/kWh	ton/a	4.2	2.6	-1.6
Purchase price	EUR	4874	6787	1913
Present value no-load loss	EUR	5661	1485	-4176
Present value load loss	EUR	5435	5435	0
Capitalised costs	EUR	15969	13706	-2263
Pay Back Time (years)				5
Internal rate of return				20%

This example shows that application of amorphous transformers in wind turbines promises such high energy savings (~40%) that they would present a good economic case, despite the significantly higher (~40%) purchase price.

NOTE: mass-scale application of amorphous-cored transformers has so far been limited to small with sizes < 100 kVA. Development of transformers > 400 kVA has so far been very limited due to several technical limitations.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

- Determining A and B loss evaluation factors statistically, considering fluctuating energy prices (no price trend), yields results equal to deterministically calculated figures e.g. by the Traloss tool. Deterministic calculations are therefore appropriate to make transformer investment decisions.
- The loss evaluation factor for the no-load (A factor) for transformers at wind turbines is high compared to transformers placed at industries or public grids. Reasons are:
    - The energy price for the production of power is higher at wind turbines (100 Euro/MWh).
    - The lifetime of a wind turbine is long (20 years).
- The loss evaluation factor for the load (B factor) for transformers at wind turbines is comparable with other distribution transformers. Although the energy price is high, the average loading of the transformer is small, because of the fluctuation of the power produced by the wind turbines.
- Although the energy production of a wind turbine is fluctuating (due to the wind speed distribution and the power curve of a wind turbine), transformer losses can be calculated easily by assuming a loading with equivalent losses.
- Energy savings of transformers at wind turbines can be calculated with the Traloss tool.
- Based on the wind speed distribution at sea in the Northern Europe, energy efficient transformers economically justified.
- Since the wind energy market is growing rapidly, there is a market to promote the use of energy-efficient transformers.
- The potential energy savings by application of energy efficient transformers at wind turbines is about 116 GWh at 2010.
- The range of the transformers depends on the size of the wind turbines. Since the size of the wind turbines is growing, the range of the transformers will also be growing. The range of the transformers for the future years will be between 1000 and 2500 kVA.
- A study performed with a small wind turbine (300 kW) and an amorphous core transformer, shows that at wind turbines amorphous transformers are the best choice.
- Energy efficient transformers tend to have larger weights and sizes than the transformers placed so far at wind turbines.

Some **QUESTIONS & ANSWERS** answered by the study presented in this report

Q: Is there a difference in the results using average prices or the distribution of the prices?
A: No, there is no difference in the results. For fluctuating prices around a stable mean the deterministic version of Traloss can be used for the optimal transformer selection.

Q: Is there a difference in the results using the average load or the distribution of the load of a wind turbine?
A: Yes, there is a large difference in the B factor and in the optimal transformer choice.

Q: What is the influence of probabilistic calculations on the A and B factor?
A: The A and B factor will have a distribution as well. Because of the dependence of the B factor to the load (in a quadratic way) there is a large difference between the deterministic B factor and the probabilistic B factor.

Q: Is Traloss (a deterministic model) good enough to determine the A and B factor (and with these the optimal transformer for a certain user) or should a probabilistic model be used?
A: If there is only a fluctuation in the prices and not a growth the deterministic version of Traloss is good enough to deal with this problem. For the fluctuations in the load there has to be found a rule of thumb to deal with the uncertainty. Just taking the average loads leads to wrong conclusions.

Q: Is it possible to find a rule of thumb between deterministic answers and probabilistic answers?
A: Yes, this is possible.

6.2 Recommendations

- The price model was only calculated for a small industry. For a utility also the clearance prices have to be included. Especially because a utility does not know its future load so precisely. Therefore apart from the variation in prices, a variation (uncertainty) in the load will arise. We propose to determine the influence of this combination.
- Instead of changing Traloss into a probabilistic model to deal with wind turbines it is possible to find a method for different wind speeds and wind turbines to be included into Traloss.
- The model has not tested the effect of a growth in a certain parameter (price, load). The effects of this should be tested.

- It is recommended to investigate the application potential for amorphous transformers in wind turbines, including the technological feasibility.

6.3 Action plan to promote energy-efficient distribution transformers

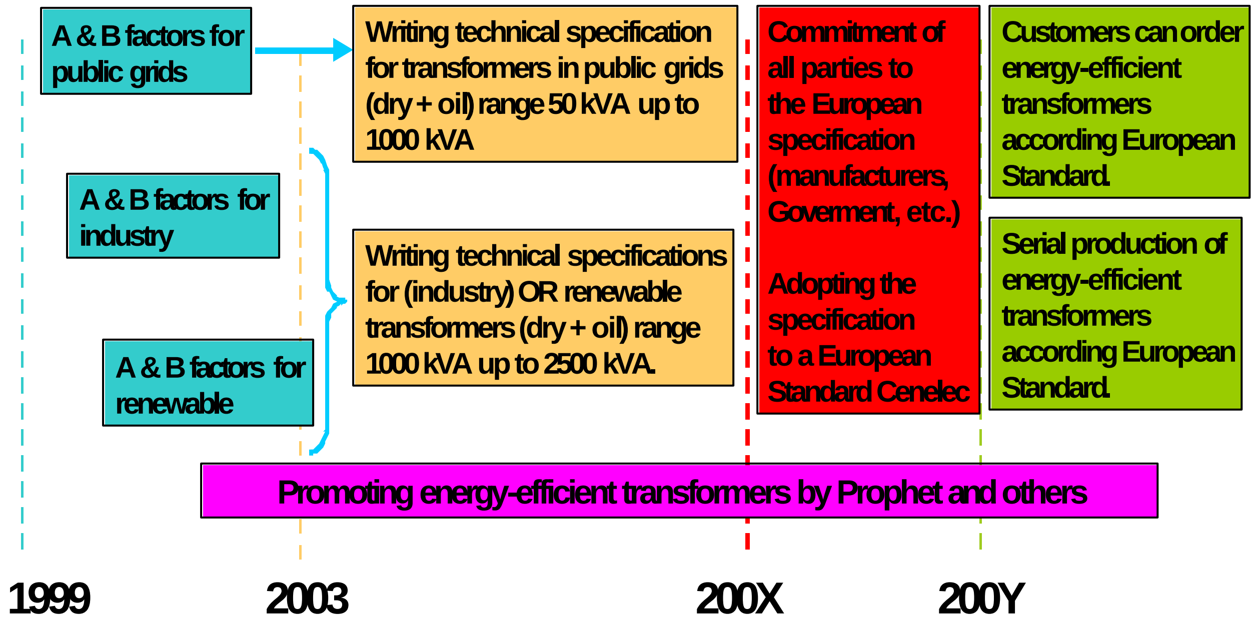


Figure 16 Recommended action plan.

Since 1999 several studies on energy-efficient distribution transformers have been performed. The results presented in this report and in [1,3] all have the same result: technically and economically, energy-efficient distribution transformers are a real alternative to conventional transformers. Next to the technical and economical issues, energy-efficient transformers reduce the CO_2 pollution. The studies so far focused on:

- Distribution transformers in public grids (50 kVA up to 1000 kVA)
- Distribution transformers located at industries (1000 kVA up to 4000 kVA)
- Distribution transformers at wind turbines (1000 and 1600 kVA).

However national governments and the EU do not yet facilitate or promote the use of energy-efficient transformers. Even nowadays it is a rule that grid companies considering investing in energy-efficient components, do not get the (economical) benefits. The users pay for the losses in the grid, which means there is no financial incentive for the grid owner to buy energy-efficient transformers. Regulators should pay attention to this problem, as it is strange that governments, on one hand, want to lower the CO_2 emissions, and on the other hand do not give any incentive for energy-efficient components. **First step: national governments**

(or EU) should promote energy-efficient components and provide incentives for energy-efficient measures.

Even if regulators do promote the use of energy-efficient transformers, it is not likely that every transformer will be replaced with an energy-efficient transformer on the short term. The technical lifetime of transformers is 30-50 years. However if a transformer should be replaced energy-efficient transformers should be promoted.

In all the studies so far, the assumed purchase prices of the distribution transformers are based on serial production. If it is not possible to build energy-efficient transformers in serial production, the cost price of the transformers is expected to be that high, that it is not possible to earn back the investment. Therefore all EU countries should work together to specify a range of energy-efficient transformers. As long as customers do not know these transformers, no one will buy them. **The second step in the action plan is to make a European specification for a range of energy-efficient transformers (to be made in serial production).** This is the most critical step, since every country has it own specification and range. **Before this step can be done the feasibility to get one EU specification should be studied**. This can be done for several customers. For example the transformers with a range up to 1000 kVA can be manufactured specially for the grid owners and transformers above 1000 kVA up to 2500 kVA should be made for industries and renewables. Perhaps the range should be set up for oil- and dry-type transformers.

The third step is to promote energy-efficient transformers by education of (possible) costumers. This means they should not only look at the purchase price of a transformer, but should be capable to make their own calculation to see what the benefits of an energy-efficient transformer for his/her company are. Education by writing articles or giving presentations at conferences gives goods opportunity.

The last (or perhaps the first step) is to give an energy-efficient transformer a sensational name instead of a D-D' energy-efficient transformer. A good example of a marketing aspect in the Netherlands is the way a grid company promotes renewable energy. The company does not talk about renewable energy, but gave it the name “groene stroom” (green current). The name became that well-known that some customers were asking competitors for “groene stroom”. Why not give the energy-efficient transformer a name? Maybe a purchaser feels more convenient if (s)he can say (s)he is buying “green transformers” to make his/her contribution to the environment. Instead of given the transformer a name it is also possible to give transformers energy labels (similar to cars and household equipment).

References

[1] The scope for energy saving in the EU through the use of energy-efficient electricity distribution transformers, European Copper Institute, December 1999.

[2] Article: “Financial considerations of Small-scale wind power installations” magazine Renewable energy 2003, L. Pichler AG.

[3] Energy savings in industrial distribution transformers, W.T.J. Hulshorst, J.F.Groeman, KEMA 2001

[4] www.efficient-transformers.org/traloss.htm

[5] European Wind Energy Conference & Exhibition in Madrid on 16, 17 and 18 june 2003.

[6] Wind Force12, EWEA 2002.

[11] J & P Transformer book, twelfth edition 1998, Martin J. Heathcote.

APPENDIX A: DATA SHEET TRANSFORMERS

For a previous study [3], Pauwels Trafo made basic designs for different types of transformers rated between 1000 and 4000 kVA for industrial use. Since the range of these transformers can also be used for transformers placed at wind energy, the same transformers have been used in this document. Typical data of the transformers are given in the table below.

As can be seen, four different transformers were chosen with rated powers of 1000, 1600, 2500 and 4000 kVA (second row). The information is based on oil-immersed transformers and dry-type transformers. For each type of transformer calculations have been made with the losses according to or in line with HD 428 or HD 538 and losses with 15% reduction. It should be noted that the values given in table A are rough indications and can only be used for the purpose of this study. The prices are based on the year 2001.

Table A Calculated losses for industry transformers (source: Pauwels)

Typical Industry Transformer Parameters																	
rating	**kVA**	**1000**				**1600**				**2500**				**4000**			
HV	**kV**	**10**				**10**				**10**				**10**			
LV	**V**	**420**				**420**				**420**				**420**			
Uk	**%**	**6**				**6**				**8**				**8**			
LOSS-LEVEL		Oil CC'	Oil DD'	Dry base	Dry Low	Oil CC'	Oil DD'	Dry base	Dry Low	Oil CC'	Oil DD'	Dry base	Dry Low	Oil CC'	Oil DD'	Dry base	Dry Low
NO-LOAD LOSSES	W	1100	935	2000	1735	1700	1445	2800	2670	2500	2125	4300	4130	3800	3230	7000	5540
LOAD LOSSES 75 ºC	W	9500	8075	8600	7270	14000	11900	10000	9350	22000	18700	18000	14930	34000	28900	27000	26630
TOTAL MASS	kg	2715	3157	2530	2800	3900	4210	3840	3900	4925	6065	5350	5410	8885	10108	7660	7710
HEIGHT	mm	1890	1800	1560	1620	2090	2090	1830	1820	1925	1915	2040	2130	2485	2415	2470	2410
LENGTE	mm	1500	1540	1710	1690	1875	1795	1920	1840	2360	2370	2160	1980	2545	2545	2310	2360
WIDTH	mm	950	1800	940	940	1155	2090	940	940	1235	2370	1230	1230	1375	2545	1230	1230
T HS (F)	K	65	65	100	100	65	65	100	100	65	65	100	100	65	65	100	100
T LS (H)	K	65	65	100	100	65	65	100	100	65	65	100	100	65	65	100	100
SOUND POWER	dB(A)	56	51	68	61	68	57	70	67	69	59	74	73	72	60	80	77
EFFICIENCY (*)	%	98,94	99,10	98,94	99,10	99,02	99,17	99,20	99,25	99,02	99,17	99,11	99,24	99,06	99,20	99,15	99,20
UNIT COST	Euro	8007	10353	10074	11108	10865	12832	14451	14990	13670	17887	17951	19073	24987	29402	25527	27494
UNIT COST	%	**100**	129	126	139	**100**	118	133	138	**100**	131	131	140	**100**	118	102	110

(*) at full load and cos phi = 1