Prof. em. Dr. Gustav M. **OBERMAIR**
Swakopmund, Namibia

Prof. Dr. L. **JARASS**, M.S. (Stanford Univ./USA)
Hochschule RheinMain, Wiesbaden, Germany

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Efficient grid extension for strongly fluctuating energy sources
Wirtschaftlich effizienter Netzausbau für stark fluktuierende Energien

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Kurzfassung

Die statistische Verteilungsfunktion einer Energiequelle mit fluktuierender Produktion wird gewöhnlich als ´Leistung-Dauer-Kurve´ dargestellt. Es wird gezeigt, dass die entscheidende ökonomische Funktion, die den Grenznutzen einer solchen Quelle wie z.B. Windenergie angibt, direkt aus dieser ´Leistung-Dauer-Kurve´ abgeleitet werden kann.

Als eine Anwendung wird die ökonomisch optimale Erhöhung der Übertragsleistung von Höchstspannungsleitungen (´Netzausbau´) bestimmt als Schnittpunkt der Grenznutzenkurve der durch den Netzausbau zusätzlich einspeisbaren Windenergie und der Grenzkostenkurve des Netzausbaus.

Abstract

The statistical distribution function of the yield of a source of strongly varying output is usually presented as a ´power-duration-curve´. We show that the decisive economic curve representing the marginal benefit of such fluctuating sources like wind energy can be derived directly from this distribution function. This may allow to determine the optimum investment in renewable energy systems.

As one application we determine the economic optimum limit power of high voltage lines devoted to long distance transmission of wind energy as the intersection of the marginal-benefit-curve of the energy produced and the marginal-cost-curve of the transmission line.

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1 Starting point: cost-benefit-analysis

The problem of finding the economic optimum design for components of renewable energy systems with their strongly fluctuating output plays a decisive role in the ongoing large-scale development of wind as one of the dominant new energy resources.

On the more general level of the public power supply system as a whole the determination of the economic optimum has lately become a really urgent and hotly debated problem, involving investments of billions of Euro, since the rapidly growing share of wind generated energy has to be absorbed and transmitted by the grid. It is here that the interests of the wind energy trade conflict with those of the utilities that have to provide the required high voltage transmission capacity. But: How much is required? This issue has caused serious disputes and court proceedings in recent years. There are two central questions for which a rational approach will be developed in this paper:

- What is the economically optimal limit load to which the grid has to be extended: 100%, 90% or maybe only 65% of the total generator power of all wind parks feeding into the adjacent control zone of the grid?
- How much of the typical annual wind energy production will be discarded (e.g. by regulating the power production of the wind turbines), 0.3%, 1%, 3%, if the grid is not extended to 100% of the installed wind generator capacity, but only to the economic optimum?

Both the benefit of non-polluting energy generation and the cost of additional transmission capacity are passed on to the population at large as part of their electricity bill. Hence the search for the cost-benefit-optimum is a problem of general economics for which in theory there is a well-known solution: The optimum is reached at the point where the marginal benefit of an investment equals its marginal cost, see sec. 2.

The paper is organized as follows:

After this introduction sec. 2 gives a short sketch of the general theory of optimization and of a more specific and precise model of benefit and cost within a public or at least government regulated power supply system with a large and growing share of renewable resources. The decisive independent variable that largely determines benefit and cost is the limit (electrical) power P available or permissible in the system.

Sec. 3 presents a new result that is essential for any strongly fluctuating source of electrical energy (and, at least in principle, of any other commodity). Starting point is the statistical distribution function F(P) of the stochastic variable momentary power P(t). The function G(P) = 1 – F(P) gives the relative duration, e.g. hours per year, for which the available power equals or exceeds the value P. This same function G(P) is then shown to represent the marginal energy benefit of a limit power increase, i.e. additional annual energy yield per additional limit power.

Sec. 4 deals with the problem of valuation and monetarization of the energy yield described by the function G(P) and its benefit for the investor and for society at large. After defining the appropriate monetarization factor m representing the valuation of an energy input in Euro/kWh, the function m*G(P) indeed yields the marginal benefit of an increase of the limit power (additional Euro/year per additional kilowatt of limit power). This is the function needed to determine the economic optimum for the technical specification of the system.

Sec. 5 gives some results of a recent study. One important result: Long distance transmission lines that are to transmit additional GW of power generated by wind parks near the German coast on the North and Baltic Sea should be built up to no more than the economic optimum; this optimum limit power lies at about two thirds of the total installed wind generator power. Yet in spite of this limitation only around 0.5% of possible wind energy generation would have to be discarded by so-called production management by which the transmission line operator reduces the power output of the wind turbines when an overload of the grid is to be expected during the brief and very rare interludes of simultaneous strong wind in the entire region.

2 Optimum problems within renewable energy economics

A theory of optimization was originally formulated in neoclassical economics in terms of general equilibrium theory based on the (not altogether realistic) model of a perfect market economy: i.e. non-monopolistic structures, transparent market prices, high velocities of adjustment and low transaction cost. In this model the rates of deployment of the different production factors are then introduced as independent variables in a variation principle calculation to determine the equilibrium point in the multidimensional state space. This point represents the optimum (i.e. a maximum with restraints) of the assumed benefit function.

The problem to be treated here is the optimum design for components of an electricity supply system with a large and still growing share of renewables like wind, see (Desire, 2008) and (Hulle, 2009). This reqires a rather different approach: a somewhat less complex but more realistic and precise model involving only one predominant independent variable, the limit power (kW, MW, GW) of the critical component, e.g. of the electrical generators of the power stations or of the conductors, transformers etc. of the relevant grid. This limit power P serves as a satisfactory proxy for the deployment of the production factor capital C involved in the modernization and reinforcement of the power supply.

The other essential difference with respect to the free market model sketched above lies in the fact that in practically all European countries parts of the power supply sector is strongly regulated for several reasons:

- The entities that own, control or operate the grid, whether public or private utilities, have a ´natural´ monopoly in their national or regional control zone.
- By legal regulation in many European states a lower limit for the remuneration of the suppliers of renewable energy has been set in order to support the growth of the renewable sector.
- On the other hand the tariffs for transmission and delivery of electric energy are controlled by legal regulation in most of the states in order to prevent monopolistic extra profits.

In spite of these non-market elements an economic optimum of the system can be determined: For lack of market forces the pressure for cost efficiency of the electric energy supply may be brought about by government regulatory agencies. The benefit of renewables for society at large consists of the avoided cost of fossil fuels plus the avoided social cost of CO_2-emission and other pollution. Hence the average annual energy input that can in fact be fed into the grid serves as a measure for the gross benefit of this non-fossil and non-nuclear energy supply. Since both the amount of this input and the cost required to provide it are determined by the permissible power P of the generators or the relevant transmission lines, the net yield Y, i.e. the difference between gross benefit N and cost C becomes a function of this independent variable P:

$$Y(P) = N(P) - C(P). \tag{2.1}$$

For the gross benefit N(P) the general rule of decreasing marginal benefit holds, for the cost C(P) the rule of approximately constant ´scale´, i.e. marginal cost holds. This is shown in fig. 1 for N(P) and C(P), in fig. 2 for the derivatives $N_P(P)$ and $C_P(P)$:

Fig. 1 : Benefit and cost as a function of permissible power

Gross benefit N and cost C in arbitrary monetary units as a function of relative permissible power p.

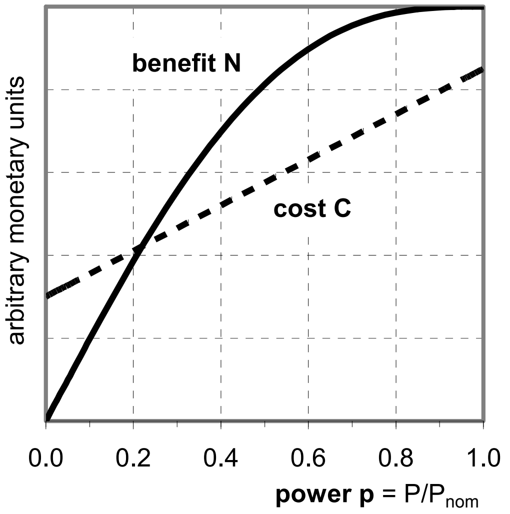
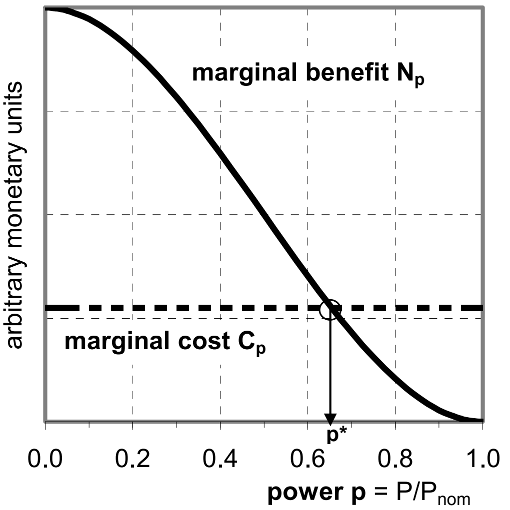


Fig. 2 : Marginal benefit and marginal cost as a function of permissible power

Marginal gross benefit $N_p = dN(p)/dp$ and marginal cost $C_p = dC(p)/dp$
in arbitrary monetary units as a function of relative permissible power p.



In these schematic drawings and in all further figures the independent variable P is replaced by the dimensionless relative quantity p, i.e. by a fraction of the nominal power installed in the respective system

$p := P/P_{nom}$. (2.2)

The range of values of p is the interval [0,1] in each case, allowing a uniform graphic representation of quite different situations.

Benefit N, Cost C and the net yield $Y = N - C$ will be shown in arbitrary, but identical monetary units.

In equations, the above-mentioned rules read as

$N_p = dN/dp > 0$ and $N_{pp} = d^2N/dp^2 < 0$. (2.3)

Moreover, we assume the benefit to saturate at the limit and hence

$N_p(p=1) = 0$. (2.4)

These statements are strictly true for the production and transmission of the benefit wind energy:

- for the individual wind turbine, because its efficiency has to be decreased at and above the design wind speed (between 12 m/s and 15 m/s for modern large plants) and the power output has to be strictly limited when it approaches $P = P_{nom}$ in order to avoid mechanical or electrical overload;
- for a total of wind parks in a large region, because simultaneous strong winds at all sites producing the nominal power of each generator, are an extremely rare meteorological situation.

Thus in both cases $N_p \rightarrow 0$ for $p \rightarrow 1$.

For the cost C(p), as already mentioned, we assume the usual rule of constant scale cost; hence the marginal cost C_p is constant at a given choice of technology:

C_p := constant at a given technology, (2.5)

with jumps to higher marginal cost at the thresholds where a more costly technical solution (like probably in the future cables for very high voltage DC) becomes necessary.

To find the equilibrium point p*, where the net yield has an extremum, we rewrite eq. (2.1) in terms of the relative power p, take the derivative with respect to p and set it equal to zero:

$Y(p) = N(p) - C(p)$, (2.6a)

$dY(p)/dp = N_P - C_P =! 0$ at $p=p^*$. (2.6b)

Hence

$N_p(p^*) = C_p(p^*)$; (2.7)

the intersection of the marginal benefit and the marginal-cost-curves determines the optimum limit power p*, cf. fig. 2.

To make sure that this equilibrium point is indeed an economic optimum, one decisive constraint has moreover to be taken into account: At the equilibrium point p* the net yield $Y^* := Y(p^*)$ must be positive and the profit rate sufficiently high to justifiy the investment.

Eq. (2.7) together with this constraint define the economic optimum for power supply systems. The consequences for systems with strongly fluctuating sources will be treated in the following section.

As eq. (2.2) and the sketch in fig. 2 indicate, the typical marginal-benefit-curve decreases throughout and approaches zero for high values of the permissible power. Hence the intersection of this curve $N_p(p)$ and the marginal-cost-curve $C_p(p)$, giving the optimum limit power p* sought after and hence the optimal investment in terms of the power for which the system ought to be designed, depends very critically on a precise knowledge of this marginal-benefit-curve for strongly fluctuating sources.

3 Marginal energy benefit of a fluctuating energy source

3.1 Statistical properties of a fluctuating energy source

Again the momentarily available power P(t) delivered by the system or subsystem of power supply under consideration will be expressed as the fraction $p(t) = P(t)/P_{nom}$, where P_{nom} is the actually installed power capacity of the equipment.

To characterize the statistical properties of a fluctuating quantity like this momentary power p(t) delivered by a renewable energy source, one may start with its probability density f(p), that is the relative frequency with which the values of p between 0 and the maximum P_{nom} occur during a period of one year or several years. f(p)dp gives the fraction of this period during which p is found in the interval from p to p+dp. The function f(p) has the properties

$$f(0) = 0, \qquad (3.1a)$$

$$f(p) = 0 \text{ for } p > 1, \qquad (3.1b)$$

$$\int_0^1 f(p)dp = 1 : \text{normalization}, \qquad (3.1c)$$

because the total probability to find the value of p anywhere between 0 and 1 must be equal to 1.

The (indefinite) integral

$$F(p) = \int_0^p f(q)dq \qquad (3.2)$$

where F(1) = 1 because of eq. (3.1c),

is called distribution function of p(t); it gives the relative duration, i.e. the fraction of the entire period, during which the power of the source assumes values between 0 and p.

The complement of F(p), defined as

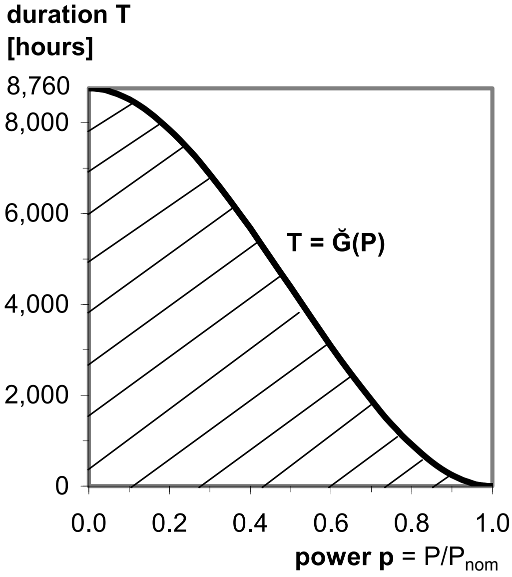
$$G(p) = \int_p^1 f(q)dq = 1 - F(p), \qquad (3.3)$$

gives the relative duration T during which the delivered power exceeds p. The function T = G(p) is usually called duration-power-curve; its inverse $p = G^{-1}(T)$ is known as the power-duration-curve.

Institutes monitoring the production of renewable energy, e.g. (Fraunhofer, 2009), regularly publish this inverse for wind energy in Germany, where the delivered power as a fraction of P_{nom} is plotted on the vertical axis against T, the duration as a fraction of the total period considered.

Fig. 3 gives a schematic plot for a duration-power-curve for a wind park in one year at a very favourable site like offshore in the North Sea, rescaled such that duration T is given in hours of the year from 0 to 8,760 hours.

Fig. 3 : The rescaled duration-power-curve T = Ğ(p)



3.2 Marginal-energy-benefit-curve

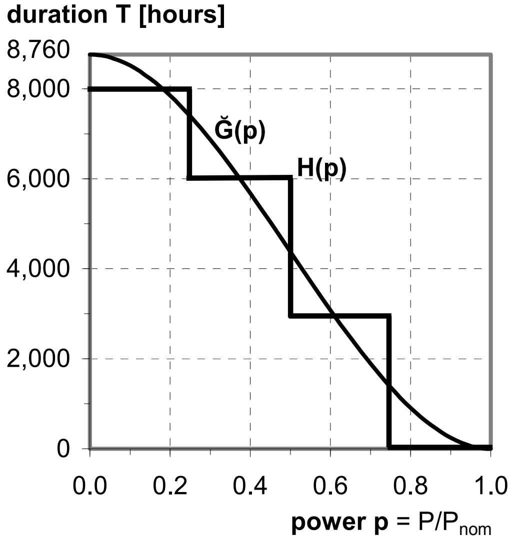
The first decisive step from statistics to economics lies in the following insight: The cross-hatched area below the function Ğ(p) multiplied with the value of P_{nom} – the total generator power of the fluctuating power stations feeding into the grid – is proportional to the possible total annual energy benefit E_{nom} of these sources. This cross-hatched area is given by

$$E_{nom} = P_{nom} * \int_0^1 \check{G}(p)dp. \qquad (3.4)$$

E_{nom} is the total possible annual energy production of the power stations under the condition that at any time all power available can indeed be absorbed by the grid up to the limit $P = P_{nom}$.

The insight is based on the simple fact that energy equals power times duration. This connection between the function Ğ(p) and the total energy obtainable from fluctuating sources may become more obvious in fig. 4, that shows a staircase shaped curve, the graph of the stepwise constant function H(p) approximating the original curve Ğ(p).

Fig. 4 : The stepwise constant function H(p) approximating the original curve Ğ(p)



It is easy to see that H(p) describes the following deployment of some power station:

- 75% of its nominal generator power P_{nom} is supplied for 3,000 hours;
- for another 3,000 hours the station runs at 50% of P_{nom},
- and for another 2,000 hours at 25% of P_{nom}.

Adding up these contributions this corresponds to a total energy delivered of 4,250 hours * P_{nom} [kWh/year].

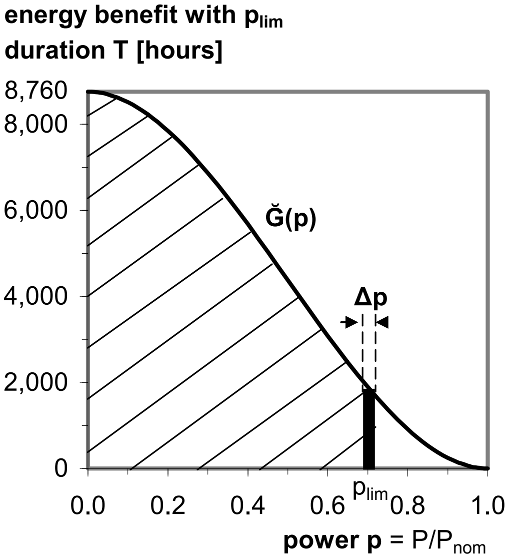
A calculation using the function shown as Ğ(p) in fig.s 3 and 4 gives the result that an energy of 4,380 hours * P_{nom} can be obtained as the ´energy benefit´ of the source described by Ğ(p), always under the assumption that the limiting power P_{lim} which the connecting lines allow to transmit from each component of the generating system to the high voltage grid is at least equal to the total nominal power of the generators involved, i.e. $P_{lim} \geq P_{nom}$ and hence $p_{lim} = P_{lim}/P_{nom} \geq 1$.

What, however, happens if P_{lim} is slightly smaller than P_{nom}, so that the occasional but rare and short power peaks approaching P_{nom} have to be cut down to P_{lim} by appropriate control of the generators or turbines, the so-called ´production management´? Obviously the energy benefit is then reduced to

$$E_{lim} = E(P_{lim}) = P_{nom} * \int_0^{p_{lim}} \breve{G}(q)\, dq. \qquad (3.5)$$

As shown graphically in fig. 5, this limited energy benefit corresponds to the cross-hatched area under the curve that, in horizontal direction, extends only to the vertical line $p_{lim} = P_{lim}/P_{nom} = 0.7$. The blank little area to the right of this line corresponds to the amount of energy E_{nom} minus E_{lim} that has to be omitted or discarded due to the limitation.

Fig. 5 : Energy benefit with power limitation



This observation leads to the function that was sought after, i.e. the energetic marginal-benefit-function:

If an investment increases the limit power $P_{nom} * p_{lim}$ by a

$\Delta P = P_{nom} * \Delta p,$ (3.6)

the additional possible energy benefit ΔE is obviously proportional to the area of the narrow black rectangle (in fig. 6) of width Δp, height Ğ(p), area Δp * Ğ(p). Hence ΔE amounts to

$\Delta E(p) = P_{nom} * \Delta p * \breve{G}(p).$ (3.7)

In the limit Δp → 0 the ratio of ΔE and ΔP goes to the differential quotient, i.e. the derivative dE/dP, which is the marginal energy benefit that we wanted to obtain. According to eq. (3.6) and (3.7) this ratio is

$E_P = dE(p)/dP = (P_{nom} * \Delta p * \breve{G}(p)) / (P_{nom} * \Delta p) = \breve{G}(p).$ (3.8)

This is the central result:

The duration-power-function Ğ(p) itself is identical with the function that was sought after, the marginal energy benefit E_p as a function of $p = P/P_{nom}$, the available or permissible power of the system.

Mathematically this result is simply the basic theorem of calculus: When physics tells us that the energy yield E(p) is the integral of the duration-power-function Ğ(p) up to the limit p, then mathematics tells us that the derivative dE(p)/dp, i.e. the marginal energy benefit, is nothing but the function Ğ(p) itself.

4 Monetarization: From ´energetic´ to economic marginal benefit

To bring the optimum problem from the abstract level of theoretical economics, cf. sec. 2, to the practical world of energy supply systems, one has to define an appropriate valuation of the benefit achieved and of the cost to be borne for each kilowatt-hour of renewable energy produced, transmitted and distributed to the customers. The question is: Who defines the monetary value of the benefit on what basis and who pays for the cost?

There is one simple case, where the beneficiary and the cost-bearer are one and the same, e.g. a person or company that invests in a renewable power station and is paid a government regulated price for the energy delivered. The investor´s optimization strategy in this case is described in sec. 4.1 below.

The controversial cases are those already sketched in sec. 1, where the conflicting interests of several parties are involved and the benefit is essentially a social benefit, because it consists not only of avoided costs for non-renewable energy resources but of avoided social costs for the avoided emission of carbon dioxide and other pollutants; thus the final beneficiary is the world population at large for a slowing down of the climate change. The cost consist of those of the investors for the renewable energy power stations and those of the utilities for the extension of the transmission grid. The final resting place for both parts of the cost is, of course, via the electricity bill the consumer of electrical energy and of the goods and services produced with it.

Now there seems to be a general agreement that the remuneration which the suppliers of renewable energy get for each kilowatt-hour delivered may be considered as a reasonable proxy for this social benefit. The total remuneration depends on the limit power P_{lim} of admissible transmission. The derivative of the benefit with respect to P_{lim}, i.e. the marginal benefit, must then be balanced against the marginal cost for the increase of this transmission limit. This proxy-definition of the benefit is also used in the German Renewable Energy Act of 2004, where an upgrading of the grid is defined as economically viable and hence obligatory for the utilities concerned, if the achieved additional revenue for the suppliers of renewable energy exceeds the additional cost for the upgrading of the grid.

Even with this apparently clear specification of the monetary benefit from renewables the actual amount of remuneration is fixed quite differently in different countries and under different circumstances. The two typical regimes are:

- Legal remuneration as presently in Germany and in many other European countries: the remuneration rate m [Euro/kWh] is constant, independent of the supply P, cf. sec. 4.1.
- Remuneration at general market prices, cf. sec. 4.2.

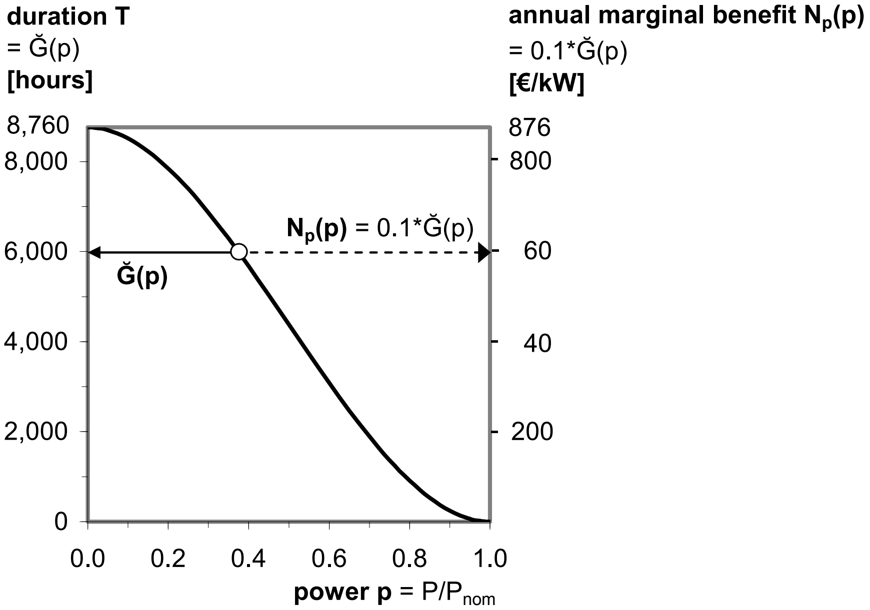
4.1 Fixed remuneration for renewable energy

Rates m in Euro per kWh are fixed by law, with different rates for the different renewables, with a fixed decrease according to year of admission and some slight differences according to location and specific circumstances. For wind energy generated onshore this rate m amounts presently in Germany between 0.07 and 0.10 Euro per kWh for the first 20 years, for offshore generation to 0.15 Euro per kWh for the first 12 to 15 years depending on water depth and distance from shore. The transmission companies adjacent to the sites are obliged to accept, transmit and pay the rates for the renewable energy supplied, utilities which deliver electrical energy to the final customers have to take renewable energy proportional to their electric energy share. The difference between payed renewable energy rates and received prices are passed on to all German electricity consumers in the form of a ´renewable energy levy´.

In this case of constant remuneration the marginal-benefit-function $N_p(p)$ is obtained from the rescaled duration-power-function $\check{G}(p)$ shown in fig. 3 by simple multiplication with the appropriate constant value of m. This is shown schematically for an average payed renewable energy rate m = 0.1 Euro per kWh in fig. 6.

Fig. 6 : Duration-power-curve and marginal-benefit-curve at constant remuneration

Marginal-benefit-curve $N_p(p)$ = m * duration-power-curve $\check{G}(p)$
at constant remuneration m = 0.1 Euro/kWh independent of wind energy supply.



This curve representing $N_p(p)$ enters the optimization: Its intersection with the marginal-cost-curve for the annualizied investment plus maintenance of the required additional transmission power of the grid determines the equilibrium point, where the net yield Y(p) for society at large has its maximum.

The system of remuneration for the supply of renewable energy described above has not been changed when a kind of market has been introduced from 2010 onwards for the distribution of electrical energy in Germany: All renewable energy, after having been paid to the producer at the described regulated rates by the utilities, must now be offered on the spot market at the European Energy Exchange (EEX) in Leipzig/Germany or other energy exchanges. As before the difference between payed renewable energy rates and received EEX-rates is passed on to all German electricity consumers in the form of a ´renewable energy levy´. For periods of large supply (e.g. periods of strong wind) and low demand, the price may approach zero, in the opposite case it may by far exceed the legal remuneration of around 0.07 to 0.15 Euro/kWh. The supplier of renewable energy, however, is also in the foreseeable future paid at the regulated rates in Germany.

4.2 Remuneration for renewable energy at general market prices

Remuneration for renewable energy at general market prices has been introduced long since in some countries: All suppliers of electrical energy, both conventional and renewable, offer packages of a certain power and duration on an exchange or spot market for the following hours. The remuneration thus depends strongly on the balance of supply and demand and is governed by the marginal production cost of the last power plant to be deployed. The incentice for investment in new generating facilities, both renewable and conventional, is clearly lower than in the case of fixed rates. Yet particularly insecure are, in this case, investments in renewables due to the unpredictability of their supply: In contrast to conventional power stations they cannot be safeguarded by long-term contracts for fixed amounts of supply to customers.

In the case of such remuneration at fluctuating market prices the marginal-benefit-curve must be corrected downwards for strong wind periods and upwards for low wind periods in countries where wind energy has reached a large share like 10% or more of the total installed nominal generator power and hence a strong impact on the spot market prices. Looking at the duration-power-curve $\check{G}(p)$ of wind energy production in fig. 3 this means that the transformation to the marginal-economic-benefit-function has to take the decrease of the rate of remuneration with growing wind energy supply into account. Since at least in central and northern Europe there is hardly any correlation between high and low energy demand on the one hand and high and low wind energy supply on the other, they may be treated as statistically independent. Therefore the curve $\check{G}(p)$ for the total wind energy production in a large region should not be multiplied with a constant remuneration rate m. Instead the remuneration rate m_{market} should be high for low wind energy supply and be low for high wind energy supply, i.e.

$$m_{market} = m_{market}(p), \qquad (4.1).$$

where now the variable p shall denote some reasonable measure for the total amount of wind-generated power offered on the market for the time slot considered.

In the following fig. 7a we assume that the market price with no wind supply (p=0) is one third higher than remuneration rate $m_{constant}$ of 0.1 Euro/kWh (approx. the German wind remuneration rate in 2010). Instead – averaging over high and low demand periods – the remuneration rate m_{market} should enter the marginal-benefit-curve with a higher value at low wind energy supply and with a lower value at high wind energy supply; i.e. it may fall linearly to a price two thirds lower than the constant remuneration factor $m_{constant}$ at maximum wind energy supply (p = 1):

$m_{market}(0) = 4/3 * m$,
$m_{market}(1) = 1/3 * m$.

As a result of this assumption the average attainable market price for wind energy would lie 16% below the assumed constant remuneration rate $m_{constant}$.

Fig. 7a : Decreasing remuneration with increasing wind energy supply

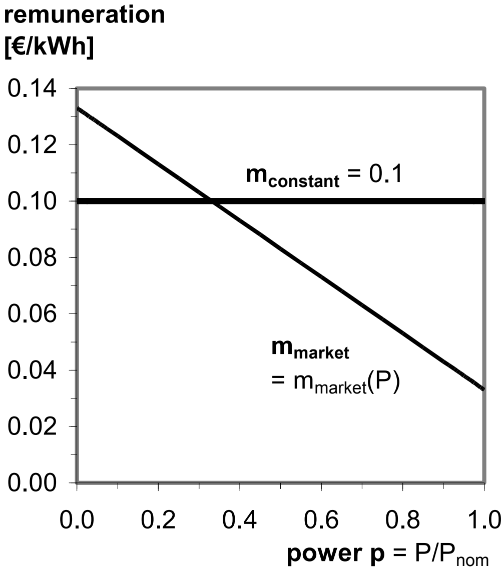
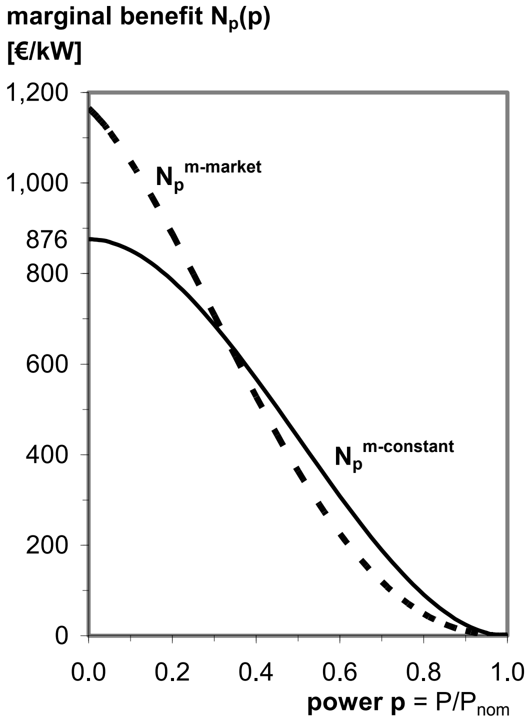


Fig. 7b shows the marginal-benefit-curve at constant and at variable market remuneration.

Fig. 7b : Marginal-benefit-curve at constant and at variable market remuneration

Marginal-benefit-curve at constant remuneration: solid curve $N_p^{m\text{-constant}}(p) = m_{constant} * \breve{G}(p)$, see fig. 6, versus that at variable market remuneration: dotted curve $N_p^{m\text{-market}}(p) = m_{market}(p) * \breve{G}(p)$.



For $P < 0.3\ P_{nom}$ the new dotted curve showing the marginal benefit $N_p^{m\text{-market}}(p)$ at market remuneration lies above the solid curve that refers to constant remuneration at m = 0.1 Euro/kWh. When wind energy contributes more than 30% of its installed power, i.e. $P > 0.3\ P_{nom}$ and hence the market remuneration goes lower and lower, the dotted curve goes to zero faster than the solid curve.

For P in the region 0.6 … 0.9 P_{nom}, where the marginal-benefit-curve typically intersects the marginal-cost-curve for a reinforcement of the transmission lines, this lowering of the dotted curve with respect to the solid curve obviously shifts the intersection point further to the left, i.e. to lower values of P_{opt}. This consequence for the optimum limit transmission power will be further discussed in sec. 5.2.3 below.

5 Application: Optimizing the limit power of transmission lines devoted to wind energy

In the following we study the optimization of transmission lines required for feeding wind energy into the high and very high voltage grid. Three cases with rather distinct requirements will briefly be sketched here, based on (Jarass et al., 2009, sec. 10.3). For the estimated cost of transmission system and their annualized cost see (Jarass et al., 2009, tab. 10.1).

5.1 High voltage lines for connecting onshore wind parks near the coast

If the energy from one or from several adjoining wind parks in a limited area with relatively homogenous meteorological conditions is to be fed into the grid one expects a relatively high simultaneity factor for the production of the individual generators particularly in strong wind periods. Hence the peak power to be transmitted into the high voltage grid may amount to around 95% of the total installed generator power of all individual plants for up to hundred hours per year. The required transmission lines connecting with the existing grid must, therefore, allow a peak load of 95% (Jarass et al., 2009, sec. 10.3.1).

5.2 High voltage cables for connecting offshore wind parks

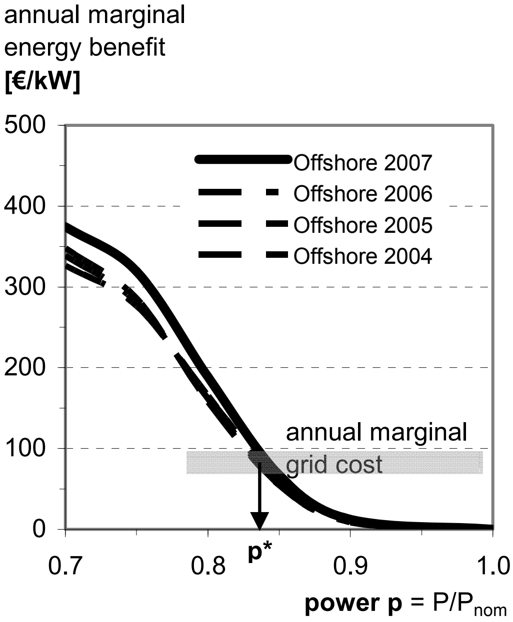
Obviously offshore wind parks have to be connected with the onshore very high voltage grid by cables on the sea bottom. For distances from the coast well above 25 km like for the wind parks presently under construction in the North Sea transmission by AC-cables must be excluded because of their high capacitive load and the ensuing reactive power. Instead DC-cables at 150 kV, later at 300 kV are to be used which – together with the AC-DC-AC-converters at both ends of the cable – may with their cost for investment plus maintenance contribute around one fourth to the total cost for the offshore wind power systems.

At the sites far off the coast the measured excellent wind characteristics promise – in theory – duration-power-curves for wind parks well above those for onshore, particularly at the upper end of the scale above $p \approx 0.8$. There are, however, in practice several effects to reduce the duration-power-curve for a wind park at higher values of p: shadowing of wind in the wake, nonsimultaneity of gusts at the individual turbines and, in addition, technical nonavailability for longer periods, an effect that may be quite marked especially in the early offshore years. Taking these effects into account one arrives at a rough estimate for a realistic duration-power-curve and, scaled with a remuneration of 0.1 Euro/kWh for offshore energy, for a provisional marginal-benefit-curve, as given in fig. 8.

In addition it shows an estimated marginal-cost-curve for the transmission system of converters and cables. Their annualized cost for the first installations for distances close to 100 km are up to 100 Euro/kW (Jarass et al., 2009, tab. 10.1).

Fig. 8 : Marginal-benefit-curve for an offshore wind park

Annual marginal energy benefit [Euro/kW] at constant remuneration m = 0.1 Euro/kWh; 400 MW wind park located close to FINO I wind measurement station 80 km north off the German-Netherlands coast.



Source: Jarass et al., 2009, fig. 10.5.

As explained the respective curves are based on first estimates and hence should rather be replaced by bands of appropriate width. Thus there is an intersection region for permissible values of p*: The economic limit power of the transmission system is somewhere in the interval from 80% to 90% of the total installed wind generator power (Jarass et al., 2009, sec. 10.3.2). Some years of experience with the offshore wind parks will show whether this limit should be chosen closer to 80% or to 90%.

A future monetarization at market prices – c.f. sec. 4.2 – would lower the marginal benefit for p above 0.7 considerably and shift the probable optimum limit power of the transmission system to values below p = 0.8, i.e. below 80% of the total installed wind generator power.

If we take into account that most of the offshore wind energy cannot be consumed in the coastal areas and hence has to be transmitted to faraway centers of demand, the additional grid costs shifts the intersection region in fig. 8 upwards and to the left, resulting in an optimum limit power even further below p = 0.8, i.e. even further below 80% of the total installed wind generator power.

At the assumed remuneration rate of 0.1 Euro/kWh the total annual benefit of the offshore wind parks may be in the range of 300 Euro/kW to 400 Euro/kW of installed generator power and thus still surpass the annual cost of transmission to the general grid by at least a factor of three. This ratio is generally considered to be sufficient to accept such transmission projects as economically feasable.

5.3 Optimizing long distance very high voltage transmission for fluctuating renewable energy

In many areas of the world the most favourable regions for harvesting renewable energy – biomass, solar or wind – do not coincide geographically with the regions of high electric energy demand. Hence a massive increase of renewable energy requires necessarily new or stronger long distance transmission lines from regions of low population and infrastructure density to the urban and industrial centers. The big utilities responsible for this task typically bundle the output of a large number of renewables´ power stations of varied character from huge inhomogeneous areas and then have to transmit the electrical energy with powers of one or several gigawatt over distances of many hundred kilometres to the centers of energy demand.

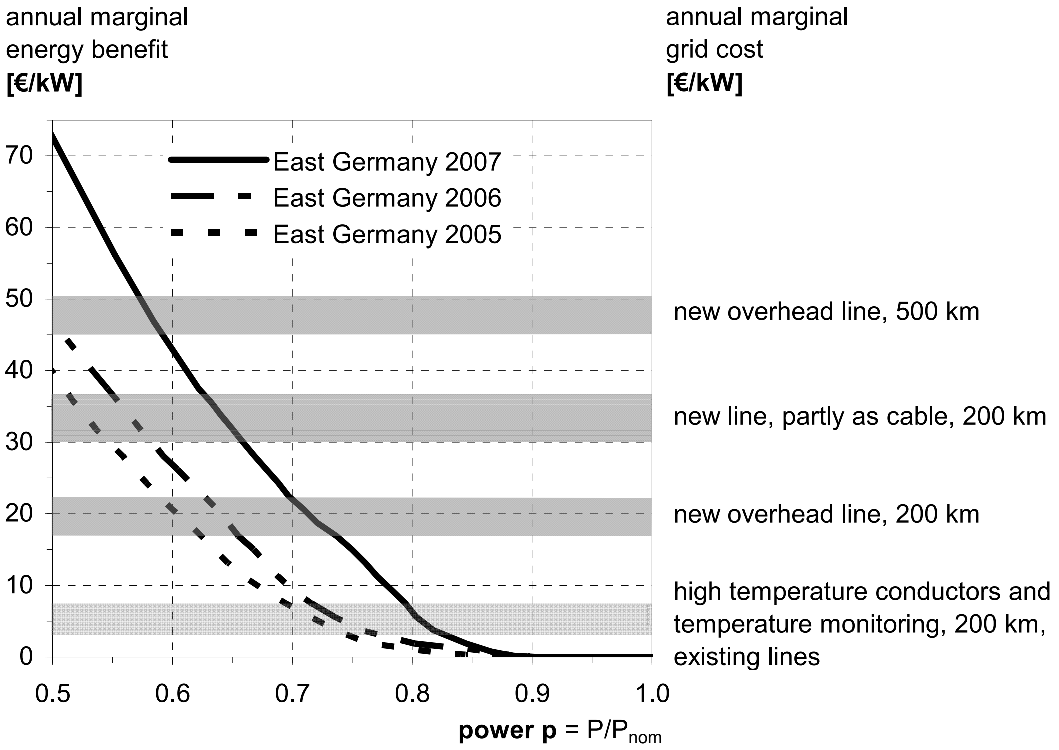
A typical example is wind energy production on the northwestern coast of Spain or in Germany´s coastal lowlands. Transmission to the big cities and industrialized regions must be achieved by upgrading existing very high voltage transmission lines (high temperature conductors and temperature monitoring) or by building new ones.

There is one utility operating the entire control zone of the former German Democratic Republic extending along the Baltic Sea from east of the city of Hamburg to the Polish border and 400 km south to the mountain ranges along the Czech border. The total generator power of all wind energy plants in this huge and climatically quite inhomogeneous region amounted to roughly one third of that of all Germany: more than 8 GW already in 2007 with high growth rates.

Fig. 9 gives the upper half of the marginal-benefit-curves for three years, two normal and one, 2007, exceptional, based on figures published by the utility. Also shown in fig. 9 are horizontal bands for the estimated annual marginal cost of different technical solutions for the required additional transmission capacity.

Fig. 9 : Marginal-benefit-curve for all wind energy fed into the East German control zone

Annual marginal energy benefit [Euro/kW] at constant remuneration m = 0.075 Euro/kWh for onshore energy; East Germany wind parks had a total installed power of around 8,000 MW in 2007.



Source: Jarass et al., 2009, fig. 10.6.

Even taking the best wind year as the upper limit for the marginal-benefit-curve and the least costly case of an additional purely overhead line of 200 km length, the intersection indicates an economic optimum transmission power of only around 70% of the total nominal wind generator power (Jarass et al., 2009, sec. 10.3.3).

One can compare

- the area below the marginal-benefit-curve from $p = 0.0$ to $p = 0.7$ ($p < 0.5$ not shown in fig. 9), amounting to a total benefit of around 120 Euro/kW per year, and
- the area from $p = 0.7$ to $p = 1.0$; this is the energy benefit to be discarded by ´production management´, amounting to less than 1 Euro/kW in most years.

It is thus obvious that the optimization by installing only a transmission power of 70% of the total installed wind generator power still allows more than 99% of the potential wind energy yield to be actually transmitted to the consumers. It becomes also evident that the total cost of the required transmission lines is by a large factor lower than the total benefit of wind energy production.

If the constant remuneration rate of 0.075 Euro/kWh used in fig. 9 is replaced by a variable market remuneration as described in sec. 4.2 (fig. 7a), the remuneration at high and medium wind energy supply will on average be considerably lower. Hence monetarization at market prices would lower the marginal-benefit-curve for all values of $p > 0.5$

shown in fig. 9. As a consequence this would lead to an even smaller value of p at intersection than p* = 0.7, that is to an even lower optimum limit power of the transmission system, let us say to p* = 0.6. If the grid were to be built or fortified only to these 60% of the total wind generator power feeding into it, a somewhat larger percentage of the potential wind energy production would have to be discarded by production management. But due to the lower remuneration at high and medium wind energy supply, the additional monetary loss would be pretty small.

6 Outlook

In the medium term, probably after 2025, if the installed wind power in Germany may actually have grown to above 50 GW (total renewable close to 100 GW; Leitszenario 2009, p. 90, tab. 5), in Europe well above 300 GW (Pure power 2009), completely new technical and economic questions will have to be solved:

- Will it make sense to transmit that part of energy produced at strong wind that exceeds the regional demand to far distant centers of population and industry in Europe over distances of 1.000 km and more as proposed by recent studies (Hulle 2009, EWIS 2010)?
- Will many new reserve- and storage-power-stations be available, including possibly hydro power in Norway, Austria and Switzerland (Pumpspeicherkraftwerke 2010)?
- Will hence new – and probably very costly – transmission technology like DC ultra high voltage underground systems be a solution?
- Or will other solutions become ecomically competitive like hydrogen production, local storage and hybrid power plants?

There are no clear answers to these questions available yet.

However: What ever the solutions may turn out to be, the problem of technical and economic optimization of systems with strongly fluctuating, intermittent sources, delt with in this paper, will persist.

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