Division Water, Energy and Transport

Technical and Economic Potential of Wind-Powered Water Desalination

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Wind Energy Programme

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Deutsche Gesellschaft für
Technische Zusammenarbeit (GTZ) GmbH
Postfach 5180
65726 Eschborn
T +49 61 96 79-0
F +49 61 96 79-11 15
E info@gtz.de

Internet:
www.gtz.de/wind

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Author:
Witold Teplitz-Sembitzky
On behalf of Deutsche Gesellschaft für Technische Zusammenarbeit GmbH

Editor:
Christian Schwarz

Contact person at the Federal Ministry for
Economic Cooperation and Development (BMZ):
Department 313

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List of abbreviations

ED	electrodialysis
g	gram
kWh	kilowatt-hour
l	litre
m	metre
MED	multi-effect distillation
mg	milligram
MJ	megajoule
MSF	multi-stage flash distillation
MVC	mechanical vapour compression
MWh	megawatt-hour
ppm	parts per million
R&D	research and development
RO	reverse osmosis
s	second
TDS	total dissolved solids (1 mg/l = 1 ppm)
WEC	wind energy converter

Contents

Summary

As wind energy converters supply mechanical or electrical energy, only vapour compression, reverse osmosis or electrodialysis methods come into consideration for wind-powered water desalination. All three desalination techniques have been tested more or less thoroughly in combination with wind energy converters in pilot projects or under R&D conditions. To date, however, no wind-powered desalination plants have yet established themselves on the market. In most cases the experience gathered in the pilot projects has only been evaluated at an academic level and is not sufficient to draw reliable conclusions regarding use in conditions encountered in developing countries.

Wind-power water desalination plants can be operated in island mode (with or without an additional supply of electrical energy, for example from a diesel generator set) or in grid-parallel mode. What makes the use of wind energy converters appear attractive for water desalination, especially when operating solely in island mode, is the fact that the wind energy – which as a rule is not continuously available – can be stored in the form of desalinated water and thus be adapted to meet a constant demand (such as constant daily volumes of drinking water). However, storing water does not solve the technical problem that if the desalination plant is directly coupled to the wind power station (with no additional energy sources), it has to cope with fluctuations in the availability of wind energy. A further factor that has to be taken into consideration, irrespective of the need for technical adaptation of the desalination facilities to wind-powered operation, is that (marked) load variations and (long) periods of calm or storm are associated with relatively low capacity utilisation of the desalination unit and consequently increase the specific desalination costs.

In terms of cost criteria, wind energy is in competition with other sources of energy. For wind energy to be economic for water desalination, therefore, the specific energy-related desalination costs should at least be no higher than those incurred with alternative energy sources. Assuming this precondition is met, it is possible to differentiate between two scenarios:

- Sites where autonomous wind-powered desalination allows provision of acceptable water supplies at the lowest possible cost: in this case wind energy would be preferred to other solutions because of its cost advantage.
- Sites where wind energy can be provided more cost-effectively than electricity supplied from the grid or diesel generators, but where supplementing wind energy makes it possible to provide a product water volume that is constant over time (or demand-driven), and/or improved capacity utilisation of the desalination unit: in this case the most advantageous design variant is the one in which supplementing wind power with grid or diesel power minimises the specific water production costs.

A number of system manufacturers and engineering consultancies have developed and in some cases also tested wind-powered water desalination technologies. The search for customers for these products is primarily directed at the Mediterranean region (tourism niche) and countries where water desalination by conventional means is already known. To date, however, none of the systems has achieved market success.

Because of the lack of market-ready wind-powered water desalination plants, cost estimates are highly speculative in nature. This applies in particular to use of as yet untested technology in developing countries. The uncertainties primarily relate to the capital outlay and operating costs for the desalination component. Studies and expert reports examining the economic efficiency of wind-powered water desalination not only arrive at different results regarding the water production costs, they also disagree about which wind-powered desalination method is cheaper.

As calculation of the water production costs in wind-powered desalination plants is based on a series of assumptions, which because of the absence of operational experience and the lack of market-ready plants can be neither supported nor investigated, published estimates should be treated with caution. Despite all the uncertainties, however, there is no doubt that wind-powered water desalination too is a costly form of providing water, even if wind conditions are favourable. Realistically, production costs of more – presumably considerably more – than 1 EUR/m^3 must be expected.

Comparatively expensive applications such as water desalination should only be considered for use in developing countries on condition that the potential for (more inexpensive) measures and strategies to make better use of available water resources has been fully exploited . Before wind-powered water desalination is even short-listed, further prerequisites must be satisfied at the location. The most important essential requirements can be summarised as follows:

- Significant demand for drinking water and service water (industrial water) (> 120 m^3/day).
- Impossibility of meeting demand for the supply of drinking water and service water cost-effectively with the available water resources even after exploiting all potential savings.
- Availability of sufficient quantities of raw water at low cost.
- Suitable wind conditions (> 7.5 m/s mean wind speed, with only minor fluctuations around the mean).
- Financially sound water utility companies, which also have the capability to deal with wind power systems and water desalination plants.
- Water tariffs based on the production costs of water desalination are compatible with the ability and willingness of consumers to pay for them.
- Environmentally sound disposal of the residual product (brine).

Upon rational reflection, it must be concluded that the opportunities for using water desalination plants and also for wind-powered water desalination plants in developing countries are limited. At present all that can be considered are pilot or demonstration projects, which reduce the considerable technical and commercial risks of the use of this technology to an acceptable level through financial incentives and technical support. Even with this qualification, it will probably not be easy to find suitable locations meeting the criteria outlined above.

1 Wind energy: an overview

The first commercial wind energy converters entered service back in the 1980s, although the wind energy boom as such did not begin until the mid 1990s, when the total installed wind generation capacity in the world was only 5,000 MW. Since then the installed capacity has increased at double-digit rates of annual growth. By the end of 2006 global installed capacity had reached 74,233 MW, and the wind industry estimates that this will rise to 145,000 MW by 2010. Almost without exception, the installed systems are used to generate electricity. The largest market at present is still Europe, where some 48,545 MW (65%) is installed; of this, 22,000 MW is located in Germany (figures from end of 2006). Germany is also a leader among the system manufacturers. Four German companies are counted among the world's major manufacturers, and the German component industry supplies gearboxes, clutches and other assemblies to numerous producers in other countries.

Even if it remains a matter of dispute whether wind energy would still be competitive without promotional support, it is beyond doubt that the wind industry has made considerable progress. While in the early 1990s the cost of systems still averaged almost 1,300 EUR/kW, in the meantime specific investment costs have fallen to around 900 EUR/kW. The advantages of mass production have been further boosted by considerable increases in the efficiency of turbines (greater hub height, larger rotor diameter etc.), which have improved the economics of wind energy. There are now turbines on the market with a rated output of up to 6 MW, for example. This trend further illustrates that the growth market in the wind industry is mainly seen in electricity generation and grid feed-in.

2 Water desalination: an overview

2.1 Background

Of all the water present on Earth, 96.5% consists of seawater. The remaining 3.5% is freshwater, but half of that is tied up in ice and consequently not usable. All in all, significantly less than 1% of the world's water resources are exploitable as drinking water.

Drinking water is characterised by a high degree of purity, which among other things means a low salt content. There are often directives and regulations governing the permissible salt content in drinking water (such as the Drinking Water Ordinance in Germany). According to the limit defined by the World Health Organisation[1], a salt content of up to 0.5 g/l is harmless to human health. Occasionally, though, the opinion is also heard that water with a salt content of up to 1 g/l is drinkable. The distinction between freshwater, brackish water and seawater is equally inconsistent. In German usage, the term brackish water usually relates to water with a salt content of 1 – 10 g/l, while in the Anglo-Saxon world water is still referred to as brackish if the salt content is as much as 18 g/l. Seawater has an average salt content of 35 g/l, although salinity can vary between 2 and 45 g/l depending on the locality. Whatever the case, obtaining drinking water or service water from salty seawater or brackish water calls for removal of salt (and other minerals) from the untreated raw water. This is done by separating the raw water into product water, with a low salt content, and brine, with a high salt content.

There are numerous desalination methods, some of which have been in use in large plants for over 100 years. The common, tried-and-tested desalination technologies can be divided into *thermal methods* (distillation or vaporisation processes) and *membrane methods* (see Table 1). In addition there are simple (solar) evaporation systems and complex techniques, not yet used commercially, such as freezing (water separation) and ion exchange (salt separation).

Table 1: Thermal and membrane methods of water desalination

Thermal methods	**Market share (2005)**	**Membrane methods**	**Market share (2005)**
Multi-stage flash distillation (MSF)	36%	Reverse osmosis (RO)	46%
Multi-effect distillation (MED)	3%	Electrodialysis (ED)	5%
Vapour compression (VC)	5%		

In early 2005 there were more than 10,000 desalination plants with a daily output of at least 100 m^3 in service world-wide. The plants are situated in coastal locations where there is a shortage of drinking water, or in semiarid/arid areas where only brackish water is available. The principal consumers are towns, cities and local communities (63%). Desalination plants are also occasionally used on ships. However, the total installed desalination capacity of about 36 million m^3/day met only just under 0.3% of global demand for fresh water. The majority of installed desalination plants

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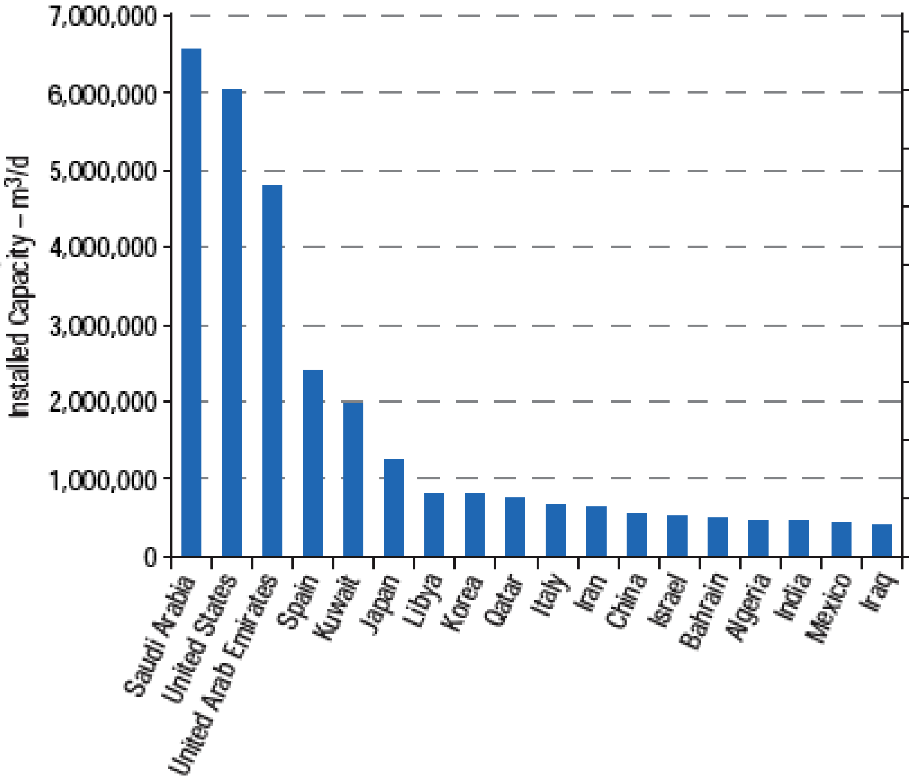
[1] For current limits, see: www.WHO.int

(53%) are used for seawater desalination; 24% operate with brackish water, 9% treat surface water, and 6% are designed for treating wastewater (Pacific Institute, 2006).

Roughly half the installed desalination capacity is located in the Middle East, the Persian Gulf and North Africa (Figure 1); thermal methods are preferred there, mostly in conjunction with combined heat and power plants (cogeneration stations). In countries such as Saudi Arabia, Kuwait and the United Arab Emirates, the main source of water is seawater. In the USA, which accounts for 17% of global desalination capacity, mainly brackish water and surface water is treated (70% on the basis of reverse osmosis).

Figure 1: Distribution of water desalination capacity by country[2]



Source: Pacific Institute (2006)

2.2 The most common desalination methods

Thermal methods

The underlying principle behind thermal methods is that the raw water is brought to boiling temperature and the condensed steam is separated from the brine. As the boiling point depends on pressure (water evaporates at 100°C under atmospheric pressure), the principle can be applied in several process stages, gradually reducing both pressure and boiling temperature. The lower the pressure, the less thermal energy is needed for evaporation. All thermal desalination methods make use of the thermodynamic principle that the evaporation process can be optimised by reducing pressure and boiling temperature (cf. Wangnick 2001, Pacific Institute 2006).

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[2] Other Sources (SWCC) indicate diverging data for Saudi Arabia, United Arab Emirates and Spain

Mechanical vapour compression (MVC)

Of the various thermal methods, above all vapour compression enters into consideration for wind-powered desalination. As with all the thermal methods, in vapour compression evaporation takes place by reducing the boiling temperature as a result of reducing pressure. However, the process heat required for evaporation is normally generated by a mechanical – electrically operated – compressor and not provided by a steam generator.[3] Therefore *mechanical vapour compression* is the only distillation method operated solely with electrical energy. Usually the mechanical plants consist of a single stage, and reach daily capacities of up to 3,000 m^3. They are considered to be reliable and have low maintenance requirements (no biofouling or scaling), are simple to operate, and require only little additional outlay on pretreatment and post-treatment of the raw water and product water. Their specific power demand (compressor, feed pump) is in the region of 7 - 12 kWh/m^3.

Membrane methods

Reverse osmosis

This method came onto the market at the end of the 1960s and is based on the idea of reversing the natural tendency to balance the level of concentration between two solutions (osmosis).[4] Reverse osmosis counteracts the osmotic pressure by forcing the salty raw water through membranes in the direction opposite to its “natural” direction of diffusion, leaving the dissolved salt behind. The greater the difference in concentration between the salt solutions in the raw water and the required product water (i.e. the greater the osmotic pressure), the more pressure has to be exerted by reverse osmosis. The amount of electrical energy required for reverse osmosis (usually with high-pressure pumps) therefore rises in direct proportion to the salt water content of the raw water [for a given level of product water quality and product water yield] and to product water yield [for a given salt content in the raw water]. In seawater desalination plants with pressure recovery, specific power consumption (high-pressure pump, feed pump, flushing) ranges between 2.5 kWh/m^3 and 7.5 kWh/m^3; highly efficient plants are said to consume as little as only 2 kWh/m^3.[5] Thanks to modular construction methods, plants vary in size from 100 m^3/day to 400,000 m^3/day, with specific investment costs of 500 – 1,300 USD/m^3/day. There are also micro desalination plants for domestic purposes or mobile use (≥ 2 litres/minute). Membrane methods such as reverse osmosis are used not only for water desalination, but also for treating wastewater.

Depending on the available raw water, the product water yield and the required product water quality, smooth operation of the plants requires more or less elaborate pretreatment of the raw water

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[3] In addition to mechanical vapour compression plants there are also types known as thermo-compression plants which operate with process steam and use several evaporation stages.

[4] In a tank separated by semi-permeable membranes (permeable to water but not salt), with fresh water on one side and salt water on the other, the salt level on the salt water side would rise with respect to the fresh water side (osmotic pressure).

[5] The theoretical minimum is 0.78 kWh/m^3 [= 3 MJ = 28 bar (osmotic pressure of seawater) x 0.1 MJ/m^3]. The osmotic pressure P (bar) is obtained from the equation $P = c \times R \times T$, where c = 1.12 mol/l (corresponding to a salt content of 3.5 g/l), R = 0.0831 (gas constant) and T = 300.05 K (=273.15 + 27°C). However, since the pressure required for desalination has to be higher than the osmotic pressure of the seawater and since the ratio of product water to raw water is less than one, it is impossible to achieve the minimum.

(filtration and addition of chemicals), regular flushing (in some cases with automatic flushing programmes), frequent replacement of the membranes, avoidance of pressure fluctuations at the membranes (alternating operation), and where applicable post-treatment of the product water (filtration, disinfection).

Important characteristics of the various desalination methods are summarised in Table 2.

Table 2: Characteristics of water desalination methods

	MSF	**MED**	**MVC**	**RO**	**ED**
Primary energy source	Steam	Steam	Mechanical / electrical	Electrical	Electrical
Max. salt concentration of raw water (g/l)	100	100	100	45	3
Product water yield	≤ 50%	≤ 50%	30-50%	≤ 50% (Brackish water: ≤ 85%)	Brackish water: ≤ 97%
Product water quality (mg/l)	< 10	< 10	< 10	< 500	< 500

3 Options for wind-powered water desalination

In the following, wind-powered water desalination is taken to mean a combination of a wind energy conversion system and a desalination plant. Although wind energy in this connection is primarily used to operate the desalination unit, any excess energy can also be passed on to other consumers, for example in the form of electrical energy, if appropriate via the power grid. However, this study does not consider the case of a wind power plant that is built to feed electricity into a transmission grid via which power is also supplied to a desalination plant (regardless of whether or not the wind power plant exists).

As wind energy converters supply mechanical or electrical energy, only vapour compression, reverse osmosis or electrodialysis come into consideration for wind-powered water desalination. All three desalination techniques have been tested in combination with wind turbines in pilot projects or under R&D conditions. Most of the pilot plants are located in the Mediterranean region (or Canary Islands) and serve the purpose of seawater desalination, using reverse osmosis, with daily capacities of up to 2,500 m^3. There have been a handful of tests with electrically powered vapour compression plants (Rügen, Canary Islands). No practical experience has been obtained with vapour compression or reverse osmosis plants powered by mechanical wind energy. Trials with wind-powered desalination of brackish water using electrodialysis have been carried out on the Canary Islands (Veza 2004).

Despite all the pilot schemes and tests no wind-powered desalination plants have established themselves on the market yet. In addition it must be stated that the experience gathered in pilot projects and tests has mostly only been evaluated for the purposes of academic debate and also is only accessible through such channels, and furthermore that there is still no reliable database available which would allow conclusions to be drawn regarding possible use under the conditions encountered in developing countries.

3.1 Operating modes

Wind-powered water desalination plants can be operated in island mode (with or without an additional supply of electrical energy, for example from a diesel generator set) or in grid-parallel mode. The proposal was therefore made to categorise plant configuration according to the proportion of wind energy in the desalination unit’s total energy consumption (Käufler 2006). This would result in systems with a low, medium and high wind penetration rate (extent to which energy needs are met by wind).

Island mode with water storage

What makes the use of wind energy converters appear attractive for water desalination, especially when operating solely in island mode, is the fact that the wind energy can be stored in the form of desalinated water and thus be adapted to meet demand (such as constant daily volumes of drinking water). Water storage facilities mitigate the problem that the wind-dependent load curve of a wind power plant does not necessarily match the time profile of energy demand (or of demand for product water). Provided there are no lengthy periods of calm or storm, an additional water storage facility to compensate for wind fluctuations causes only little additional cost and would reduce the cost otherwise incurred by alternative solutions such as overdimensioning of the wind power plant (with a high proportion of unusable excess electricity), battery storage or the provision of backup or emergency generating systems.[6]

Load fluctuations

Storing water does not, however, solve the technical problem that the desalination plant has to cope with fluctuations in the availability of wind energy when it is directly coupled to the wind power plant (without additional energy sources).[7] Load fluctuations do not constitute a significant impediment for vapour compression because the power demand of the desalination unit can be largely adapted to match the availability of wind. In the case of reverse osmosis it is true that a modular design can be used to counter changing wind conditions, but even then a constant operating regime is required for the individual modules. Load fluctuations mean that a complex control system is required (frequent startup and shutdown procedures), increasing the risk of material fatigue and faults or failures. A further factor applicable to island mode, irrespective of the need for technical adaptation of the desalination facilities, is that (pronounced) load fluctuations and (long) periods of calm or storm are associated with relatively low levels of capacity utilisation of the desalination unit and consequently increase the specific desalination costs.

Backup by diesel generator or grid-supplied power

One important question therefore is whether the additional costs associated with focusing solely on island mode (technical adaptation of the desalination unit, downtimes, additional water storage facility or lack of constant water supply) can be justified when compared with other practicable solutions. However, there is insufficient experience to estimate with any precision the costs and risks involved in variable (island) operation, especially of RO plants. Most wind-powered RO pilot plants have been designed so that they can be run at constant load using additional energy sources (grid-supplied energy or diesel generator). It is questionable, though, whether this design is the result of prior optimisation calculations. The fact that providing backup for wind-powered water desalination plants from the grid or running them in association with diesel generators allows the plants to be operated uniformly or in line with demand, and helps improve their capacity utilisation rate does not necessarily mean that this configuration is always the most advantageous. Conversely, however, it is equally difficult to maintain that the benefit of wind power primarily depends on saving diesel-generated electricity or substituting grid-supplied energy. As shown by numerical examples below, under certain circumstances it may well be worth bringing in relatively expensive diesel or grid power in order to increase the capacity utilisation of a wind-powered desalination plant.

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[6] Additional water storage for wind operation means that the storage volume is greater than the storage needs that would be planned anyway to allow for consumption peaks, for example, or for interruptions owing to operational disruptions or to regulate pressure fluctuations in the piping system.

[7] It can be seen from the Weibull distribution of the (measured) wind speeds whether the wind fluctuations are pronounced: the greater the form factor, the more closely the wind speeds are distributed around the mean (lower standard deviation).

Cost efficiency

As a general principle, wind energy which is specifically more expensive than other available energy sources does not become cheaper by being used for water desalination. On the contrary, economic use of wind energy presupposes that the wind energy is cost-efficient from the outset. It follows, then, that a necessary condition for economic use of wind energy for water desalination is that it at least does not increase the specific energy-related desalination costs. Assumingthat this is the case, the following scenarios can be distinguished:

1. Sites where autonomous wind-powered desalination allows provision of acceptable water supplies at the lowest possible cost: in this case wind energy would be preferred to other solutions anyway because of its cost advantage. The fact that wind energy thereby implicitly substitutes grid power or diesel power would be a secondary effect that arises from the cost saving.
2. Sites where wind energy can be provided more cost-effectively than electricity supplied from the grid or diesel generators, but where supplementing energy allows provision of a product water volume that is constant over time (or demand-driven) and/or improved capacity utilisation of the desalination unit: in this case the most advantageous design variant is the one in which the additional use of grid or diesel power minimises the specific water production costs. Drawing grid or diesel power beyond the cost-minimised level would be uneconomic.

Low wind penetration rate

It is difficult to imagine, however, that there are sites where minimal-cost water desalination can be achieved with low wind penetration.[8] Why should anyone design a desalination plant to be run mainly on electricity from the grid or diesel generators if wind power is a cheaper energy source? The most obvious explanation would be the lack of availability of sufficient wind resources, although this would be difficult to reconcile with the assumption that wind energy is the most cost-effective energy source. It is also conceivable that, although on an annual average the wind regime could provide for good capacity utilisation of the wind power plant (low wind energy costs), in fact it would only be used to a limited extent for water desalination because of considerable fluctuations in load. Capacity utilisation of the desalination unit would then be extremely low without massive support from the grid or diesel generators. The scenario of a water desalination plant to which a wind energy conversion system is coupled merely in order to save small amounts of external energy is therefore more likely to be ranked among the examples of uneconomic use of wind energy. It would at least be appropriate to doubt the economic efficiency of wind-powered water desalination plants if wind is not their primary energy source.

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[8] It should be noted that in such a case this is not a matter of wind energy that is fed into an isolated grid which supplies electricity to, among other things, a water desalination plant, but a water desalination plant that is operated under wind power, if appropriate backed up by the electricity grid or another additional energy source.

Excess electricity

If the wind energy conversion system generates electricity and is also connected to a grid, any excess energy not required by the desalination plant could be fed into the grid. If the electricity generated by the wind power plant is cheaper than power from the grid, and if the excess energy can be sold at a price that at least covers the prime costs of the wind energy, the average cost of wind-generated electricity will fall, and hence also the cost of desalination. The same also applies of course if the wind energy is more expensive than the grid power, but excess wind-generated electricity can be sold at a feed-in tariff that covers the costs of generation. In that case, though, wind-powered desalination would of course be an uneconomic proposition: why should a desalination plant be run with wind power if cheaper power is available from the grid?

3.2 Plants

As yet there are no commercially available wind-powered desalination plants. Only a few manufacturers of wind turbines offer their products in turnkey solutions in combination with desalination plants (Enercon, Vestesen), and occasionally also as hybrid wind-diesel systems in conjunction with a desalination unit (Enercon). Otherwise it is mainly engineering companies and consultancies that advertise various plant configurations, although these have not yet been proven in practice (DWC DecRen Water Consult, Synwater, Aerodyn Energiesysteme).

The standard plants on offer are designed for a desalination capacity of between 350 m^3/day (Enercon) and 3,800 m^3/day (Vestesen), and can provide greater desalination output up to any required level by adding further desalination modules; in part-load operation they permit desalination output to be slowed down to as little as 100 m^3/day. As a rule, the solutions offered by plant manufacturers and consultancies are based on the reverse osmosis method. Wind-powered desalination plants operating with vapour compression units are offered by a very few consulting engineers (Aerdyn Energiesysteme, WME).

It is barely possible to assess the quality of the few products whose development has reached market release stage because as yet there has been no market launch, let alone the emergence of a market segment. Nor is there any price transparency. The providers do not provide any binding information as to how much the plants cost, or the terms under which they are available. Price estimates have been made in several studies and expert reports, however.

3.3 Costs

Because of the lack of market-ready wind-powered water desalination plants, cost estimates are highly speculative in nature. This applies in particular to technology as yet untested under the conditions encountered in developing countries. The uncertainties primarily relate to the capital outlay costs and operating costs for the desalination component. Little is known, either, of the practical requirements for operation in developing countries. There are no empirical values for the service life of plant components, operating and maintenance costs, the availability of qualified personnel, or other parameters affecting desalination costs. Although adequate price information is available for the commonly marketed wind energy converters, the additional costs – or if applicable even cost savings – associated with adaptation of the systems and operation in connection with a desalination unit cannot be reliably estimated.

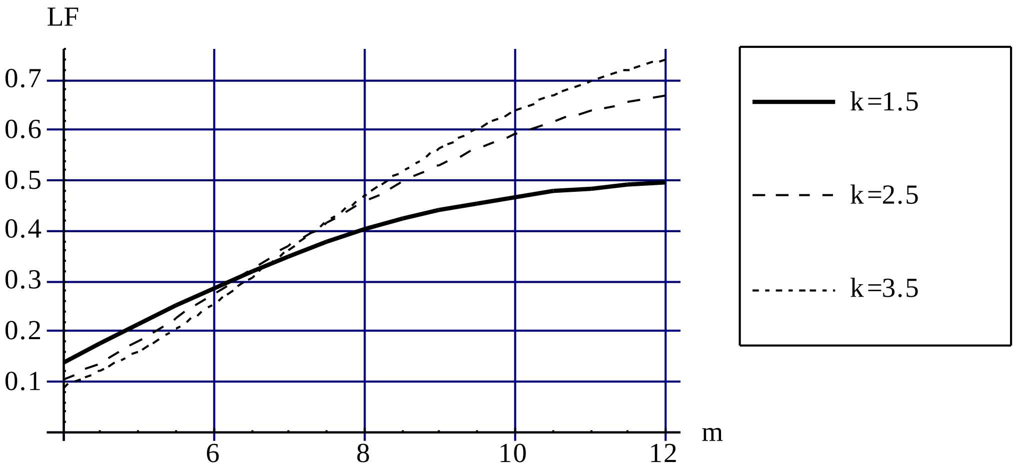
Accordingly there is considerable variation in the cost estimates used by various experts and institutions in their simulation calculations. For example, estimates of the investment costs for a reverse osmosis plant with a nominal capacity of 1,200 m^3/day range from 892 EUR/m^3/day (WindDesalter Engineering, 2004) to 1,600 EUR/m^3/day (Zelji, 2002). For comparable vapour compression plants the range extends from 1,125 to 2,500 EUR/m^3/day. There are similarly large differences in the assumptions of plant-specific energy consumption. The spread is less wide, on the other hand, for the assumed costs of the wind energy conversion system (900 – 1,200 EUR/kW for an installed capacity of 600 kW), which is no surprise, as the market for wind energy converters is well developed and transparent.

The various studies not only arrive at different results regarding the water production costs, they also disagree about which wind-powered desalination method is cheaper. Depending on case study and desalination technology, the estimated water production costs range between 0.90 and 1.65 EUR/m^3 (Garcia-Rodriguez, 2001), 1.42 and 2.44 EUR/m^3 (Zelji, 2002), 1.10 and 1.50 USD/m^3 (Forstmeier, 2007) or 1.26 and 3.01 EUR/m^3 (WindDesalter Engineering, 2004). Because of the lack of market maturity of wind-powered desalination plants, no evidence-based conclusions can be drawn as to possible cost trends. It would be premature, however, to assume that the specific costs could fall quickly or markedly. When classifying the existing cost estimates it must also be remembered that they generally only include expenditure on energy and desalination, and disregard the possibly equally considerable ancillary costs of supply and preliminary treatment of the raw water, discharge of the brine, storage of the product water and piping it to the end consumers. Accordingly, if end consumer tariffs are to cover costs, they may be well above the mere production costs of the product water, depending on the location.

Wind regime and plant utilisation

The main difficulty in simulating wind-powered desalination plants has to do with the design of the desalination unit and its utilisation rate that is dependent on the wind regime. For example, cheap wind energy does not necessarily mean low specific desalination costs because the latter depend to a large degree on the utilisation coefficient of the capital-intensive desalination plant. However, given certain plant costs, wind energy can be produced more cheaply the better the installed wind generation capacity is utilised. Figure 2 illustrates the rule of thumb (“good wind conditions”) that the mean wind speed has to be at least 7 m/s for utilisation of the wind energy converter to reach at least 35%. Beyond this “critical” mean wind speed, though, utilisation depends heavily on the variability of the wind regime, for which the form factor (a parameter of the Weibull distribution) is an indicator. The higher the form factor, the smaller the standard deviation of wind speeds around the mean and the better the capacity utilisation of the plant, especially if the mean wind speed is high.

Figure 2: **Utilisation coefficient of a wind energy converter as a function of mean wind speed (μ) and form factor (k)*)**



*) Enercon E48 (800 kW), 10% losses

As the utilisation of the desalination unit is determined not only by the average wind availability but also by its distribution over time, knowledge of the mean wind speed or of the total quantity of energy that can be generated (e.g. annual energy) is not enough to give us any precise information about the utilisation coefficient of a desalination plant matched to the installed wind generation capacity. An approximation of the precise utilisation coefficient can only be calculated by simulating plant operation for a given wind distribution. In the above-cited studies, no such calculations were performed when estimating the desalination costs of wind-powered plants, apart from a few exceptions (e.g. Paulsen and Hensel, 2007). In some cases there was even an incorrect assumption of 100% utilisation in island mode. Simulations indicate, however, that a utilisation rate of 60 % is more realistic for wind-powered desalination plants without diesel or grid backup, and in fact is a good rate to achieve (Paulsen and Hensel, 2007).

Example: WindDesalter

Table 3 contains estimated figures for water production costs that were calculated on the basis of WindDesalter technology, broken down according to reverse osmosis (RO) and mechanical vapour compression (MVC), in order to illuminate the importance of individual parameters.[9] The technical design details of the plants are based on the supplier's design (Witte 2003, WindDesalter Engineering 2004). A list of all the assumptions used here is given in Annex 1.[10]

The results suggest that in the case under consideration, vapour compression represents the cheaper option (1.76 EUR/m^3 compared with 2.08 EUR/m^3 for RO) as an island solution, despite its higher specific energy demand (and hence higher energy costs). The cost advantage of vapour compression is derived above all from avoidance of the need to replace membranes and lower consumption of chemicals.

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[9] On account of their illustrative nature, the figures are not an exact estimate of what a WindDesalter plant would actually cost if it were to be built.

[10] This estimate relates to current parameters. No account has been taken of possible price rises for fossil fuels in future.

The absolute estimates of water production costs are less interesting than the potential for reducing costs by providing backup from the grid or diesel generation. For both desalination methods the utilisation coefficients of the desalination unit are below 50%, despite favourable wind conditions (WEC load factor: 43%; wind energy prime costs: 53.65 EUR/MWh). The utilisation coefficient of the desalination plants could be improved with the aid of additional energy sources. It is apparent that using additional energy even at the specific cost of 186 EUR/MWh assumed in the example – almost 3.5 times the cost of wind energy – would lower the specific water production costs of the reverse osmosis method (because of greater utilisation of desalination capacity); in the case of vapour compression, on the other hand, desalination would be more expensive on account of this method’s high specific energy consumption. The example illustrates the following fundamental correlation:

- *Support from grid power or diesel power is always worthwhile if the variable production costs of the product water that can be obtained with the input of additional energy – i.e. essentially the cost of the additional energy – are lower than the (fixed plus variable) water production costs in purely standalone operation.*

Table 3: Estimated water production costs for WindDesalter

		RO	MVC
Installed capacity Wind power	kW	600	600
Annual capacity Product water	m3	996.450	511.000
Annual production without Diesel backup	m3	276.593	205.160
Utilisation factor	%	27,76%	40,15%
Additional Annual production with Diesel backup	%	10,00%	10,00%
Additional Annual production with Diesel backup	m3	27.659	20.516
Annual production with Diesel backup	m3	304.252	225.676
Utilisation factor	%	30,53%	44,16%
Production costs Wind energy	EUR/MWh	53,64	53,64
Water production costs: without Diesel backup	EUR/m3	2,08	1,76
thereof energy	EUR/m3	0,44	0,59
With diesel backup	EUR/m3	2,00	1,80
Specific costs Diesel backup	EUR/m3	1,22	2,13

Example: Enercon EDS SW 1200

The estimated water production costs for the reverse osmosis method shown in Table 4 relate to design data for the EDS SW 1200 water desalination plant offered by Enercon, with a daily capacity of up to 1,400 m^3. As the price of the plant is not known, the costs of the desalination unit have been put at 1,100 EUR/m^3/day for illustrative purposes, based on the assumption that this plant type will be specifically more expensive than the reverse osmosis technology proposed for the WindDesalter design.

Table 4: Estimated water production costs for Enercon EDS SW 1200 (reverse osmosis)

		RO	**MVC**
Installed capacity Wind power	kW	600	600
Annual capacity Product water	m3	511.000	255.500
Annual production without Diesel backup	m3	296.166	177.376
Utilisation factor	%	57,96%	69,42%
Additional Annual production with Diesel backup	%	10,00%	10,00%
Additional Annual production with Diesel backup	m3	29.617	17.738
Annual production with Diesel backup	m3	325.782	195.113
Production costs without Diesel backup	EUR/m3	1,32	1,44
Production costs with Diesel backup	EUR/m3	1,26	1,49
Specific costs Diesel backup	EUR/m3	0,72	2,07

The principal advantages of the Enercon desalination unit are its (according to the manufacturer) relatively low energy consumption, its adaptability to fluctuating wind conditions, and the fact that no chemical pretreatment of the raw water is required.[11] The plant is compared with mechanical vapour compression technology, for which investment costs are estimated to be somewhat higher and energy consumption somewhat lower than for the WindDesalter design (see Annex 2).

The results of the sample calculation show relatively low water production costs, with the reverse osmosis plant being the slightly cheaper variant at 1.32 EUR/m^3. The low water production costs can be explained by the relatively low specific energy consumption and the good utilisation rate. Nevertheless, providing additional diesel-generated power could slightly reduce average water production costs for the reverse osmosis plant, even at specific costs of 186 EUR/MWh, thanks to better utilisation of the installed desalination capacity. The additional consumption of diesel-generated power would not be worthwhile for vapour compression, however, as the specific costs of diesel backup are higher than the production costs in island mode.

Table 5 shows the makeup of the production costs estimated for the EDS SW 1200 reverse osmosis plant.

Table 5: Estimated production costs for Enercon EDS SW 1200

Reverse Osmosis (EDS SW 1200)**:**			
Production costs wind energy	EUR/MWh	65,70	
Production costs product water	EUR/m3	1,32	
Investment costs	EUR/m3	0,64	48,63%
Membrane replacement costs	EUR/m3	0,13	9,54%
Operating and maintenance costs	EUR/m3	0,13	9,87%
Chemicals	EUR/m3	0,00	0,00%
Energy costs	EUR/m3	0,42	31,96%

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[11] The simulation results are included in Paulsen (2007).

In summary it can be stated that calculation of the water production costs for wind-powered desalination plants relies on a series of ad hoc assumptions. As so little marketing has taken place to date, no reliable data or empirical values from operation are available yet. At present, therefore, all cost calculations can only be hypothetical in nature and merely serve to estimate future potentials.

Despite these uncertainties there is no doubt that wind-powered water desalination is a technically challenging solution whose cost-effectiveness has to be examined on a case-by-case basis, even when wind conditions are excellent. Realistically, the water production costs should be assumed to be significantly higher than 1 EUR/m^3. These would be supplemented by ancillary costs arising for delivering the product water and other services. The window within which this option would be applicable in the development context should therefore be considered rather small at present; nonetheless, it cannot be ruled out that the conditions for successful and economically justifiable use may be met at certain locations.

3.4 Plant manufacturers

Various plant manufacturers and firms of consultant engineers, mainly from Germany, have developed and in some cases also produced and tested wind-powered water desalination technologies.[12] That said, none of the plants has proved itself on the market yet. It is also observable that the suppliers of wind-powered desalination plants currently assume their main group of customers to be situated in the Mediterranean region (tourism industry, agriculture) and the Middle East (coastal locations).

The most important companies and types of plant include the following:

Enercon

Enercon offers a modular wind-powered water desalination system on the basis of reverse osmosis suitable for both standalone and grid-coupled operation.[13] The desalination unit consists of a low-pressure pump (22 bar) and a three-piston storage system. The latter raises the pressure to the level required for the raw water (56 bar for seawater or 28 bar for brackish water) and recovers the remaining energy from the brine to return it to the desalination process (pressure recovery). Although this technique has a product water yield of only 25% (seawater; 50% for brackish water), it allows the product water flow to be flexibly adapted to the available load or water demand (175 – 350 m^3/day, depending on desalination unit) and is comparatively energy-efficient (according to information from Enercon 2 - 2.5 kWh/m^3 for seawater). The manufacturer states that no chemical pretreatment of the raw water is necessary. Whether the plant can meet this promise is impossible to check at present. The system is available as a package consisting of up to four RO modules, wind turbines and control software. It can be connected to the public grid or integrated with a diesel generator. With four desalination units, product water output can vary between 350 m^3/day and

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[12] The focus on German manufacturers, market leaders in wind energy converters in any case, is explained by the fact that their products are comparatively well described. This does not mean, however, that there are no other suppliers of wind-powered desalination plants. These include in particular the Danish company VESTESEN A/S.

[13] Information available on the Enercon website and in Paulsen and Hensel (2005, 2007).

1,400 m^3/day (seawater desalination), or for brackish water can reach as much as 2,800 m^3/day. The system has so far only been tested in pilot projects (Norway, Greece) and for simulation purposes (Aurich). No binding information is available from the manufacturer regarding the cost of the desalination modules.

Synwater

Synwater is a product line of Berliner Synlift Systems GmbH. The wind-powered water treatment plant that it offers can be configured on a modular basis and is suitable for desalinating seawater and brackish water, but can also be used to treat wastewater or surface water. The water treatment module operates according to the principle of reverse osmosis and can be dimensioned for a daily capacity of 500 – 2,000 m^3 (product water), in combination with a wind turbine of the 750 – 1,500 kW output class. The system is suitable for isolated operation, with or without an integrated diesel generator.

So far no customers have been found for these systems. The manufacturer’s suggested prices are not known. Synlift Systems is currently putting itself forward for several projects: a wind turbine (750 kW) erected on the island of Sir Bani Yes near Abu Dhabi is to be coupled to a seawater desalination unit for demonstration purposes. Together with the Moroccan Centre Développement des Energies Renouvables (CDER) the company has planned a three-phase project in the city of Tan Tan (Morocco), which the Office National de l’Eau Potable (ONEP) intends to implement. The project consists of a grid-coupled 11.2-MW wind farm that is to supply electricity to an RO desalination plant with a daily output of 11,232 m^3. According to information from the Managing Director of Synlift Systems, there are also plans to install a wind-powered desalination plant in Jordan (daily capacity: 6,000 m^3).

WME GmbH

The plant type developed by WME GmbH (Dranske, Rügen) is based on mechanical vapour compression and can be operated as an isolated system; it has been tested on the islands of Borkum and Rügen for desalinating brackish water. The pilot plant installed on Rügen operates with a compressor output of up to 250 kW and has a daily capacity of up to 360 m^3 (product water). It is powered by a 300 kW wind turbine. Specific energy consumption is over 9 kWh/m^3. No information is available about the behaviour of the plant when processing raw water with a high salt content. No plant has been marketed yet.

Aerdyn Energiesysteme GmbH

This Rendsburg-based company specialises in developing wind energy systems. It advertises a design (“WindDesalter”) – not yet tested in pilot projects –suitable for isolated operation, powered by mechanical wind energy and that can optionally be fitted with a vapour compression unit ($\leq$ 1,400 m^3/day) or RO modules ($\leq$ 2,730 m^3/day). The estimated total plant energy demand lies in the range 4 - 8 kWh/m^3 (RO) or 7 - 12 kWh/m^3 (vapour compression). Studies have been conducted on the design and economic efficiency of these plant types (Witte 2003, WindDesalter Engineering 2004).

4 Opportunities for using wind-powered water desalination in developing countries

It is well known that there are inadequate supplies of good-quality water in large areas of the world. According to the most recent World Water Development Report by UNESCO (2006), only 15% of the world's population have convenient access to drinking water; some 20% have to manage with no appreciable water supply, while 65% have only low to moderate levels of drinking water provision. The contribution that water desalination plants in general and wind-powered desalination in particular can make to solving the supply problems is limited by a number of constraints. The most important requirements for sustainable operation at a particular location can be summarised as follows:

- There is significant demand for drinking water and service water at the location (> 120 m^3/day).[14]
- Sufficient quantities of the raw water intended for desalination are available, and at low cost.
- Suitable wind conditions prevail at the site (> 7.5 m/s mean wind speed, with only minor fluctuations around the mean).
- A water utility company is on hand which is also capable of dealing with wind power systems and water desalination plants.
- Water tariffs based on the production costs of water desalination are compatible with the ability and willingness of consumers to pay them.[15]
- It is impossible to guarantee the supply of drinking water and service water to meet demand more cost-effectively and in accordance with minimum standards of safety and hygiene using the available conventional water resources.

It would be desirable for the plant supplier to have already established a foothold in the region or for there to be a functioning maintenance and repair infrastructure in place. At inland locations in particular safe disposal of the brine must also be assured.[16]

The list of criteria suggests that project developers will not find it easy to choose suitable locations for wind-powered water desalination plants. The greatest challenge is presumably to find a location with a suitable water utility company and consumers who are able to absorb the costs associated with water desalination.

It is apparent from Table 6 that customary water tariffs in developing countries are on average below 0.5 USD/m^3 and usually do not even cover the operating costs of the water utility company. While it is true that the water prices demanded in informal markets are often well above the official

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[14] The lower limit is determined among other things by the fact that the dimensions of wind-powered desalination plants cannot be reduced at will, because no correspondingly small wind energy converters are available. For a daily capacity of 120 litres a 30-kW WEC would be required, a size that is not commonly available on the market. Given average per capita consumption of 120 l/day, therefore, at least 1,000 consumers could be supplied. The amount of water that is actually consumed at individual locations or in specific areas depends on factors such as the available water resources, income, climate etc.

[15] If possible, pricing that is not cost-dependent should be avoided in favour of economically sustainable operation. Nevertheless, in practice the water price is often a political price.

[16] In the case of seawater desalination plants that return the brine and possibly also chemicals to the sea, there is a risk of polluting maritime ecosystems. This problem has not yet been adequately researched, however.

level, such prices usually only apply to small volumes and as a rule are also only paid in areas without an intact water supply infrastructure. The general conditions of informal markets are not exactly a recommendation for locating water desalination plants.

Upon rational reflection it must be concluded that the opportunities for using wind-powered water desalination plants in developing countries are limited. At present all that can be considered are pilot projects or demonstration schemes which reduce the considerable technical and commercial risks associated with such plants to an acceptable level by providing financial incentives, technical support, and if appropriate partnerships between private investors and the public sector. The promotion instruments of German development cooperation could also be used in this connection.

Table 6: Average water tariffs and cost recovery ratios

	Average tariff private households (USD/m3)		Insufficient to cover operating costs
	Mean	Median	Proportion of utilities
Country income level			
High	1.00	0.96	8%
Upper middle	0.34	0.35	39%
Lower middle	0.31	0.22	37%
Low	0.11	0.09	89%
Region			
OECD	1.04	1.00	6%
Latin America + Caribbean	0.41	0.39	13%
Middle East + North Africa	0.37	0.15	58%
East Asia + Pacific	0.25	0.20	53%
Europe + Central Asia	0.13	0.16	100%
South Asia	0.09	0.06	100%

Source: World Bank (2006)

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Annex 1: Assumptions for WindDesalter technology (in German language)

Windkraftanlage		
Installierte Leistung WKA	kW	600
Lastfaktor	%	45,00%
Bruttoenergieertrag WKA	MWh	2.366,55
Verfuegbarkeit WKA		1,00
Eigenverbrauch WKA	%	4,20%
Nettoenergieertrag	MWh	2.267,15
Anlagenausnutzungsgrad	%	43,11%
Spezifische Investitionskosten	EUR/kW	1.170,00
Jaehrliche Betriebs- und Wartungskosten	% Inv.Kosten	5,00%
Meerwasserentsalzung: Umkehrsosmose		
Nennproduktionsleistung	m3/Tag	2.730
Verfuegbarkeit Entsalzungsanlage		0,80
Schwankungsverlustfaktor Entsalzung		0,90
Teillastfaktor Entsalzungsprozess		1,00
Spezifischer Energieverbrauch mechanisch (Hochdruckpumpe)	kWh/m3	3,60
Energieanteil mechanisch		61,00%
Gesamtenergieverbrauch	kWh/m3	5,90
Jahresproduktion	m3/Jahr	276.593
Tagesproduktion	m3/Tag	758
Auslastungsgrad		27,76%
Spezifische Investitionskosten	EUR/m3/Tag	892,00
davon Membrankosten	%	17,00%
Membranlebensdauer	Volle Jahre	5,00
Jaehrliche Betriebs & Wartungskosten	% Inv.Kosten	2,50%
Chemikalien	EUR/m3	0,125
Meerwasserentsalzung: Bruedenkompression		
Nennproduktionsleistung	m3/Tag	1.400
Verfuegbarkeit Entsalzungsanlage		0,95
Schwankungsverlustfaktor Entsalzung		0,90
Teillastfaktor Entsalzungsprozess		0,84
Spezifischer Energievebrauch mechanisch (Verdichter)	kWh/m3	8,26
Energieanteil mechanisch		73,17%
Gesamtenergieverbrauch	kWh/m3	11,29
Jahresproduktion	m3/Jahr	205.160
Tagesproduktion	m3/Tag	562
Auslastungsgrad		40,15%
Spezifische Investitionskosten	EUR/m3/Tag	1.126,50
Jährliche Betriebs- und Wartungskosten	% Inv.kosten	2,50%
Chemikalien	EUR/m3	0,030
Sonstige Parameter		
Anlagenbauzeit	Monate	15,00
Betriebsdauer	Volle Jahre	20,00
Kapitalkosten	%	10,00%

Diesel Generator		
Spezifische Investitionskosten	EUR/kW	620,00
Lebensdauer	Jahre	15,00
Verfuegbarkeit		0,80
Brennstoffverbrauch bei Vollast (Heizoel)	l/kWh	0,235
Teillastfaktor		0,60
Effektiver Brennstoffverbrauch	l/kWh	0,282
Kosten Heizoel	EUR/l	0,60
Jaehrliche Betriebs- und Wartungskosten	EUR/kW	2,00
Auslastungsgrad		0,56
Stromgestehungskosten	EUR/MWh	186,22

Annex 2: Assumptions for Enercon EDS SW 1200 (in German language)

Windkraftanlage		
Installierte Leistung WKA	kW	600
Lastfaktor	%	40,00%
Bruttoenergieertrag WKA	MWh	2.103,60
Verfuegbarkeit WKA		0,95
Eigenverbrauch WKA	%	5,00%
Nettoenergieertrag	MWh	1.898,50
Anlagenausnutzungsgrad	%	36,10%
Spezifische Investitionskosten	EUR/kW	1.200,00
Jaehrliche Betriebs- und Wartungskosten	% Inv.Kosten	5,00%
Meerwasserentsalzung: Umkehrsosmose		
Nennproduktionsleistung	m3/Tag	1.400
Verfuegbarkeit Entsalzungsanlage		0,80
Schwankungsverlustfaktor Entsalzung		0,75
Teillastfaktor Entsalzungsprozess		1,00
Spezifischer Energievebrauch mechanisch (Pumpen)	kWh/m3	2,50
Energieanteil mechanisch		65,00%
Gesamtenergieverbrauch	kWh/m3	3,85
Jahresproduktion	m3/Jahr	296.166
Tagesproduktion	m3/Tag	811
Auslastungsgrad		57,96%
Spezifische Investitionskosten	EUR/m3/Tag	1.100,00
davon Membrankosten	%	17,00%
Membranlebensdauer	Volle Jahre	5,00
Jaehrliche Betriebs & Wartungskosten	% Inv.Kosten	2,50%
Chemikalien	EUR/m3	0,000
Meerwasserentsalzung: Bruedenkompression		
Nennproduktionsleistung	m3/Tag	700
Verfuegbarkeit Entsalzungsanlage		0,95
Schwankungsverlustfaktor Entsalzung		0,90
Teillastfaktor Entsalzungsprozess		0,84
Spezifischer Energievebrauch mechanisch (Verdichter)	kWh/m3	8,00
Energieanteil mechanisch		73,17%
Gesamtenergieverbrauch	kWh/m3	10,93
Jahresproduktion	m3/Jahr	177.376
Tagesproduktion	m3/Tag	486
Auslastungsgrad		69,42%
Spezifische Investitionskosten	EUR/m3/Tag	1.200,00
Jährliche Betriebs- und Wartungskosten	% Inv.kosten	2,50%
Chemikalien	EUR/m3	0,030
Sonstige Parameter		
Anlagenbauzeit	Monate	15,00
Betriebsdauer	Volle Jahre	20,00
Kapitalkosten	%	10,00%

Diesel Generator		
Spezifische Investitionskosten	EUR/kW	620,00
Lebensdauer	Jahre	15,00
Verfuegbarkeit		0,80
Brennstoffverbrauch bei Vollast (Heizoel)	l/kWh	0,235
Teillastfaktor		0,60
Effektiver Brennstoffverbrauch	l/kWh	0,282
Kosten Heizoel	EUR/l	0,60
Jaehrliche Betriebs- und Wartungskosten	EUR/kW	2,00
Auslastungsgrad		0,56
Stromgestehungskosten	EUR/MWh	186,22

Deutsche Gesellschaft für
Technische Zusammenarbeit (GTZ) GmbH

Dag-Hammarskjöld-Weg 1-5
65760 Eschborn/Germany
T +49 61 96 79-0
F +49 61 96 79-11 15
E info@gtz.de
I www.gtz.de