UNIVERSIDADE FEDERAL DO PARANÁ

NADINE GABOR

ENERGY SOURCES IN GERMANY AND BRAZIL
GENERAL ASPECTS AND FOUNDATION SOLUTIONS FOR EOLIC STRUCTURES

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Dissertação apresentada ao Curso de Pós Graduação em Construção Civil, Área de Concentração em Geotecnica, Departamento de Construção Civil, Setor de Tecnologia, Universidade Federal do Paraná, como parte das exigências para obtenção do titulo de Mestre em Construção Civil.

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TERMO DE APROVAÇÃO

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Dissertação aprovada como requisite parcial para obtenção do grau do Mestre no Programa de Pós-Graduação em Construção Civil, Setor de Tecnologia, Universidade Federal do Paraná, pela seguinte banca examinadora:

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Ao Sebastian, meu marido,
e à minha filha Lara.

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cm	centimeter
c_p	Power coefficient
$c_{p,\ Betz}$	Betz's power coefficient
kg	kilogram
mm	millimeter
P_n	Theoretically usable (maximum) power
ρ	Air density
r	Radius of the circular rotor area of a wind turbine with horizontal axis
t	Time
v	Wind speed

List of Abbreviations

A	Ampere
AC	Alternating Current
AEE	Agentur für Erneuerbare Energien (engl.: German Agency for Renewable Energies)
ANEEL	Agência Nacional de Energia Elétrica (engl.: Brazilian Agency for Electricity)
API RP2A (LRFD/WSD)	American design codes on Load Resistant Fatigue Damage and Load and resistance factor/Working Stress Design
ASTM	American Society for Testing Materials
AVG	Abfall-Verwertungs-Gesellschaft mbH, German company
BMU	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (engl.: German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety)
BMWi	Bundesministerium für Wirtschaft und Technologie (engl.: German Federal Ministry of Economics and Technology)
BWE	Bundesverband WindEnergie (engl.: German WindEnergy Association)
CE	Ceará, Federal State of Brazil
CGH	Central Geradora Hidrelétrica (engl.: Hydrolelectric Generating Plant)
CHP	Combined heat and power generation
CPT	Cone Penetration Test
CPTU	Piezocone Penetration Test
dB	decibel, logarithmic unit
DENA	Deutsche Energie-Agentur (engl.: German Energy Agency)
DNV	Det Norske Veritas, independent foundation with the purpose of safeguarding life, property, and the environment
DWD	Deutscher Wetterdienst (engl.: German weather service)

EEG	Erneuerbare-Energien-Gesetz (engl.: German Renewable Energy Sources Act)
EIA	Energy Information Administration
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit (engl.: German association for technical cooperation)
GWEC	Global Wind Energy Council
HVDC	High Voltage Direct Current
IEC	International Electrotechnical Commission
kV	Kilovolt
LED	Light Emitting Diodes
MG	Minas Gerais, Federal State of Brazil
MME	Ministro de Estado de Minas e Energia (engl.: Brazilian Federal Ministry for Mines and Energy)
NABU	Naturschutzbund Deutschland e.V. (engl.: German Nature and Biodiversity Conservation Union)
ONS	Operador Nacional do Sistema Elétrico (engl.: Brazilian Electric System National Operator)
OWEN	Offshore Wind Energy Network
PAC	Programa de Aceleração do Crescimento
PCH	Pequena Central Hidrelétrica (engl.: Small Hydroelectric Plant)
PE	Pernambuco, Federal State of Brazil
PI	Piauí, Federal State of Brazil
PR	Paraná, Federal State of Brazil
PROINFA	Programa de Incentivo a Fontes Alternativas de Energia Elétrica (engl.: Brazilian Program of Incentives for Alternative Electricity Sources)
RJ	Rio de Janeiro, Federal State of Brazil
RN	Rio Grande do Norte, Federal State of Brazil
RS	Rio Grande do Sul, Federal State of Brazil

SC	Santa Catarina, Federal State of Brazil
SIN	Sistema Interligado National, sum of the high voltage power lines in Brazil
SPT	Standard Penetration Test
TVA	Tennessee Valley Authority
UHE	Usina Hidrelétrica (engl.: Hydroelectric Power Plant)
USA	United States of America
WEC	Wind Energy Converter
WKO	Wirtschaftskammer Österreich (engl.: Austrian Federal Economic Chamber)
WWEA	World Wind Energy Association

Abstract

Without energy our lives are inconceivable: we need energy for cooking, for working, for travelling, for resting, and so on.

Since our main energy sources are getting scarce and are causing problems such as exhaustibility (fossil origin) and hazard potential (nuclear origin), mankind is searching for better ways to produce energy. The reason is not only to gain independence from fossil and nuclear sources but also to live in harmony with environmental demands. For these purposes, energy from renewable sources appears to be the best solution, so the commissioning of plants from regenerative origin will gain greater importance as time goes.

In this context, the present work emphasizes general aspects of power supply in Brazil and Germany, discussing the role of renewable energies, particularly wind power generation.

Even though mankind has been utilizing this kind of energy since early times, wind energy stands still in a very primary stage today - both in energy amount being generated worldwide and as far as its technological development. Therefore questions regarding the significance that wind energy has at the present time (internationally, in Brazil and in Germany), and what potential has not yet been materialized, are discussed in this paper.

A description of wind energy plants follows, focusing performance and efficiency, as well as function and structure-types of wind powered turbines, that are treated together with the requirements for sites and problems that a few equipment solutions may cause.

The last important aspect of the work is the wind energy plant foundation. A wind power plant must be securely anchored in the ground, as other structures as well, but a few details for foundation solutions are particular, such as height, embedment in soil or rock, wind pressures, working conditions, wave effects, pole cross section, vibrations, maintenance and corrosion, among others.

Obviously, the subsoil conditions are extremely important, requiring careful in situ and laboratorial data acquisition, interpretation and foundation design for such important energy producer structures.

Resumo

Sem energia, a nossa vida é inimaginável: precisamos dela para cozinhar, trabalhar, viajar, nos divertir, descansar, etc.

Sabendo-se que tradicionais fontes de energia estão associadas a problemas como limitação de depósitos (fonte fóssil) e riscos na geração (fonte nuclear), a humanidade está procurando por uma melhor alternativa de produzi-la. A razão é não somente para ganhar independência dessas fontes usuais, mas também para ficar em harmonia com a natureza e garantir adequada proteção ambiental ao planeta. Para isso, fontes de energia renováveis apontam solução melhor do que as atuais, indicando as alternativas ambientalmente mais corretas que certamente prevalecerão mundialmente.

Nesse contexto, na presente dissertação, após considerar os aspectos gerais do fornecimento de energia no Brasil e na Alemanha, a atuação de energia renovável com especil atenção à eólica, está enfatizada.

Apesar da energia originada pelo vento vir sendo utilizada há muito tempo no mundo, o seu desenvolvimento tecnológico aparenta estar ainda insipiente, o que justifica este enfoque.

Questões relativas ao seu significado econômico, tanto internacionalmente quanto no Brasil e na Alemanha, são discutidas. Aspectos de projeto, execução, detalhes de equipamentos, manutenção e outros são também tratados e exemplificam esta grande alternativa para geração de energia limpa.

Por fim, as fundações de estruturas para máquinas eólicas são também tratadas, enfocando-se tipos de perfil geotécnico, levantamento de dados, análise e solução, com algumas aplicações em casos reais.

1 Introduction

1.1 Problem

For our everyday life, we need energy. Energy that is provided by nature in numerous types: fossil, nuclear or renewable. For a future independence from fossil (exhaustible) and nuclear (risky) energy sources and in harmony with the demands of nature and conservation, the commissioning of plants from regenerative sources will gain greater importance for the production of energy. Regarding the implementation of such plants, the question of "where" arises with the question of "how" and “what types”.

1.2 Objective and procedure

In this Master Thesis, the general aspects in the power supply of Brazil and Germany is elaborated upon with regard to the role of renewable energies and particularly wind power. Subsequent examinations are conducted, pertaining to which aspects have to be taken into account for the creation of a wind power station.

To the extensive subject matter of renewable energies, an overall view of the structure of the current production of Brazil and Germany is reflected upon.

With regard to the enormous requirements for the foundation of wind power stations, these shall be examined in detail in chapter 6 of the work at hand.

2 The Generation of Power

This chapter explains the basics for understanding the present case study. After basic explanation of units and energy used, the particularities of the Brazilian and German power generation is discussed.

2.1 Fundamentals

2.1.1 Units

In this thesis, it will often be referred to the units of watt (W) and watt-hour (Wh) or the multiples thereof. To clarify the difference of these units, both are delimited from one other here briefly. (ABNT NBR ISO 1000:2006)

- **Watt**

Watt is the international unit of power and equals one 1 joule per second (1 W = 1 J/s). In electrical engineering, the following applies to direct current and to alternating current provided there is no phase shift: 1 watt = 1 volt · 1 ampere.

The following prefixes are usable:

1 W (watt)	1 W
1 kW (kilowatt)	1 000 W
1 MW (megawatt)	1 000 000 W
1 GW (gigawatt)	1 000 000 000 W
1 TW (terawatt)	1 000 000 000 000 W

- **Watt-Hour**

A measurement unit of work, and with that an energy unit, is the watt-hour. A watt-hour corresponds to the energy, which a machine with a continuous power of one watt delivers or takes in one hour. The kilowatt hour (kWh) is the unit most frequently used in electrical engineering for energy or work. If, for example, a wind power station converts wind power into electrical energy with the

power of one kilowatt for one hour, then this corresponds to an amount of energy of one kilowatt-hour.
The following prefixes are used here:

1 Wh (watt hour)	1 Wh
1 kWh (kilowatt hour)	1 000 Wh
1 MWh (megawatt hour)	1 000 000 Wh
1 GWh (gigawatt hour)	1 000 000 000 Wh
1 TWh (terawatt hour)	1 000 000 000 000 Wh

2.1.2 Energy

Usually energy is transformed from one type to another (e. g. windenergy into electric energy) forming a chain of successive transformations. At the beginning of an energy chain, a primary energy exists. This primary energy is defined as one which occurs in nature in free or bound form, like for example mineral oil, brown coal or fissile material. Through transformation processes such as combustion or fission, secondary energy emerges (i. e. gases, electric energy, gasoline or district heating), which is made available after further transmission to the consumer as final energy. So final energy is the energy which the consumer actually receives (gas, current from the house connection, fuel oil in the tank…). One calls the energy, that the consumer really can use in the end, utility energy (e. g. heat, light, mechanical work…).

The extraction of electrical energy from primary sources is described as electricity generation and is structured in

- Gross electricity generation (the electric energy created in a power station), and
- Net electricity generation (gross electricity generation minus the consumption of the power station itself).

2.2 Power Generation in Brazil

Both the government and private companies have steadily expanded the Brazilian generation capacity in recent years. A large portion of the installed capacity is focused on the states of Minas Gerais, Paraná and São Paulo. (HELMKE, 2009)

The installed power generating capacity in Brazil was approximately 101 336 MW by mid-2008. Electricity imports from the countries of Argentina, Paraguay, Uruguay and Venezuela amounted to an additional 8 170 MW. An overview of the current Brazilian production matrix can be found under Table 2-1.

Table 2-1: Installed power generation capacity (kW) in Brazil 2008 (ANEEL, 2008)

generator/energy source		**installed capacity (details)**			**installed capacity (total)**		
		number of power plants	**kW**	**%**	**number of power plants**	**kW**	**%**
hydroelectricity		683	77 281 166	70.57	683	77 281 166	70.57
gas	natural gas	83	10 216 482	9.33	112	11 397 510	10.41
	process gas	29	1 181 028	1.08			
mineral oil	diesel	580	3 296 602	3.01	600	4 572 296	4.17
	residual oil	20	1 275 694	1.16			
biomass	sugar cane bagasse	247	3 159 663	2.89	293	4 310 597	3.94
	black liquor[1]	13	859 217	0.78			
	wood	27	231 207	0.21			
	biogas	3	41 590	0.04			
	rice husk	3	18 920	0.02			
nuclear energy	PWR reactors	2	1 980 000	1.81	2	1 980 000	1.81
coal	mineral coal	8	1 455 104	1.33	8	1 455 104	1.33
wind energy		20	339 100	0.31	20	339 100	0.31
	subtotal	*1 714*	*101 335 773*	*92.54*	*1 714*	*101 335 773*	*92.54*
imports	Paraguay		5 650 000	5.16		8 170 000	7.46
	Argentina		2 250 000	2.05			
	Venezuela		200 000	0.18			
	Uruguay		70 000	0.06			
	total	**1 714**	**109 505 773**	**100**	**1 714**	**109 505 773**	**100**

[1] mixture of organic and chemical waste products from the Paper Industry

Solar power is not mentioned in this context, since it is not supplied with current in national grid. Nevertheless, the usage of solar panels in Brazil is equally important; amongst others in the generation of domestic hot water in residential buildings. (GERMANY TRADE AND INVEST, 2, 2009)

Power consumption has significantly increased in recent years (Table 2-2), just as the installed capacity has. An average growth of 5.2 % p. a. is assumed. Power consumption can amount to approximately 618 000 GWh (GTZ, 2007) which corresponds to a power factor of approximately 70 %.

Table 2-2: Power Consumption in Brazil 1999-2006 (MME & EPE, 2007), (EIA, 2010)

Year	**Power Consumption [GWh]**
1999	315 753
2000	331 638
2001	309 729
2002	324 365
2003	342 213
2004	359 945
2005	375 193
2006	389 950
2007	402 000

But since there are transmission loses, there have to be produced more electric power than consumed. So Brazil generated 438 800 GWh of electric power in 2007 (Figure 2-1). (CENTRAL INTELLIGENCE AGENCY, 2009) However due to the decline in industrial power demand, the Brazilian energy consumption shrunk. From a high stage in 2007: 402 000 GWh (Table 2-2), between November 2008 and November 2009 it only reached 385 203 GWh. (MORNINGSTAR, 2009)

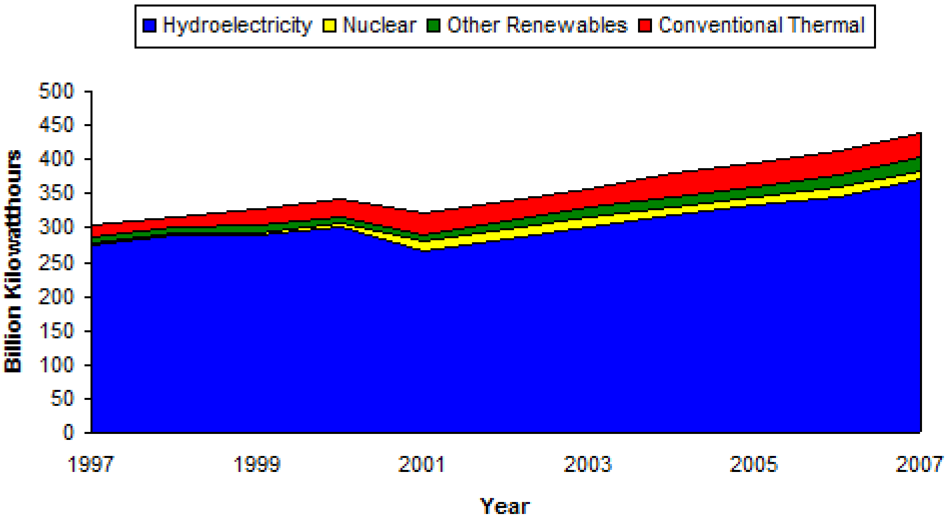


Figure 2-1: Electricity Generation in Brazil, by Source (EIA, 1, 2009)

In 2006, as can be seen in Figure 2-2, Oil, with 49 %, has the largest share of Brazil's total energy consumption. It is followed by hydroelectricity with 36 % and natural gas with 7 %. Coal (5 %), nuclear (2 %) and other Renewable Energies (2 %) form the remaining share. (EIA, 1, 2009)

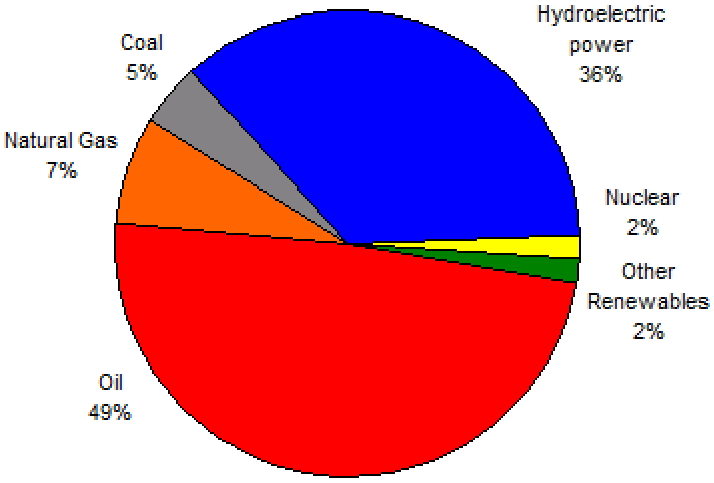


Figure 2-2: Total Energy Consumption in Brazil, by Type (2006) (EIA, 1, 2009)

2.2.1 Hydroelectricity

Brazil is the third largest hydroelectricity producer in the world after China and Canada. (WIKIPEDIA, 2009) Brazil generated 371 000 GWh of hydroelectric power in 2007 – nearly 85 % of its total electricity generation, as can be seen in Figure 2-1.

Brazil owns the half of the Itaipu Hydroelectric Power Plant on the Paraná River, which is located on the border between Brazil and Paraguay. The Itaipu is the world's largest generator of renewable and clean energy (ITAIPU BINACIONAL, 2009) According to Itaipu Binacional, the Itaipu power plant generated 91,7 GWh in 2009.

With just under 71 % (Table 2-1) hydro generation capacity is relatively high, whereas this capacity is located primarily far inland. Thus, the generated electricity must be transported over long distances to the consumption centers which, however, lie predominantly at the coast. This results in high transmission and distribution losses.

Another aspect is the heavy reliance on hydroelectricity. This, especially during periods of below-average rainfall, has caused some issues in the past. (EIA, 2, 2009)

With nearly 90 %, Hydropower offers a very good capacity factor. (WIKIPEDIA, 2009)

2.2.2 Conventional Thermal

A small part of Brazil's power supply is provided by conventional thermal generating sources, contributing about 7 % in 2006. Shown in Figure 2-3, the largest contributor to Brazil's conventional thermal power generation was natural gas with 45 %. It was followed by petroleum products with 34 %, and coal with 17 %. (EIA, 2, 2009)

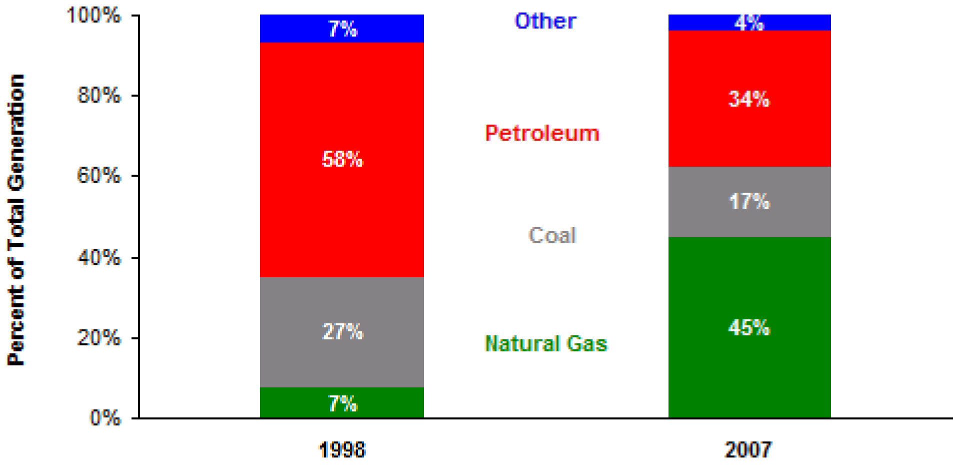


Figure 2-3: Conventional Thermal Generation in Brazil, by Type (EIA, 2, 2009)

The capacity factor amounts to round about 86 %. (DIE PRESSE, 2009)

2.2.3 Nuclear Power

Brazil currently has two nuclear power plants: Angra-1 with a capacity of 630 MW and Angra-2 with a capacity of 1 350 MW. Construction of Angra-3 (also a capacity of 1 350 MW), started in 1986, and after a long interruption begun again in 2008. Completion is stated for 2014. In addition to Anga-3, plans are to build at least four new nuclear power plants by 2030. (EIA, 2, 2009)

The capacity factor of Nuclear power is between 30 and 40 %. (WIKIPEDIA, 2009)

2.2.4 Wind Power

In 2008 Wind Power in Brazil amounts to an installed capacity of 339.1 MW. At an average, Wind Power has a capacity factor of 30 %. (PRO-UMWELT, 2010) For detailed information about Brazilian Wind Power see Chapter 4.3.

2.2.5 Digression: PROINFA

The Brazilian electricity production is based on decades of large hydropower plant construction (Table 2-1). Insufficient investments in power plants in the 90's and a drought in 2001 led to an energy crisis, which led to a rethinking of Brazilian energy policy. The diversification of electricity production has since become a major goal of the Brazilian energy policy to ensure the security of supply. In 2002, the PROINFA was adopted: a program to promote alternative energies, with a total of 3 300 MW capacity based on small hydro, biomass and wind power to be applied to the grid. The biomasses as well as small hydro power generation are established technologies in Brazil, while wind energy is still a relatively new technology, with a higher risk in financing. This does not apply to the plants themselves which were already installed around the world thousands of times, but rather to the network connection and possible infrastructure deficiencies on-site.

Basically there is a similarity between the PROINFA and the EEG (Chapter 2.3.8): The basic principle is based on feed-in tariffs and a long-term power purchase guarantee of 20 years.

2.2.6 Prospects

If the economic development in Brazil continues to grow dynamically in the future, a further rise in power consumption can be expected. Generating capacity should be increased to meet this growing demand. As a result, the Brazilian energy policy initiated investments in the energy sector under the PAC (Programa de Aceleração do Crescimento). This program was passed in January 2007 to accelerate the development of infrastructure and stimulate growth.

Relying completely on hydroelectric power has caused problems in the past (Chapter 2.2.1) mainly because the very complex stochastic nature of streamflows was poorly understood and not fully considered in the planning process.

Also the increased alternative use of water (e. g. irrigation) has reduced plant generation capability over time. To cope with potential shortages of public power supply, the expansion of thermal power plants based on natural gas was pursued, which in turn carries a disadvantage in increased CO_2 emissions (HELMKE, 2009) and increased cost.

An overview of the new installations (Table 2-3) suggests that Brazil is primarily seeking the addition of thermal power plants and large hydro power plants for the future. Wind energy stands at second place in this regard. (HELMKE, 2009)

Table 2-3: Construction in progress and planned production capacity in Brazil (2008) (ANEEL, 2008)

	under construction			**Projects with a building license acquired from 1998 to 2008, which have not yet been implemented**			**total projects**	
Type	**Number**	**Capacity [kW]**	**%**	**Number**	**Capacity [kW]**	**%**	**Capacity [kW]**	**%**
Run-of-water power station (CGH), maximum capacity 1 MW	1	848	0.01	75	51.189	0.19	52.037	0,15
Wind energy	16	149 430	1.92	65	3.306.263	12.51	3.455.693	10,10
Small hydroelectric power plant (PCH)	81	1 342 330	17.24	158	2.343.240	8,87	3.685.570	10,77
Hydroelectric power plant (UHE)	21	4.317.500	55,46	16	9.265.300	35,05	13.582.800	39,70
Thermal power plant	24	1.975.434	25,37	155	11.465.347	43,38	13.440.781	39,28
Total	**143**	**7.785.542**	**100**	**469**	**26.431.339**	**100**	**34.216.881**	**100**

2.3 Power Generation in Germany

In 2008 the electricity generation in Germany totalled 614 430 GWh whereas brown coal (23.5 %), nuclear energy (23.3 %) and hard coal (20.1 %) represented the largest columns. (Table 2-4) Next to 15.1 % through renewable energy sources (Hydropower, Biomass, Wind Power, …), natural gas contributes 13.0 % to the current production. The remaining 5.0 % are covered through heating oil (1.6 %) and other, not renewable energy sources (3.4 %). (AG ENERGIEBILANZEN, 2009) German electricity consumption reached 547 300 GWh in 2007.

Table 2-4: Shares of German electricity production in % (AG ENERGIEBILANZEN, 2009)

	2004	2005	2006	2007*	2008*
Nuclear energy	27.2	27.2	26.3	22.0	23.3
Hard coal	24.1	22.9	21.7	22.3	20.1
Brown coal	26.1	25.7	23.7	24.3	23.5
Natural gas	10.1	10.0	11.5	11.9	13.0
Heating oil	1.7	1.7	1.9	1.5	1.6
Others, not renewable	1.5	2.2	3.2	3.8	3.4
Renewable Energies	9.3	10.3	11.7	14.2	15.1
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

*temporary, estimated in part

With nearly 93 000 GWh, the share of renewable energies in 2008 amounted to 15.1 % of the German power supply (Table 2-5). In 2007, its contingent was 87 605.4 GWh. For 2008, wind power stands at first place with 6.5 %. Biomass (3.7 %), waterpower (3.4 %), biogenous share of refuse (0.8 %) and photovoltaics (0.7 %) deliver the remaining 8.6 % of electricity through renewable energies for the Federal Republic of Germany. (BDEW, 2009) The share of electricity from geothermal plants for the German supply of power is diminutive in comparison to the remaining renewable sources of energy.

Table 2-5: Electricity production (final energy produced) in GWh and shares of regenerative energy sources in the overall German gross electricity consumption in % (BÖHME et al., 2009)

	2004	2005	2006	2007	2008	2008 [%]
Wind Power	25 509	27 229	30 710	39 713	40 400	6.5
Biomass	8 347	10 495	15 593	19 438	22 518	3.7
Hydroelectricity*	21 000	21 524	20 042	21 249	21 300	3.4
Biogenic share of waste**	2 116	3 039	3 675	4 130	4 543	0.8
Photovoltaics	557	1 282	2 220	3 075	4 000	0.7
Geothermal Energy	0.2	0.2	0.4	0.4	18.0	0.0
Total	**57 529.2**	**63 569.2**	**72 240.4**	**87 605.4**	**92 779.0**	**15.1**

* pumped storage power plants with electricity solely from natural inflow

** Percentage of biogenic waste valued at 50 %

2.3.1 Conventional Thermal

Coal (43.6 %), natural gas (13 %) and oil (1.6 %) accounted for 58.2 % of the German gross electricity generation in 2008 (Table 2-4). Therefore, the thermal power stations in Germany play the largest role as a whole.

2.3.2 Nuclear Power

On 14 June 2000, the German government resolved to phase out nuclear energy, which includes the planned closure of nuclear power plants by 2021. Moreover, other nuclear power plants will not be erected in Germany in the frame of this decision.

Presently, 17 nuclear power plants are being operated in Germany with an electrical gross output of 21 497 MW. These nuclear power plants generated 148.8 billion kWh of electricity in 2008.

2.3.3 Wind Power

The total capacity of the wind-powered turbines in Germany amount to about 23.9 GW in 2008. For detailed information about Wind Power in Germany see Chapter 4.4.

2.3.4 Biomass

In 2008, biomass made up 3.7 % of the gross electricity consumption of the Federal Republic of Germany and therefore is one of the most important renewable energy sources.

Farming provides much biomass for energy recovery use, as well as wood from forestry. In 2007, energy crops were cultivated in Germany on more than 10 % of the area used agriculturally. Additionally, residual materials and refuse of biogenic origin are also available. (BMU, 2010)

The current electricity production from biomass has grown considerably since the Renewable Energy Sources Act (EEG) was passed in March 2000, compared with the remaining renewable energy sources. Production in 2008 had increased to 27 000 GWh, compared to the previous year with 22 800 GWh.

Solid biomass together with refuse biomass generates 15 400 GWh, and therefore represents the greatest quota of electricity made of biomass. In 2008, about 210 biomass/wood thermal power stations were online with a performance total of 1.04 GW. (AEE, 2010)

With nevertheless 0.8 %, the utilization of the renewable share of refuse stands in next to last place in the current production from renewable energies. The amended EEG therefore reinforces the utilization of refuse materials and remnant materials in combined heat and power plants. (BMU, 2010)

The capacity factor of Biomass is relatively small: 0.2 to 10 %. (ENERGIEINFO, 2010)

2.3.5 Hydroelectricity

Diverted flow (Figure 3-6), reservoir (Figure 3-7) and pumped storage power plants (Figure 3-8) are used primarily in the Federal Republic. (AEE, 2010) The first of which alone constitute about 72 % of the large water power plants in Germany. (BMWI, 2008)

Although the yet useful potential allows only slight growth rates, the share of water power is considerable at the entire energy mix. The current won out of run-of-river water power plants represents the single form of the renewable energies, which momentarily can be drawn upon for the coverage of the base load.

The largest potentials lie in the replacement, the modernization and in the reactivation of available plants, as well as in new construction at existing edifices.

Why sea current power plants in Germany offer no contribution to the supply of power, lies in the fact that there are no suitable locations within the Federal Republic of Germany where these power plants could be economically taken into operation. (WIKIPEDIA, 2009)

A total of approximately 20 800 GWh were produced out of water power utilization in 2008, which corresponds to a share of 3.4 % in the current production.

2.3.6 Photovoltaics

The EEG was also the driving power in the area of photovoltaics for the strong development of the installed plants. (BMWI, 2008) Subsequently, photovoltaics already covered 0.7 % of the gross electricity consumption in 2008.

The capacity factor in field is declared between 5 and 17 % whereas under laboratory conditions a capacity factor of 13 to 24 % can be achieved. (SOLARSERVER, 2010)

2.3.7 Geothermal Energy

Due to the fact that only two plants are in operation, the geothermal current production in Germany stands yet at the beginning. About 18 GWh current were won out of geothermal energy in 2008. Therefore, the contribution to the supply of power is minimal. (BMU, 2010)

Here the capacity factor is round about 30 – 40 %. (ERDWÄRME-ZEITUNG, 2010)

2.3.8 Digression: EEG

The Renewable Energies Sources Act (EEG) was passed on August 1st, 2004 and regulates the acceptance and payment of electricity derived from renewable energy sources by the grid operator. The law aims to increase the share of renewable energies in Germany's electricity supply by at least 20 % to the year 2020. According to the EEG, renewable energy sources are: hydropower, wind power, solar radiation energy, geothermal and biomass energy. SOLARSERVER, 2010

3 Renewable Energy

It is certain that plants from renewable sources will gain greater importance for the future production of energy. But renewable energy sources also have drawbacks. Before explaining the generation of electricity from the various renewable energies, both the advantages as well as the problems of these energy sources are discussed.

3.1 Positive and negative aspects

Renewable energy is a sustainable energy source, which, measured in human time periods, is available on a continuing basis; quite in contrast to conventional fossil fuels and nuclear fuels, whose occurrence steadily decreases with continual extraction.

For the purpose of energy conservation, energy cannot be renewed or regenerated - strictly speaking, the concept of renewable energy is therefore false. The use of renewable energy is understood as a process of energy conversion, which receive energy constantly without the consumption of limited resources.

Strictly speaking, fossil energy sources such as coal or petroleum are also renewable. Because its formation, however, usually takes several million years to complete, its renewability does not have reference to human time periods. The usual use of the concepts renewability and regeneration refer therefore exactly to this distinction. (WIKIPEDIA, 2009)

The basic natural energy sources continuously available are:

- radiation on the basis of nuclear fusion in the sun,
- the existing heat in the earth’s interior,
- the earth's rotation and associated effects.

These energy sources can be used by people in the form of sunlight and sun heat, wind power and waves, hydropower, tidal power, biomass and geothermal energy.

The combined solar energies such as wind, water, biomass, solar thermal and photovoltaic unite further broad advantages: In terms of the carbon footprint the eco-balance is equalized and the energy consumer countries receive more independence whereby the dependency on the corresponding suppliers of raw material decreases.

But the problem with an alternative form of energy, especially wind and sun, is the continuous fluctuation of generation capacity. Wind turbines do not produce electricity with still air, just as photovoltaic systems are dormant during hours of darkness. A brief gust of wind can operate the generator of a wind turbine at 100 % capacity. And even a partially cloudy day leads to a permanent change of generation capacity with photovoltaic systems.
If weather-dependent solar and wind power is developed further, the power plant management will face problems with variations in demand as well as a fluctuating power supply, as even the best predictions can be deceptive (Figure 3-1).

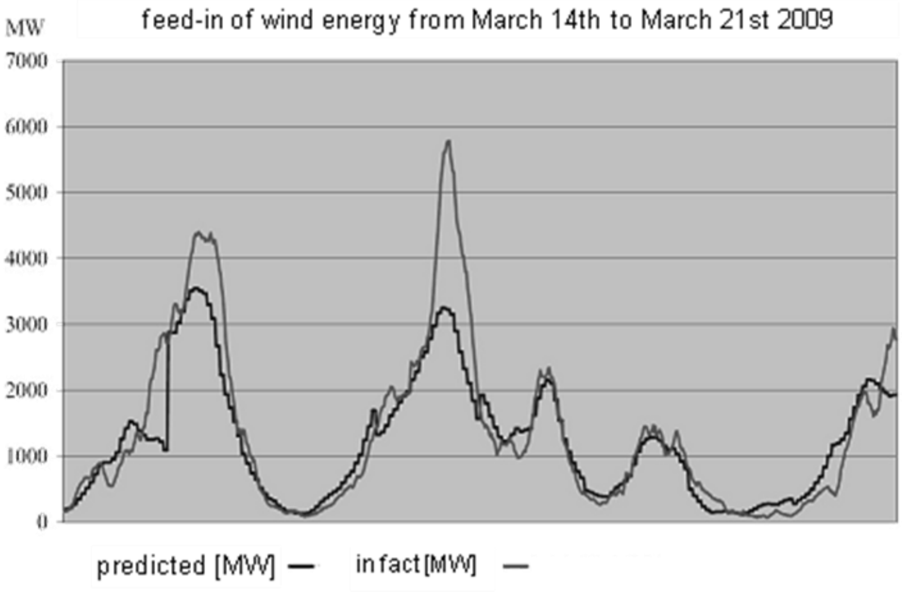


Figure 3-1: Wind energy feed predicted and actual (EON NETZ GMBH, 2009)

If the total energy able to be produced by wind power stations is to be fed into the system grid, the remaining conventional power stations must show a great operational flexibility, because they have to provide only and exact the missing energy.

Because in the summer, the wind in Germany is weaker and less frequent, German wind turbines produce nearly twice as much energy in the winter season than during the summer (Figure 3-2).

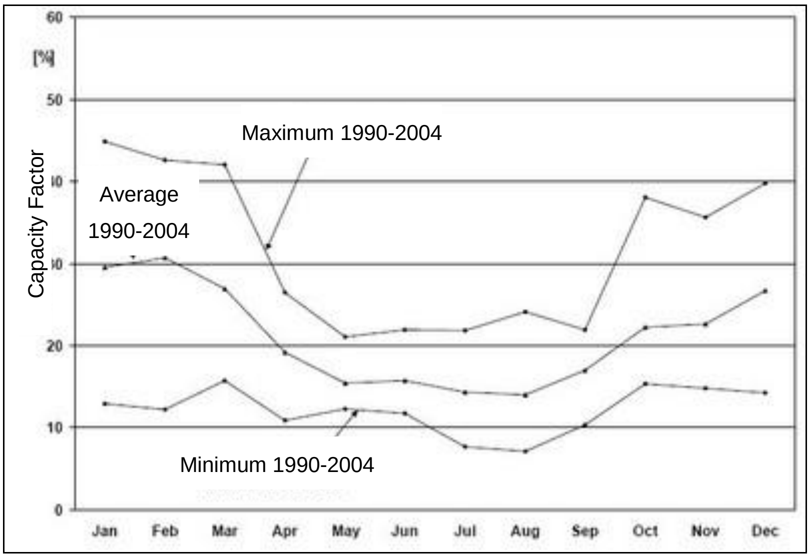


Figure 3-2: Monthly mean utilization factor of wind energy in Germany (1990-2004) (ISET, 2005)

Compared to the evening, the wind blows on average stronger and more frequently during the day – the periods of calm are fewer, showing the wind is not a constant but varies continuously. When fed into the system grid, not only the performance of a single wind turbine must be considered, but also the wind energy must be produced by a large area or by several plants. In Figure 3-3 the top diagram depicts the supply of a single plant into the supply network, the middle diagram the supply of a wind farm and in the lower diagram the supply of all wind turbines in Germany, each over a period of ten days. The larger the surface area, that is the more wind turbines involved, the more even the supply will be. Thus, the burden of fluctuations in the electrical grid is much smaller than with a single wind turbine alone.

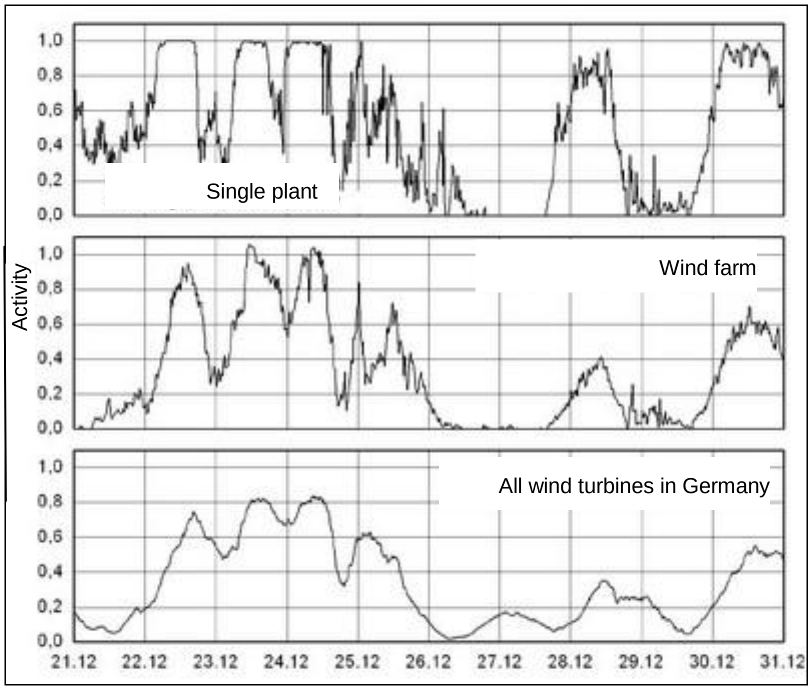


Figure 3-3: Example for supply of a single plant into the supply network, supply of a wind farm and supply of all wind turbines in Germany (21.-31.12.2004) (ISET, 2005)

Since fluctuations are unavoidable, it is important to predict wind performance, ideally with the help of meteorological applications. (WIND-ENERGIE, 2010)

Because of these fluctuations the electric energy derived from wind can only be used in combination with other energy sources for the supply network.

Discrepancy problems between supply and demand are intensified by the expansion of offshore wind energy use (Chapter 5.2.3). These facilities have great potential, but ultimately wind power can only be generated when the wind blows. This may not always coincide with periods of high electricity demand.

Some measures are already proposed to compensate for power fluctuations, such as: (GABOR, 2009)

- **Provision of standard capacity**

  For stable mains operation the balance between production and demand is an important condition. So standard capacity has to be provided for a steady current supply. For this can be used:

  - transaction of rapid conformation of capacity in adjustable power plants,
  - starting of rapid start-up power plants like gas turbine power stations or

  - operation of pump storage power plants.
- **Combination of (control) zones**

  Operators of the national grid have to balance the different amounts of current immediately.

- **Intelligent power usage**

  In the electricity market till now only marginal communication between producer and consumer exists. But new technologies make a temporarily phase out of temporal flexible current consumers possible, to anticipate a collapse of the grid.

- **Energy Storage like**

  - Pump storage power stations

    These power stations store electricity by transmutation of electric energy into potential hydro power.

  - Compressed air storage power stations

    With an electric compressor compressed air is stored in underground excavations. When needed, this air is channeled into a gas turbine where the fully capacity of the compressed air can be used for a generator.

  - Hub storage power plants

    These power plants are using gravity and are therefore working within the same physical law like pump storage power plants. The bulk used in pump storage power plants is water, in the hub storage power plants different bulks like concrete or iron are used.

  - Flywheel mass storage

    In this system a fly wheel is accelerated to high speed by electricity, so that the energy is stored as rotational energy. By decelerating the rotor, energy is rewon.

  - Accumulators

    An accumulator is a storage for electric energy, mostly with a basis of an electrochemical system.

  - Electrolytes
    Here the electric energy is stored in chemical compound like in accumulators, but in liquid.
  - Plug-In-Hybrids
    Because of the batteries in the high amount of cars, operation of a fleet can form a big storage.
  - Superconducting Magnetic Energy Storage
    Here via direct current electric energy is produced in a superconducting magnetic field.
  - Hydrogen
    Via electroanalysis hydrogen can be produced, stored and traded.
  - Double-layer capacitors
    Alternative for accumulators.
  - Condenser
    An electrical component, able to store electric energy.
- **Virtual power plant**
  Single, local power plants are networked and connected with a central control unit via information technology.

- **Conventional power producers**
  Some conventional power plants are just working with part load continuous, to be accelerated to full load if necessary.

With regard to the expansion of renewable energies and the growing potential of concomitant variation, these must further be explored and developed, or other options taken into consideration.

3.2 Photovoltaics

The direct transformation of solar radiation by means of solar cells is the task of photovoltaic systems. The solar cells convert the sunlight into direct current, which can be used for the operation of electrical equipment or stored directly into batteries. This direct current can be fed into the public supply network after being converted into alternating current (Figure 3-4).

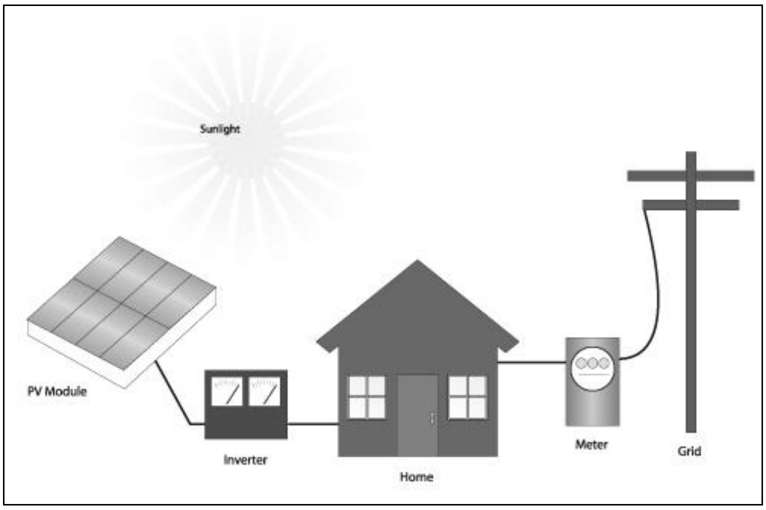


Figure 3-4: Scheme of a photovoltaic system (ACME, 2010)

These systems cover a power spectrum of a few kW (in privately used homes) up to and including several MW. The large plants, or solar thermal power stations, produce current by concentrating and intensifying the sunbeams through the use of reflectors. The radiation is converted into steam, powering the turbine-generators to produce electricity. (AEE, 2010)

3.3 Wind Energy

For the sake of integrity, Wind Energy will be discussed only briefly at this point. This topic will be discussed in detail starting in Chapter 4.

To produce electrical current from wind energy, Wind Energy Converters (WEC) convert the kinetic wind energy into electrical energy. For this, the wind moves the blades and therefore the rotor into a circular motion. The energy of the rotor is then passed on to a generator, which in turn produces electric energy (Figure 3-5). (WIKIPEDIA, 2009)

Figure 3-5: Structural design of the hub and the gondola of a wind turbine (GAIA, 2009)

3.4 Hydroelectricity

The hydrologic cycle represents the basis for the use of water power. With this in mind, the part of rainfall draining through rivers across differences in elevation is used for the generation of power.

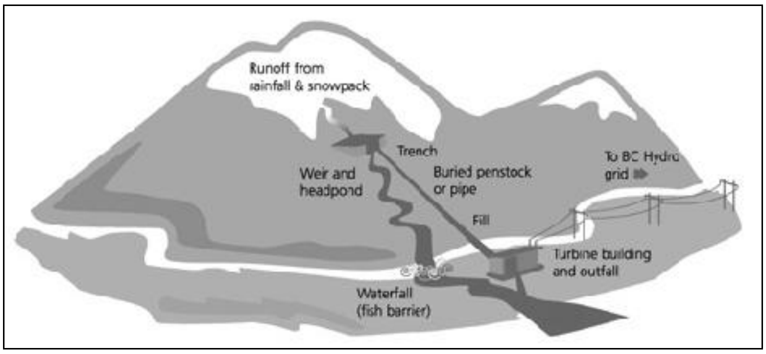


Figure 3-6: Scheme of a run-of-river power plant (TREEHUGGER, 2010)

Hydroelectric power plants are subdivided in the following:

- **Run-of-river** (Figure 3-6)
  Run-of-river power plants require no dam, reservoir or flooding to generate electricity. Only the natural flow and elevation of a river are used to create power. A share of the water from a fast-moving river is diverted and channeled by a penstock or pipe to a turbine. (RUNOFRIVERPOWER, 2010)

- **reservoir** (Figure 3-7)
  Water with a natural flow is stored in a reservoir. If required the water is channeled by pipes and directed to the cavernous power station. In the turbine house, where the pipes are ending, the water activates a turbine, which generates electric power. (WIKIPEDIA, 2009)
- **pumped storage** (Figure 3-8)
  In pumped storage power plants, pump turbines transfer water to a high storage reservoir during off-peak hours. The energy used for pumping the water is derived from other energy sources (nuclear, fossil and renewable power plants). The stored water can be used for power generation to cover temporary peaks in demand. (ALSTOM, 2010)

In any case water driven turbines transfer their energy to generators. Run-of-river plants are plants without significant water storage and thus their generation is subject to daily discharge fluctuations. Reservoir plant has a significant storage capacity which allows them to modulate their generation according consumption demand. Pumped storage plants have a reservoir tilled by pump at low demand hours and generating only at high demand hours. These ultimately generate the electricity that is fed into the supply network. (BMWI, 2009) The energy able to be generated is proportional to the product of discharge and height differences.

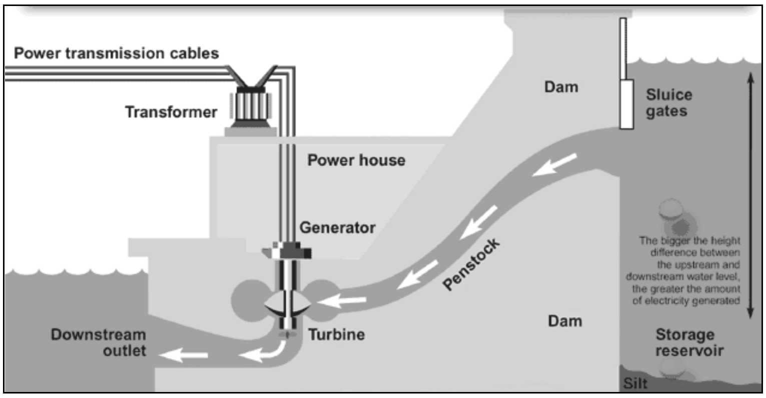


Figure 3-7: Scheme of a reservoir power plant (TVA, 2010)

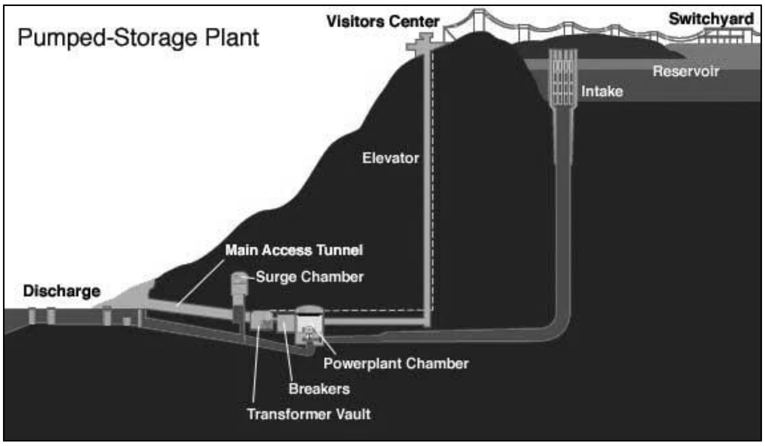


Figure 3-8: Scheme of a pumped storage power plant (ELECTRICAL & ELECTRONICS, 2010)

Energy can also be produced from the sea. Ocean current power plants are utilized to generate energy from large sea currents (Figure 3-9), tidal power stations use head differences during flood and ebb and, using the energy of single waves, wave power plants are in use.

Figure 3-9: Scheme of some marine current turbines (ISET, 2005)

Furthermore, so-called osmosis power stations exist in the sea. These convert the difference in temperature into energy with the help of the seawater salt content between torrents of water of different depths. (AEE, 2010) Ocean power stations have a relatively low fluctuation rate, since ocean currents are continuous and are only insignificantly dependent on current weather conditions. In addition, performances of tidal power plants are very predictable, and the only fluctuation occurs at the change between low and high tide. (WIKIPEDIA, 2009)

3.5 Biomass

Bioenergy is the energy that is available through the energetic utilization of biomass. Among other things, wood, alcohol from sugar cane, vegetal oil and organic waste count as useable biomass. [Wiki. oil] Electricity can therefore be produced from both solid and liquid, as well as gaseous biomass. Biomass can be burned just like fossil fuels in a conventional condensation power plant (Figure 3-10). The water brought to boil produces steam and pressure in the boiler. Electricity is produced with a steam turbine connected to a generator.

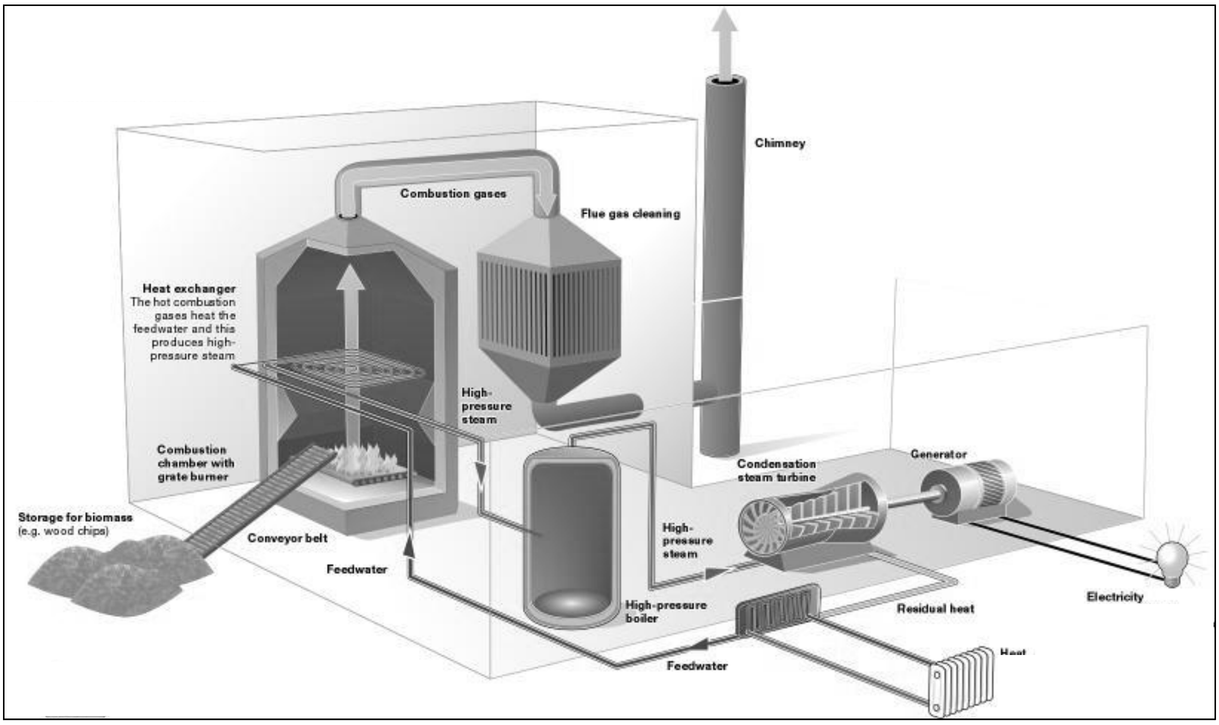


Figure 3-10: Scheme of a Biomass Power Plant (Combined with Heat) (AEE, 2010)

Since only 35 % of the primary energy of the biomass can be converted with conventional technology into Electricity, biomass is ideally used in a cogeneration of heat and power (CHP). The waste heat produced is used to provide building complexes or industrial plants with heat by way of a network, for example. (AEE, 2010)

In this context, the biogenic share of waste also plays a role. The energy contained in waste is used and transformed into electricity and/or heat. This happens in waste incineration plants (Figure 3-11), which are divided into refuse-fired heating plants, garbage-to-energy plants or waste-heat plants, according to task. (WIKIPEDIA, 2009)

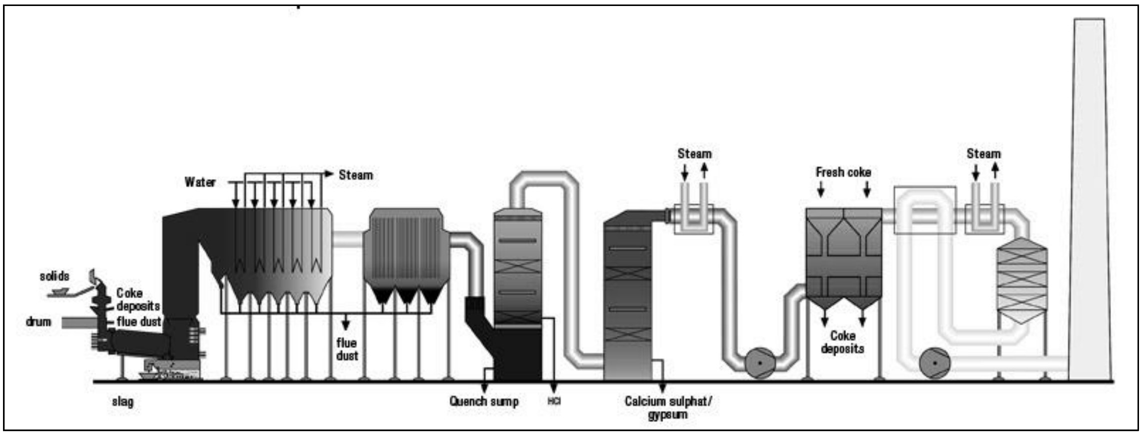


Figure 3-11: Scheme of a waste incineration plant (AVG, 2010)

The rubbish is burned slowly at temperatures between 850 and 1 000 degrees Celsius in the waste incineration plants. The accumulating slag is deposited at a landfill after cooling and the separation of iron parts.

In the combustion of the refuse, heat is also produced for use in district heating networks, which can also be used for steam production. This can be passed on to surrounding industrial plants as process steam, or used for the production of electrical energy by means of turbines, which is then fed into the public network. (ZMS, 2009)

3.6 Geothermal Energy

If geothermal heat is used to obtain electricity, heating or cooling energy, it is called geothermal energy (Figure 3-12). It is differentiated into near-surface and deep geothermal heat.

With this form of energy generation, one makes use of the Earth's internal temperatures of up to 6 000 degrees Celsius. Since the temperature increases by only 3 degrees Celsius per 100 m of depth in the Central European area, drillings must be appropriately deep to achieve sufficiently high temperatures.

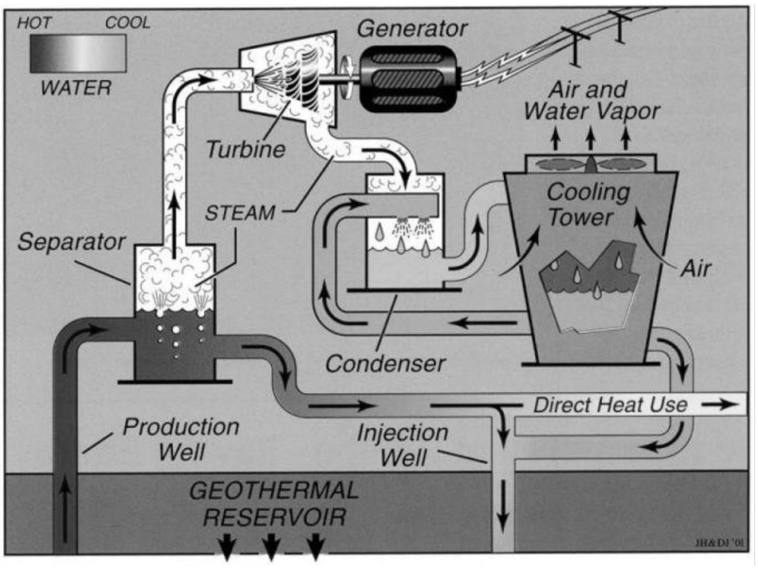


Figure 3-12: Scheme of a geothermal plant SOLCOMHOUSE, 2010

Since the near-surface geothermal energy encounters temperatures of only 8 to 12 degrees Celsius in Earth layers of up to 400 m, deep-geothermal drilling must be used for the generation of electricity. Temperatures are much higher at depths of 400 to 5 000 m and therefore utilizable for an economic means of power generation. The greatest advantage of geothermal energy is the permanent availability. (AEE, 2010)

4 Wind Energy

Mankind has used wind energy since the beginning of time – in spite of this, wind energy stands in a very early stage of its career. Questions' regarding what significance wind energy has at present, and what potentials have not yet been exhausted, are discussed in this chapter.

4.1 Fundamentals

Low and high pressure areas differ with respect to air pressure and temperature. They arise from differential solar radiation according to geographic latitude. Also the difference in specific heat of oceans and land contribute to differences in air pressure. Atmospheric depressions are the result as the air rises over strongly heated regions. High pressure areas form in cooler regions. As a balance between these low and high-pressure areas, combined with effects of earth rotation, wind emerges.

Wind power is kinetic energy accordingly, and the available energy at rotor increase proportional to the third power of its speed. This consists of

- the instantaneous kinetic energy of wind per unit volume increases linearly with air density (mass per volume unit) and the square of the velocity,
- and the volume which passes through the rotor per unit time is proportional to the air speed and the cross-sectional area covered by the rotor.

Thus the gross available wind energy E is defined by: (HEIER, 2007)

$$E = \left(\frac{\rho \cdot v^2}{2}\right) \cdot (\pi \cdot r^2 \cdot v) \cdot t = \frac{\pi}{2} r^2 \cdot \rho \cdot v^3 \cdot t \qquad (1)$$

v: Wind speed
ρ: Air density
r: Radius of the circular rotor area of a wind turbine with horizontal axis
t: Time

Therefore, the wind power increases strongly with increasing wind speed, which means that for the location of wind turbine plants, sites with high average wind speed are of particular interest. As an example the resulting kinetic energy, in one second at an air density of 1.22 kg/m³, a wind speed of 8 m/s and a rotor diameter of 100 m will be (EQUATION (1))

$$E = \frac{\pi}{2} \cdot \left(\frac{100}{2}\right)^2 \cdot 1.22\ {}^{kg}/_{m^3} \cdot 8\ {}^{m}/_{s} \cdot 1s = 2.45\ Mega\ joule = 0.68\ kWh.$$

A wind map such as that shown in Figure 4-1 can be used to identify locations with the highest measured winds. The colors denote the energy content of the wind, red high and blue low (on shore) energy content, respectively white (high) and dark blue (low) offshore. Wind maps are calculated for heights of 10 m and 80 m above the ground. Wind data is calculated for the entire world from readings that were registered for decades at different stations. (DWD, 2010) The height above sea level is considered as well as the geographic location, the terrain and the type of land use.

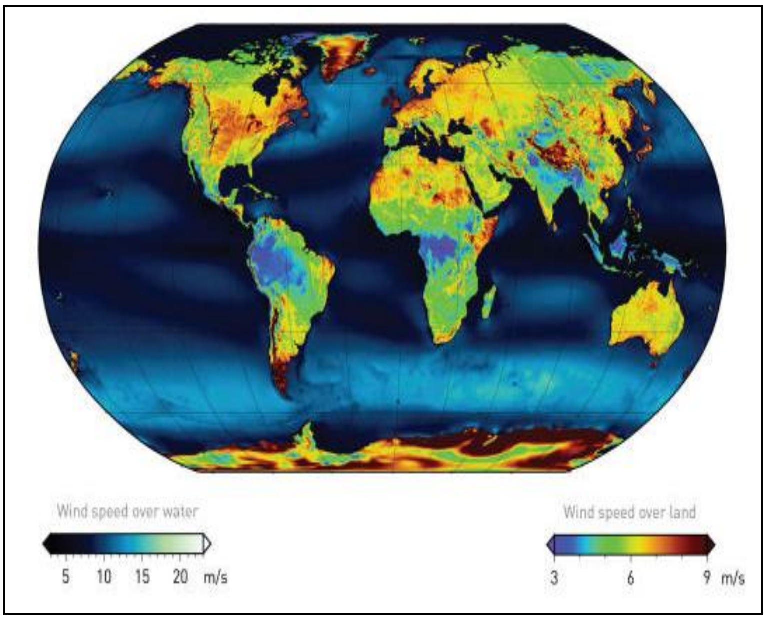


Figure 4-1: Global Wind Map (BUILDING GREEN, 2010)

4.2 International Wind Energy

4.2.1 Current

As can be seen in Figure 4-2, the worldwide capacity in 2008 reaches 121 188 MW, out of which 27 261 MW were added in 2008 (Figure 4-3).

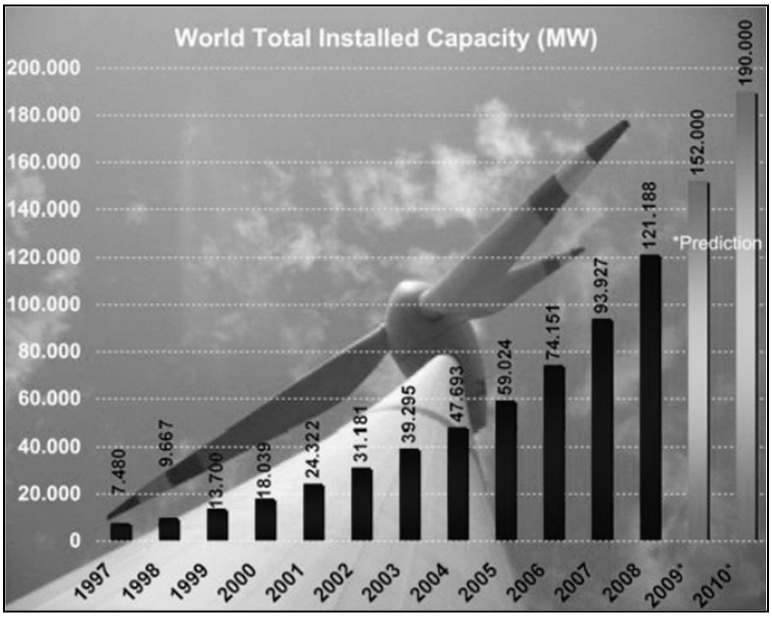


Figure 4-2: World Total Installed Capacity (MW)
(WORLD WIND ENERGY ASSOCIATION, 2009)

So again wind energy is the most dynamically growing energy source – a worldwide success story. The market for new wind turbines showed a 42 % increase and reached an overall size of 27 261 MW. For comparison: Ten years ago, the market for new wind turbines had a size of 2 187 MW, what is less than one tenth of the size in 2008. (WORLD WIND ENERGY ASSOCIATION, 2009) So at the moment Wind power produces about 1.5 % of worldwide electricity use. (WORLDWATCH INSTITUTE, 2009)

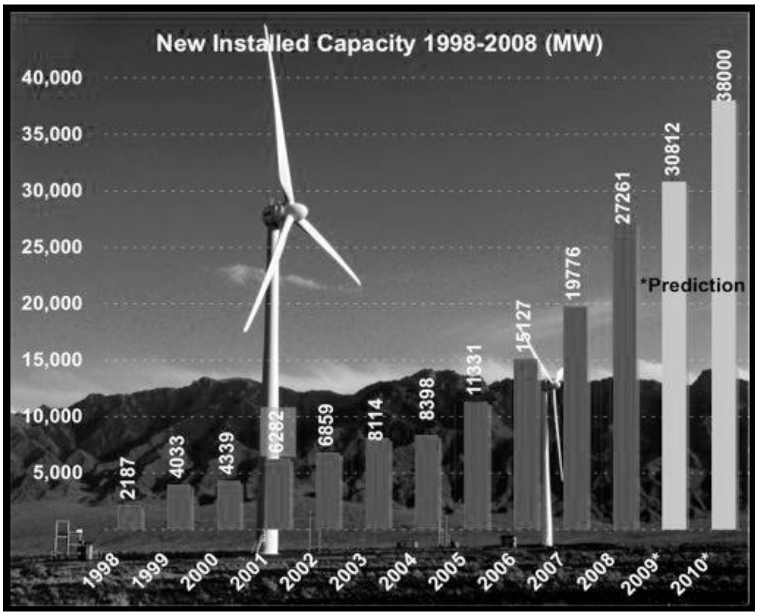


Figure 4-3: New Installed Capacity 1998-2008 (MW)
(WORLD WIND ENERGY ASSOCIATION, 2009)

With regard to Figure 4-4, the USA is taking over the global number one position from Germany.

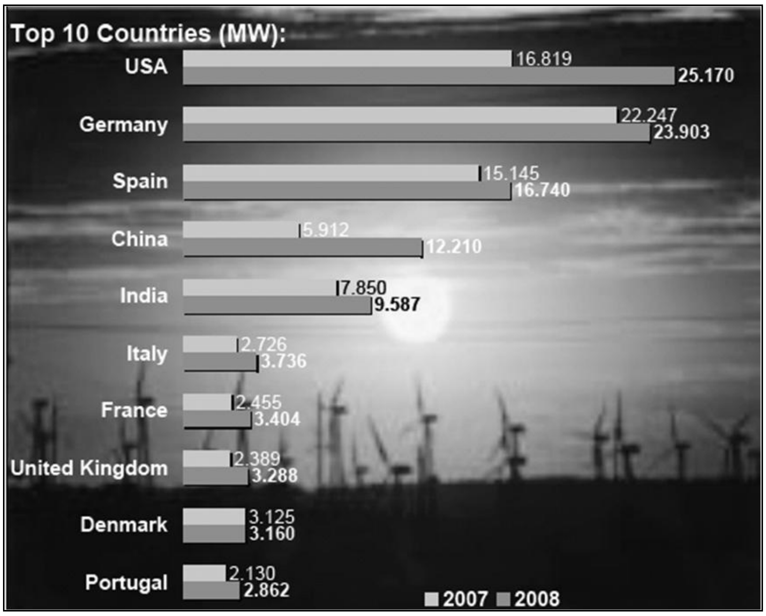


Figure 4-4: Top 10 Countries (MW) (WORLD WIND ENERGY ASSOCIATION, 2009)

There is great potential in wind power use at sea (offshore). The world's largest offshore wind farm, Horns Rev II, went into operation in November 2009. The park can supply a maximum of approximately 210 MW of electric power. Each of the 91 turbines in this case has a rated capacity of 2.3 MW. (INNOVATIONS-REPORT, 2009)

The next increase is also in planning: The offshore wind park London Array. It will be the largest of its type worldwide, consisting of 175 wind power plants with a capacity of 630 MW (what means 3.6 MW per piece), after its completion in 2012. (SIEMENS, 2009)

4.2.2 Future

Wind power is one of the most promising renewable power sources of the future, next to solar energy: Therefore, wind power will continue its rapid development of the previous years (Figure 4-5). According to estimates from the World Wind Energy Association (WWEA), wind power will cover 12 % of the global energy demand in 2020. A study just recently released by the Energy Watch Group assumes that worldwide an installed performance of 7 500 GW will be able to produce 16 400 TWh in one of four scenarios in 2025. (RECHSTEINER, 2009) Wind and solar energy will comprise a 50 % market share of new power plant installations worldwide. (WORLD WIND ENERGY ASSOCIATION, 2009)

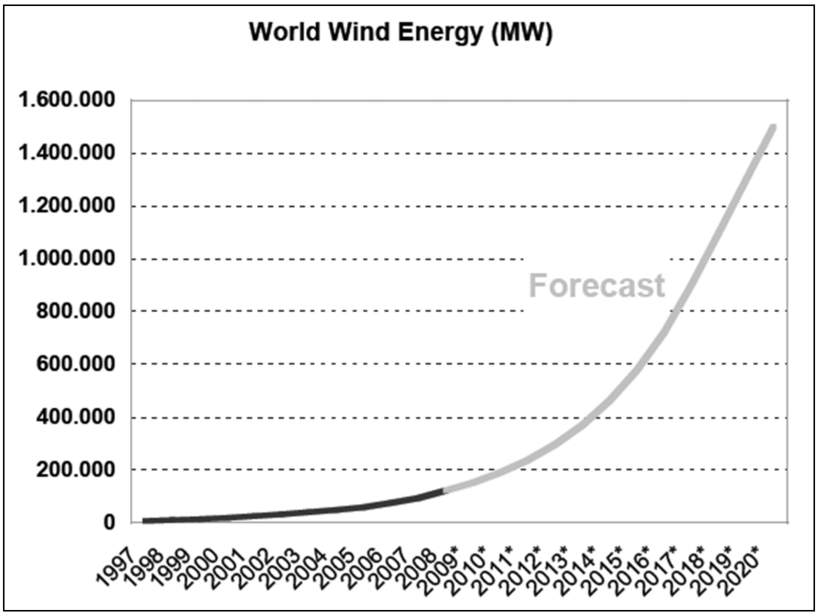


Figure 4-5: World Wind Energy (MW) (WORLD WIND ENERGY ASSOCIATION, 2009)

4.3 Brazilian Wind Energy

4.3.1 Current

The Brazilian Wind Energy Plants in use as of 2008 are listed in Table 4-1. According to this table, wind power in Brazil amounts to an installed capacity of 339.1 MW (Table 2-1). From this listing can be perceived, among other things, that larger wind parks with an installed capacity in the lower five digit kW area were first implemented in the context of the PROINFA program (Chapter 2.2.5)

Table 4-1: Installed wind power plants in Brazil, 2008 (GWEC, 2010)

	Commissioning	**Wind farm**	**State**	**Total capacity [kW]**
1	1992	Eólica de Olinda	PE	225
2	1994	Eólica do Morro de Camelinho	MG	1 000
3	1998	Eólica de Taíba	CE	5 000
4	1999	Eólica Prainha	CE	10 000
5	1999	Eólio-Elétrica de Palmas	PR	2 500
6	2000	Eólica de Fernando de Noronha	PE	225
7	2002	Mucuripe	CE	2 400
8	2002	Eólica de Bom Jardim	SC	600
9	2003	Parque Eólico do Horizonte	SC	4 800
10	2006	RN 15 – Rio do Fogo	RN	49 300
11	2006	Eólica Água Doce	SC	9 000
12	2006	Parque Eólico Osório	RS	50 000
13	2006	Parque Eólico Sangradouro	RS	50 000
14	2006	Parque Eólico dos Índios	RS	50 000
15	2008	Eólica Millennium	RS	10 200
16	2008	Parque Eólico Beberibe	CE	25 600
17	2008	Eólica Canoa Quebrada	CE	10 500
18	2008	Eólica Paracuru	CE	23 400
19	2008	Pedra do Sal	PI	17 850
20	2008	Taíba Albatroz	RJ	16 500
			Total:	**339 100**

4.3.2 Future

Due to the announced special auctions which the Energy Department had set for the end of November 2009, the opportunities for wind power have increased significantly. 71 wind power projects in five different states received the bid.

The contracts include over 1.8 GW, where Brazil’s wind power production capacities are expected to triple. The new wind parks will be erected mainly in the northeast of Brazil as well as in the south. (WKO, 2010)

The national wind potential is reflected by the Brazilian Wind Atlas (Figure 4-6) of the Electric Power Research Center – CEPEL/ELETROBRAS of 2001 with 143 470 MW at a wind speed of more than 7 m/s for a height of 50 m. (CAMARGO DO AMARANTE et al., 2001) The economically feasible potential of wind energy, on the other hand, is estimated to be only 60 000 to 70 000 MW. (WINROCK INTERNATIONAL, 2002) Especially in the states of Ceará, Rio Grande do Norte, Rio Grande do Sul, Pernambuco and Piauí and in the mountainous areas of Bahia, winds are available with more than 8.5 m/s, providing very good conditions. Further prospective wind locations are the coasts of the State of Espírito Santo, Rio de Janeiro and Santa Catarina and the backcountry of São Paulo and Minas Gerais. Characteristic for Brazil are very steady wind patterns and a relatively small variation in wind direction. (DUTRA, 2007)

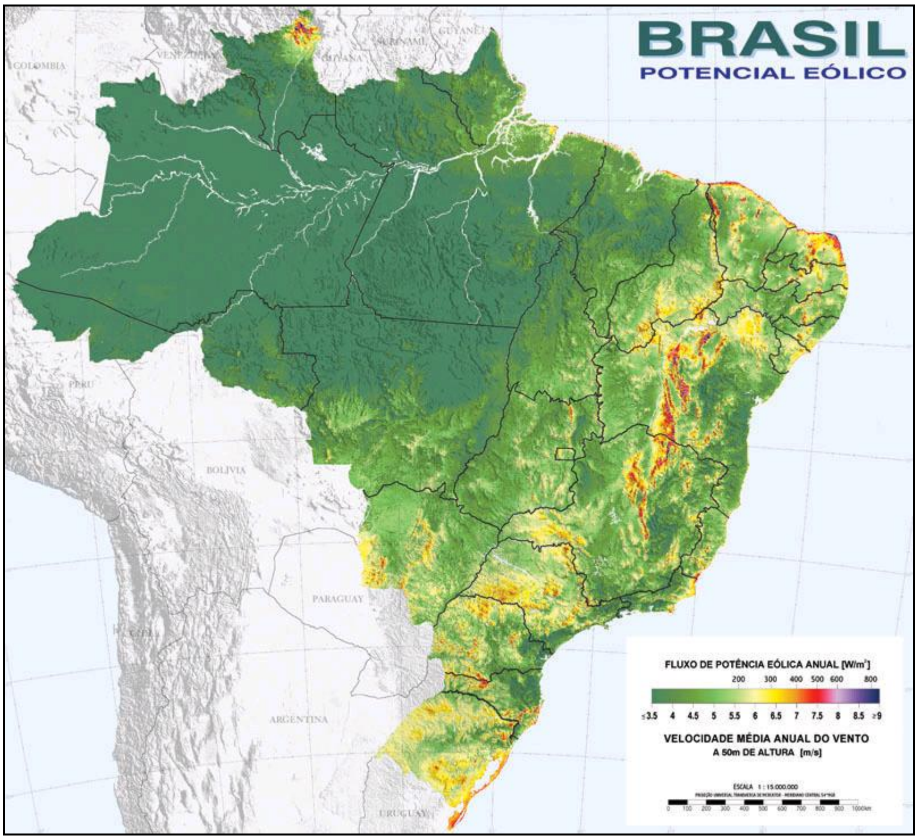


Figure 4-6: Mid-annual wind speed at 50 m height in m/s (MME, 2001)

Wind and water power show complementary characteristics in the northeast and south of the country with regard to the current production: The São Francisco River in the northeast of the country contributes, with eight hydro plants, largely to the power supply of the region; low water periods combine with good wind regimes and vice versa (Figure 4-7). During the dry season, an increased integration of wind power into the current production could minimize possible supply disruptions, or prevent them completely.

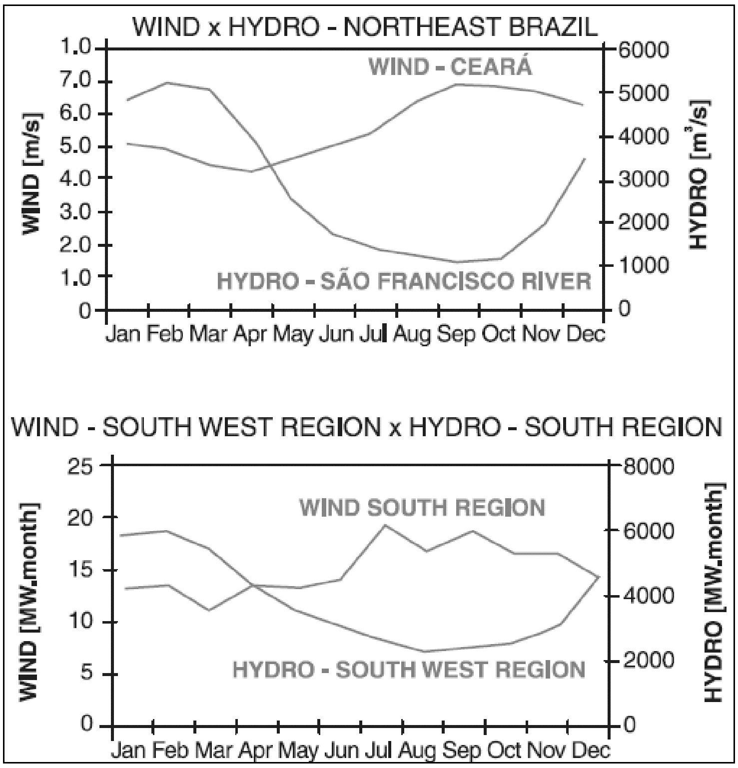


Figure 4-7: Complementary Wind and Hydrological Patterns throughout the Year (WINROCK INTERNATIONAL, 2002)

According to Camargo Schubert, a consulting firm in Brazil, very good and consistent wind conditions prevail in the states of Piauí and Maranhão in the northeast of the country. The majority of installed capacity as of yet, however, is located in Osório in the southern state of Rio Grande do Sul (Table 4-1). The Camargo Schubert Company allocates the estimated wind power potential in Brazil as follows (Table 4-2):

Table 4-2: Wind power potential per region (CAMARGO-SCHUBERT, 2009)

Region	Capacity [GW]
northeast	75.0
southeast	29.7
south	22.8
north	12.8
middle/west	3.1

However high costs did not make wind power competitive in previous auctions of energy production capacities. (GERMANY TRADE AND INVEST, 1, 2009) During the auctions in November 2009 a middle grid induction tariff of R$ 148.39/MWh (approx. € 60/MWh) was set forth. This price, although internationally competitive, is essentially higher than Brazilian water power plants. For example, the facility in Jirau on the Madeira River in Rondônia State was subcontracted with an average grid induction tariff of R$ 71.40/MW/h. And even the average grid induction tariff in current Brazilian hydro plants of R$ 105/MW/h (approx. € 40/MW/h) is essentially lower than the wind power facilities now assigned. Only thermal power plants generate electricity more expensive than wind power plants. (WKO, 2010)

The dimensions of the country represent a further problem. The areas in the northeast with a large wind potential are far away from those places where electricity is needed most. Therefore, the use of these potentials implies major investments in transmission. (GERMANY TRADE AND INVEST, 1, 2009)
Brazil currently has 88 939 km of power transmission lines. The voltages vary between 230 kV and 750 kV. (HELMKE, 2009) The high voltage network has steadily expanded in the last years (Table 4-3).

Table 4-3: Extension of high voltage transmission lines in Brazil 2000-2009 (ANEEL, 2009)

Year	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008***	**2009***
Extension [km]	2 080	1 150	2 437	4 979	2 313	3 035	3 198	995	2 977	4 217

* temporary

The high voltage transmission lines are summarized in the Brazilian interconnected system of SIN (Sistema Interligado National) (Figure 4-8), which currently connects the main coastal centers of consumption and large hydropower plants in the interior.

Figure 4-8: SIN (ONS, 2010)

If economic growth in Brazil should remain high, on average 4 % p.a., the construction of about 41 000 km of additional power transmission lines is estimated for the year 2015. (HELMKE, 2009)
The Eletrobrás Company will expand the power grid network with 10 386 km by 2012. (GERMANY TRADE AND INVEST, 2, 2009)

To use the abundant wind energy potential, a low-loss electric power transmission is needed over long distances. The high voltage direct current (HVDC) could be suitable for this. This is a method of transmitting electric energy with high voltage direct current of 500 kV. This method may include long distances – starting at about 750 km – as the HVDC converters show less total loss than the transmission line with three-phase AC current. (WIKIPEDIA, 2009)
Electric energy in power plants is almost always made by generators that produce three-phase AC electricity.
The transfer of large capacities (about 1 000 MW) over distances of hundreds of km strictly enforces flows below 5 000 A, and thus very high voltages – above

400 kV – are needed, if the wire diameter should stay reasonable. These voltages can be produced in case of alternating current with very good efficiency through power transformers. At the lower end of the power transmission line this high voltage must be stepped down in substations to lower AC voltages such as 69 kV, or medium voltage of 13.8 kV. (WIKIPEDIA, 2009)
However simple and effective transmission does not exist with direct current. In addition to AC transformers, suitable high voltage and technically sophisticated inverters are needed.

4.4 German Wind Energy

4.4.1 Current

Within the last two decades, the use of wind power has greatly increased in Germany. The total capacity of the wind-powered turbines in the Federal Republic climbed from approx. 0.1 GW to about 23.9 GW in the period of 1991 to 2008. This was caused mainly by the "Current Feed Law" (StrEG) which for the first time ever set forth a regulatory minimum reimbursement for electricity from regenerative energy sources, and guaranteed the acquisition of wind electricity by the network operator. (BMWI, 2008)

At the end 2008, the Federal Association of Wind Energy (BWE) reported that 20 288 wind power plants were connected to the grid network Germany wide, (WIND-ENERGIE, 2010) that lead to a first place ranking with 6.5 % of wind energy under the renewable energy sources. The wind power plants delivered 40 200 GWh, whereby the potentials in the Federal Republic have not been completely accessed – the technical development has already advanced quite far in this sector. (BMWI, 2008)

Up to 12 August 2009, wind power had been produced exclusively from on shore plants. Since then, the German grid network is supplied moreover through new offshore wind power plants. (BMU, 2010)

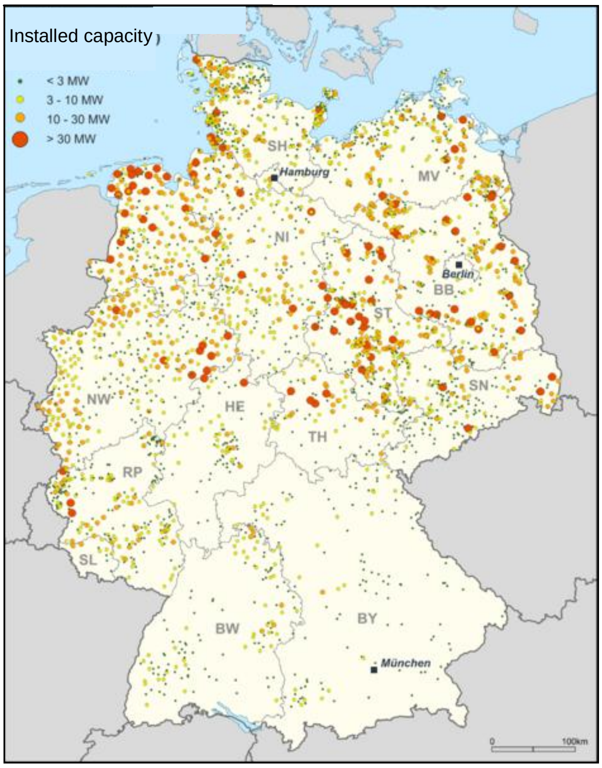


Figure 4-9: Arrangement of the German wind energy plants (WIKIPEDIA, 2009)

Germany installed 866 new wind turbines with a capacity of nearly 1 667 MW in 2008 (Table 4-4). These delivered 40.4 TWh in 2008 alone, which corresponds to a share of 6.6 % of gross electricity consumption. Nearly 23 897 MW of wind power were installed by the end of 2008 (Table 4-4). (BMU, 2010) Therefore, Germany is the world's second largest user of wind power at the end of 2008, right after the USA (Chapter 4.2.1). How can be seen in Table 4-4, after the first half of 2009, more than 20 600 wind turbines are located in the German federal area (Figure 4-9).

Table 4-4: Installed capacity and number of wind power plants in Germany (MOLLY, 2009)

Year	Installed Capacity p.a. [MW]	Accumulated installed capacity [MW]	Number of WEC p.a.	Accumulated number of WEC
1990	36.53	55.06	228	405
1991	50.85	105.90	295	700
1992	68.29	173.74	399	1 084
1993	152.00	325.74	591	1 675
1994	292.61	618.35	792	2 467
1995	503.72	1 120.87	1 062	3 528
1996	427.64	1 546.38	806	4 326
1997	533.62	2 079.97	853	5 178
1998	793.46	2 871.48	1 010	6 185
1999	1 567.68	4 439.16	1 676	7 861
2000	1 665.26	6 104.42	1 495	9 359
2001	2 658.96	8 753.72	2 079	11 438
2002	3 239.96	11 994.22	2 321	13 752
2003	2 644.53	14 609.07	1 703	15 387
2004	2 036.90	16 628.75	1 201	16 543
2005	1 807.77	18 414.92	1 049	17 556
2006	2 233.13	20 621.86	1 208	18 685
2007	1 666.81	22 247.39	883	19 461
2008	1 667.12	23 896.91	867	20 288
1. half of 2009	801.65	24 694.46	401	20 674

4.4.2 Future

An installed performance of 32.9 GW is expected onshore in 2020, whereby approximately 66 000 GWh/a of electricity can be allocated. Offshore is seen to achieve an installed performance of 9 GW, whereby approximately 30 000 GWh/a of electricity can be made available (Table 4-5). So wind turbines will provide 96 000 GWh/a of power in 2020, which is about 17 % of the total gross energy production.

Table 4-5: Electricity generation [TWh/a] per renewable energy source (NITSCH & WENZEL, 2009)

	2005	**2008**	**2010**	**2015**	**2020**	**2025**	**2030**	**2040**	**2050**
hydroelectricity	**21.5**	**21.3**	**21.9**	**23.6**	**24.5**	**24.6**	**24.8**	**24.9**	**25.0**
wind energy	**27.2**	**40.4**	**48.1**	**65.3**	**96.3**	**129.8**	**163.4**	**209.0**	**228.2**
-Onshore	27.2	40.4	47.7	57.9	66.1	70.7	75.3	81.7	85.8
-Offshore	-	-	0.4	7.5	30.2	59.1	88.0	127.3	142.5
photovoltaics	**1.3**	**4.0**	**7.0**	**14.1**	**20.0**	**23.0**	**25.9**	**28.6**	**32.5**
biomass	**13.5**	**27.0**	**32.1**	**42.7**	**50.6**	**53.0**	**55.3**	**56.3**	**56.6**
-biogas, digester gas	5.8	11.4	13.6	19.8	25.1	25.6	26.2	26.3	26.3
-hard biomass	4.6	10.9	13.6	17.5	20.1	22.0	23.7	24.6	24.9
-biogenic decay	3.1	4.7	4.9	5.4	5.4	5.4	5.4	5.4	5.4
geothermal energy	**0**	**0.02**	**0.09**	**0.57**	**1.9**	**4.4**	**7.0**	**16.2**	**37.1**
Electricity by Renewable Energies	**63.6**	**92.8**	**109.3**	**146,3**	**193.3**	**234.8**	**276.3**	**335.0**	**379.3**

Figure 4-10 shows that the more northerly and higher, the stronger the wind. The darker the color, the higher the wind speed.

So good wind sites are found on the North Sea and Baltic coasts, in the coastal lowlands and the exposed layers of the Central German Uplands. The technically usable potential in Germany for the installation of wind farms on shore is about 128 TWh/a (PIEPRZYK & ROJAS HILJE, 2009). A major expansion of this potential can be reached, however, by offshore wind turbines that are in the coastal waters.

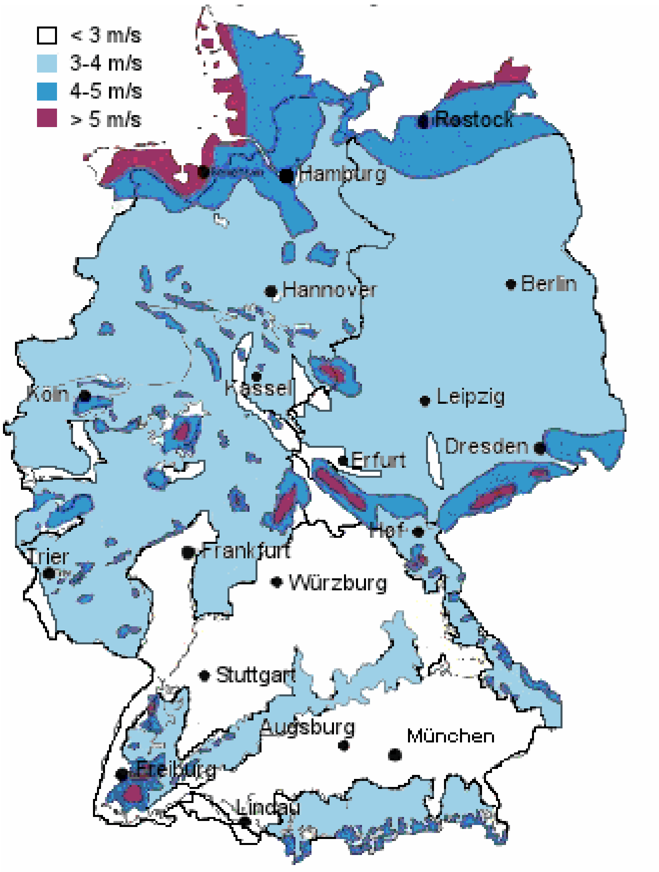


Figure 4-10: Mid-annual wind speed at 10 m height in m/s in Germany (GLEIS & GROTH, 2010)

In both the North and in the Baltic Sea, the ocean's depths are relatively low and the speed of the wind very high. These are ideal conditions for offshore installations. The estimated potential of offshore wind energy depends on the water depth and distance to the coast, according to the German Wind Energy Association (BWE) (WIND-ENERGIE, 2010):

- up to 10 m water depth and 10 km from the coast, it is 20×10^9 kWh,
- up to 20 m water depth and 20 km away 130×10^9 kWh and,
- up to 30 m water depth and 30 km away, in fact 200×10^9 kWh.

5 Wind Energy Plants

This chapter describes the wind turbines. Performance and efficiency as well as function and structure-types of wind turbines are treated the same as the requirements for the sites and the problems that such equipment brings with them.

5.1 Performance and Efficiency

Twenty years ago, while small plants with a capacity of less than 100 kW were part of a standard, increasingly larger units of 1 000 kW came to use in the new millennium. Meanwhile, plants are often used in the multi-megawatt range. (BMWI, 2009)

This installed capacity, also rated output, is a technical size which indicates the highest possible power output of the wind power plant. The actual achieved output, however, depends largely on the wind conditions on site.

In order to run economically, a wind power plant requires a productive wind as long as possible at strengths between its switch-on speed, with which it starts the current production, and its shutdown-speed, where it must be shut down for safety reasons.

Many wind power plants reach their rated output at wind speeds of 12 to 13 m/s (about 45 km/h). From this (rated) wind speed, a wind turbine with a rated capacity of 2 MW of electricity per hour actually produces this amount. The plants, however, begin to work at much lower wind speeds of around 4 m/s. (DENA, 2010) Then, however, they produce less than the rated amount.

Above the rated wind speed, the performance of the plant is kept constant, as otherwise the strain on all system components could lead to an overload. The plant is usually turned off to prevent damage at a specified shutdown with very high wind speeds of about 25 to 30 m/s.

Since the wind is not a constant size factor, the expected annual yield cannot be concluded from the specified nominal power. To calculate this, a knowledge of local conditions and wind characteristics is needed, such as wind speed and frequency distribution, as well as characteristics of the plant.

To estimate the generated electric energy, the installed capacity is multiplied by the number of full-load hours. Full-load hours are those designated hours which a plant would have produced if it had continually produced with the installed capacity. For inland plants, 2 000 full load hours can be considered as realistic, for plants near the coast about 2 500 hours, and for future offshore installations 3 800 full load hours are given. (PEHNT et al., 2009)

An important parameter for wind turbines is also the efficiency with which wind energy is transferred to the rotor. This decreases the wind speed at the rotor through the kinetic energy taken from the air. However, the wind cannot be brought to a stop – otherwise there would no longer be an after-flow.

The Betz's power coefficient ($c_{p,\ Betz}$), named after the physicist Albert Betz (1885-1968), says that theoretically only up to 59.3 % of the energy contained in wind can be obtained. With the capacity contained in wind power (capacity = energy/time) of P = 2.45 MW, a theoretically usable (maximum) power P_n at the rotor can be calculated as follows: (UNIVERSITY OF MÜNSTER, 2010)

$$P_n = 0.593 \cdot 2.45\ MW = 1.45\ MW \tag{2}$$

The theoretical maximum, as with all machines, cannot be achieved - not even with wind turbines.

Modern wind turbines achieve a power coefficient of (UNIVERSITY OF MÜNSTER, 2010)

$$c_p = 0.45\ to\ 0.51 \tag{3}$$

The aerodynamic efficiency of a plant can be phrased on the relationship of the power coefficient of the machine to the Betz's power coefficient, and is therefore around 70 % to 85 % – depending on wind conditions and construction. (UNIVERSITY OF MÜNSTER, 2010). To calculate the overall efficiency, the system effectiveness of all machine parts must also be taken into consideration – both mechanical and electrical.

5.2 Function/Design

5.2.1 Basic Components of a Wind Turbine

The basic components of a wind turbine (Figure 5-1) are

- The foundation (Chapter 6)
- The tower
- The gondola
- The rotor blades
- The hub
- The transformer (although important, is not part of the plant in a strict sense)

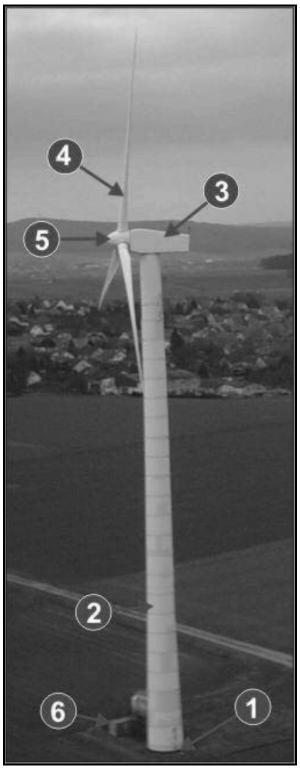


Figure 5-1: Wind Energy Plant: 1.Foundation 2.Tower 3.Gondola 4.Rotorblades 5.Hub 6.Transformer (RYABENKIY & SCHINEWITZ, 2010)

(1) The Foundation

The foundation fixes the Wind Turbine into the ground, so it must accomplish tremendous achievements. For detailed information see Chapter 6

(2) The Tower

Wind turbines with a horizontal axis must be high enough to bring the rotor into wind conditions as uniform as possible. The tower, which is necessary for this purpose, is usually the largest and heaviest part of a wind turbine – it can weigh several hundred tons. The height of the tower in network feeding plants amounts from 1 to 1.8 fold of the rotor diameter.

The gondola is installed on the tower of a wind turbine, and can weigh up to several hundred tons. The tower is therefore a heavily loaded technical component that must safely withstand the vibrations of the gondola, as well as the wind forces at all times.

In addition, the tower makes up 15 to 25 % of the price of the entire wind turbine and is responsible for a large part of the transportation and installation costs. (WIND-ENERGIE, 2010)

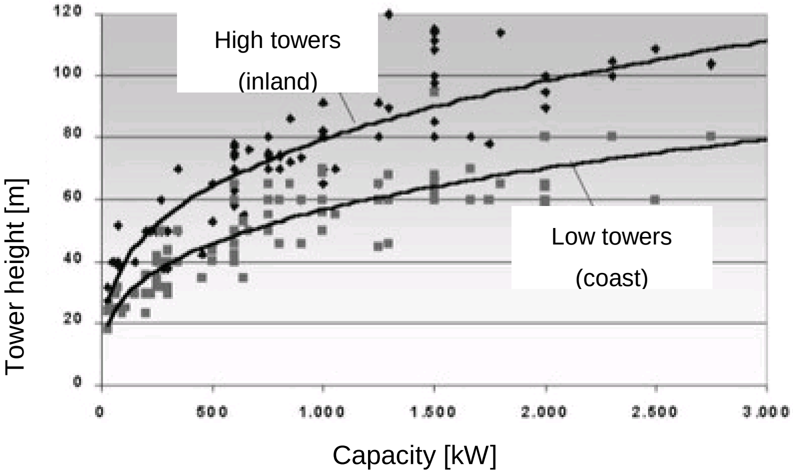


Figure 5-2: Tower height in connection with rated power (WIND-ENERGIE, 2010)

The height of the tower is a relevant factor for the profitability of a wind turbine, since the turbulence, induced at higher altitudes by the ground roughness (Chapter 5.3), is much lower and thus the wind blows stronger and more evenly: the higher the tower, the higher the energy yield. However, many coastal locations, compared to inland sites, usually have relatively small towers as they are

sufficient for these areas (Figure 5-2).
The construction height of the towers is limited, however: first through the structural analytics, and secondly, by planning and building permits. The system costs increase with increasing tower height. Therefore, the constructors of wind turbines are constantly searching for compromises between tower height and energy yield.

There are different types of tower execution (DENA, 2010):

- Lattice Towers

Lattice towers are built of steel. They are relatively inexpensive, as they consume little material - about half as much as steel tube towers (WIND-ENERGIE, 2010) - and are therefore lighter and easier to manufacture. Moreover, they are only slightly susceptible to wind.
Lattice towers are used primarily for very large towers. Due to a high amount of labor required, this type of tower is used mainly in countries whose labor costs are low. (WIND-ENERGIE, 2010)

- Steel Towers

The most common type of tower is a steel tubular tower. These can be cylindrical or conical.
However, the transport of the individual tower segments of very large wind turbines (two to five segments, each 20 to 30 m in length (WIND-ENERGIE, 2010)) is problematic, as highway bridges are usually lower than the diameter of the tower segments.
The weight should also not be underestimated: A multi-megawatt wind power plant with a 60 to 100 m high steel tower weighs 60 to 250 tons. (WIND-ENERGIE, 2010)

- Concrete Towers

Concrete towers are built of reinforced concrete, are much thicker and about five to six times heavier than steel towers. (WIND-ENERGIE, 2010)

Concrete towers are usually built conically, just as steel towers and they are either assembled from precast segments or built directly on the site with in-place cast concrete. Transportation is no longer necessary with in-place cast concrete, however the quality is difficult to control.

- Guyed Masts

Guyed masts are thin tubular columns, which are braced by means of steel cables. Such masts are used mainly for small wind turbines up to a maximum power of 250 kW. (WIND-ENERGIE, 2010)

An advantage is that the tower is very light, inexpensive and easy to transport. The mast can therefore be installed in poorly accessible locations, such as in the mountains. In addition, the tower can be temporarily apportioned for maintenance and repair purposes (Figure 5-3).

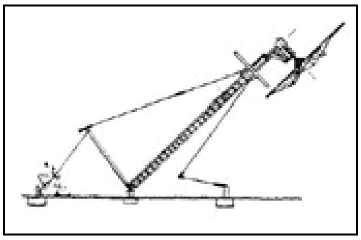


Figure 5-3: Drawing of a guyed mast (WIND-ENERGIE, 2010)

This property is beneficial in countries with a high probability of tornados: To prevent damage, the plant will be apportioned before the tornado, and afterwards the facility can easily be erected again.

(3) The Gondola

In the gondola are the hub, the shaft, the gearbox and the generator.

The rotor is located at the front of the gondola. Due to the central mounting of the rotor blades, the lift motion is converted into a rotational movement. The rotation of the rotor blades is transmitted via the rotor hub and the drive shaft to the gearbox and finally to the generator, which then generates electricity. (DE-NA, 2010)

(4) The Rotor (Blades and Hub)

The rotor of a wind turbine consists of the rotor hub and the rotor blades. With this, the wind energy is extracted from the air and fed to the generator. Rotor blades are optimized on one hand for a higher efficiency; on the other hand for noise reduction, since they are responsible for a large part of the operating noise. Currently, rotor diameters from 40 to 90 m are the norm, with a trend towards larger diameters. (WIND-ENERGIE, 2010)

Modern rotor blades are currently made of fiberglass reinforced plastic. Some manufacturers also use carbon fibers in the production of rotor blades. Usually the blades are equipped with a lightning protection system, directing the discharge to the ground of the machine house.

In addition, some rotor manufacturers offer a rotor blade heater to prevent ice formation on the blades. The warm exhaust air from the gondola is blown into the hollow rotor to achieve this.

Modern wind turbines also offer the possibility to adjust the rotor blades. Here, the individual rotor blades rotate about their longitudinal axis and thereby alter their position to the wind. The resulting benefit is that high wind speeds, that could cause potential damages, are not transferred completely to the generator. In return, plants whose blades are not adjustable have a disc brake that is mounted between the gearbox and generator. This way the rotor can be slowed down to a safe speed for the generator or stopped completely. (DENA, 2010)

5.2.2 Types of Construction – Wind Turbines

In principle, many different designs of wind turbines are available. Ultimately, however, one design has prevailed which allows a constant power output and has the fewest problems with vibrations: Today's standard wind turbines have a horizontal axis of rotation and a three-wing rotor, which as a so-called upwind armature (upwind= the windward side facing the wind) that is turned into the wind. This method of construction has been a standard for wind turbines, based on their reliability and robustness.

Designs were also developed that have one-, two- or four-winged rotors. Similarly, wind shadow armatures were developed, where the rotor is opposite to the windward side of the plant tower. Due to uncontrollable vibration developments and an uneven operation, these construction types did not prevail. (DENA, 2010)

a. Horizontal Axis of Rotation

Wind turbines with horizontal rotor axis must be tracked to the wind direction. The gondola is attached horizontally to the tower in a pivoted manner with a so-called Azimut bearing. The wind direction is set forth using wind direction sensors. The orientation of the rotor into the wind is then carried out with the help of servo-motors.

There is a distinction between

- Windward armatures
  (The rotor is located on the upwind side of the tower)
- Wind shadow armatures
  (The rotor is located on the tower side sheltered from the wind)

Small plants, which are designed as downwind armature, do not require a yaw control mechanism. Thus, the wind rotates the rotor automatically in the proper direction and provides for a so-called passive yaw control. Furthermore, the risk of rotor blade contact with the tower is much less. However, there will be discontinuities in the rotor speed when a rotor blade passes through the wind shadow of the tower; In addition there are mechanical vibration symptoms and electrical variations (harmonic component), because the drive torque varies momentarily.

b. Vertical Axis of Rotation

Wind power plants with a vertical axis of rotation exist as a so-called Savonius-rotor or Darrieus-rotor, in particular the H-Darrieus-rotor.

The Savonius-rotor consists of two (affixed on a vertical axis) counter-curved blades that are attached between two circular disks (Figure 5-4).

Figure 5-4: Savonius-rotor (WIKIPEDIA, 2009)

Darrieus-rotors (Figure 5-5) are elliptically shaped and the rotors are as long as the masts to which they are attached. With the H-Darrieus-rotor, the H-shaped rotor is mounted on the tip of a mast.

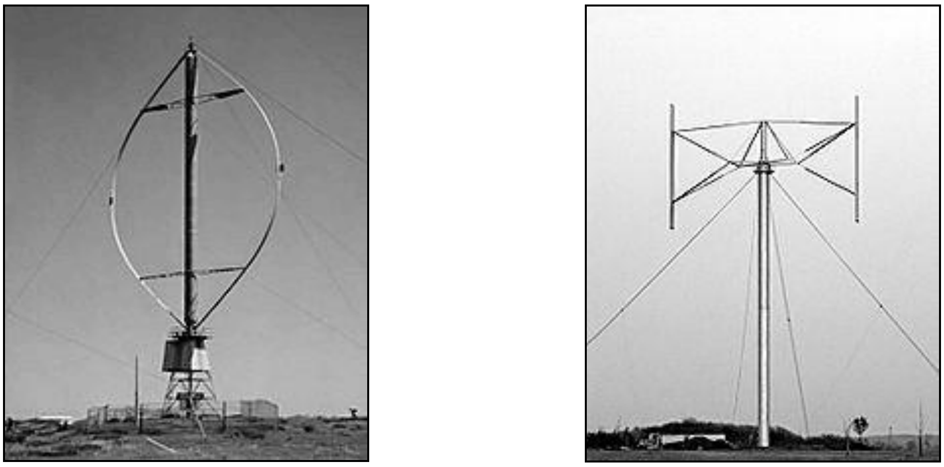


Figure 5-5: Darrieus-rotor (left) and H-Darrieus-rotor (right) (WIKIPEDIA, 2009)

Advantageous for plants with an upright vertical axis of rotation is that the rotor must not be placed in the direction of the wind. The simple design – and thus a safe operation – of the plant are aided by the fact that the generator can be connected directly on the ground. Due to the uniform gravity load of the wings, materially stressful oscillations do not occur. Turbulences – occurring in 80 % of possible locations with good wind conditions, especially near the ground – are used by plants with vertical rotation axis trouble free, without any significant efficiency losses.

A disadvantage, however, is a permanent, energetically unfavorable and unusable position; this in approximately one quarter of the rotor radius directed to the flow. Three quarters, at best, of the rotating radius can convert the energy of wind into electricity. Thus, it is clear that a power coefficient of about 0.3 is very good for a plant with a vertical axis of rotation. Additional disadvantages are vibrations and strains on the wing design and mounting kits, which are caused by the cyclical load changes. Depending on which side of the radius running through the flow, they change the side from which they are blown against. This effect of load change is similar to one caused by uneven distribution of mass imbalance, and leads to relatively high stress loads to the structure itself. (WIKIPEDIA, 2009)

In comparison to systems with horizontal axes of rotation, relatively low efficiency and problems with the storage of the rotary elements, which are subjected to high load cycles, caused developmental worries with plants having vertical axis of rotation, ensuring that they would probably not prevail. (DENA, 2010)

5.2.3 Offshore Equipment

If a wind power plant is built on the open sea, it combines a number of advantages: the wind speed is more constant and higher in the middle, with less turbulence compared to the midland. In addition, a huge construction site bearing no restrictions such as visual aspects, noise, roads, cities, radar stations, etc. exists. (WIND-ENERGIE, 2010)

Offshore wind power plants are, however, strongly susceptible to corrosion by the aggressive, salty ocean air. For this reason, additional safeguards are necessary: If possible, one uses seawater proof materials, improves corrosion protection and encapsulates certain modules completely.

In addition, the plant must be designed for higher average wind speeds. The oscillations which the sea waves produce could cause a self-reinforcing effect under unfavorable conditions. These oscillations must therefore be considered in construction and management.

Ultimately, the distance to the mainland still plays another decisive role: the plant must be made accessible in some manner (e. g. by means of a helicopter platform) and the power generated must be transported to a feed-in point on the mainland. For this, high-voltage lines are laid as undersea cables. (WIND-ENERGIE, 2010)

5.2.4 Start-Up and Cut-out Wind Speed

Control electronics is responsible for ensuring that the wind turbine operates at profitable wind speeds (Figure 5-6), including start-up speed, and are again turned off to avoid damage due to mechanical overload when high wind speeds prevail (Cut-out wind speed). The wind speed is determined by an anemometer, or on the basis of the speed of the rotor.

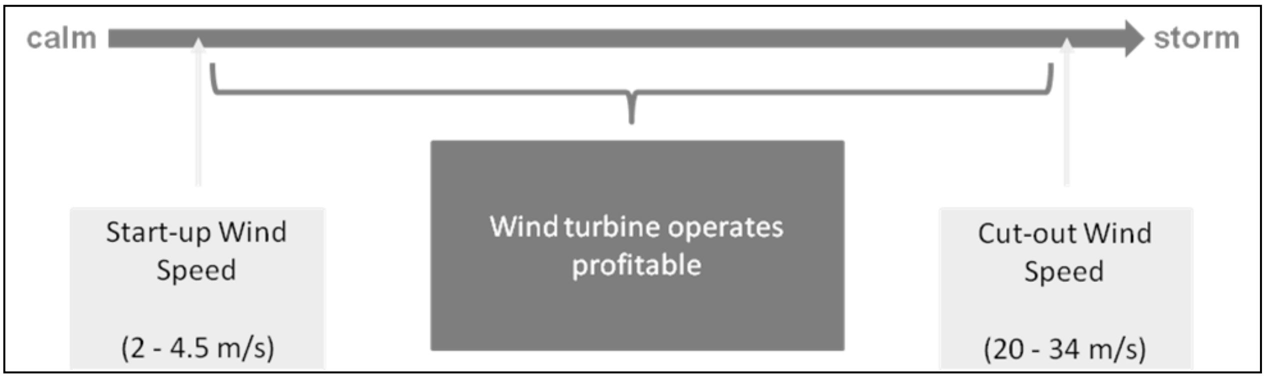


Figure 5-6: Start-up Wind Speed and Cut-out Wind Speed (AUTHOR, 2010)

If the wind speed is too low for economical operation, the rotor will not be completely stopped, as this would overload the bearings more than an idle or spin state. (QUASCHNING, 2008)

The typical start-up speed is 2 – 4.5 m/s, the typical shutdown speed lies at 20 – 34 m/s. (QUASCHNING, 2008)

New plants, however, have a storm regulation system, where the plant runs in a reduced safe operation only. Therefore, the plant runs at almost any wind speed. This regulation provides for, in the event of a slight weakening of the storm, a smooth engaging of the plant so that the voltage level is preserved in the power grid. (QUASCHNING, 2008)

5.2.5 Airflow Alignment

Wind power plants with a horizontal axis must be aligned with the wind direction to make optimal use of the wind power (Figure 5-7). Energy losses increase with the angle between the wind direction and the rotor axis. To reduce the power of the wind turbine in strong wind (in order to avoid an overloading of the components) these losses can be evoked intentionally. This, however, is done only with very small wind turbines.

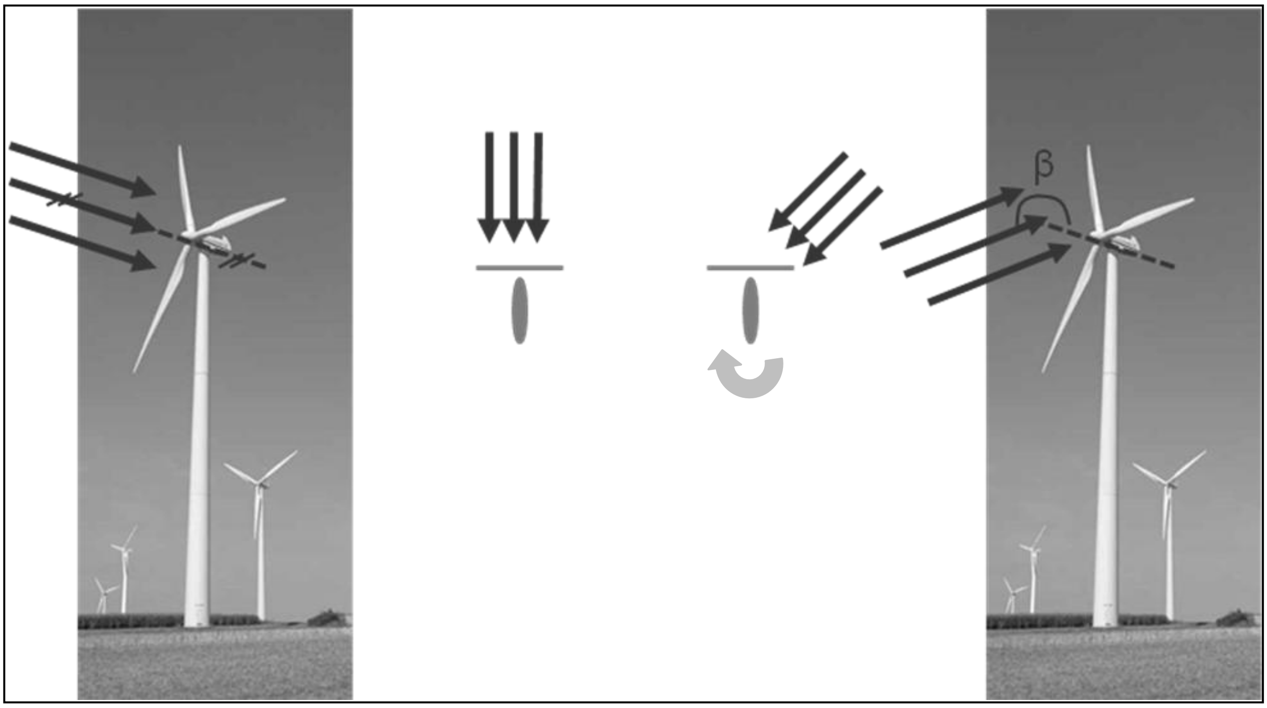


Figure 5-7: Airflow Alignment (AUTHOR, 2010)

One way to align the facilities with the wind are the passive systems: in the case of downwind rotors, wind tracking is accomplished by independent trailing; with windward rotors with the help of wind flags. These passive systems are only used for very small wind turbines up to about 15 m in diameter or 30 kW rated power. (WIND-ENERGIE, 2010)

The air flow alignment of modern wind power plants is guaranteed by active systems like hydraulic or electric motors (azimuth drive), after the direction of the wind had been determined by sensors.

Due to continuous fluctuations in wind direction, the gondola can beat back and forth at the gear of the tower collar, wearing out very quickly in this manner. Therefore, the gondola is secured with brakes, which are released only with air flow alignment.

To prevent the electrical and signal carrying cables within the plant from twisting, the turbine house must not turn more than 2 to 5 times (device-dependent) in the same direction. (WIND-ENERGIE, 2010) The position of the gondola is therefore monitored by the central control system. The system will ensure that the gondola rotates to the opposite direction with no wind or weak wind conditions, thus “untwisting” the turbine. (WIND-ENERGIE, 2010)

5.3 Locations

First and foremost, one can assume that the stronger and more constant the wind blows, the more suitable the site will serve as a location for a wind power plant.

The bundling of the wind in the direction of the wind turbine would therefore be desirable. Such devices, also called Wind Concentrators, which bundle the wind from a larger area onto the rotor surface, have found no access to the modern-megawatt wind turbines for economic reasons. A form of wind concentration is possible, however, through the favorable choice of location. The wind on hillsides, for example, reaches higher speeds than in the surrounding area, which is caused by the updraft. (WIKIPEDIA, 2009) The speed of the wind, therefore, depends very much on the geographical location.

To classify the various potential sites for wind power plants regarding the wind strength, the International Electrotechnical Commission (IEC) compiled international standards for wind classes: Table 5-1. The wind classes reflect the design of the plant for high or low wind areas. Characteristic of wind power plants, which are positioned at sites of higher classes with less wind, are larger rotor diameters for the same rated power and often a higher tower. The wind speed at hub height will serve as a reference value, next to the 50-year extremal value (the value that statistically occurs at average once within 50 years). That value is computed as the average speed within a 10-minute interval. (WIND-SOLARSTROM, 2010)

Table 5-1: IEC Wind Classes (WIND-SOLARSTROM, 2010)

IEC wind classes	**I**	**II**	**III**	**IV**
50 Year Extremal Value	50 m/s	42.5 m/s	37.5 m/s	30 m/s
Annual average wind speed	10 m/s	8.5 m/s	7.5 m/s	6 m/s

The speed and direction of the wind will change greatly due to local hindrances. The wind follows mostly the Earth's surface in its flow behavior: hills, mountains, forests and buildings cause vertical deflection of the wind. Also these hindrances cause unfavorable turbulence and weak wind zones which may affect the wind power plants. (BINE INFORMATIONSDIENST, 1999) Therefore, as a rule applies the distance between the wind power plant and the obstacle should be at least 15 to 20 times as great as the height of the obstacle itself. (BMWI, 2009) Or one builds the wind power plant larger than the obstacle itself.

But the wake-induced turbulence has far more impact than the ambient turbulence intensity. Decreasing the spacing between the individual wind turbines increases the turbulence induced by the wakes of neighboring wind turbines, meaning that there are limits how close the turbines may be. (BMWI, 2009) In the prevailing wind direction a minimal distance of 5 to 9 multiplied by the rotor diameter is essential. (WIND-ENERGIE, 2010)

Flow inclination is another parameter which has to be checked when developing a layout – also known as velocity tilt or in-flow angle. The wind might hit the rotor not perpendicular but at an angle that is related to the terrain slope, when wind turbines are to be placed on steep slopes or cliffs. Effect of terrain slope is reduced with increasing height above ground level – for estimating the velocity tilt terrain slope is only of indicative use. So a large in-flow angle both reduces the energy production and leads to a high level of fatigue of some of the basic components such as the bearings due to transverse stresses. (BMWI, 2009)

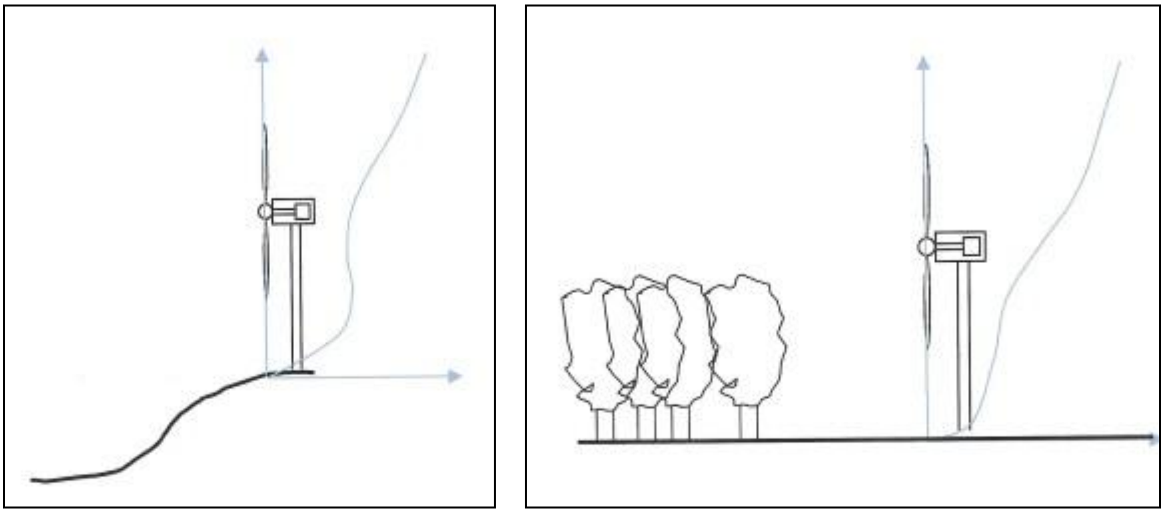


Figure 5-8: Distorted wind profile at steep slope (left) and behind a forest (right) (BMWI, 2009)

A steep slope also might cause a negative gradient across some parts of the rotor (Figure 5-8), because energy losses increase with the angle between the wind direction and the rotor axis.

In the mountainous regions, the influence of hills and rough terrain is very large on the wind speed. Therefore, the wind supply in this case must be determined by direct measurements at the site. These values are compared with nearby weather stations or wind atlases (Chapter 4) to adjust them on a typical wind year.

The farther the measurement is carried out above the ground, the higher the wind speed. This is due to the fact that the wind is slowed by rough terrain. It is therefore important that the measurement takes place at hub height (generally measure is at 20 m) of the proposed plant or using an appropriate velocity profile.

Significantly better wind and location conditions prevail on the open sea, because of the minor roughness. So-called offshore wind power plants make use of these conditions. The greater the distance between the offshore plant and the coast, the less other uses of coastal waters are influenced (for example shipping).

Frequently, other factors must be considered in addition to the wind conditions. For example, the existing infrastructure such as transmission lines and roads and adverse climatic conditions such as extreme cold play a major role. Other uses of the considered location can appear more sensible, for example the construction of housing or use as a nature reserve or leisure places (e. g. beaches).

5.4 Negative aspects

Next to plenty and tidiness, Wind energy is renewable and widely shared. But even this, at first glance, solution of energy production perfect appearing has its down sides. As with other plants for power generation, wind turbines interact with the environment. In addition to affecting wildlife, noise generation, the casting of shadows or the influence of the landscape takes form (WIKIPEDIA, 2009). Also, subjective feelings, habits and social attitudes in the aesthetic evaluation play an important role. Not at least cost consideration is also important while comparing to other energy sources.

5.4.1 Wildlife

According to a 2005 study by the Nature and Biodiversity Conservation Union (NABU) approximately one thousand birds die in Germany each year by colliding with a wind power plant. In contrast, about five to ten million birds die in the same time period in road traffic and in power lines.

Similarly, bats have expired in collisions with wind turbines. These collisions increase particularly during migration, in forests or in the vicinity of forests. To prevent these incidents as much as possible, particularly hazardous locations should be avoided or plants should be forced to shut down during certain seasons or weather conditions (wind speeds). For this, it is necessary that bat activity on site and their interaction with the wind power plant is known. Further studies by the University of Calgary/Canada has revealed that no direct contact between bats and wind turbines is necessary to induce death, but rather the animals suffer a pulmonary barotrauma – the bursting of the lungs caused by differences in pressure near the plants. (BADISCHE ZEITUNG, 2008)

The lower revolution rates of newer systems benefit flying animals around the world, since the turbine movement is easier for the animals to calculate.

5.4.2 Landscape Consumption

A predominant share of present wind turbines are located on areas that are used for agricultural purposes. Basically, only the location area and access roads for maintenance are required for a wind power plant. However, the approval of new plants can prevent the designation of new commercial and residential areas in the vicinity of wind turbines on the basis of distance regulations.

5.4.3 Impact on Sites in the Sea

To take advantage of the significantly stronger winds at sea, offshore wind farms will come into increased planning for the future.
Problematic may be collisions with ships that have gone off course. But also damage to marine ecology, such as underwater noise levels during foundation construction, is to be expected. Also uncertain are the effects of offshore wind farms on marine mammals such as dolphins and whales.

The actual impact on marine ecology is still unclear and needs to be studied further in the future.

5.4.4 Shadowing

Shadowing is defined as the periodic alternation of light and shadow: The cause is the rotating rotor of the turbine, which is located between the sun and a building under unfavorable conditions. Depending on weather, location and size of the wind turbine, this shadow casting is regarded by residents as very disturbing.

5.4.5 Disco Effect

The periodic light reflections of the rotor blades are also known as a "disco effect". This is often confused with shadow-casting of the rotor. As the shiny paint on the rotor blades has been replaced with a matte, non-reflective paint, the disco effect no longer plays a role in the nuisance estimation of modern wind turbines.

5.4.6 Obstacle Lighting

Obstacle lights are mounted on wind turbines in excess of 100 m in height for air traffic safety. Neon tubes are used on older plants, where light emitting diodes (LED) or flashing lights are used on newer installations. The characteristic flashing patterns, particularly on wind farms, can be discomforting to local residents.

5.4.7 Radio Interference

Interference, such as interactions of electromagnetic waves from broadcasting stations, results from the reflections off the rotor blades of a wind turbine. Locally, this leads to fluctuating electromagnetic field strengths, tropospheric propagation or multipath reception. In essence, these effects are limited to analog TV reception under poor reception conditions.

5.4.8 Sound

The noise of wind turbines is mainly caused by vibrations of the rotating blades in the wind. Common values of sound levels, which are determined according to standardized procedures of acoustic measurements, are between 92 dB and 109 dB.

Table 5-2: Examples of Wind Turbines and their sounds (VESTAS, 2008)

Producer	Name	dB
Vestas	V52-850 kW	92 to 102
Vestas	V82-1.65 MW	101 to 103
Vestas	V100-1.8 MW	95 to 106,5

But the energy of acoustic waves in the air decreases with the square of distance. So the noise at ground, supposed at a turbine with a tower of 70 m height, is just round about 60 dB, what is more quiet than a car at road (Table 5-3). (WIND-ENERGIE, 2010) The greatest perceptibility was acquired at wind speeds between 10 m/s and 12 m/s at hub height, which is about 95 % of the rated output (WIKIPEDIA, 2009). The acoustic intensity is less at lower wind speeds; at higher wind speeds, the acoustic capacity is superposed by natural wind noise such as the rustling of the trees, etc.

Table 5-3: Examples of sound levels (WOLF, 2010)

dB	Sound Source
0	hearing threshold level
20	whisper
50	normal conversation
70	car at road
80	vacuum cleaner
90	horn on a motor vehicle
100	motorbike
120	airplane if the distance is short

One way to avoid such problems are variable-speed wind turbines. These can be brought to a sound reduced operating condition if they are near residential areas, and during certain noise-sensitive times, such as during the night. The speed of the wind turbine is lowered, as the acoustic emission particularly depends on the peak blade speed and the gear box. The disadvantage of this measure is, however, the revenue loss for the operator which is inevitable.

6 Wind Energy Plant Foundations

When a wind power plant is built, it must provide the capacity required and also withstand the power of the wind for many years to come. All components – from the rotor to the foot of the tower – are designed according to these requirements. One part, that is not openly evident, must accomplish tremendous achievements – the foundation. The dynamic complexities of a wind turbine are hardly taken into account in the calculations for the foundations. Particular attention is therefore devoted to this important component in the present chapter.

A wind power plant must be securely anchored by a foundation in the ground. So for the development of the foundation, the geotechnical ground characteristics, the maximum wind velocities, the characteristics of the tower and the machine house of the wind power facility as an overall-system must be taken into consideration for the groundwork. (KÜHN, 2001)

Again it is advisable to seek highly precast systems as long as standardized design weather conditions can be taken into account, which permit a short construction period. Furthermore, it makes sense for reasons of environmental protection when the foundation structures can be deconstructed after use. This aspect in the design of the foundations should already be taken into consideration to avoid unnecessary costs and efforts later.

6.1 Stresses and strains

The foundations are cyclically and dynamically burdened due to wind loads and also waves in the case of offshore structures. Therefore, and also by an accumulation of deformations, permanent changes may result in the subsoil which can change the bearing capacity of the foundation. The estimation of deformation development of a structure with an increasing number of load cycles is very important, especially when considering the serviceability of a design for a structure.

The limited state of fatigue plays a major role with wind power plants. For offshore structures – beyond the scheduled cyclic and dynamic loads wind, waves and tides must be taken into consideration.

At the Karlsruhe Institute for Technology in Germany engineers predict long-run deformations at wind energy plants offshore. For example the forces on foundations at the German Bight are considered. They are consisting of an aerodynamic (wind towards rotor und tower) and a hydromechanic share (current and waves) and occur cyclical (Figure 6-1). (WICHTMANN et al., 2009)

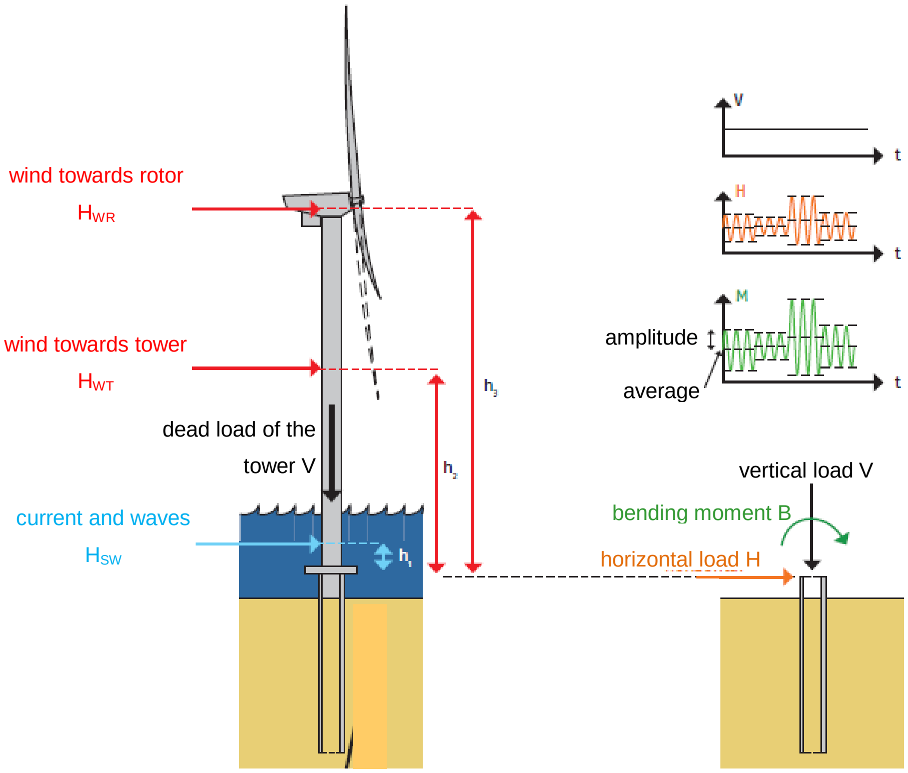


Figure 6-1: Forces on an offshore wind energy plant (WICHTMANN et al., 2009)

During the lifetime of an offshore wind energy plant, billions of stress cycles impact on the foundation with various amplitudes: Storms generate some few cycles with high amplitudes, whereas the normal operation of the plant is characterized by a lot of cycles with small and medium-sized amplitudes. Via the cyclical burden, permanent deformations accumulate in the soil, by what the wind energy plant can get more and more bevel. A further negative consequence of the cyclical burden of a pile foundation is the possibility of decrement of the soil tension on the pile (relaxation of soil).

In the last resort the burdened piles can be extracted from the soil after a specific number of cycles. The pore space of the seabed is saturated with water. So at hardening of the sand, how it occurs in consequence of small and middle-sized cycles, a share of the water is pushed aside. But if a saturated soil is burdened cyclical too fast, or the permeability is low (clay soil), this limits the draining of the excessive pore water. In the pore water, next to the hydrostatic force, a so called pore water overpressure arranges. This countervails the tensions at the contact points of the proximate grains of sand, what ultimately reduces the rigidness of the soil. (STUDER et al., 2008)

But also positive scenarios are possible: Is the inclination of a wind energy plant, occurring at a storm, combined with a loosening of the surrounding ground, a subsequent normal operation with cycles with small amplitude could cause a self-healing effect. The soil can compact itself, by what the inclination can be minimized.

The burden of the bending moment on the foundation is depending on the distance between the point of attack (wind, waves) and the seabed (Figure 6-1). Also the dimensions of the plants are important to the forces on the foundation. (ABNT NBR 6122/96)

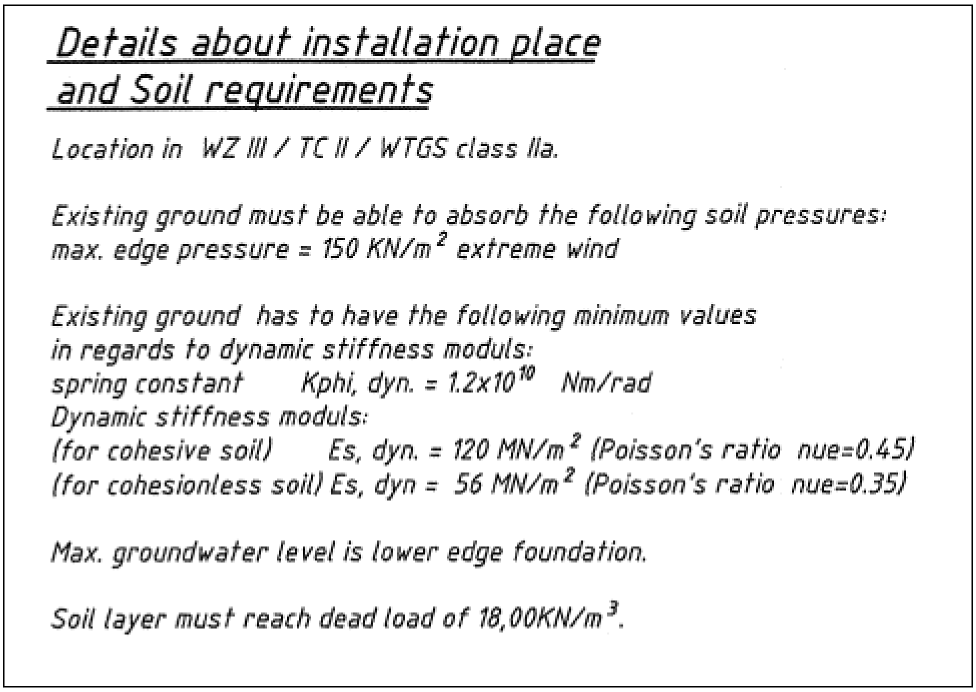
6.2 On Shore

The technical data of the foundation depend on (ABNT NBR 6122/96):

- location (geology, soil type, shape of foundation and soil embedment of the foundation),
- meteorological conditions,
- wind power station (dimensions, etc.)

The foundations are built of concrete and steel. For soft subsoil, pile foundations are required. The type can be octagonal, circular or crosswise, for example, depending on construction of the tower. (WIND-ENERGIE, 2010)

If homogeneous and viable (Figure 6-2) soil is present at the site of the wind power station, the plant can then be built on a raft foundation. The foundation slab is located under a layer of earth below the top ground surface. For non homogeneous soil conditions, a soil exchange may be necessary to improve the carrying capacity. If the ground at the planned site is very soft, i. e. insufficiently stable, then the loads must be transferred into more sustainable levels by means of a deep foundation. (WIKIPEDIA, 2009)



Details about installation place and Soil requirements

Location in WZ III / TC II / WTGS class IIa.

Existing ground must be able to absorb the following soil pressures:
max. edge pressure = 150 KN/m^2 extreme wind

Existing ground has to have the following minimum values
in regards to dynamic stiffness moduls:
spring constant Kphi, dyn. = $1.2x10^{10}$ Nm/rad
Dynamic stiffness moduls:
(for cohesive soil) Es, dyn. = 120 MN/m^2 (Poisson's ratio nue=0.45)
(for cohesionless soil) Es, dyn = 56 MN/m^2 (Poisson's ratio nue=0.35)

Max. groundwater level is lower edge foundation.

Soil layer must reach dead load of 18,00KN/m^3.

Figure 6-2: Soil requirements for a slab foundation (ENERCON, 2005)

The common foundation types of wind power plants on land are: (BMWI, 2009)

- A slab foundation (Figure 6-3) is built by a large reinforced concrete plate under the earth as the footing of the generator. This type is one of the most commonly used.
- Pile foundations: Here the foundation plates are fixed with piles into the earth. This is especially necessary in soft subsoil.

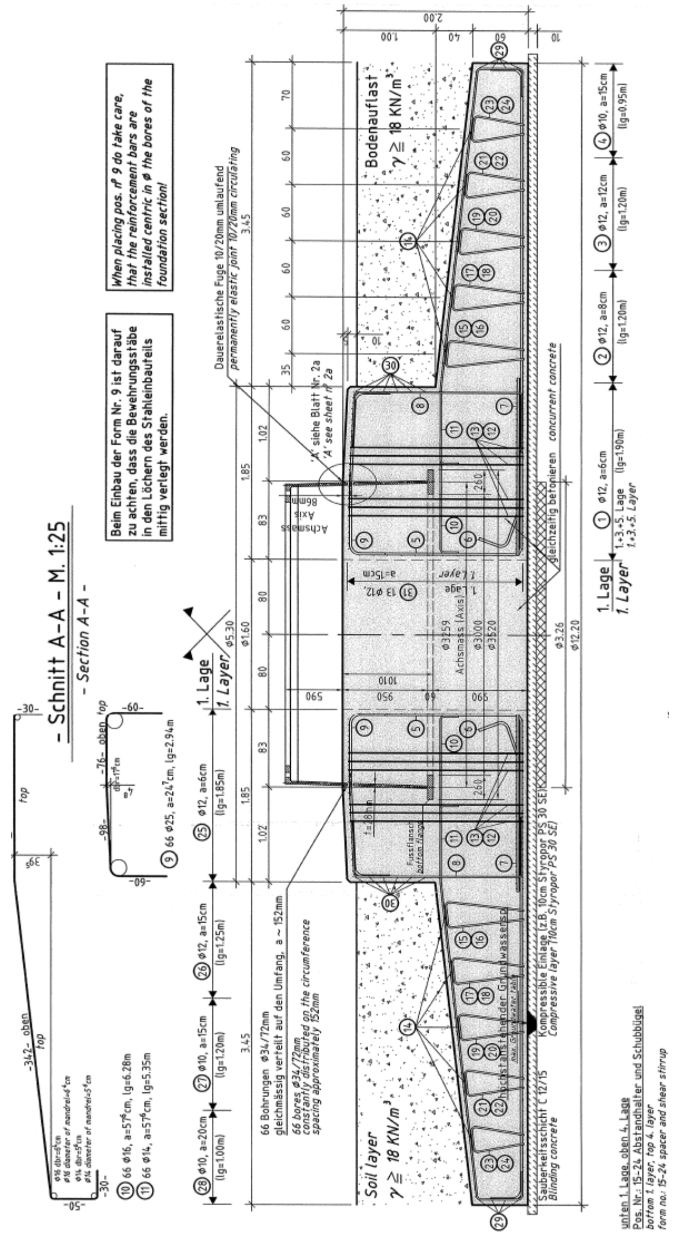


Figure 6-3: Building plan of a slab foundation (ENERCON, 2005)

Ummenhof/Germany

In the year 2000, in Ummendorf, a location in the south of Germany (Figure 6-4), a new wind power station was planned. Since at operation of a wind power station there are high dynamic burden, the dynamic soil parameters had to be collected in the course of exploration of the soil at site. This exploration was arranged by a combined research program – three direct outcrops by scrape and seismic measurements. For that purpose, the speed of propagation of a compression wave and a Rayleigh wave in the subsoil was determined by geo-phones.

Figure 6-4: Location of Ummendorf in Germany (WIKIPEDIA, 2009)

At location of the wind power station the terminal moraine is present in form of deep weathered silt and mixed granular soils, what lies on material of a ground moraine: bed load block silt. In the foundation level of the wind power station an adequate sustainable alteration tilt is present (consistency: rigid to semisolid).

The analysis of the different possible foundation types results that a slab foundation (Figure 6-5) is the best solution for this wind power station.

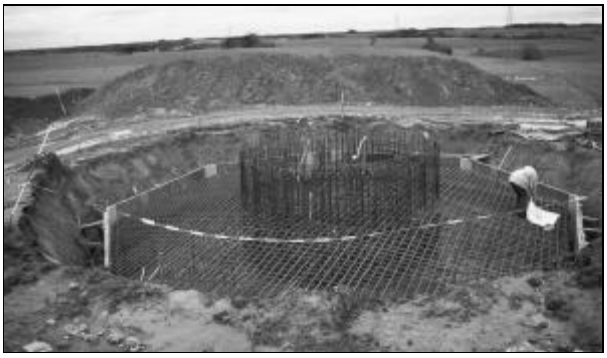
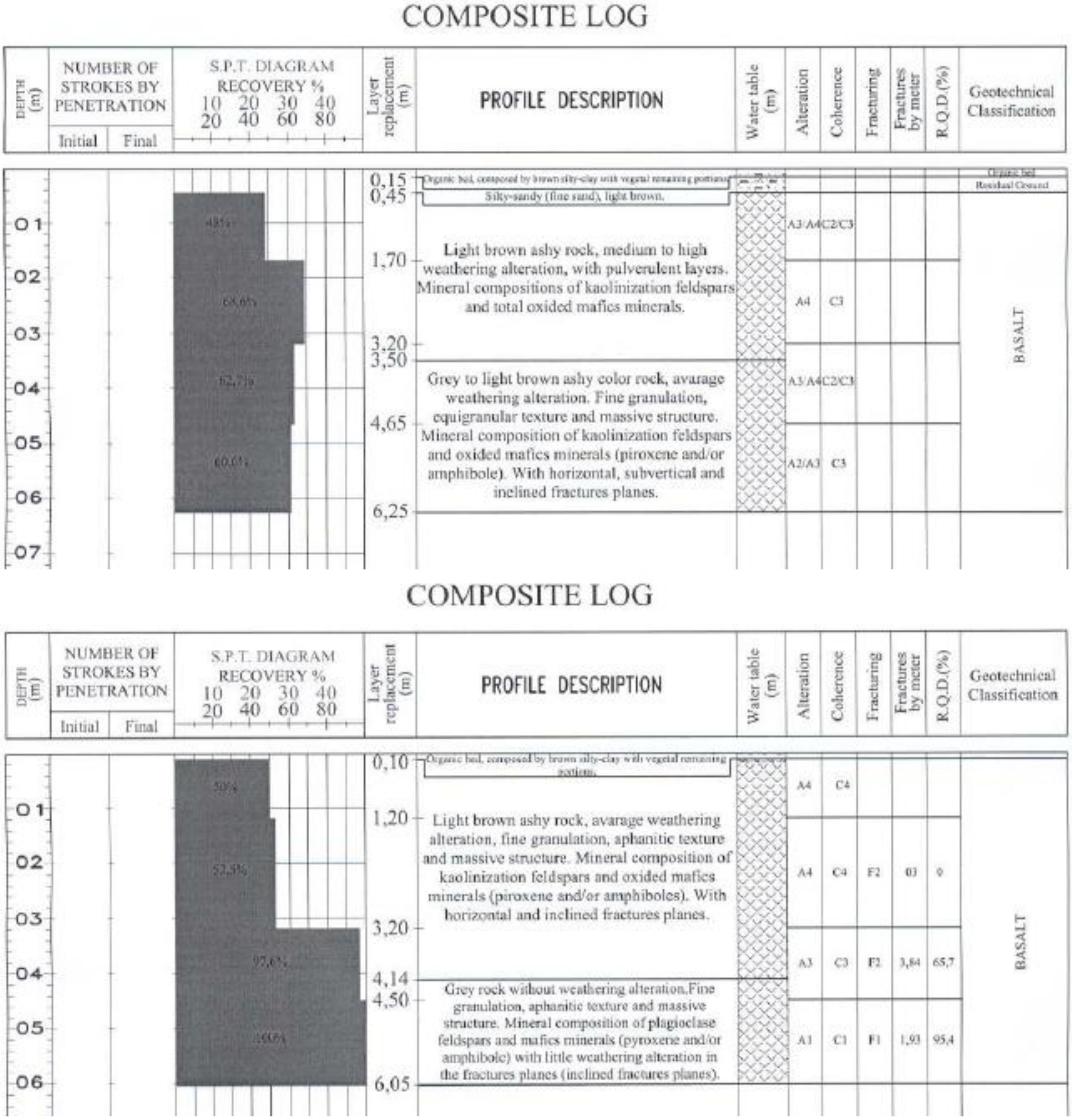


Figure 6-5: Reinforcement of the slab foundation (HENKE, 2010)

Água Doce/Brazil

In 2003 the geotechnical investigation of the Água Doce Windfarm in Santa Catarina, a federal state in the Brazilian south, was conducted.

For this, 15 holes of Mixed Prospection were executed by rotative prospection (Figure 6-6).


COMPOSITE LOG

Organic bed, composed by brown silty-clay with vegetal remaining portions.

Silty-sandy (fine sand), light brown.

Light brown ashy rock, medium to high weathering alteration, with pulverulent layers. Mineral compositions of kaolinization feldspars and total oxided mafics minerals.

Grey to light brown ashy color rock, avarage weathering alteration. Fine granulation, equigranular texture and massive structure. Mineral composition of kaolinization feldspars and oxided mafics minerals (piroxene and/or amphibole). With horizontal, subvertical and inclined fractures planes.

COMPOSITE LOG

Organic bed, composed by brown silty-clay with vegetal remaining portions.

Light brown ashy rock, avarage weathering alteration, fine granulation, aphanitic texture and massive structure. Mineral composition of kaolinization feldspars and oxided mafics minerals (piroxene and/or amphiboles). With horizontal and inclined fractures planes.

Grey rock without weathering alteration.Fine granulation, aphanitic texture and massive structure. Mineral composition of plagioclase feldspars and mafics minerals (pyroxene and/or amphibole) with little weathering alteration in the fractures planes (inclined fractures planes).

Figure 6-6: Some profiles of the prospected perforations (SONDAGEL, 2003)

6.2.2 Soil boring (SPT)

The Standard Penetration Test (SPT) is a dynamic probing, that is operated in a bore hole, based on the bottom of it and is standardized by the American Society for Testing Materials (ASTM) and by ABNT NBR 6484 in Brazil. The SPT presents good details concerning density respectively consistency of the type of soil in-situ, also in major depth.

The pile driver with a weight of 63.5 kg and a height of fall of 76.2 cm (30 inches in Figure 6-7) is conducted in a casing, waterproof in the case of offshore wind farms. The outer diameter of the sensor has 50.8 mm and the inner diameter has 34.9 mm. Since there are different types of sensors, soil samples can be extracted simultaneously – depending on the type of soil.

At pile driving, the number of hammer blows that is necessary for penetrate the sensor in the first 15 cm (it is assumed that the top of the test area has been disturbed by the drilling process) and in the proximate 30 cm, is counted. For analysis of the SPT, only the last 30 cm are used. (ETH, 2010)

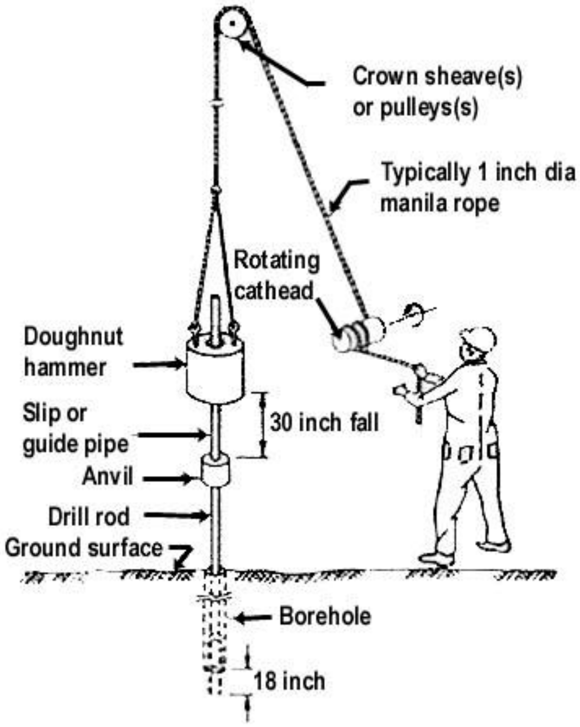


Figure 6-7: Schema of the SPT (FSU, 2010)

6.3 Offshore

The solid foundation of wind turbines at sea is a major challenge in the generation of offshore wind power. Next to dead weight and buoyancy of the structure, the influence of wind, waves, currents and temperature effects will load offshore wind installations. Additionally, the design must resist ship impact as well as anchor damage, movement of the seabed, scour and erosion. Subsequently, the design must be engineered for corrosion/deterioration of the structure and the effects of bio-fouling. (WATSON, 2000)

The selection of the foundation solution is determined decisively by the prevailing water depth, as well as specific plant loads and the subsoil. The start-up costs represent a major factor in the construction of an offshore wind park. (DIMAS & RICHERT, 2001)

The main structural design considerations (e.g. the American Standard API RP2A LRFD/WSD, classification society rules (e.g. DNV), national regulations and industry guidelines) for an offshore wind energy installation are (WATSON, 2000):

- **Dynamic response and interaction**

Conditional on size and nature of the offshore wind structures, interactions and dynamic responses are likely to be more significant for offshore wind structures than for traditional structures.

- **Strength**

The structure must be tested for its behavior in situations of extreme wind, waves and current conditions. In extreme waves, the buoyancy loads may alter by +/-20 %.

- **Fatigue**

Onshore, the design of wind turbine structures is dominated by fatigue considerations – this is also very important in offshore facilities.

- **Serviceability**

When excessive deformation in the structure causes significant reduction of the operating efficiency of the turbines, serviceability is likely to become important.

- **Reliability**

Reliability is essential, since it is very difficult accessing and maintaining offshore structures.

6.3.1 Ground conditions

The technical and economical optimization of the foundation requires trusted skills about the soil behavior at site. (WEIHRAUCH, 2003)

Before a foundation can be conceived, the ground and its behavior must be closely examined at the future site of the facility. Yield point, plasticity, soil layers, friction angle (weight and volume relationships), shear strength, dynamic behavior, etc. must be established.

The technical and economical feasibility of different foundation types is regulated by the present water depth in particular (Table 6-1). (DNV, 2003)

Table 6-1: Feasible Foundation types in dependance on water depth (DNV, 2003)

Water depth [m]	Technical and economic feasible foundation type
0 – 10	Gravity foundation
0 – 30	Monopile
> 20	Tripod / Jacket
> 50	Floating foundation

Loose sand and soft clays are very susceptible, compared with the currents arising at the base of the foundation. This can result in sediment scour, which is prevalent in areas with strong currents or waves. Each foundation type reacts differently to these washouts:

Pile foundations suffer

> *“from a localized reduction in over-burden pressure and a loss of lateral resistance at the seabed. Gravity base structures may undergo erosion of soil from beneath the base of the structure.” (WATSON, 2000)*

There are therefore two ways to deal with scour: To include it in the design of the foundation, or to monitor the occurring scour and replace the material.

6.3.2 Examples

a) Borkum, Germany

The water depth at the sites in the German North and Baltic Sea are between approximately 20 and 45 m. (MITZLAFF & UECKER, 2002) So as foundation types for the offshore wind power plants Monopile, Tripod and Jacket are possible (Table 6-1). So the strategy of the geological analyses has to be coordinated concerning the type, the extent and depth of the exploration. (WEIHRAUCH, 2003)

For exploration of soil for the research platform FINO 1 (Figure 6-8) at the Borkum reef in the German North Sea in October 2001 the subsoil data was obtained by drilling and Cone Penetration Test (CPT). The water depth at site has approximately 28 m. The subsoil data resulted that the soil under purchase (drilling and sounding) to the end of the drill hole (approximately 32 m) exists of consistent sand with clay inclusions in places. The CPT results that the sand predominantly is present compact and very compact, in some places middle compact. (WEIHRAUCH, 2003)

The analysis of the different possible foundation types (Table 6-1) results that a Jacket-Structure is the best solution for the platform. Financial and structural results confirmed this decision. (FINO, 2010)

Table 6-2: Parameter of the foundation (FINO, 2010)

Piles	4
Diameter of the pile	1.5 m
Length oft he pile	38 m
Weight oft he pile	37 tons
Dimension of the Jacket-Structure	26 x 26 m at the ground

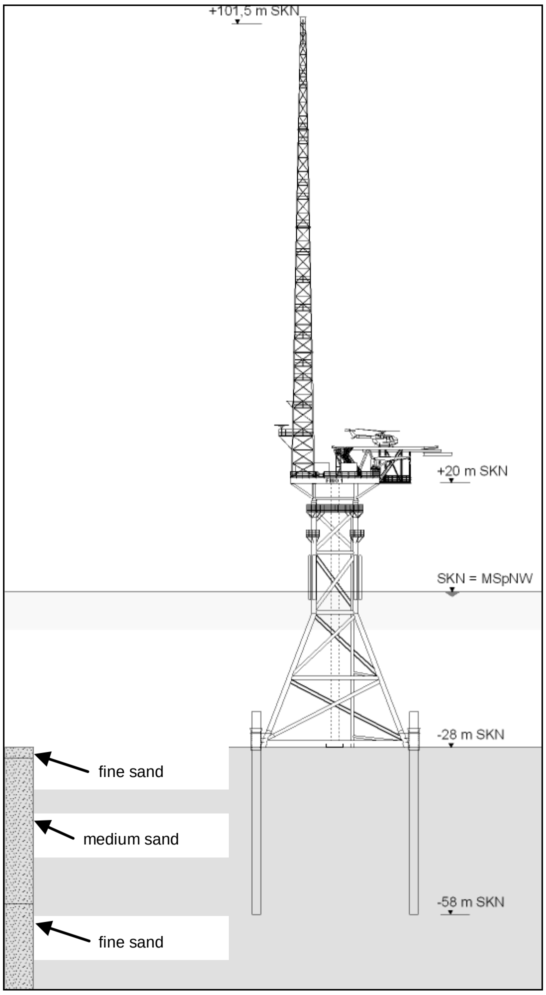


Figure 6-8: Construction of the FINO 1 research platform (FINO, 2010)

b) Middelgrunden, Denmark

The wind farm in Middelgrunden, near Copenhagen, consists of 20 turbines, each with 2 MW of installed capacity.

The water depth at site is 3-6 m and the seabed consists of a layer of polluted sand (the shoal has been used as a dumping area and is filled with materials from harbor construction work, building materials, etc.). But at the north sites was in general more waste than to the south. The original subsurface consists of limestone with large agglomerates of flint stone and is destroyed in the upper surface by the passages of the glaciers 10-15 000 years ago. The thickness of glacial sand and clay was, depending on site, from 20 cm up to 4 m.

So at 7 sites the foundation could be placed directly on the glacial deposits (shear strength: 300 kPa), at the remaining 13 sites the deposits including glacial deposits have to be removed to obtain sufficient shear strength of 150 kPa. (SØRENSEN et al., 2000)

On site, at 50 m height, wind speeds of 7.2 m/s are expected and waves have a maximum height of only 3.8 m. But sea ice (thickness: 0.6 m, dimensions: size: 2 x 2 km, speed: 1.0 m/s) is a factor that has to be considered.

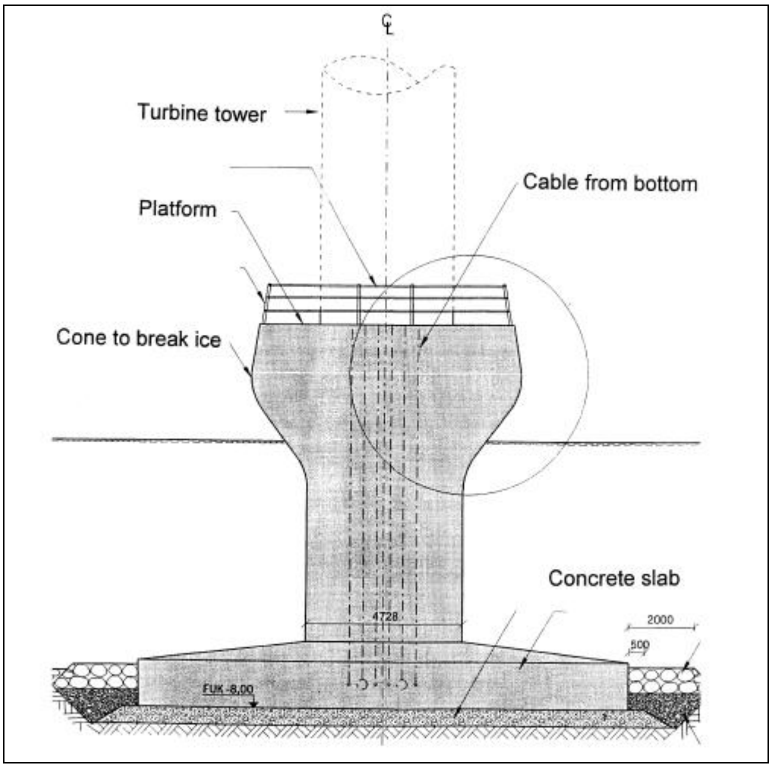


Figure 6-9: Design of the concrete gravity foundation (SØRENSEN et al., 2002).

Ice loads are reduced (factor 5-10) by an included ice-cone (Figure 6-9). So these loads are no longer the main aspect in designing the structure and foundation. Because wave loads at site are relatively small, the main (environmental) loads are induced by the wind.

To find the most cost-effective solution, possibilities (next to concrete and steel design) were left open to bids based on alternative solutions e.g. a monopile. During the evaluation of the bids for the foundations, it was concluded (SØRENSEN et al., 2000) that:

- Due to the presence of a special type of limestone, the monopile was not feasible for the actual site. The shallow water and the relatively marginal waves and current at sea favored a gravity type of foundation
- The steel caisson type cannot compete in shallow water with concrete. At a larger water depth (>10 m) other types of steel foundation will be more competitive than the standard gravity solution (ELSAMPROJEKT, 1997)

- At larger wind farms with a lower number of turbines located in shallow waters (<10 m depth), rationalization can be expected especially with respect to the placement of the foundation, but concrete is still expected to be the cheapest solution

The most cost effective solution was chosen – the solid concrete plate foundation. Here the hollow steel cylinder is arranged between the concrete plate and the tower. To protect the steel from corrosion, the tower is surrounded by a layer of concrete, which also forms the ice-cone. No ballast is added to the base plate but additional ballast (sand) is filled in the steel cylinder.

The ballasted steel caisson and monopile foundations were estimated at 10-20 % and 20-40 % more in costs, respectively, than the concrete plate option.

6.3.3 Types of foundations and foundation dimensioning

Today, many different designs for offshore foundations (oil platforms etc.) are in use. Some can be used for designing foundations of offshore wind installations. Some distinctions must be considered however (Table 6-3):

Table 6-3: Differences between offshore structures (WATSON, 2000)

	Traditional offshore structures	Wind energy structures
Water depth	20 - 120 m	10 - 25 m
Loading - vertical	5 000 - 30 000 tons	100 - 300 tons
Loading - horizontal	10 % - 20 % of vertical load	70 % - 150 % of vertical load
Overturning moment	Water depth x horizontal load	(Water depth + 50 m) x horizontal load
Number of installations	1	20 - 100

Of course, foundations are available for wind turbines in shallower water and must be able to accommodate smaller vertical loads. Therefore, the horizontal load and also the overturning moment are much higher.
Aside from this, the cost per base should be significantly lower, as approximately 20 to 100 foundations (Table 6-3) are required for a wind farm. Means: The investor of a wind farm has to invest in 20 to 100 installations instead of 1 installation (e. g. oil platform).

Basically, there are six construction types for foundations: either a monopod or tripod structure, each supported by gravity base, caisson or pile foundation. The tripod structures result in complex structures, so they are not as attractive geotechnically. During the planning stage of several plants, it is necessary to keep the design as simple as possible. Each of the monopod structures has advantages and disadvantages: in homogenous soils gravity base and caisson foundations are likely to be particularly good – pile foundations will be better in highly variable soils. So in every situation different solutions will be the best.

Dr. Lesny and her Team from the University of Duisburg-Essen/Germany developed a concept for dimensioning foundations for wind power plants on open sea (Figure 6-10):

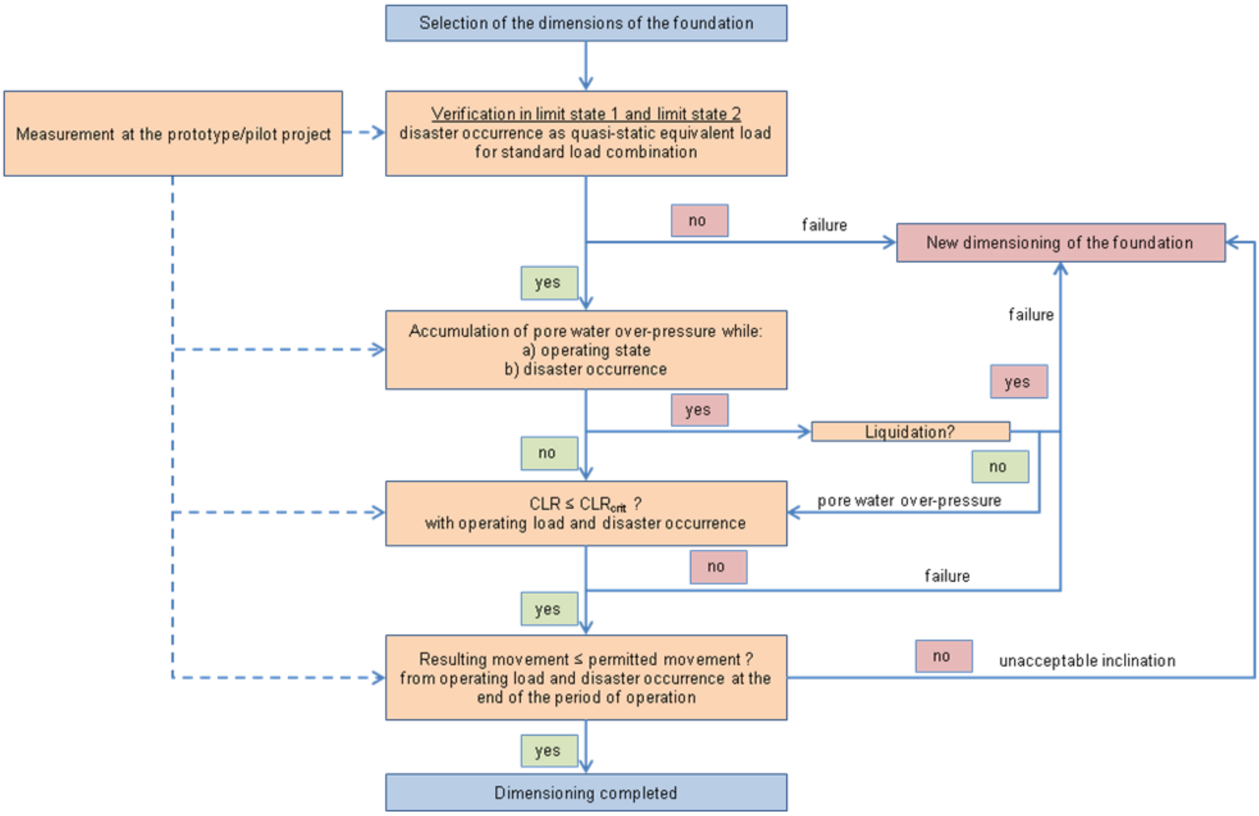


Figure 6-10: Concept for dimensioning a foundation for wind energy plants on open sea (LESNY et al., 2007)

Currently, monopile foundations are mainly used. In the long run however, this does not have to be the most economical type of foundation. Ultimately, the design of foundations for offshore wind turbines depends on the following individual aspects:

- **Cost of installation**
  Crucial to economic feasibility
- **In service performance**
  The foundation must sustain repeated cyclic loading and large overturn-

ing moments. Furthermore, the design is likely to be governed by serviceability rather than failure, and at some sites sediment scour could be very severe.

- **Removal**
  If offshore wind turbines are decommissioned, all components of the system will be removed – even the foundation. Therefore, decommissioning should already be included in the initial planning, feasibility and cost calculations.

At present, the following foundations are therefore being utilized (QUAST, 2003), (OFFFSHORE-WIND, 2010):

6.3.3.1 Tripod

The basis of a tripod consists of a three-legged structure. This is constructed from steel tubes and by smaller posts, which at the corners become one, thus resulting in an equilateral triangle driven into the ground and anchored into the seabed. For better load support, the posts can also be tilted. A central tube is then applied to the three-legged structure, whereas this tube itself is not inserted into the seabed (Figure 6-11).

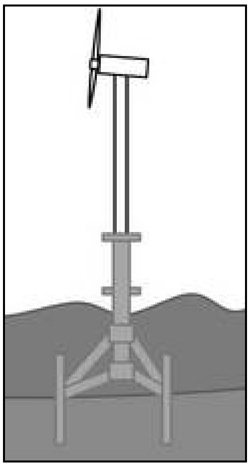


Figure 6-11: Structure of a Tripod (OFFFSHORE-WIND, 2010)

Advantages:

- Deployable for use in water depths > 20 m
- Small post diameters in comparison to monopiles (Chapter 6.3.3.3)
- Only minor preparation of the seabed necessary

- Simple underwash protection (scour)

Disadvantage:

- No suitability with stone obstacles

6.3.3.2 Jacket

The jacket tubes form a spatial lattice. The four feet of the jacket (Figure 6-12) are anchored with piles. This concept has proven itself with the foundation of oilrigs in greater depths of water. (QUAST, 2003) Due to the relatively large base of the structure, a high degree of stiffness can be achieved. (PEIL, 1980) 40-50 % of steel can be saved with Jacket structures compared to monopolies. (OFFFSHORE-WIND, 2010)

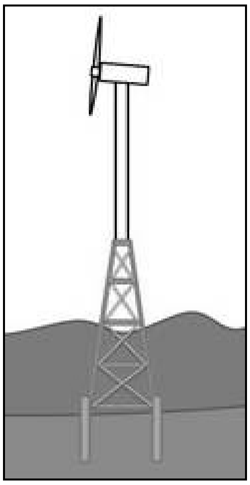


Figure 6-12: Structure of a Jacket (OFFFSHORE-WIND, 2010)

Advantages:

- The project costs increase relatively little with the water depth
- Use also in large depths of water possible
- Wide range experience exists (oil and gas industry)
- The individual components are relatively small and the production is practically fully automated

Disadvantages:

- Security against collision is minimal

6.3.3.3 Monopiles

A monopile is a hollow cylindrical pile, driven into the seabed with a pile driver (Figure 6-13).

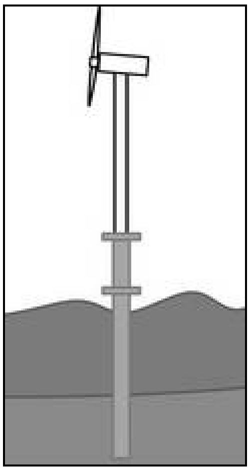


Figure 6-13: Structure of a Monopile (OFFFSHORE-WIND, 2010)

The steel plant tower is inserted into the hollow post and the gap space is filled with high strength mortar. This assembly known as a "grouted joint" allows the correction of possible misalignments of the foundation pipe. (SCHEER et al.)

The vertical load transfer takes place via the jacket friction and the pile end capacity, the horizontal lateral load transfer over the pile foundation. The horizontal load transfer approach contains a substantial empirical content, partly based on model experiments.

Particularly notable are the effects of dynamic or cyclic load interference, as well as the threshold loads and change loads. Thus, the load-displacement behavior and serviceability must be compatible – the allowable pile stress must not be exceeded.

Certain wind directions prevail in German offshore regions, for example, so there is a certain long-term risk: a gap can form in the soil with a pole displacement on the windward side, which fills itself with soil, thus preventing the pole to return to its original position at release or change in direction. A permanent misalignment of the pile can be the result with multiple occurrences of this phenomenon. (QUAST, 2003)

To prevent this, monopile structures can be guyed by steel cables (Figure 6-14)

– which however cause barriers to shipping, and thus complicate the accessibility to the plant.

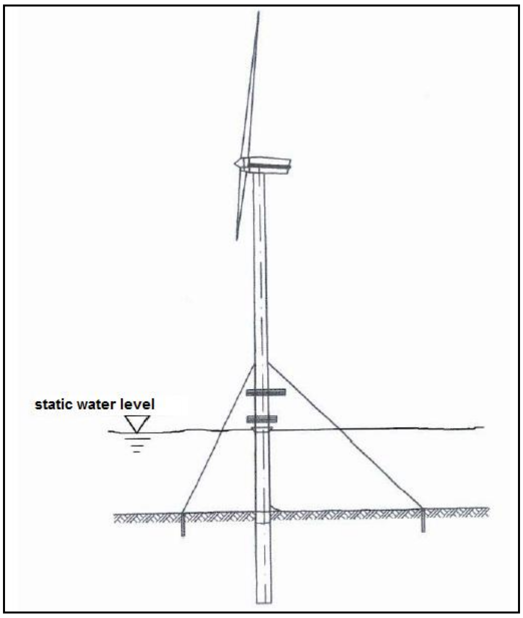


Figure 6-14: Monopile with cable tension (QUASCHNING, 2008)

Monopiles are suitable mainly for the establishment of offshore facilities in the 2-3 MW class, in water depths up to about 20 m. Since larger facilities (3-5 MW) demand higher material costs for the massive foundation pipes, the monopile is economical only in water depths up to about 15 m. (OFFFSHORE-WIND, 2010) Due to the relatively simple handling of monopiles, it would be sensible to look for new paths for larger water depths. For this purpose, the development of the following would be conceivable: larger pile caps for larger pile diameters, the use of drilling fluid or other pile-drive facilities, and the use of pre-bored holes with subsequent annular pressing operations, or to telescope with subsequent boring of the respective upper part.

Advantages:

- Fast and easy installation possible
- Only minor preparation of the seabed necessary
- Simple underwash protection (scour)

Disadvantages:

- Heavy driving devices necessary

- No suitability with stone obstacles
- Currently deployable < 30 m depth of water

6.3.3.4 Gravity Foundations

Gravity foundations are presently being successfully used in bridge construction. For this purpose, floating dry dock boxes are constructed of either steel or concrete, and then transported afloat by ship to the wind park. The foundations are covered with ballast (sand and gravel) and are then sunk onto the seabed at the place of installation. The foundation is therefore fixed to the seabed by the weight of the base body (Figure 6-15). (QUAST, 2003)

Deep-water gravity foundations are very expensive. They are therefore used in shallow water (< 10 m). (OFFFSHORE-WIND, 2010)

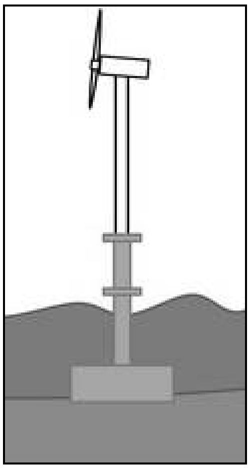


Figure 6-15: Structure of a gravity foundation (OFFFSHORE-WIND, 2010)

For scour protection and other reasons of stability, piling aprons must be installed at the outer edges of the foundation, which penetrate the ocean body while lowering. Furthermore, deep injection is necessary in the seam between the ocean bed and base plate. (QUAST, 2003)

Advantages:

- Considerable strength to ice-drift
- Can be built on rocks
- No risk with deep-seated obstacles in the soil, just as cables etc.
- No noise emission as pile driving is not required

- Lower expenditure of steel for concrete foundations reduces costs
- Relatively low maintenance

Disadvantages:

- Relatively high costs for large depths
- Elaborate deep injection required

6.3.3.5 Bucket

The bucket foundation is carried out as a pail type steel foundation, the so-called "Bucket" (Figure 6-16). This bucket is turned upside down, set on the seabed and then pumped dry. The resulting vacuum and the overburden pressure of the water causes the bucket to attach itself firmly and the base material that is sucked into the bucket stabilizes this structure. (OFFFSHORE-WIND, 2010) The mast is closely fixed to the bucket (Figure 6-17).

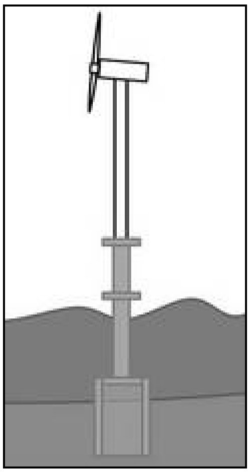


Figure 6-16: Structure of a Bucket (OFFFSHORE-WIND, 2010)

Figure 6-17: Bucket foundation at transport (BLADT, 2010)

The bucket solution is a relatively simple structure with easy dismantling capabilities. (PEIL, 1980)

Advantages:

- Does not require pile driving
- Low steel consumption
- Relatively simple production

Disadvantages:

- Usable only for homogeneous soil

6.3.3.6 Floating Foundation

Floating foundations – for particularly large depths of water – are in planning. Experience is already available with oil platforms; however, the forces acting on a wind turbine are considerably larger.

A gravitational anchor should anchor floating foundations to the seabed. There are different concepts for the float. Figure 6-18 shows the so-called Sway foundation that acts like a fishing bobber in the water. Another detailed example od a floating foundation can be seen in Figure 6-19.

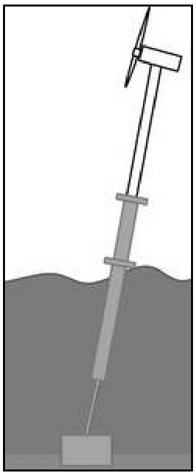


Figure 6-18: Structure of a floating foundation (OFFFSHORE-WIND, 2010)

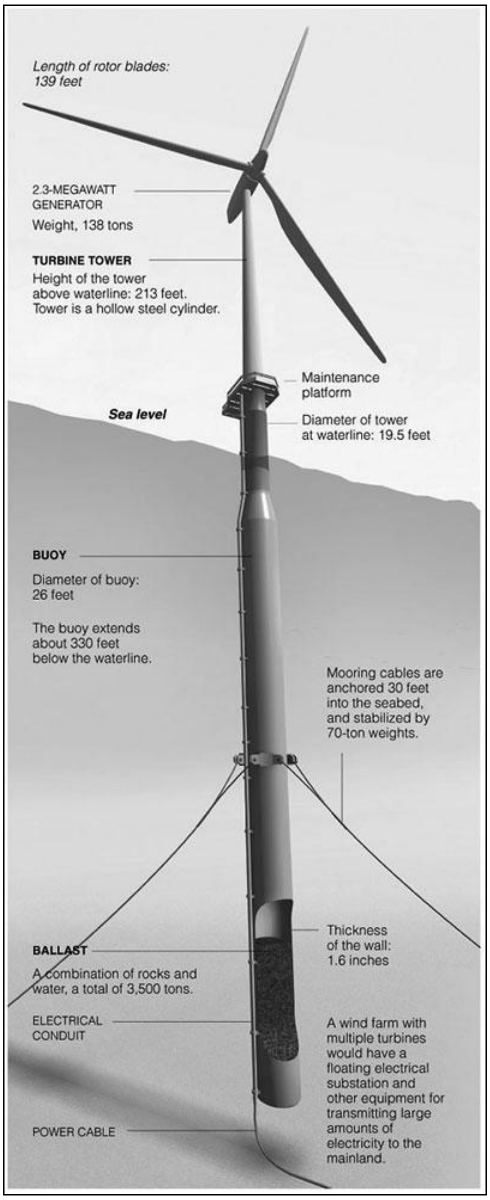


Figure 6-19: Detailed example of a floating foundation (NEW YORK TIMES, 2009)

Advantages:

- No pile driving needed
- Minimal use of materials
- Towing ashore possible

Disadvantages:

- Has not been adequately tested so far
- Additional requirements for the design of the wind energy plant caused by strong movement of the float

6.3.3.7 Collision Safe Foundations

Collisions present a risk not to be underestimated for offshore wind turbines. Research is currently focused on the development of foundations that will withstand a possible ship collision, whereas any damage to the ship would not cause oil or chemical leakage.

The Technical University Hamburg-Harburg (BIEHL, 2009), Germany, simulated such collisions between various foundation structures and different types of vessels (Table 6-4):

Table 6-4: Collision risk (BIEHL, 2009)

	Double-hulled tankers	Container ship	Single-hulled tankers	Bulker
Tripod	b	b	b	b
Jacket	a	a	c	c
Monopile	a	a	a	a

a	The design can be regarded as collision proof.
b	It was possible to identify hazardous scenarios and propose countermeasures. The design can be regarded as conditionally collision safe for each of the vessels specified.
c	It was possible to identify hazardous scenarios without the proposal of countermeasures. The design is considered unsafe without a fundamental change in geometry.

- Monopile:

  In case of a collision the Monopile can’t absorb the collision energy from the ships. So first, structural failure occurs at contact area and the tower is pushed away by the ship. After that, the pier can’t absorb the energies and moments caused by coving, because the relative fast deformation in the soil causes a high pore water pressure and so resistance is increasing. The pile kinks. But the damages at the analyzed ships are marginal. No leakage emerged.

- Jacket

  The fine tubes of the Jacket can’t offer important resistance. So the deeper the ship is entering the structure of the Jacket, the bigger the damages are – the rigidity is lost. After that, the Jacket collapses back upon itself and the gondola can fall on the ship.

- Steel-Tripod
  The Tripod is hit – depending on draft of the ship and design of the Tripod – at the diagonal bar, what comes along with a heavy damage of the ship. After that the hull bears against the construction of the tower, so that one pier is exposed to driving power. With high kinetic energy of the ship, maybe the pier can’t transmit the tension to the ground and is lifted. In this case, the tower is tilting away from the ship. If not, the construction can break down local.

6.3.4 Digression: Corrosion

Since the wind at sea blows much stronger than over land (Chapter 5.3), the operation of wind turbines there is usually more attractive. However, the installations at sea are exposed to extreme weather conditions. Economically speaking, a plant can operate at sea only if the construction is designed for longevity and does not necessitate costly maintenance and repairs. Corrosion protection, therefore, also plays an important role. The production of even larger wind turbines requires an adjustment of all supporting parameters. One example is noted at this point – the pilot project "Beatrice" in the North Sea: The tower segment on this project has a length of 66 m, which meant that the tubes had to be divided into three sections, as otherwise they would not have fit into the blasting and painting cubicle. Thus, a complex planning and execution process was required. Process reliability will be set forth, most likely only after a longer period and in larger lot sizes.

Basically, the systems should be designed so that they can operate for 20 to 25 years – maintenance free if possible. The corrosion protection system must be selected very carefully, taking all relevant parameters into consideration. Basic coating systems are, for the most part, inadequate for offshore wind turbines: at the "Horns Rev" wind farm, which was established in 2002 in the west of Denmark, extensive damage had appeared in just a few years due to a basic coating system that was used. (INNOVATIONS-REPORT, 2010)

6.3.5 Soil boring (CPT)

Soil borings for offshore wind farms can be operated by CPT (Cone Penetration Test) units. With these, the point pressure at sensor and the local skin friction can be recorded continuous. In some cases the Piezocone Test (CPTU), a CPT with additional measurement of the porewater pressure on the penetrometer surface can be practicable. (LESNY & RICHWIEN, 2004)

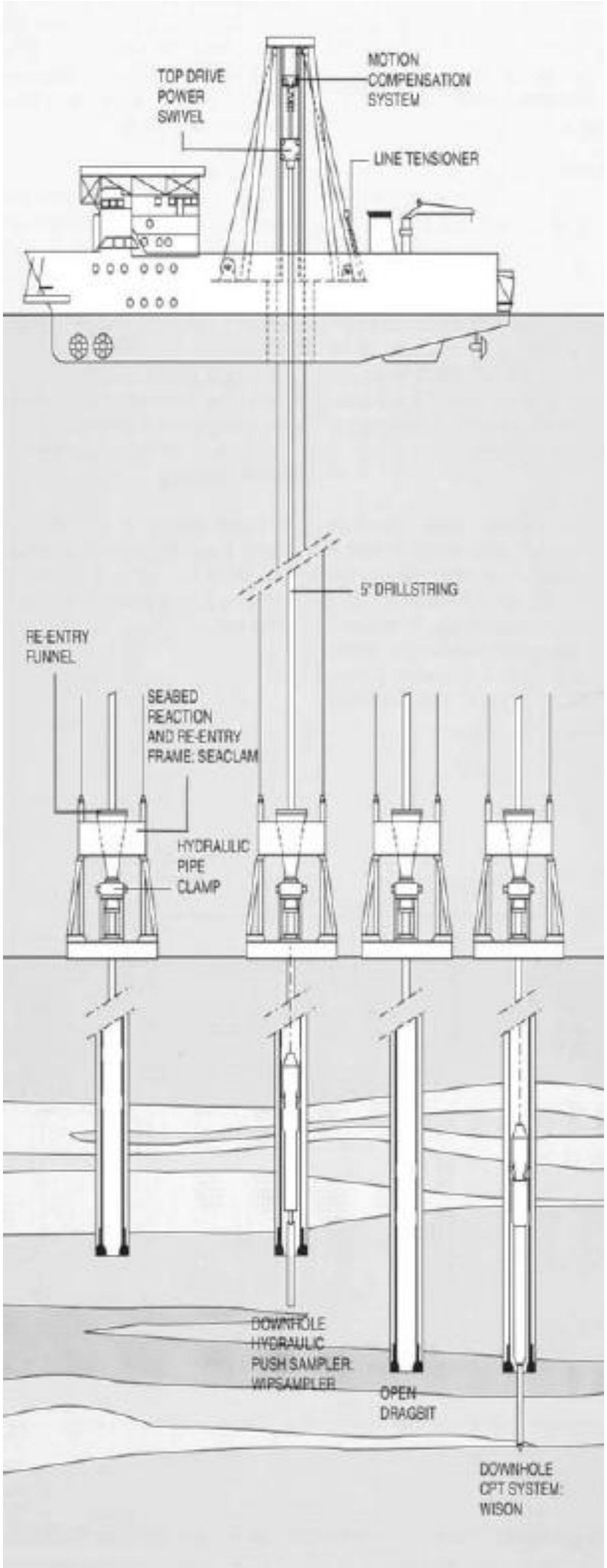


Figure 6-20: Schematic diagram of the operational procedures for drilling, push sampling and in-situ testing using a cone penetrometer (FUGRO, 2002)

CPT always have to be carried out in conjunction with one boring at least, so that the conclusions of sounding can be calibrated with the help of the boring.

Offshore, borings are operated by a drilling ship or an elevating platform: (LESNY & RICHWIEN, 2004)

Drilling ship

+ Lower costs
- boring depends on weather

Elevating platform

+ boring is extensively independent on weather

- relocation depends on weather

- higher costs

Mostly, CPT are operated with sensors, whose dead weight (Seabed Reaction and Re-Entry Frame in Figure 6-20) is settled on the sea bed. Depending on the density of the soil in-situ, the depth of sounding is limited by mass of the dead weight (common: 16 tons to 20 tons). (LESNY & RICHWIEN, 2004)

7 Conclusion & recommendations

Not only the environment and climate change summits in Rio de Janeiro (Brazil, 1992), Kyoto (Japan, 1997), Johannesburg (South Africa, 2002) and Bonn (Germany, 2004) led to the discovery that renewable energy must be advocated. High level objectives were also agreed upon: for example, 20% of the required energy in the EU should be covered by alternative energy by 2020. Concerning the feasibility of the ultimate goal – the complete supply from renewable energy sources – and whether this is possible, conclusions cannot yet be drawn.

The fact is, however, that renewable energy worldwide has grown much faster than forecasted. Previsions made by the European Union (EU) and the International Energy Agency (IEA) differ strongly with the actual development. Primarily, wind energy is underestimated on a regular basis:

- In the 1994 "PRIMES" forecast up to 2020, wind energy was already 36 % above the predicted values in 2008.
- In Europe, the use of wind energy in 2004 was greater than the 2020 forecast of the "Advanced Scenario" of the European Union in 1996.

For more than ten years, global wind energy development has increased over the previous year by an average of 30 % per year (Figure 7-1). (PIEPRZYK & ROJAS HILJE, 2009)

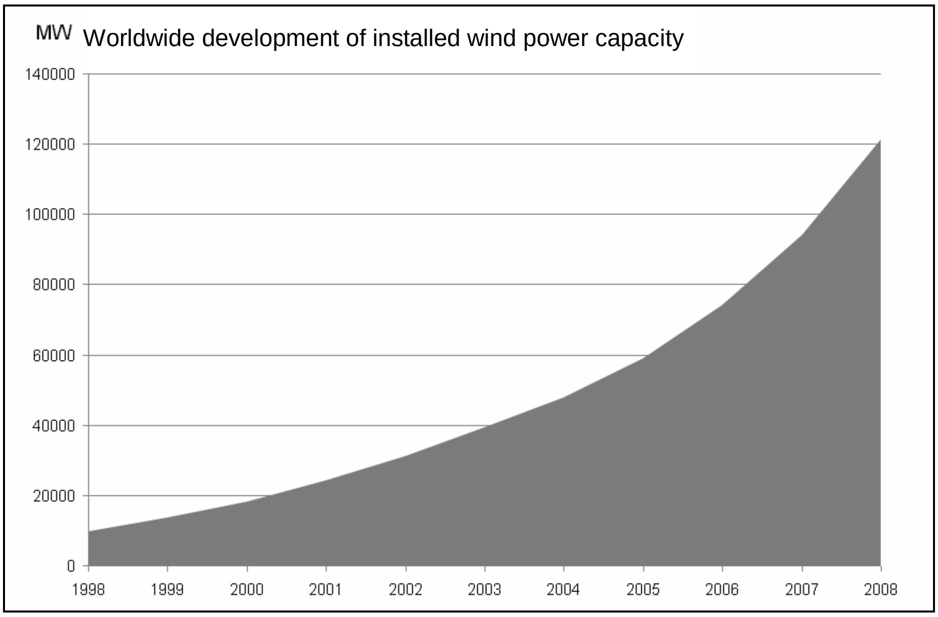


Figure 7-1: Worldwide development of installed wind power capacity 1998 – 2008 (WORLD WIND ENERGY ASSOCIATION, 2008)

In recent years, wind energy was transformed into a leading expansion market in the energy sector. Although the electricity from wind energy must still be subsidized to be competitive (Chapter 2.2.5 and Chapter 2.3.8), the savings from the lack of environmental damage compensates for excess expenditures. (RYABENKIY & SCHINEWITZ, 2010) Also, the rising prices for depleting oil, gas and uranium sources move the development of costs gradually in favor of renewable energy sources.

There are many different ways to design wind power plants. For example wind energy plants with horizontal or vertical rotor axis, windward armature or wind shadow armature. But wind power plants with horizontal rotor axis and a windward armature prevail (Chapter 5.2.2).

Which location is practical for the installation of a wind power, depends on many parameters. Next to the obviously important wind behaviors, local hindrances like hills or buildings play a big role, amongst other aspects.
Chiefly, wind and location conditions are better on the open sea, so that the greatest potential lies with wind turbines located offshore at sea (Chapter 5.3). However, problems on both the transport of the generated electricity to the coast and on the underwater installation of the wind towers are present. So the foundation of an offshore wind turbine (Chapter 6.3) must withstand – next to

the impacts on foundations onshore – different types of impacts like waves, scour, collision etc., whose influences are important on the overall design and construction technology.
But also the ground conditions (Chapter 6.3.1) of the site have a big influence, on choosing the optimal foundation. Looking on the planned offshore wind energy plants in the German North Sea for example, there are no comparable plants concerning size, water depth and stresses and strains, which have been in operation for years. So, there is not yet possibility of comparing results to learn from them. (STAHLMANN et al., 2005)

Furthermore, in depth research in the promising field of wind turbine foundations is vital if offshore wind turbines are to make a decisive contribution to future global electricity production.

A complete dimensioning of an offshore wind power plant is possible with the concept presented in Chapter 6.3.3. Anyhow some questions arise, for which requirements in research exist:
Scour for example is playing a big role in dimensioning a foundation for an offshore wind power station. So far, either the maximum of the expected scour depth is considered in designing, or scour protective measures are arranged beforehand. (LESNY et al., 2007) The first solution requires a good forecast of the scour depth, whereas the second one involves uncertainties. Above all, for both solutions, a continuous monitoring of the foundation behavior is mandatory. The related costs can, very likely, be significant and impact the profitability of the projects.
For future studies, such subjects can be pointed out. Particularly, laboratory reduced models could be established and, along with computational models, represent real situations of stresses, strains and close behavior compared to the real performance of wind structures for electricity generation units.

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