TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

# MASTERARBEIT

## The Social Costs and Benefits of Wind Energy:

Environmental Impact and Life-Cycle Assessment of Wind Turbines

ausgeführt zum Zwecke der Erlangung des akademischen Grades
eines Diplom-Ingenieurs

unter der Leitung von
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E 280/3

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Wien, am 01.06.2012 Unterschrift:

# Acknowledgments

I want to thank everyone who helped and supported me to write this thesis: First of all I would like to thank my parents, Anna and Willibald, for their extensive moral and financial support in all of my endeavours. Unfortunately, my father died before I gained my first university degree, and I know that he always wanted to see his son finishing university. I want to dedicate this thesis to both my father and my mother. I am also very grateful to my friends Oliver, Marian and Martin for the frequent discussions we had on wind power. Marian instructed me very professionally how to use the software Latex and also supported me with troubleshooting inputs. Special thanks are also due to my adviser, Professor Michael Getzner, who gave me his professional advice and assistance throughout the work on this thesis. He kindly supported all of my ideas and always had plenty of time for me. Thank you very much indeed.

Further thanks to:

- Damir Zivkovic from the Centre of Public Finance and Infrastructure Policy for supporting me with literature and assistance
- Florian Maringer from IG-Windkraft. He gave me his support and also much valuable knowledge and reports on wind power
- Mr. Markandya, Bigano and Prochia for providing me with the special results from the ExternE framework CASES
- Elizabeth Enfield proofread my thesis and, as a qualified native speaker, advised me in a friendly way on the correct use of the English language. Thank you for your professional assistance
- Philipp Preiss from the Institute of Energy Economics and the Rational Use of Energy (IER)
- Michael Klein from 7reason for supporting me by teaching me some very useful software skills

# Abstract

Although wind power has a reputation as having a neutral effect on the climate, there are still some environmental issues associated with the whole life cycle of a wind turbine. In view of the fact that the generation of electric power by means of wind turbines is increasing rapidly, a sentient and comprehensive view of the possible impacts on the environmental resulting from the utilization of wind turbines is essential. Effects on the environment can be defined as negative externalities or as external costs that have an unprofitable influence on the welfare of society and the economy. In this thesis the economics of externalities are analyzed and the effects of wind turbines on the environment are assessed, by using the life-cycle assessment, which is a method that evaluates and analyzes all stages of the life cycle of the energy system. However, renewable energy sources are hardly profitable on account of the high private costs at the moment, whereas conventional power plants have set the price on the current market. A full cost assessment, including private and external costs, for a set of different power plants is quantified to gain an insight into the true costs of generating electricity using wind power. The existence of environmental goods as receptors of pollutants makes it difficult to evaluate the true extent/degree of impairment. The utilization of wind power brings about some site-related impacts that have to be taken into account. Thus, a comprehensive discussion on almost all of the impacts of wind energy on the environment has been carried out. The results show that the utilization of wind power to generate electricity causes fewer environmental impact than is caused by the implementation of conventional technologies using other sources of fuel. However, as site-related impacts are difficult to assess, they have to be considered in another light and to be dealt with accordingly. The cost structure is such that the conventional power plants are no longer preferable. The energy pay back time of wind power plants is extremely low.

# Kurzbeschreibung

Die Nutzung von Windenergie zur Erzeugung elektrischer Energie hat einen nahezu klimaneutralen Effekt auf die Umwelt. Bei einer genaueren Analyse des gesamten Lebenszyklus eines Windkraftwerks ist die Erzeugung von elektrischer Energie jedoch mit einigen Auswirkungen auf die Umwelt verbunden. Mit rasant zunehmender installierter Leistung von Windenergieanlagen in den letzten Jahren sowie in naher Zukunft ist ein Überblick über alle auftretenden negativen Wirkungen von Windkraftanlagen zu schaffen und deren Nutzung auf mögliche Gefahrenpotentiale hin zu untersuchen respektive zu bewerten. Negative Einflüsse von Windenergie auf die Umwelt werden als externe Effekte bezeichnet. Diese, nach einer Monetarisierung sogenannten externen Kosten, verursachen einen gesamtgesellschaftlichen Wohlfahrtsverlust (Marktversagen) aus ökonomischer Sicht. Mit Hilfe von Life-Cycle-Assessment sollen alle negativen Effekte die von einer Windkraftanlage über ihren kompletten Lebenszyklus (d.h. vom Abbau der Rohstoffe über die Produktion, Konstruktion vor Ort, Betrieb, Demontage inkl. Recycling) hervorgerufen werden analysiert, quantifiziert und monetär bewertet und mit anderen Energieträgern verglichen werden. Betrachtet man nur die Kosten aus betriebswirtschaftlicher Sicht, so sind Erneuerbare Energieträger heutzutage nur teilweise wettbewerbsfähig im Vergleich zu konventionellen Energieträgern. Zweitere bestimmen heutzutage eindeutig den Marktpreis von elektrischer Energie. Eine Betrachtung der sozialen Kosten ändert das Bild: Eine Berücksichtigung oder Internalisierung externer Kosten macht Windenergie zu einer konkurrenzfähigen Technologie. Trotz geringer negativer Einflüsse von Windkraft auf die Umwelt, gibt es einige, die trotz ausgereifter Bewertungsmethoden sehr schwer bewertet werden können, da für sie keine Marktpreise vorhanden sind. Diese sogenannten standortgebundenen Einflüsse (Störung des Landschaftsbildes, Lärm, etc.) sollen anhand einer Literaturrecherche lokalisiert, sowie vorgestellt und näher beleuchtet werden. Es ist zu erkennen, dass Windenergie wesentliche Vorteile mit sich bringt. Aus ökonomischer und ökologischer Sicht sind sie in diesen Tagen konventioneller Energieerzeugung weit überlegen. Dies bestätigt nicht nur ihre geringe Energierücklaufzeit.

# Contents

# 1. Overview

There are currently two major issues that concern almost everybody these days, namely, energy prices and environmental pollution. For the former, especially the prices of fossil energy increase daily and a drop in these prices, within the near future, is not foreseeable at present. The latter is related to human activities and the consumption of energy that is required all over the world for these activities. Energy is essential to economic development and a social way of life, but it is wasted as it is generated cheaply en masse, more or less regardless of whether the environment is polluted or not. In the energy branch, electricity is generated mostly by conventional power plants using fossil fuels. This contributes to a very great extent to the environmental pollution that is to be found almost worldwide with such consequences as the release of excessive amounts of carbon dioxide, depletion of the ozone layer and the production of acid rain which results in global warming, harm to flora and fauna as well as to human health and to natural and man-made environments.[1]. Although the prices of fossil fuels (primarily oil and gas) continue to increase the general supply of electric power is generated by conventional methods and still dominates in the market for decades[2]. The reason for this development is that electricity generated by using fossil fuels is extremely cheap because external costs are not considered. The low share of renewable energy sources could indicate that they are currently too expensive despite the fact that, at present, they hardly negatively affect the climate and environment compared with conventional electricity-generating technologies. On the market for energy, renewable forms of energy barely compete with conventional energy production in spite of diminishing investment costs for the former over time. However, wind power has become a topical subject in the past few years. Wind turbines are reputed to have a neutral effect on the climate as well as being more or less competitive in the relevant markets on account of the technological progress that has been made in the past decade[3]. The electricity produced by wind power plants accounts for 21% of the total amount of renewable electricity produced in the EU in 2008. In 1994, 1,683 megawatts of wind power were installed across the EU, and by the end of 2005 this had increased 24-fold i.e. to 40 gigawatts of cumulative installed capacity. Of all the electrical power produced all over the world, approximately 2% is generated by wind power. This is expected to increase in the future according to the projected low-emission objectives stated by many countries. Following the catastrophic nuclear accident in Fukushima (Japan) in March 2011, the German Government passed a law to shut down all nuclear power plants until 2020 and now intends to concentrate on generating electricity by using renewable energy sources. The paper *Energiewende*

[1]human health, toxicity, acidification, eutrophication, global warming potential and so on
[2]do not forget that the electricity bill increases, too
[3]renewable energy is still sponsored with feed-in tariffs for green power feeding the grid

*2011* states that especially wind energy is in the top position as a key technology. There is already the intention to install further offshore wind turbines, as well as to replace and modernize older wind turbines on-land. It is thus evident that wind energy and all the other renewable energy technologies will play a major role in the future despite the higher total costs these methods incur at present.

However, is the production of wind energy really absolutely neutral with regard to climate, in general, as it is so often asserted? And if there are any negative effects, what are they and to what extent are they negative? The utilization of wind energy involves some operational issues that are often related to the site and are thus difficult to handle. This statement raises a lot of questions that demand an answer.

For this thesis the major question can be explained as follows:

*What sort of external costs can be localized for wind turbines concretely and how can potential impacts on the environment be assessed? In which dimension can externalities of wind energy be classified anyway, and does wind energy compete with other electricity-generating technologies with regard to the social costs?*

In addition to these questions, there are still some other, rather specialized, questions that might be interesting for this thesis:

- What sort of environmental impacts on wind turbines can be localized/characterized, how and to what extent do they affect the environment?
- Can environmental impacts be classified in a sensible way?
- What are externalities and what is their interrelationship to environmental issues and market activity?
- How much energy can be produced with a typical wind turbine both theoretically and in fact/practically?
- What sort of technical construction is available?
- What factors control the power output of wind turbines?
- What methods, procedures and limits exist to evaluate the externalities of energy suppliers, and especially wind facilities?
- Is there a way to evaluate environmental impacts with no market value, i.e. the influence of wind turbines in a landscape?
- From an economic point of view, does wind energy (or other renewable forms of energy) generally compete with conventional energy suppliers on the markets?
- What are the social costs of wind energy? Is it possible, or does it even make sense, to compare full costs with other electricity-generating technologies?

- Is it possible to expand decentralized power plants rapidly without other subsequent consequences?

The aim is to provide a general view of all the relevant environmental issues related to the utilization of wind energy. This belongs to the evaluation of private and external costs, as well as a significant description from a scientific point of view, of potential effects on the environment as a consequence of using wind turbines. The methods used in this thesis are based primarily on the relevant literature, and are also used to summarize the most important and latest facts on wind turbines. This includes an assessment of all life-cycle stages, as well as an analysis of valuations of different energy systems, although focusing primarily on wind power.

To obtain a general view of the entire economic context related to the impacts which wind energy has on the environment, the fundamental theoretical approaches of economic theories are discussed in Chapter 1. This starts off by describing how the imperfection of markets may cause market failures from a welfare economic point of view. Then the discussion turns to public goods and externalities, in which two major reasons that lead to inefficiencies are described in some detail. The concept of social costs is introduced. The environment is then associated with the characteristics of economic goods because they react in a similar way. Since environmental issues are often difficult to assess, a short summary of valuation methods will be presented which have been taken from the relevant literature. Before social costs can be calculated, a look is taken at the evaluation of external costs of different electricity-generating technologies. A widespread, accepted and implemented assessment framework, i.e. the life-cycle assessment approach, is introduced. This last part of Chapter 1 familiarizes the reader with the life-cycle assessment on energy systems, which is a method that focuses on the evaluation of externalities that occur in all the stages of a product's lifespan from the beginning (extraction of materials) to the end (decommissioning and dismantling)[4]. Chapter 1 provides the theoretical fundamentals of what is referred to as environmental impacts and costs of wind energy and their relation to economic activities throughout the world. The characteristics and technical specifications of wind applications are presented in Chapter 2. Beginning with the most recent facts considering wind energy development and future plans, another part analyses the physical function and limits (power output, energy yield) of a wind turbine. This analysis includes physical principles as well as details regarding design and construction. Factors influencing the power output or energy yield of a wind facility are considered, too. Finally the cost structure of wind power projects is presented. In Chapter 3 a comparison is made of both the private and external costs of different electricity-generating technologies. An analysis is made of an assessment framework to obtain a general view of the social costs of conventional power plants (coal, gas, nuclear) and nearly all the common renewable energy sources to see the dimension of both external and private costs of wind energy in comparison with other technologies. The advantage of a full cost assessment is that an insight can be gained into the true costs of electricity generation. Extensive research in the relevant literature concerning

[4] e.g. the entire life of a wind turbine from manufacturing to disposal

the localization and evaluation of the environmental effects of wind applications provides the fundamentals for the next chapter. In Chapter 4. an impact overview is introduced. The impact overview is a complete catalogue of impacts on the environment caused by wind turbines with regard to their full life cycle. The next two sections concentrate on the calculation (how external costs are calculated) and interpretation of the external costs of wind energy using the life-cycle approach. Part one compares the results of onshore and offshore wind farms and discusses the factors that influence the amount of externalities. In a fair number of analyses some of the impacts of wind energy technology are not taken into account. These effects, which are mostly negative, are site-related and take place during the operation phase of a wind turbine. Since they are difficult to assess and much discussed by the public, the author, starting a detailed literature research, presents the most important facts concerning these site-related impacts. In the conclusion, the most essential and important findings of this thesis are summarized and commented on. Subsequently, some recommendations are made with reference to the usage of wind energy as it is at present and what it might be in the future.

In this thesis, the author often refers to the terms *environmental impacts*, *environmental effects* or just *impacts* on or of something (e.g. impacts on climate, impacts of wind turbines). These terms refer to the negative externalities that affect the environment, climate, etc. and can, in general, be also understood as effects – the only difference is that impacts are usually harder and always negative.

# 2. Theoretical part

There is much literature available concerning the theoretical background of this paper. Thus, the author restricts himself to some basic reference works after long and intensive investigation. To comprehend this paper only a basic knowledge of the economic theories is required. So long explanations have been dispensed with deliberately and reference is made instead to additional literature.

In this section the comprehension of social costs is discussed, to show how they affect the markets and what sort of effects they have on welfare to society. This is discussed in a theoretical way and limited to the neoclassical economics theory. In other words, how social costs can be classified or interpreted from an economic point of view. Furthermore, the basic reasons are described that lead to an imperfection of markets which causes market failures and burden excess. The following is a simple example to illustrate this point: The owner of an apartment wants to lease it and to receive the rent that belongs to the market price of apartments in the same category[1] as his. The property, however, is located next to a power plant that pollutes the air drastically. Consequently, the owner will never obtain the full amount of money, which equals the market price because every potential tenant would demand a reduction on account of the bad air conditions. The owner foresaw these unfair consequences and probably asked himself the following question: Why do I have to pay the external costs of the environmental impact, how much in monetary units is the reduction for the pollution?

To answer the first (for us important) part, a theoretical understanding of economics and the relevant terminology, concerning especially the efficiency of markets in, and diverging from, a perfect competition model[2] is necessary. This overview is followed by an attempt to explain the variety of reasons why the respective circumstances cause such inefficiency. Furthermore, the topic *externalities* will be dealt with in some detail theoretically, including their origin and classical methods of internalization. This paper concentrates on the negative externalities with regard to the energy branch, and goes into detail in describing the externalities that affect the environment negatively, or, in other words, the impacts of wind energy in the environment.

The following questions can be answered in this chapter:

- What are markets and why can they fail?

[1] category means objects with the same location factors

[2] In this paper limited to the approach of the neoclassical economics, because there are different kinds of criticism concerning the perfect competition model (the assumption of perfect competition as the foundation of price theory for product markets) – see public choice, Austrian school [41; 91] or marxian [95]

- What sort of market failures can occur?
- What is the relation between markets and externalities?
- Can environmental goods be compared to economic goods?
- Environmental goods are consumed and used for production but why are they not traded on markets?
- What are environmental impacts, and how are external costs related to the topic of this paper?

## 2.1. Market and efficiency in economics

To be able to understand the phenomen of *market failure* (caused by atmospheric pollution for instance), how it originates and which conditions cause the impacts, they have on the assessment of externalities, a look must be taken first of all at the term *market* under a *welfare-economically optimum allocation theory*[3] and clear some situations. In addition, the concept of market failure is essential to the topics and concepts of environmental economics. But what does this mean exactly? The author wants the reader to understand in what kind of / which theoretical and practical dilemma humankind finds itself in the presence of externalities, and he discusses their principle and purpose. These effects have both directly and indirectly negative effects on humans (i.e. air pollution can cause health risks, such as cancer). Furthermore, the presence of social costs can cause a deadweight loss, in other words a loss of economic efficiency that can occur when the equilibrium for a commodity or service is not Pareto optimal. For a better understanding, it is necessary to deal with some of the basics of economic theory[4].

Economics have been concerned with markets for a long time in an intensive way. Therefore, the *perfect competition model* has been developed[5], which is a part of the welfare economics theory. *Welfare economics* or *allocation theory* focuses on questions how, and with which instruments, can welfare in a society as a whole be maximized, "including especially various propositions relating competitive general equilibrium to the efficiency and desirability of an allocation." [47] For Stiglitz, welfare economics focuses on the organization of economics, on what or how something should be produced, for whom and who decides this. Economists utilize a criterium termed the *Pareto efficiency*, named after the sociologist Vilfredo Pareto, which is important to understand as relations concerning utility improvements between individuals on exchanging commodities and consequently the origin of market failure.

It is a fact that people want to increase their utility. For that reason two human beings, equipped with goods, exchange these assuming that everybody has preferences and try

[3]optimally for the purposes of the model of the perfect competition with idealized conditions
[4]the national economy apprenticeship consists of many branches, here, microeconomics, welfare economics and environmental economics are dealt with, respectively
[5]more about this in the following section

to improve their individual utility[6] [62, pp. 8 sq.]. The utility, which it is attempted to measure, is the benefit a person has from the consumption of that person's combination of goods – the more goods that person has, the greater the utility for that person is possible [141, p. 63]. To measure the utlitity (efficiency, benefit, etc.) of one individual, economists make use of the Pareto principle. "Resource allocations that have the property that no one can be made better off without someone being made worse off are said to be Pareto efficient, or Pareto optimal." [141, p. 57] Figure 2.1 on the following page shows four quadrants with the utility of two individuals and their utility possibilities curve. Point $C$ as origin, quadrant $I$ and $III$ will not be evaluated on account of the decrease of one person's utility (see [62, p. 31]), a shift to quadrant $II$ would mean a decrease of utility for both overall. A shift to quadrant $IV$, which is also called Pareto-region, would always be an increase of utility/efficiency – regardless of whose utility increases. Point $A$ would increase the utility of person one without a decrease of utility for person two, which is also Pareto efficient. A shift from $C$ to $E$ is an increase for both. But we have to consider one fact when we talk about Pareto efficiency. A free market (or exchange of utility in this figure) in a competitive economy can be efficient under the first theorem of welfare economy but there is nothing mentioned about equity or the distribution of income. So, along the frontier, every point is efficient (exchange efficiency is given), even if one person gets nothing. The distribution is not rateable with Pareto efficiency[7].

An improvement of utility for each individual results in an increase of welfare for the entire national economy because welfare/utility of each individual is aggregated. If one goes back to the economy with two individuals and considers Figure 2.2 on page 19, a different exchange (or level of utility) in the situation of each individual's commodities can be seen in an *Edgeworth-Box*. With regard to this figure *exchange efficiency* (which is one of the three required aspects of Pareto efficiency to reach an optimum in society as a whole [141, p. 63]) point $E$ can be seen as Pareto efficient where the marginal rates of substitution of two products are equal and the tangency of the two indifference curves [141, p. 68]. Therefore, competitive markets have exchange efficiency, which is the first theorem of welfare economics[8] The second theorem implies that

> every Pareto efficient resource allocation can be obtained through a competitive market process[...]. This means that the forces of competition are allowed to make free a redistribution of wealth and to obtain efficiency, which explains the efficiency of a market equilibrium in a perfect competition model[9]. [152, pp. 461 sqq.]

[6]The economic model requires four basic conditions to evaluate social behaviour: methodological individualism, i.e. people act self-interested, rational and the relations between individuals are referred to exchange only [62, pp. 28 sqq.] Fritsch notes that the goods exchanged on a market do not have to be products. Exchange can also occur in a physical way in the form of a transaction of rights of disposal

[7]further information about behaviour and social choices see Stiglitz – Economics of the public sector: Chapter 5[141]

[8]The relationship between competitive markets and Pareto efficiency is described in the *fundamental theorems of welfare economics.*

[9]we will discuss this below

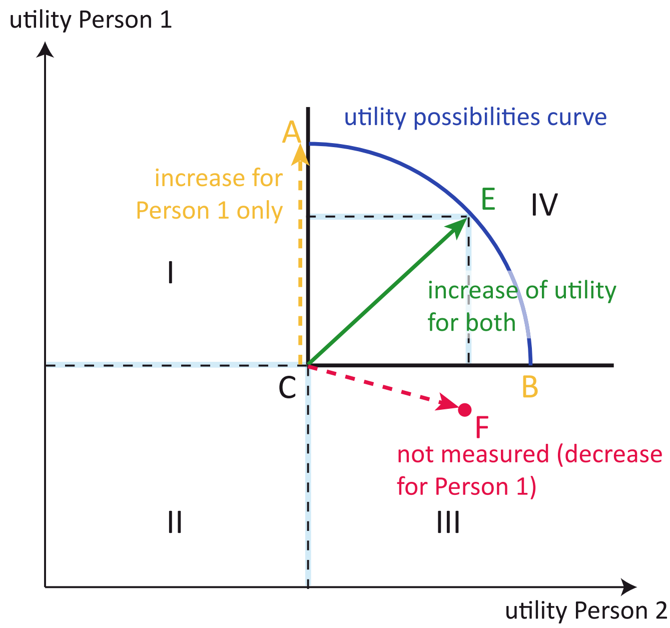



Figure 2.1.: Pareto-region and utility possibilities curve

Every point where both indifference curves touch on the black line is efficient, this set is called *contract-curve*. Here the resource allocation is in an equilibrium. Exchange takes place and a *market equilibrium* is established [152, pp. 461 sqq.]. To understand the term *market equilibrium* better, it is necessary to discuss market conditions in an economy. A market in a perfect competition model[10] is more or less any place where individuals meet their preferences by trading commodities[11] for money or barter. For Fritsch, on a market sellers of a particular commodity or service and buyers of that commodity or service have the potential for a transaction to take place [62, p. 6]. The forces of demand (byers) and supply (sellers) operate in the opposite direction[12] whereas all participants of a market influence the price of a commodity. These influences have given rise to several theories and models concerning the basic market forces. For this paper, the intersection of demand and supply is interesting. Because of the opposing progress of the two forces, an equilibrium determines. Economists refer to it as *market equilibrium*. It is the point at which quantity demanded and quantity supplied are equal and the social surplus[13] maximizes [154]. The intersection sets the price for the product, and the maximum revenues[14]. “Market equilibrium is the most advantageous condition in a

[10]it is a model used in economy to review market under idealized condition [62, p. 34]
[11]any type of goods, services, contracts, information or property rights
[12]producers demand a price for each car which increases with its quantity, but although a buyer increases his utility with one more quantity, each additional car leaves him less extra utility. In the economy, the utility function describes the relationship between the number of utilities and its extra utility, termed as marginal utility [141, pp. 96 sq.]
[13]sum of consumer surplus and producer surplus
[14]Varian describes an example concerning the housing market: It is the highest price in order that all

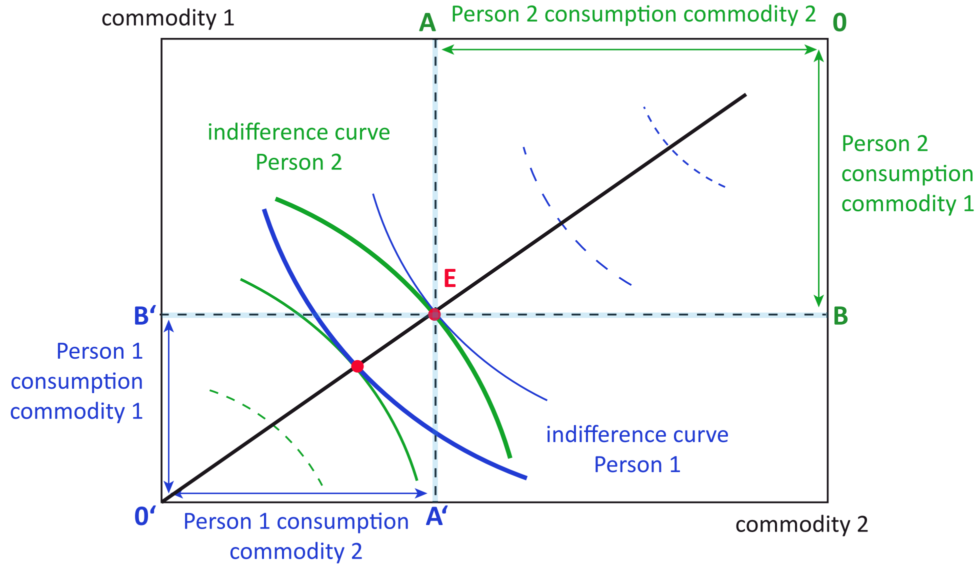



Figure 2.2.: Exchange efficiency in an Edgeworth-box

society as a whole." [62, p. 53] In other words under ideal conditions market equilibrium and its resulting efficient allocation of resource is Pareto-efficient [62, pp. 28,30 sq.; 152, pp. 82 sq.; 158]. In Figure 2.3 on the following page, the market equilibrium is seen at point $G$ between the demand curve $D$ and supply curve $S$ with the prize $P^*$ and quantity $Q^*$. By the way, as already mentioned the Pareto-condition may exist but the distribution of welfare or income could result in an unfair situation, which vindicates government intervention [152, pp. 506 sqq.].

What happens if markets fail to produce efficient outcomes, which means that a situation deviates from the model of perfect competition? Besides, the theories which were just discussed can hardly be situated in reality because the model of perfect competition is subjected to idealized conditions [62, p. 34]. Aside from the last fact "welfare economics assert that the economy is Pareto efficient only under certain circumstances or conditions." [141, p. 77] Economists mention the following conditions under which markets vary from Pareto efficiency and refer it to as *market failures*[15]:

- Imperfect competition (see subsection 2.2.1 on page 21)
- Public goods (see subsection 2.2.2 on page 22)
- Externalities (see subsection 2.4 on page 26)
- Incomplete markets (see [141, p. 81])

apartments are hired out

[15] although the theory on supply and demand has hardly changed since the 19th century, market failure is still brought into focus

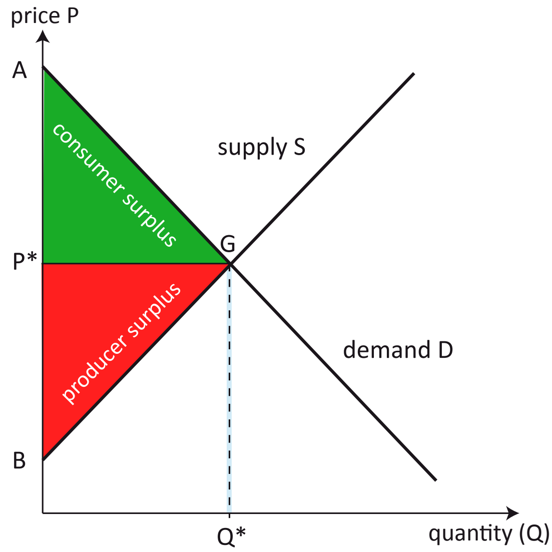



Figure 2.3.: Market under a perfect competition

- Imperfect information (see article [2])
- Unemployment and other macroeconomic disturbances (see [141, p. 85])

Further references: For welfare economics and market efficiency see Stiglitz, Economics of the public sector; Part two [141, pp. 53–124]
Optimum und Gleichgewicht in der Marktwirtschaft – Brümmerhof, Finanzwissenschaft; 3. Kapitel [31]
Der Markt – Varian; 1. Kapitel [152]

## 2.2. Market failure

In the last section, the occurrence of market failures on account of an imperfection of markets in economic theory was discussed. This section gives a short explanation of the three[16] the most important reasons concerning market failures are quoted in literature. Then the focus is centred on externalities in Chapter 2.4 on page 26. It is obvious that there may be some relationship between some subsections, but there is no need to worry about that. For instance, information asymmetries may be a condition for the existence of a monopoly, too[17].

In the first part, the author wants to show how economists measure inequality or inefficiency on markets: If a look is taken at Figure 2.3 again, the consumer surplus on the demand curve can be explained as the benefits all individuals get from a project,

[16]Externalities are discussed in detail and in 2.4 on page 26
[17]and not only caused by failures of competition according most references

measured by the total area under the demand curve. A tax $t$ on a bridge will cause an increase of the price $P^*$ to $P^* + t$ if we study the following Figure 2.4. Thereupon,

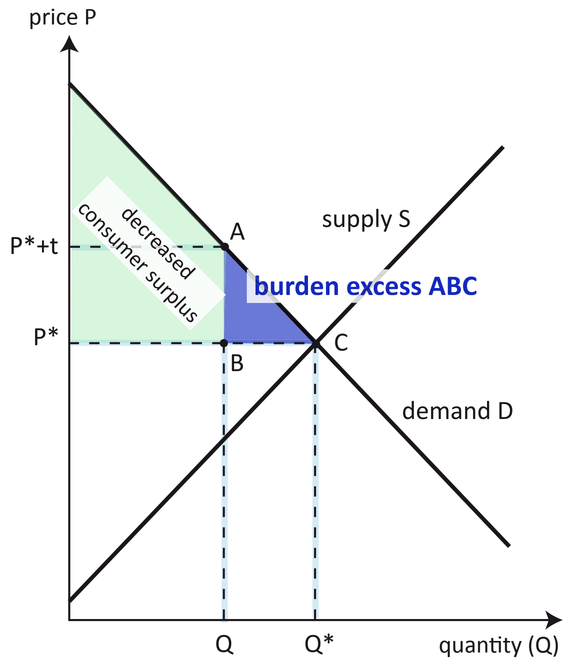



Figure 2.4.: Inefficiency owing to market failure

the quantity of consumption is reduced from $Q^*$ to $Q$ because individuals avoid purchasing the taxed commodity – they "forgo more-preferred consumption in favour of less-preferred consumption in order to avoid payments of the tax." [141, p. 111] This results in a *deadweight loss* or *excess burden* measured by the area $ABC$[18]. In such a situation the market is not (Pareto-)efficient and causes imperfection[19].

Further information:
Theorie des Marktversagens als Referenzstandard für die praktische Wirtschaftspolitik; Fritsch, Teil III, 13 [62, pp. 349-358]
Marktversagen und staatliche Koorekturmaßnahmen; 4. Kapitel [31]

### 2.2.1. Failure of competition

If there are many firms and no-one has any influence over the market price, the market is perfectly competed. It is assumed that if one agent is capable of gaining market power at such a high level, that it cannot be influenced by other agents on the market. Such

[18]also called *Hartberger triangle*
[19]for Quantifying distributional effects or inequality see [141, pp. 113 sqq.]

firms are referred to as *monopolists*[20]. Monopolists have the possibility to supply the market because they have the power to influence the market price by restricting the quantity of commodities [46, p. 70]. What does that mean and how does it affect market equilibrium? In a perfect market the price of one commodity equals its marginal costs. Monopolists have some advantageous properties. As a large concern, a monopolist has *high fixed costs* and *low marginal costs* with an increase of the *returns to scale*[21]. So one firm alone can produce more goods at less cost than several firms together, which is called *subadditivity* [153, pp. 435 sqq.]. So it is also difficult for other competitors to enter the market – as *barriers to entry* exist. Actually sub-additivity is a preferable property for supplying demands with inexpensive goods. But if a large firm monopolizes the market, the purchasers have to accept the price demanded for the commodity. By contrast, in a model of perfect competition, companies are *price takers* and do not have market power. Since every agent tries to maximize his profit, the monopolist restricts the quantity of one demanded commodity to a profitable level with a maximum of profit. In Figure 2.4 on the preceding page the profitable level for the monopolist is illustrated at point $A$[22] with the quantity $Q$ and the price $P^* + t$ for instance. The realization has just come that this behaviour causes a burden excess measured by the area $ABC$, on the one hand, and additionally a loss of consumer surplus measured by the area $P^*BAP^* + t$, in the other hand. If a monopolist supplies the market the total loss is measured by the area $P^*CAP^* + t$. Traditionally, monopolists are big public utility companies in the branches concerned with electricity, railway or delivery services, for instance: railway companies, for instance, own a big infrastructure system and supply cargo and passenger services. They are able to control the market by limiting the quantity and, simultaneously, by raising the price of their products or services, respectively. Competitors are either suppressed because they cannot survive in the market or just have to pay high lease rental charges to be able to use the infrastructure.

### 2.2.2. Public goods

Paul A. Samuelson was the first economist to develop the idea of public goods. He defined this *collective consumption good* as "[. . . ]goods which all enjoy in common in the sense that each individual's consumption of such goods leads to no subtractions from any other individual's consumption of that good [. . . ]" [124, p. 387].

Based on this citation it can be seen that public goods have specific properties, which are known, in particular, as *non-rivalry* and *non-excludability*. Non-rival consumption means, first of all that nobody can prevent another person from consuming this commodity and, secondly, one person's consumption does not detract from another person's consumption. A classic example of non-rival consumption is national defence. All of the citizens are protected without rivalry and the additional cost for national defence is

[20] or oligopolist if there are a few firms
[21] decreasing average costs with a rising output
[22] German economists call it *Cournotscher Punkt*, named after the French economist, Antoine Augustin Cournot (1801–1877)

not affected when one person joins. In contrast, if one person eats an apple, the other person is not able to consume it and so rivalry exists. The property of non-exclusion for public goods means that it is impossible to exclude any individuals from consuming this commodity. No citizen of the United States can be excluded from national defence – everybody is protected. Back to the example with the apple: if the first person eats an apple, the second person is prevented from consuming it. He or she is excluded from the consumption of the apple. To understand the theory of goods better Figure 2.1 shows different types of goods depending on the variety of their properties. The figure clearly

Table 2.1.: Types of goods

| | **Excludable** | **Non-Excludable** |
|---|---|---|
| **Rivalrous** | ***Private goods*** (e.g. food, notebook) | ***Common goods*** (e.g. fish stocks) |
| **Non-Rivalrous** | ***Club goods*** (e.g. golf course, staellite television) | ***Public goods*** (e.g. national defense, air) |

shows the impossibility to trade public goods on a market because fixing a price for one commodity automatically creates exlusion and rivalry for this good. "The primary cause of market failure involving public goods is non-excludability." [172]

According to Stiglitz *underconsumption* and *undersupply* there are two forms of market failure associated with public goods. Watching terrestrial television does not prevent other people from watching the same program, because nobody is excluded and there is no rivalry. However, if there is a charge for watching television (scrambled channels) exclusion is possible. This would result in underconsumption, although the marginal cost of one additional person is zero [23] and the marginal benefit positive. Without exclusion the problem of undersupply exists [141, p. 129].

Figure 2.5 on the following page shows the loss of welfare from an excessive consumption of a public good supplied freely. For instance, water incurs marginal costs to supply it (to purify and to deliver it). There will be overconsumption in spite of the marginal cost. People will demand water up until to the point when the marginal benefit he or she receives from the commodity is zero. "For a given quantity, individuals will not automatically self-select their optimal price, but will instead wish to pay the lowest price possible when they cannot be excluded from consuming the good." [172]

Another reason why public goods do not generate a Pareto efficient result on a market is called *free rider problem*. It implies that human beings, acting as homo economicus [24] consume a resource either without paying for it or at least less than the full costs. This leads to non-production or under-production of a public good and finally to inefficiency[25]

[23]there is a determination between pure and impure public goods where the ease of exclusion and marginal cost of use are different[141, p. 133]

[24]"[...]purely rational and purely selfish – extremely individualistic, considering only those benefits and costs that directly affect him or her.[...]" [161]

[25]or an non-operating system or a disappearing service through the market owing to the excessive use of a common property resource, respectively. The market fails to provide a good for which there is a need

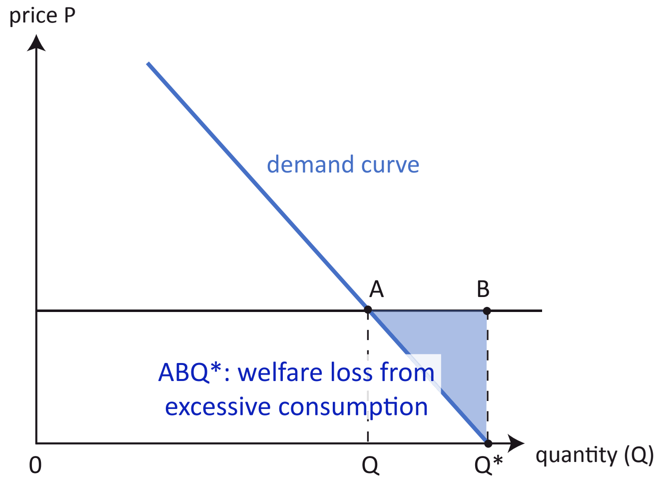



Figure 2.5.: Distortions when supplying goods freely

[141, pp. 130 sq.; 117]. In the second sentence in the previous paragraph the basics for the origin and existence of negative externalities were developed. For instance, an operator of a coal power plant produces negative impacts on the environment and does not pay the full cost to repair the environmental damages caused by emissions into the atmosphere. In 2.4 on page 26 externalities will be discussed in more detail.

## 2.3. Types of cost

If a firm produces a commodity, the production is the result of services rendered by various factors of production. Therefore, some payments have to be undertaken, which from the point of view of a firm are called factor payments, or the cost of inputs. Such expenses can either be incurred in the course of production or services, such as entrepreneurship, land or capital offered by an entrepreneur without receiving any payment for them. All in all, during the production process of a commodity several kinds of cost may be incurred, which have to be considered relevant under various circumstances. Such costs include future costs, accounting costs, opportunity costs, sunk costs, implicit costs, fixed costs, variable costs, private costs, social costs, common costs, and so on. For this paper, only those costs beyond the economically based accounting processes are necessary. Firms usually do not consider these costs in their accounting. Such costs can be defined with the existence of externalities, for instance. It is known already that externalities are a reason for market failure. To quantify externalities, they can be compared with a form of cost, i.e. an expenditure to clean a polluted river for instance. Economists often use the term *social costs* to indicate the presence of an externality. Generally, economic costs can be calculated at a micro-level and macro-level. The micro-level economic costs relate to functioning of a firm as a production unit, while the macro-level economic costs are generated by the decisions of the firm, but are paid by the public and not the firm itself.

The generation of electricity by a coal power plant is technically often associated with the presence of negative externalities (carbon dioxide). Figure 2.6 shows that, if there is a negative externality, then social costs will be greater than private costs. Social costs are the sum of *private costs* and *external costs* and often associated as the total costs to society or account for the production of a commodity. Thus, the economic costs include both the private and external costs. However, the net social costs (external costs) are the total social costs minus the private costs[88]. Private costs are the costs that the buyer of a commodity or service pays to the seller. These costs can also be described as the *costs internal* to the production function of the firm.

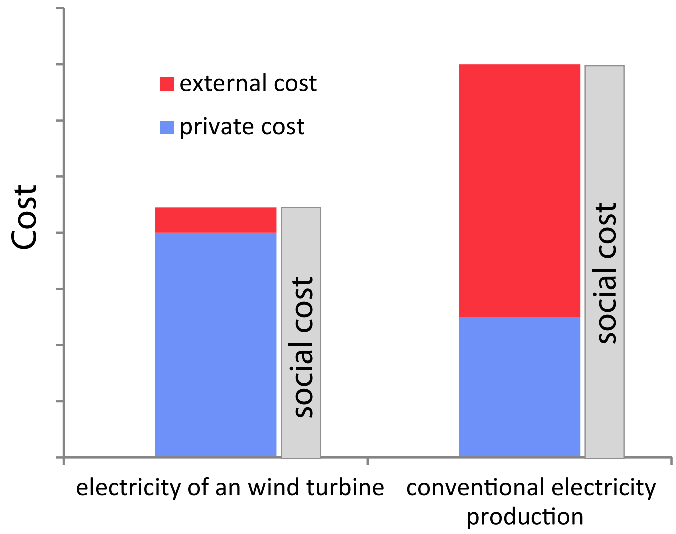



Figure 2.6.: Costs on economy's marko-level

In contrast, social costs are external to a firm from the public point of view, whereas – as already mentioned – private costs are company-internal. Economic theory asserts that entrepreneurs or consumers on markets consider only the price of the private costs and not the externality. Environmental pollution is seldom borne completely by the polluter. The manufacturer of a car does not pay the external cost and does not include them in the price of the car. External costs are often both non-monetary and problematic to quantify for a comparison with monetary values (see 2.5 on page 33). The presence of positive externalities will bring higher social benefits than private benefits: A supplier of educational services indirectly benefits society as a whole (more educated people) but receives payment only for the direct benefit received by the recipient of what was taught.

## 2.4. Environmental goods and externalities

As mentioned in a previous section, knowing about externalities is absolutely essential because most of the impacts caused by wind power plants are related to negative external effects. In Chapter 2.2 on page 20 some situations are discussed that lead to market failure and inefficiency. Externalities cause market failure, too. In this section, the focus will be on the theory of externality, as well as the terms environmental goods and natural environment, respectively. Furthermore, in section 2.1 on page 16 a description is given of the efficient conditions under perfect competition which maximize welfare and utility for people in accordance with the welfare theory. In this part, the usage of goods is discussed and an attempt is made to classify environmental goods and their relationship to externalities. Some important terms have to be explained first:

- Environment: the natural environment, which encompasses all living and non-living things, resources occurring naturally on Earth and the interaction of all living creatures[86]

- Environmental goods are a sub-category of public goods which contains clean air, landscape, clean water, flora and fauna or forests mainly accessible to all people

- Externality: a cost or benefit not transmitted through prices that is incurred by a party who did not agree to the action causing the cost or benefit[160]

### 2.4.1. The environment as an economic good

Economic goods in theory are defined as goods that can be consumed and that contribute to the satisfaction of people's needs directly and indirectly, respectively. Environmental goods have the same behaviour. They contribute to consumption goods as well as production factors. Natural environment has the following function: to be used as consumer goods, as a supplier of resources and recipient of emissions. Examples of typical consumer goods are clean air, drinkable water or flora and fauna. The natural environment may be used for energy production, fisheries, forestry or the absorption of emissions in the air, water, soil etc. . Apart from the fact that Nature has important functions necessary for the survival of human beings (such as the regulation of climate, ability to self-regulation or biodiversity), environmental goods only have an economic value with increasing conciseness. Conciseness means that there is an excluding range of applications concerning one commodity. A habitat can either be protected in a natural conservation area or in one used for a motorway, for instance. If goods are not plentiful (because there are two purposes of use) there will be opportunity costs. These are related to the lost options for the use of one commodity or service (i.e. costs for moving fauna and flora in a habitat). Finally the value of a commodity will increase, if it becomes scarce and demand[26] for this good rises[103, pp. 27 sq.]. Section 2.1 on page 16 described an efficient situation when a market allocates scarce resources to generate the greatest

[26] if many people want to buy the same house, demand increases and prices will rise

social welfare in a perfect competitive model. Environmental goods and the amount of an externality[27] can be supplied efficiently, too. The right part of Figure ( 2.7) shows an optimal utilization of environmental goods, for instance of a new natural conservation area. A natural conservation area can be regarded as a benefit or profit for the people with the assumption that the national economic marginal utility decreases[28] and the national economic marginal costs increase with the gain of a conservation area (area seen as positive externality)[103, p. 30]. With the size of the conservation are at the level $E^*$ where marginal cost equals marginal utility ($MC = MU$) there is a situation that maximizes welfare. The difference between cost and utility maximizes. Hence, if environmental goods were to be allocated in relation to the extent of their availability, the ecological problem would be solved largely, but not entirely, and reduced to an efficient level (economic activities without affecting the environment just a little only are not possible). A reduction of damage to 0 would yield to high costs of avoided damage. A deviation from point $C$ with the size $0E$ would be inefficient[62, pp. 96 sqq.] This shows the left part of Figure 2.7. A complete reduction of damages is undesirable to national economy because avoidance costs that reduce damages will exceed all the benefit people get from non-accruing marginal damage.

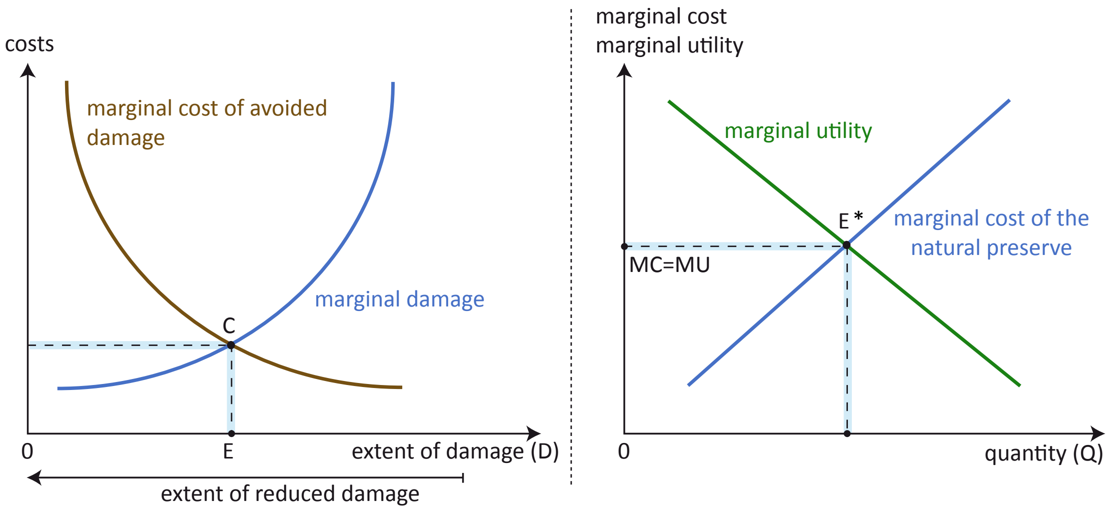



Figure 2.7.: Optimal amount of an external utility and damage

Nowadays the ecological problem is caused by the overuse of resources and that the supply of environmental goods is supplied insufficiently. Environmental goods have properties that complicate their trade on the markets (reflecting their economic value). On the one hand, environmental goods can be used from many individuals without generating competition and, on the other hand, it is impossible to exclude individuals from emitting carbon dioxide into the atmosphere, for instance. These are the properties of public goods, which have been discussed already in the subsection on public goods.

[27] a detailed definition of externality in subsection 2.4.2 on the next page

[28] for detailed information see [103, pp. 80 sqq.]

The problem concerning the free-rider-problem[29] and environmental goods is that environmental goods are often used by many people. And the benefit from having good clean air for one individual is less than the costs of allocating it. Furthermore, the free-rider-problem intensifies, if many people have to pay the expenses for environmental goods. Whenever many people consume environmental goods, no allocation on markets will come up because everybody hopes that the rest allocates it for him to use it free of charge[103, pp. 34 sq.]. The free-rider-behaviour is characterized as the usufruct of positive externalities without paying for it,too[62, p. 103].

### 2.4.2. Externalities

To understand the connection between environmental goods and externalities it is necessary to define externalities first of all. In 2.1 on page 16 efficient situations in a market were discussed. An economic activity valued by market prices is only efficient, if all national economic costs that are related to the usage of this one activity are included. For instance, if a firm manufactures a product, it might be possible that some sewage is dumped into the river that prevents the river from being used for recreational purposes[30]. The price for this product on the markets will reflect only the cost of production and not the cost of cleaning the river. In other words, mention is made of externalities when prices on a competitive market do not reflect the full costs or benefits of producing or consuming a product or service. Externalities are initiated by the activity of producers and consumers if both activities affect their level of utility, but the effects are not reflected in the prices. For Stiglitz, there is an externality "[...]whenever an individual or firm undertakes an action that has an effect on another individual or firm, for which the latter does not pay or is not paid" [141, p. 215]. Examples of externalities are noise, pollutants, overfishing, envy or knowledge spillovers. We can see that there are different kinds of effects which can be classified in either *technological*, *pecuniary*, *psychological* or *positive* and *negative* externalities[31]. In this paper the author refers primarily to negative technological externalities because they cause the most environmental impact in the (wind) energy branch. There is a direct correlation between the utility and cost function of individuals and corporations, which is not included in the market mechanism and is responsible for market failure. Typical examples of negative externalities caused by wind power plants are noise, visual intrusion or interferences with wildlife[62, p. 93]. People who suffer from the noise of a wind turbine have to move away or sell their house for less than the market price. Externalities occur when no market prices exist for environmental goods that have become scarce or the price does not reflect the full national economic cost. Marggraf implies that people only consider the prices on the markets and that an economic activity on its efficient level, which causes an externality, is practiced too intensively. Such an excessive production of goods yielding negative externalities is represented in Figure 2.8 on the next page. It shows a conventional demand and supply curve, reflecting first of all the individual's marginal benefits from the

[29] people who enjoy a benefit of having a commodity or service without paying for it
[30] other persons are excluded from using it
[31] detailed infos see [62, pp. 92 sq.] or [160]

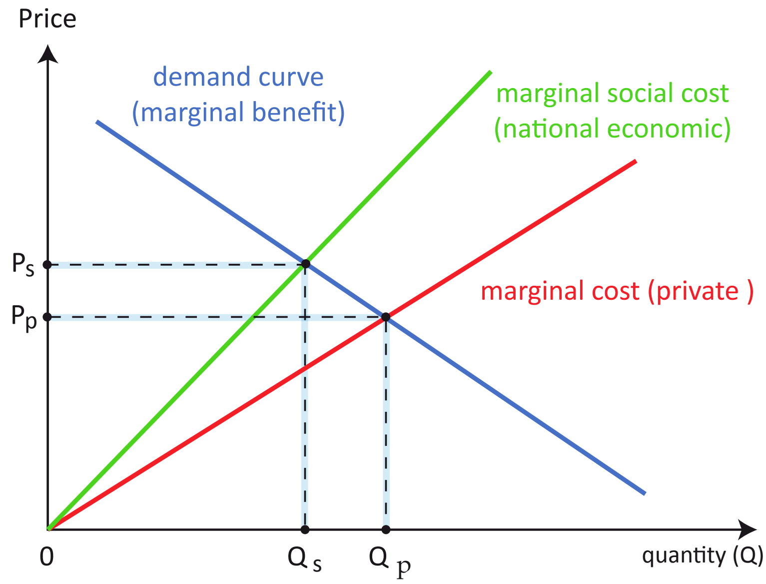



Figure 2.8.: Impact of an externality

production of an extra unit and, secondly, the marginal costs of producing an extra unit of the commodity. In the absence of externalities, the market equilibrium at point $Q^p$ is efficient. Here only private costs are borne by the producer. With the appearance of externalities the efficient quantity diminishes to point $Q^s$. If the quantity of steel produced becomes greater, the level of pollution will increase. This results in real costs that are not taken into account by the steel industry. Marginal social costs (private costs plus external costs) exceed the marginal private cost curve. This means that the consumed quantity $Q^p$ of products is an excessive and insufficient amount of the environmental good clean air. $Q^s$ is the lower but the efficient level of output with a higher price[32] and less external costs. With the presence of externalities, marginal private and national economic costs diverge. If externalities are not considered consequently, environmental goods will be primarily used as the recipients of pollutants and a insufficient amount of consumable environmental goods are allocated/provided. Pollution may be indicated as an inefficient utilization of scarce economic environmental goods[103, pp. 29 sqq.; 141, pp. 214 sqq.; 62, pp. 92 sqq.].

Besides, the consumption of positive externalities in relation to the free-rider-behaviour force third parties to consume negative external effects, because of the non-applicability of the exclusion principle. There is a close link to property rights. If they exist, the injuring party need not pay any compensation for causing pollution. Property rights can prevent the consumption of positive external effects by third parties[62, p. 102]. All in all, the existence of technological externalities is a consequence of the fact that insufficiently

[32]efficiency requires that the marginal cost equals the marginal benefit

defined property rights cannot be enforced [62, p. 106]. A more detailed discussion on the principles of externalities in the energy sector can be found in Chapter 4 on page 71

### 2.4.2.1. Internalization

This part shall provide a general view of the methods that allow an internalization of external costs. It has been shown above that an externality occurs when a decision causes costs or benefits to third party stakeholders. Manufacturing causes air pollution and imposes costs on others when making use of public goods. An externality will be internalized by bringing the cost home to the producer or consumer so that they have to pay for the clean-up. This simple explanation is sufficient to understand the importance of internalization (mostly implemented by governmental interventions). But an efficient internalization is only possible, if the cost of an externality is known. Otherwise, the costs have to be evaluated, for example a willingness to pay is prompted. A short overview of evaluation methods can be found in 2.5.1 on page 33. In literature the following methods of internalization are mentioned and summarized in Figure 2.9.

| | **private solution to externalities** | **public sector solutions** | | **accuracy** |
|---|---|---|---|---|
| | | *market-based solution: (e.g.: fines for polluting)* | *direct regulation: (e.g.: limiting* | |
| moral plea | | x | | very uncertain |
| information disclosure | | | x | uncertain |
| compensation and distribution | | | x | uncertain |
| governmental allocation | | x | | restricted |
| using the legal system | x | | | restricted |
| do's and don'ts | | | x | restricted |
| subsidies (pigouvian)[1] | | x | | restricted |
| fines and taxes (pigouvian) | | x | | restricted |
| innovation | | | x | potentially good |
| merging | x | | | potentially good |
| negotiations (coase theorem, property rights) | x | | | potentially good |
| regulation | | | x | potentially good |
| marketable permits[2] | | x | | good / practicality problem |

[1] for reducing emissions
[2] emissions reduced to 90% next year

Figure 2.9.: Internalization of externalities sorted by accuracy

The following part introduces three popular theories of internalization:

1. Piguovian tax

2. Coase theorem

3. Marketable permits

An example: A firm produces commodities and pollutes a river which will limit fish stocks for fishery. The following methods may lower the excessive amount of production to an intended internalized efficient level: The government limits the amount of production (do's and don'ts), which is not realizable for the economy as a whole, because there have to be individual limits. Another way is to levy a Pigouvian tax (named after the neoclassical economist, Arthur Cecil Pigou, born in 1877). This market-based solution is

> a special tax that is often levied on companies that pollute the environment or create excess social costs, referred to as negative externalities, through their business practices. In a true market economy, a Pigovian tax is the most efficient and effective way to correct negative externalities. [82]

Figure 2.10 on the next page shows how the Pigouvian tax functions. If there is no tax on pollution, firms will produce an excessive quantity $Q^m$ with a price set to the marginal private costs instead of quantity $Q^e$ by setting a tax. Efficiency is obtained, and area $ABCD$ represents the total pollution taxes paid. Firms can either decide to produce less or change production methods to reduce pollution[62, pp. 224 sq.]. This methodology is very efficient but is also criticized. One of the major criticisms is the measurement problem[33] or reciprocal cost problem introduced by Ronald Coase (more infos on criticisms see[115; 18; 36; 149; 19]).

An appropriate assignment of *property rights* is another way to internalize externalities. Only certain individuals should have the right to control some assets and to receive fees for the use if the property.

> The *Coase theorem* (by Ronald Coase) describes the economic efficiency of an economic allocation in the presence of externalities. The theorem states, that if trade in an externality is possible, and there are no transaction costs, bargaining will lead to an efficient outcome regardless of the initial allocation of property rights. In practice, obstacles to bargaining or poorly defined property rights can prevent Coasian bargaining. [159]

The most serious problems that arise, and which are related to this theorem, are the existence of public goods and transaction costs (lawyer, notary).

Marketable permits are a market-based approach to internalize externalities, too. This method limits the amount of pollution that any firm (is allowed to/can) emit. Such tradeable emission permits are used in an environmental regulatory scheme in which the regulated sources of the pollutant are given permits which allow only a specified quantity

[33] because it is criticized that it is impossible to measure a negative externality and to convert that measure into a monetary value

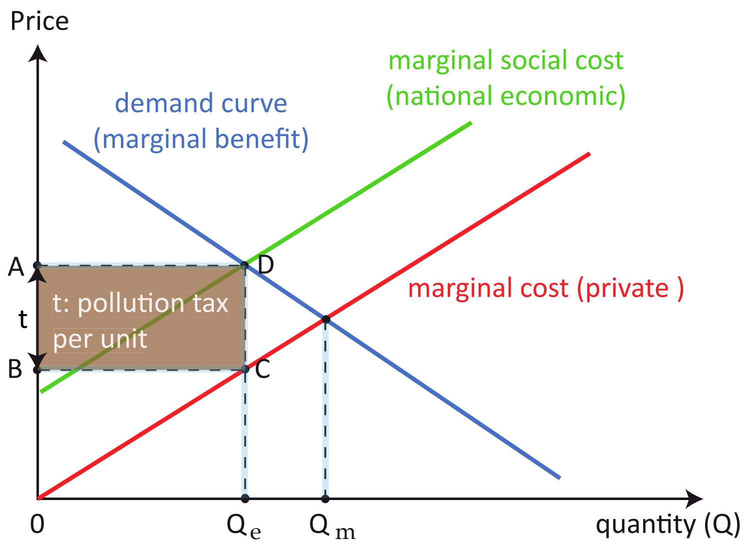



Figure 2.10.: Pigouvian tax

of the pollutant (most often an air pollutant) to be released. The government, which has to take care that the total amount of emission does not exceed the national limit, issues only so many permits as is consistent with the desired level of emissions. After a period of time, the emitted amount (number of permits) will be limited[34]. The major function of marketable permits is that the government allows the owner of a permit to trade. The owners of the permits may keep it and release the pollutants, or reduce their emissions and sell it. The fact that the permits have a value as an item to be sold gives the owner an incentive to reduce their emissions. One way to reduce emissions is innovation. Firms invent new technologies and sell the permits that are not used anymore. One advantage of permits compared with fines is that permits (should) reflect the correct price. In other words, the efficient level from an economic point of view is found independently. Although the price for a fine is determined by legal experts, it does not cover the actual welfare loss (the true amount of externalities) to society.
In the European Union the European Union Emission Trading System (EU ETS)

> [...]is a cornerstone of the European Union's policy to combat climate change and it is also its key tool for reducing industrial greenhouse gas emissions cost-effectively. Being the first and biggest international scheme for the trading of greenhouse gas emission allowances, the EU ETS covers some 11.000 power stations and industrial plants in thirty countries[...] [116]

[34] e.g. reduced to 90%

## 2.5. Valuation of environmental issues

One of the major problems dealing with externalities is the lack of knowledge regarding their worth, and thus the determination of the cost (problem of measurement a Pigouvian tax for pollution, for instance). External costs are often both non-monetary and problematic to quantify for comparison with monetary values. There are impacts which have a very complex structure. The first subsection introduces the reader into the basics of valuation methods, which can be used to evaluate and monetize environmental goods, such as landscapes. The second part of this section describes the idea of the life-cycle assessment method, a tool that allows an analysis and evaluation of environmental burdens associated with a product, process or activity.

### 2.5.1. Valuation methods

There is no method of evaluation that can optimally value or monetize externalities or public goods. However, several procedures have been developed and can be applied for various purposes. There are some good reasons why economic valuation can be useful, one of which is to protect and restore the natural environment which is affected by public or private projects, for instance. It is also necessary to provide a way to justify and set priorities for programs, policies or actions that protect or restore ecosystems and their services.[35]. There are two approaches to the valuation of ecosystems. The first is the dollar-based approach and the second is the non-dollar based approach to measurement. Dollar measures are an accepted measure of economic value because the amount that people are willing to pay for something reflects how much of all other goods and services they are willing to do without (a car for example) to enjoy the pleasure or advantages of the ecosystem services. By contrast, non-dollar measures are indicator-based valuation tools to make decisions based on the ranking or prioritizing of the expected benefits of environmental investments. The most essential facts involved in market failure are summarized once again:

1. many ecosystems provide services that are public goods. They may be enjoyed by any number of people without affecting the enjoyment of other people[36]

2. many ecosystem services are affected by externalities or the uncompensated side effects of human actions

3. property rights related to ecosystems and their services are often not clearly defined (overused because there is no incentive to conserve them)

   Ecosystem valuation can help resource managers to deal with the effects of market failures, by measuring their costs to society, in terms of lost economic benefits. The costs to society can then be imposed, in various ways, on those

[35]preservation, restoration, conservation, encourage public participation, supporting environmental initiatives, comparing benefits of different projects, maximize environmental benefits[90]

[36]people value them, although they do not have an incentive to pay the external costs

> who are responsible, or can be used to determine the value of actions to reduce or eliminate environmental impacts. [90]

An ecosystem value, which reflects the worth of an ecosystem service, is estimated by the amount of money the people are willing to pay to preserve the service, although the service is not traded on the market. As, in general, people are not familiar with purchasing such goods, the value of ecosystem services may not be clearly defined. The important aspect of valuing economic services is "[...]how much purchasing power (dollars) people are willing to give up to get the service of the ecosystem, or how much people would need to be paid in order to give it up, if they were asked to make a choice similar to one they would make in a market." [90] Several types of values have been classified by economists, and the two main categories are *use values* and *non-use values*, besides *passive use* values. The use-values are based on the actual use of the environment [37]. Non-use values are those which are not associated with actual use (i.e. existence values) or even an option to use an ecosystem or its services. Figure 2.11 on the facing page gives a general view of several evaluation methods with examples.

More information can be found in the following references:

- Hanley, Nick and Spash, Clive; Cost Benefit Analysis; 1993; Edward Elgar Publishing Company[75]
- King, M. Dennis and Mazotte, J. Marisa; Ecosystem Valuation; Feb. 2012[90]
- Bundesministerium für Umwelt, Jugend und Familie; Externe Umwelteffekte im Energiebereich (Literaturrecherche); 1997; Band 22[127]
- Hanusch, Horst; Nutzen-Kosten-Analyse; 2011[76]
- Umweltbundesamt; Ökonomische Bewertung von Umweltschäden – Methodenkonvention zur Schätzung externer Umweltkosten; 2007[129]

[37] fishing, for instance, when the Alaskan wilderness area is experienced directly by visitors, or indirectly by viewers of a television program on Alaska

| | | | | |
|---|---|---|---|---|
| indirect methods | **Market Prices – Revealed Willingness to Pay** | **Using market price methods; Some ecosystem or environmental services, like aesthetic views or many recreational experiences, may not be directly bought and sold in markets. However, the prices people are willing to pay in markets for related goods can be used to estimate their values** | **Example** | **Literature** |
| | Market Price Method | estimates the economic value of ecosystem products or services that are bought and sold in commercial markets | clean air or prices of properties | 1, 2, 3, 4 |
| | Productivity Method | estimate the economic value of ecosystem products or services that contribute to the production of commercially marketed goods | municipal drinking water: the benefits of improved water quality can be easily related to reduced water purification costs | 1, 3, 5 |
| | Hedonic Pricing Method | used to estimate economic values for ecosystem or environmental services that directly affect market prices; commonly applied to variations in housing prices that reflect the value of local environmental attributes (costs or benefits); often used to value environmental amenities that affect the price of residential properties; property markets are efficient in responding to information, records are reliable and readily available through many sources; limitations: many influences in property market and limited to housing market | environmental quality: air, water pollution, noise; environmental amenities: aesthetic views or proximity to recreational sites | 1, 3, 4, 5 |
| | Travel Cost Method (TVM) | seeks to place a value on non-market environmental goods by using consumption behaviour in related markets; estimate economic use values associated with ecosystems or sites that are used for recreation and can not be obtained through market prices; people incur travel cost expenses to visit a site, which costs are interpretated as willingness to pay. Limitations: limited option of recreation areas to choose | National Parks, Beaches, Ecosystems | 1, 2, 3, 4, 5 |
| | **Circumstantial Evidence – Imputed Willingness to Pay** | **Willingness to pay to avoid the adverse effects, if something happens; wetland: amount that people pay to avoid flood damage in areas similar to those protected by the wetland** | **Example** | **Literature** |
| | Damage Cost Avoided | estimate values of ecosystem services based on either the costs of avoiding damages due to lost services, the cost of replacing ecosystem services, or the cost of providing substitute services. not based on people's willingness to pay, they incur costs to avoid damages caused by lost ecosystem services | Valuing the water purification services of a wetland by measuring the cost of filtering and chemically treating water, or storm protection services of coastal wetlands by measuring the cost of building retaining walls. Valuing fish habitat and nursery services by measuring the cost of fish breeding and stocking programs. | 1 |
| | Replacement Cost | | | 1 |
| | Substitute Cost Methods | | | 1, 3 |
| direct methods | **Surveys – Expressed Willingness to Pay** | **Not traded in markets, and are not closely related to any marketed goods; surveys can be used to ask people directly what they are willing to pay** | **Example** | **Literature** |
| | Contingent Valuation Method (CVM) | estimate economic values for all kinds of ecosystem and environmental services, most widely used method for estimating non-use values; most controversial of the non-market valuation methods; can be conducted as in-person interviews, telephone interviews or mail surveys; easy to analyse and enormously flexible; some limitation (people's attitude of willingness to pay); | for all kinds of ecosystem and environmental services: landscape, natural preserve, habitat, impact of contamination, etc. | 1, 3, 4, 5 |
| | Contingent Choice Method | similar to CVM but does not directly ask people to state their values in dollars. Instead, values are inferred from the hypothetical choices or tradeoffs that people make (hypothetical scenario); rank options, without focusing on dollar values; suited to policy decisions where a set of possible actions might result in different impacts on natural resources or environmental services | | 1 |
| | Conjoint Analysis | a statistical technique that originated in mathematical psychology and is used in many of the social sciences and applied sciences including marketing, product management, and operations research; participants make a series of trade-offs, which will reveal the relative importance of component attributes; administered as a ranking or rating exercise | building a high rise apartment complex near an university - students are asked to order the cards from least to most appealing its attributes | 4 |
| | Participatory Valuation | a valuation technique that allows people to define the values of ressources within the context of their own, used when standard methods such as hypothetical market behaviour is not applicable, people can not indicate the quantity or value directly | Livelihood impact assessment i.e. establishment of marine protected area | 4 |

1) Ecosystem Valuation http://www.ecosystemvaluation.org; 2) Externe Effekte im Umweltbereich 1997; 3) Hanusch 2011; 4) Umweltbundesamt 2007; 5) Spash, Hanley 1993

Figure 2.11.: Evaluation methods – overview

### 2.5.2. Life-cycle assessment – historical review and basics

#### 2.5.2.1. Historical review

A *life-cycle assessment (LCA)*, also known as *life-cycle analysis* or *eco-balance* is a technique, which allows the assessment of environmental impacts that occur with all the stages of a product's lifespan (inputs, releases) from cradle-to-grave[38]. It is a tool suited as an input for assisting planners and decision-makers in performing the necessary assessment related to external costs. These techniques originated long before these names came to be used. Items that could not have easily be monetized or have been inconvenient to include, because of their indirect and often uncertain nature, have been called externalities in economic theory. Early techniques that later became incorporated into LCA were the usage of risk analyses (safety factor) whereas, in some cases, it turned out that such factors did not avert the risk. In the 1960s, scientists had the idea to expand risk analyses with the integration of externalities. When a book by Rachel Carson pointed out the threat of persistent impacts on the public, economists came to the suggestion that risks and their damage should be seen in relation to the benefits (the first rational approach to cost-benefit-analysis[39]). The idea of discounting the future, a plan for postponing the clean-up of negative impacts, was criticized by Sorensen (in 1974) as a time-displaced irresponsibility. There is still a debate over whether the fact of positive or negative impacts happening at different points in time should be components included in a life-cycle-analysis. In the early 1980s, it became clear that LCAs could be made for individual products[40]. Lists of concerns were produced to help decision-makers to be aware of the many non-technical aspects that could not be quantified. In the 1980s, a complete life cycle from *cradle-to-grave* was introduced.

From *the cradle to the grave* begins with the gathering of raw materials from the earth (the cradle) to create the product and ends at the point when all the materials are returned to the earth (the grave). All stages of a product's lifespan are evaluated (from the raw material until the dismantling phase) interdependently. This means that one operation leads to the next[41]. Often components, such as *total energy analysis* were used to make a fair comparison between *energy pay-back time* in regard to different kinds of energy and system technologies. So the environmental dimension was included more often in many studies using first of all names, such as *full-cycle analysis* or *cradle-to-grave*. Further ideas, put forward by many countries, were the implementation of the LCA methodology into the legal system, thus creating a legal document, for instance the Environmental Impact Statement (USA 1978). These deliberations and the public pressure to establish standards for performing LCAs led to guidelines that guarantee correct procedures and a simplification of different consultants – through organizations and subsequently through the international standardization procedures. Procedures for life-cycle assessment was first published in 1997 and the latest update made in 2006.
After the first guidelines for LCA were processed, the European Commission saw an

[38]cradle-to-grave will be explained in this subsection
[39]CBA is not discussed in detail in this thesis
[40]i.e. generic technologies, energy supply chains or entire regional systems
[41]a graphical overview of the stages is described in Figure 5.2 on page 98

interest in transferring these results to Europe and the Framework Programme was designed for this purpose. However, the EU introduced a first program, called ExternE, to evaluate impacts on local power plants with the result that life-cycle analyses were not carried out on account of the calculated high number of externalities in the operation phase. ExternE was reintroduced by the EU some years later, and an ISO-compliant database project was carried out, which provoked different firms to supply a series of software packages which simplified the process of an LCA and created a series of weighting and ranking possibilities, such as eco-points[42] or monetized impact values, such as dollars translated from physical impacts in different units[43].

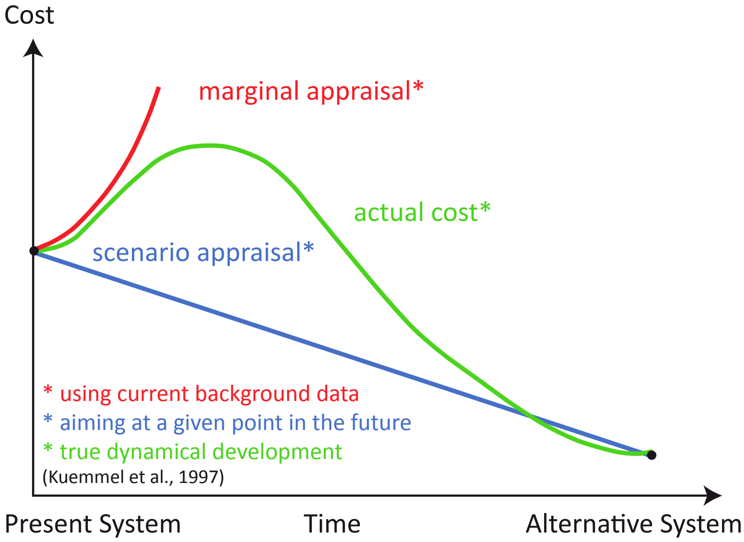



Figure 2.12.: Marginal appraisal caused by the use of generic data for background processes

Theoretical criticism with LCA:

- Discounting problem
- Marginal appraisal: future energy supplies are not assumed correctly. Most LCA do not take into consideration different times and places. The present state of globalization in manufacturing processes implies that a given component travels back and forth between Europe and Asia, for instance. If the effects of energy usage (on the environment) have to be taken into consideration, often a static energy mix (coal, gas, nuclear, etc.) is specified for an evaluation. But, in future, the energy mix will change to make more use of renewable energy sources and technology. A dynamic mix would indicate that photovoltaics panels become a viable technology

[42] indicator equivalent to monetized impact values
[43] Sorensen (2011) criticizes that this translation process is often executed in a way that there is very little transparency [135, pp. 6 sq.]

(a static mix makes PV inefficient). So if the background system is specified to be dynamic, the results of a life-cycle evaluation would change drastically. This important fact, called *marginal appraisal*, is described in Figure 2.12 on the preceding page

- Different results caused by lots of software packages with non-transparent process flows

Further references:

- Sorensen (2011), Life-Cycle Analysis of Energy Systems [135, pp. 1 sqq.]
- Curran (2006), Life-cycle Assessment – Principles and Practice [44]

#### 2.5.2.2. Life-cycle analysis and assessment

Sorensen implies that LCA procedures by ISO norms reflect only a small subset of the contents that should go into an assessment. Scientists suggest an approach that involves an inventory of process steps and flows. The emissions and their impacts on human health and/or the environment should be assessed. The scientists also underline that every kind of types of impacts, whether positive, negative, quantifiable or not should be considered and expressed in qualitative terms [135, p. 6]. The inclusion of cradle-to-grave impacts as well as of indirect impacts embedded in materials and equipment are two significant characteristics of LCA. Besides, two phases of the LCA can be distinguished:

1. Life-cycle-analysis: technical calculations of the pathways from initial events to impacts on human society, natural environment, and so on that may be affected
2. Life-cycle-assessments: prepare the assessed data to compare with other systems or presenting different impacts in a clear way by normalizing and monetizing them (i.e. a multivariate impact assessment scheme with points from minus one to plus one[44].

The ISO 14040:2006 procedure

> describes the principles and framework for life-cycle assessment (LCA) including: definition of the goal and scope of the LCA, the life-cylce inventory analysis (LCI) phase, the life-cylce impact assessment (LCIA) phase, the life-cylce interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for the use of value choices and optional elements. [137]

A practical implementation of the ISO working progress specifications in the form of a life-cycle framework flow diagram can be considered in Figure 2.13 on the next page [135, p. 11; 44, p. 2].

[44] problem or unethical when valuating the life of a human as a dollar or point value

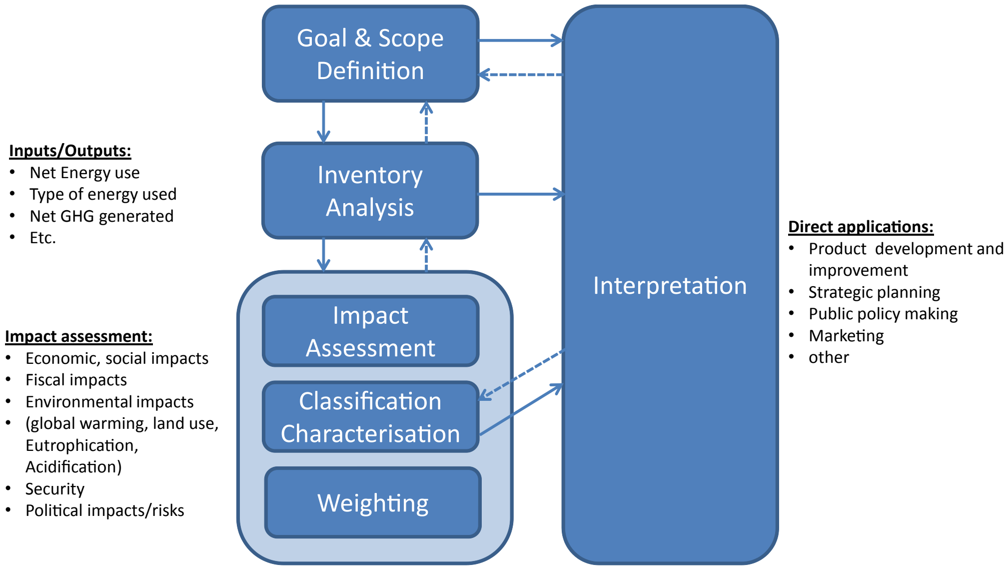



Figure 2.13.: Life-cycle framework

The LCA process is a systematic, phased approach and consists of four components according to the ISO 14040 and 14044 standards:

1. goal definition and scope
2. inventory analysis
3. impact assessment
4. interpretation

The components in this part are only briefly and theoretically described whereas in 5.2 on page 97 the life-cycle assessment on wind turbines is described in more detail.

Ad 1: Definition of the goal and scope: Definition and description of the product, process or activity (depth, aim). Establishment of the context in which the assessment is to be made. The boundary and environmental effects have to be identified and reviewed for the assessment. The analysis can either be a product LCA or a system-level LCA. The latter usually deals with energy systems, such as, a determining of all impacts from an offshore wind power array with associated power transmission to land, for instance [44, pp. 7-18].

Ad 2: Inventory analysis or *life-cycle inventory (LCI)*: Identifying, compiling and quantifying the relevant inputs and outputs of a system throughout its life cycle. LCI establishes a demarcation line between what is included in the product system and what is excluded (energy, water, material usage and environmental discharges, such as, gaseous emissions into the air, solid waste disposal or waste water and sewage disposal). Each analyzed product or service in a LCI should be followed until it has been translated into elementary flows[45] [44, pp. 19-44].

[45] emissions, natural resource extractions, land use and so on

Ad 3: Impact assessment: Evaluates the magnitude and significance of the potential environmental impacts associated with those inputs and outputs[46] identified in the inventory analysis. Four steps can be listed: Classification and characterization. Impact potentials are calculated based on the LCI results. The next two steps, normalization and weighting, are both voluntary according to the ISO standard. After a normalization, different environmental impact categories may be compared by obtaining the same unit. A LCA impact profile for coal and wind power chains is shown in Figure 2.14 [135, p. 76]. Weighting means that a weighting factor is assigned to each impact category depending its importance [44, pp. 46-53].

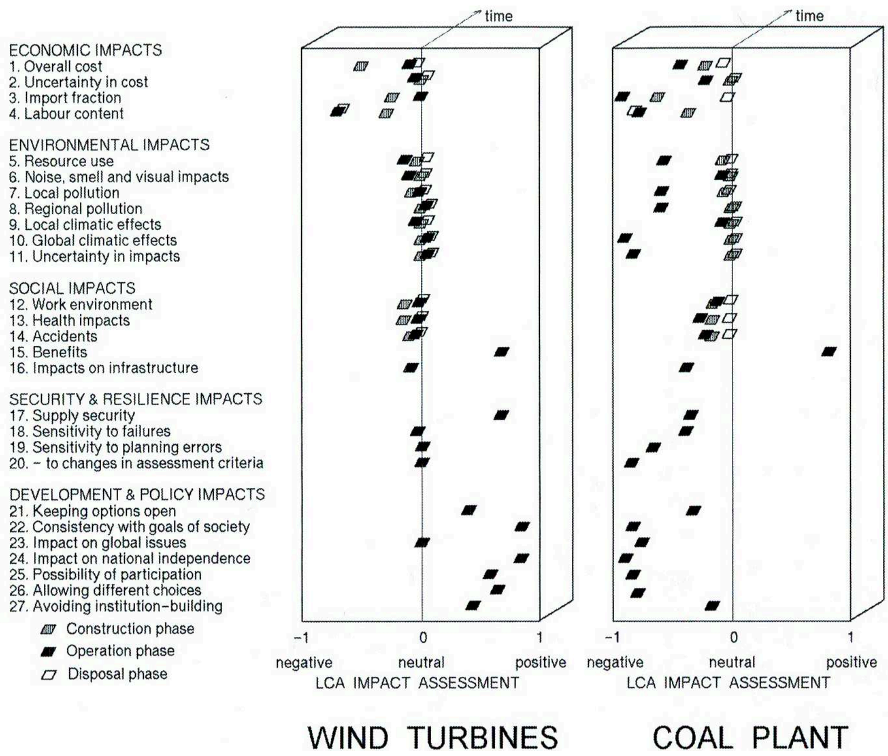



Figure 2.14.: Impact profiles assignment with weights (Scan from Hau, 2006, p.76)

Ad 4: Interpretation: Evaluate, check and qualify the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results. [44, pp. 54-60]

The impacts to be assessed are described in a typical ISO-style process in Figure 2.15 on the facing page. The impact pathway is considered for each emission through health or ecology impact categories to final aggregated endpoints. Midpoints reflect the amount (doses) of emission [135, p. 12].

[46]human and ecological effects of energy, water, and material usage and the environmental releases

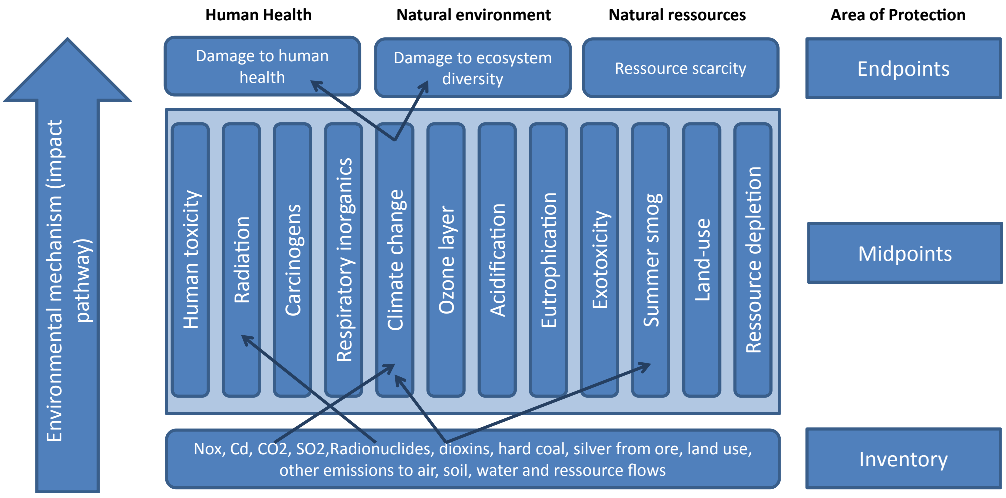



Figure 2.15.: Environmental Impact Assessment

As already mentioned, all environmental issues should be integrated in a LCA. After extensive research in the relevant literature research, the most significant and relevant impacts to be included are:

- Economic situations, such as inflation, deflation – finance crises can have an impacts on the owner's economy, national economy and fiscal policy including questions of foreign payments balance and employment
- Environmental factors, such as land use, noise, visual impact, local, regional and global pollution of soil, water, air and biota can have an impact on the climate
- Social factors, related to the satisfaction of needs, health and work environment risk, accidents can have an impact on humans and their way of life
- Security and resilience, including supply security, safety against misuse, terror actions as well as sensitivity to system failures, planning uncertainties and changes in future criteria for impact assessment
- Effects on development and politics

Additionally, a LCA can never become a computerized tool for making decisions, but "[...]an attempt to furnish more information to the political decision-maker than has previously been available." [135, p. 35] The incommensurability of different impacts cannot always be reduced to a common denominator.

# 3. Wind turbines – characteristics

In this chapter a general view of the characteristics of wind turbines, which are worth knowing and most interesting, are presented in three separate sections. General facts, with regard to energy and electricity consumption in these days and in the future, are described in section 3.1. The second part 3.2 on page 47 deals with the technical aspects of wind turbines, from their historical development and most common structure and construction details, to the influences on power output as well as the physical properties of wind conditions and factors determine the locations for wind turbines. The last part, section 3.4 on page 66, is a discussion on the cost assessment of wind power plants. Effects on the environmental are not included in this chapter, but are discussed in detail in the chapters that follow.

## 3.1. Basics and facts

Wind power has become a topical subject especially throughout the past two decades. In 2008 the electricity generated by wind power plants had a share of 21% of the total amount of renewable electricity generated in that year. This was 3.5% of the total amount of electricity generated in the EU and this percentage will continue to increase rapidly in the next decades [163]. In contrast, the streamlined energy flow trends for 2006 (EU-27), discussed in Figure A.1 on page 171 and Figure A.2 on page 172, give an interesting general view of the whole energy supply with a small share for wind energy. In future, wind energy and all other renewable energy sources will play a major role, and fossil fuel will cease to be the dominant source of energy on the relevant markets. This is because several countries already have low-emission objectives. Figure 3.1 on the following page shows scenarios with regard to the energy supply in the future [120]. In addition, the operation process of wind turbines is nearly carbon-neutral and helps to reduce the carbon dioxide emissions[1]. The potential of wind energy is enormous: A production site analysis made by the *Harvard University* showed that wind turbines, installed all over the world, may produce 1.3 million terrawatt hours. This is 1.2% of the worldwide electricity demand of 2006. At the end of 2011 the worldwide capacity of wind-powered generators was about 230 gigawatts. Annually, approximately 430 terrawatt hours can be generated. This is about 2.5% of the worldwide electricity demand [170]. The annual growth in new installations was approximately 27% in 2009, and the market penetration is expected to be 3.4% by 2013, and 8% by 2018 [40]. A major increase in new installations can be observed in China (accounting for 50% of the world market)

[1] according to a report by the *Umweltbundesamt (2011, Germany)* electricity had a share of 40% of the whole $CO_2$ emissions in Germany in 2009 [71]

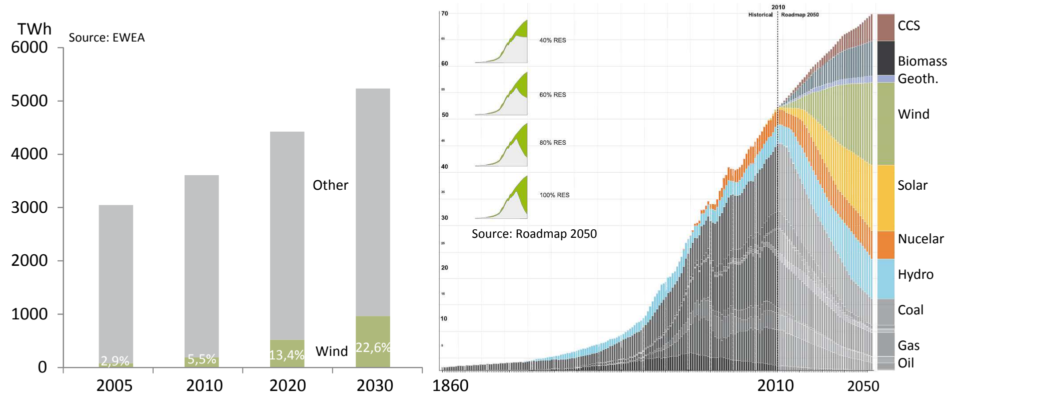



Figure 3.1.: Contribution of wind energy to European electricity consumption 2005–2050

and Eastern Europe. By contrast, a decrease in North America and a little stagnation in Western Europe has been observed. Figure 3.2 shows the development of the global wind energy market [163].

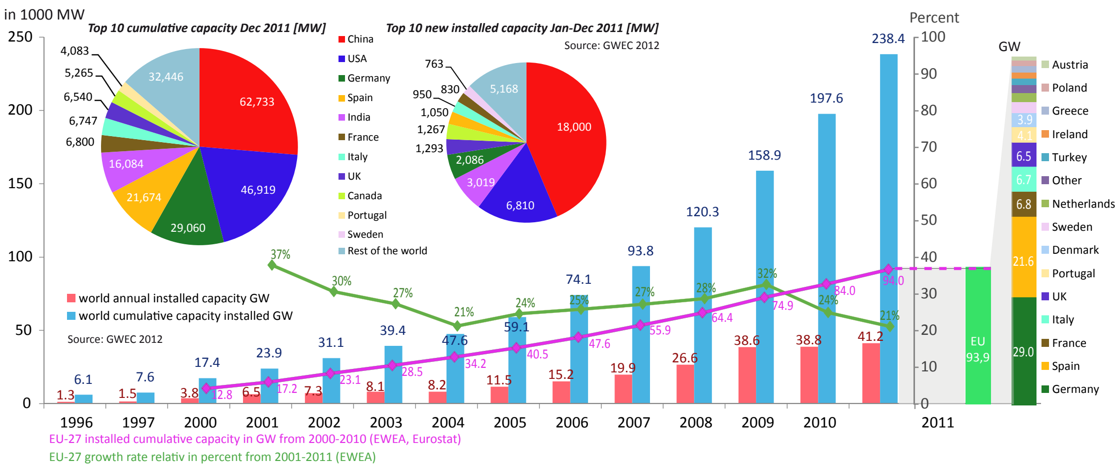



Figure 3.2.: Wind energy: Annual and cumulative capacity installed from 1996–2011 all over the world in 1000 MW

The latest news is that the amount of electricity generated by wind power is now about 1.2% of the current worldwide electricity supply. To obtain more information on the progression of conventional and renewable energy generating technologies (amounts and shares), Figure 3.3 on the facing page focuses on electricity-generating installations in the European Union. Gas (+116 GW) and wind (+84 GW) power installations have increased absolutely from 2000 to 2011, whereas both nuclear and oil fuel generating technologies have decreased, each by 14 gigawatt installed capacity. The power capacity mix change pie chart shows that the share of the total installed power capacity of wind power has increased more than fourfold from 2.2% in 2000 to 10.5% in 2011. Over the same period, the installed capacity of renewable energy sources increased by a third from 22.5% in 2000 to 31.1% in 2011 [163]. Wind power installations increased from 2010 to 2011 by 9,900 megawatt to 94,000 megawatt in the EU, and had a share of 21% of new renewable energy installations in 2011. The installed capacity does not mean that it is

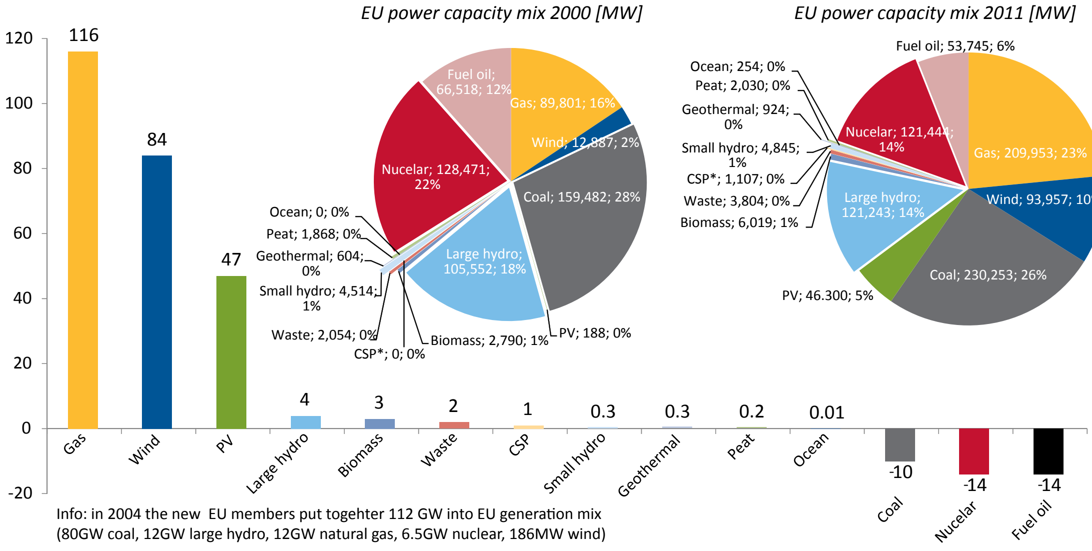
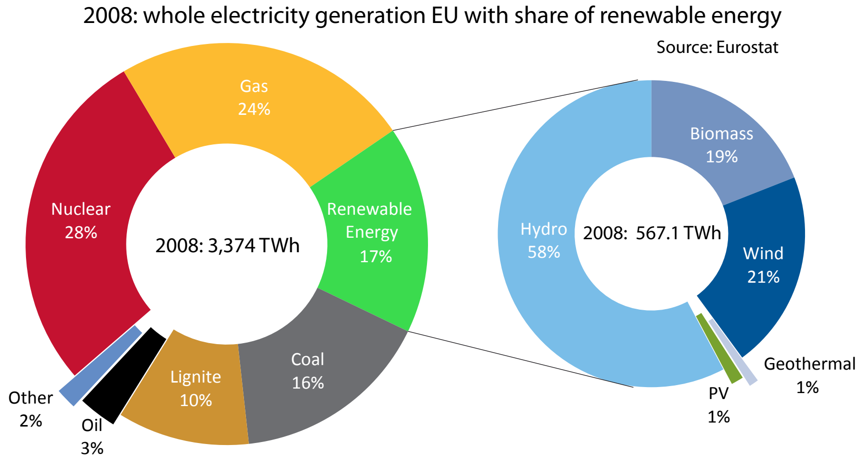



Figure 3.3.: Net electricity-generating installations in EU 2000–2011 in GW

used overall. Wind turbines cover only peak loads because their electricity production is variable (security of supply). Furthermore, the poor decentralized grid infrastructure (e.g. in Germany) may cause grid overload so that electricity cannot be supplied [166]. So the generation of electricity or *allocation of electricity* has to be considered over a period of time. Figure 3.4 on the next page shows the actual allocation of electricity in the European Union. Wind power has 20.9% of the whole renewable energy electricity generation, which is approximately 3.5% of the total electricity generation in the EU. To understand the basics of the distribution of electricity, the following items have to be considered: electricity can not be stored in huge amounts, so it has to be produced constantly and the amount has to be adjusted to current demand (see Figure 3.5 on the following page). Although the demand is mostly predictable, an allocation without a breakdown has to be ensured (security of supply). This results in a management of loads to guarantee safe distribution. The variability and unpredictable density of wind is the reason why wind energy can be provided only as a peak load[2]. Therefore, wind power plants can be used only in an integrated network. The projections for 2050 in the EU Roadmap 2050 assume that wind power may be used as a medium load in co-operation with solar energy at peak load. The next Figure 3.5 on the next page shows the load management of an electricity supply and typical demand curves on a given day and year.

[2]it is not possible to simply turn on wind energy to receive it immediately if there is no wind




**Electricity supply renewable energy in EU [TWh]**

| | 1990 | 1997 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Biomass | 17.3 | 28.7 | 40.5 | 42.8 | 49.7 | 57.9 | 68.9 | 80.7 | 90.1 | 100.8 | 107.9 | 107.9 |
| Hydro | 288.8 | 332.5 | 354.7 | 372.8 | 315.4 | 306 | 323.3 | 307.4 | 308.6 | 310.1 | 327.4 | 322.5 |
| Wind | 0.8 | 7.3 | 22.3 | 27 | 35.7 | 44.4 | 58.8 | 70.5 | 82.3 | 104.3 | 118.7 | 132.3 |
| Geothermal | 3.2 | 4 | 4.8 | 4.6 | 4.8 | 5.4 | 5.5 | 5.4 | 5.6 | 5.8 | 5.7 | 5.6 |
| PV | 0.01 | 0.04 | 0.1 | 0.2 | 0.3 | 0.5 | 0.7 | 1.5 | 2.5 | 3.8 | 7.4 | 14.7 |
| Solar | – | – | – | – | – | – | – | – | – | 0.008 | 0.016 | 0.038 |
| **Sum** | **310.1** | **372.6** | **422.4** | **447.4** | **405.9** | **414.2** | **457.2** | **465.4** | **489.2** | **524.8** | **567.1** | **583** |
| ***Share renewable energy of whole electricity demand [%]*** | ***11.8*** | ***13.1*** | ***13.9*** | ***14.4*** | ***13*** | ***12.9*** | ***13.9*** | ***14*** | ***14.6*** | ***15.5*** | ***16.7*** | ***17.2*** |

Figure 3.4.: Electricity allocation in the European Union

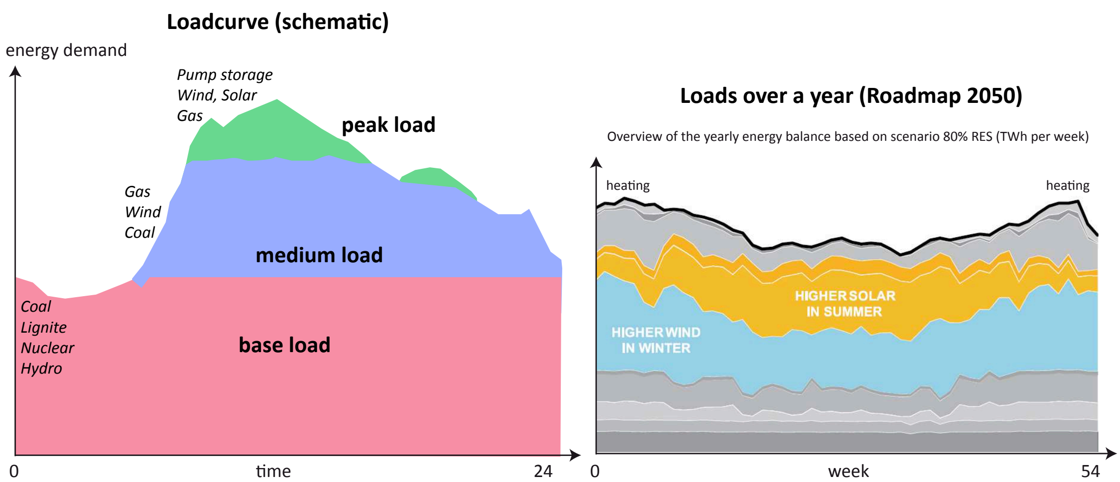



Figure 3.5.: Electricity management

The technology of wind turbines has developed rapidly over the past twenty years. Whereas in the 1980s the power of a typcial wind turbine was about 60 kilowatts, the present-day lists modern wind turbines with 2 to 3 megawatts (Figure 3.6). An off-shore wind turbine measures 90 metres in height and has a power capacity of nearly 3 megawatts[3]. Besides this, other smaller paths continue to be developed. Such installations provide the essential power for isolated communities with no connection to the grid [120; 106; 83; 14].

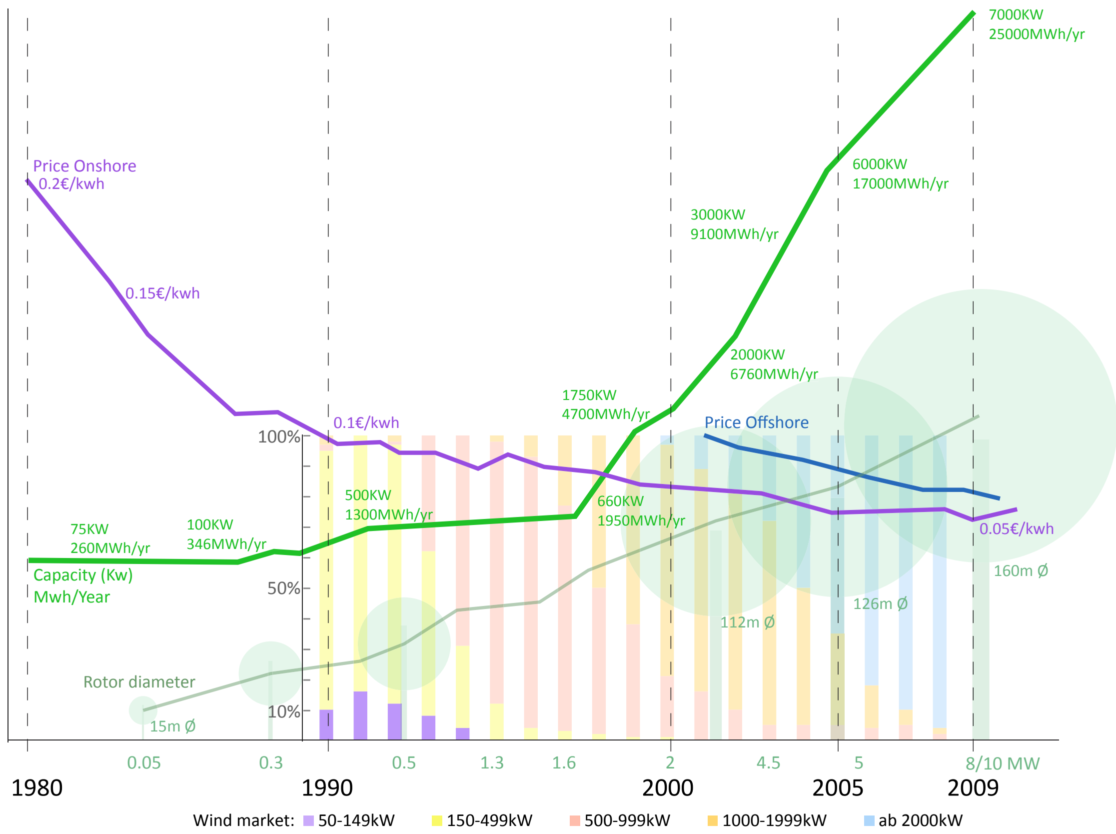



Figure 3.6.: Wind turbine developments

## 3.2. History

### 3.2.1. Windmills in ancient days

Besides the fact that boats and ships with sails have been using wind power for thousands of years and that windmills have been utilized in numerous different ways[4] since ancient times, wind power has been rediscovered as an economic factor, i.e. as an alternative to the non-renewable sources of energy to produce electricity. In antiquity early examples of

[3]Currently, offshore installations represent only a very small section of the market, but their future looks bright and this is the main incentive for large turbine technology development

[4]e.g. the usage of wind-driven natural ventilation since ancient times

wind-driven wheels, such as the prayer wheel were used[5] since the 4th century [101; 93]. In the 7th century, the first practical windmill (with sails which rotated in a horizontal plane, around a vertical axis), known as the *panemone windmill*, originated in eastern Persia. In the 9th century, in Seistan, another region in Iran, the first practical windmills were in use. They were used to grind corn and to pump water and have survived in Afghanistan up to the present time. Such windmills had long vertical drive-shafts with six to twelve rectangular sails covered in reed matting or cloth [77]. The vertical axis technology has been used in Europe[6], too. The traditional windmill with a horizontal axis was probably invented in Europe[7]. The first windmills in Europe were *post or trestle mills* built in England and they spread all over North and Eastern Europe[8] "The post windmill, in its simple and serviceable form remained in existence right into the 20th century." [78, p. 3] By the 14th century, in Holland, Dutch windmills were in use to drain areas of the Rhine River delta. Improvements were made on these windmills in the 16th century, which led to a new type called the *Dutch windmill*[9]. The Dutch windmill consisted of a fixed structure with a rotating roof cap. A mill with a firm base had the advantage of making it easier to driving machines, such as heavy pan grinders for milling dyes, or wood saws. In the 19th century the historical windmill reached its perfection because the innovation of the Dutch windmill became the dominant type both technically and economically in several variations[10]. Hau mentions that it is interesting that windmill types which evolved in the course of history were able to maintain their original forms, co-existing with each other right up to the present time. Some important innovations with regard to windmill technology have been a fantail for automatic yawing, spring sails or the Ventikanten sails [78, pp. 13 sqq.].

### 3.2.2. Wind turbines and electricity generation

The first attempt to produce electricity was realized by Prof James Blyth in 1887. He installed a windmill in his garden to charge accumulators to power the lighting of his cottage. In Cleveland, Charles F. Brush designed and constructed a larger and heavily engineered machine in 1888 with a rotor 17 metres in diameter, and with only 12 kilowatts capacity. In Europe, the Danish scientist, Poul la Cour, constructed wind turbines to generate electricity[11] to supply power to rural settlements. His concept was very successful. Various La-Cour-Lykkegard turbines were built and supplied people with electricity[12], later with aeromotors[78, pp. 23 sqq.]. Similar developments could be

[5] by 1000 AD to pump seawater for salt-making in China and Sicily [97]
[6] extensively in north-western Europe to grind flour since the 1180s
[7] independently of the vertical-axis windmills of the Orient
[8] dates from 1185 in Weedley, Yorkshire
[9] The Dutch windmill was not able to displace the simpler post windmill because post windmills were the more economical solution for milling small amounts of grain
[10] In the 18th century, windmills were also used to pump sea-water to make salt on the island of Bermuda, and on Cape Cod during the American revolution [97]
[11] started with a test station in 1891
[12] bearings and gears had to be replaced for the first time after 20 years of operation

observed in the United States in those days. The typical field of application of wind turbines was for pumping water, lighting or battery charging on farms out of reach of central-station electricity and distribution lines.

To permit larger modern high-speed wind rotors to achieve more electricity production, a good knowledge of physics, with regard to the activity and functioning, had to be acquired first. Albert Betz was the first to approach the problem of the aerodynamics of the wind rotor from a strictly scientific point of view in 1920. His formulated theoretical basis for the aerodynamic shaping of wind rotor blades has kept its validity to the present day [22]. While the Germans saw the problem mainly from a theoretical point of view, the USSR built a wind turbine with a generator-rated power of 100 kilowatts, which operated for eleven years. The plans to develop a 5 megawatt turbine fell victim to the war. Americans carried out research on the implementation of wind turbines into the public utility grid. It was interconnected to conventional power plants and installed with a 1250 kilowatt turbine, and became the world's first really large wind turbine[13]. The major problem of using wind-generated electricity was the high costs per kilowatt compared to conventional power plants. Furthermore, oil was imported and sold cheaply after World War II. The interest in wind power waned. Additionally, the practical operation process caused many problems and led to faults besides a poor organization. Despite this negative outlook, Ulrich Hütter developed high tip speed designs, which had a significant influence on wind turbine research in Germany and the US in the early 1960s. Only after the energy crisis, when environmental protection became a central theme in public discussions, many of the countries, which are dependent on oil, resumed the research work on wind turbines which they had already begun in the past. Many issues of rotor blade technology were investigated and fibre glass polyester used as material in the 1980s[14]. The small turbines from Danish and later German production brought the breakthrough in Germany, after a *feed-in compensation*, the so-called *Einspeisegesetz für Strom aus regenerativen Energien*, was introduced and established by law. To delve into the development of large wind turbines, the European Commission started two large research and demonstration programs (Joule, Thermine). The result was a scientific technical foundation created by governmental research establishments and industry to bring wind energy to its present-day level [78, pp. 36–65]. The US installed about 1,700 megawatts in a period of 15 years[15] but the attractive tax credits led to ill-designed and poorly functioned systems. Whereas, in Europe, a striking development of the wind energy market could be recognized, the growth of wind energy in California was not sustained. In the past 20 years, technology and the size of wind turbines has improved and the power generation costs[16] decreased[17]. The interests to use wind en-

[13]It operated for 1,100 hours before a blade failed at a known weak point, which was known to be weak but had not been reinforced owing to war-time material shortages

[14]Steel rotors were too heavy and aluminium too uncertain

[15]1980–1985

[16]the cost per kilowatt electricity generated

[17]for instance the possibility of pitching the blades increases power output or the elimination of idle power

ergy offshore increased when the first offshore wind parks were built at the beginning of this millennium and the first large-capacity floating offshore turbine became operational in the North Sea in 2009. Today the arguments in favour of wind power have changed from milling grain or pumping water to satisfying the enormous energy requirements of a modern industry. Wind energy still has to compete with conventional fossil fuels on account of the high private costs of wind turbines [104, pp. 122–139]. More details and information on the history of windmills can be found in Hau, Erich; Wind turbines [78, pp. 1–64].

## 3.3. Construction and technology

### 3.3.1. The physical priciples of energy conversion

As already mentioned in the last section, a founded knowledge of the aerodynamics of wind turbines was aquired by the physicist Albert Betz in the early 1920s.

> The primary component of a wind turbine is the energy converter which transforms the kinetic energy, contained in the moving air, into mechanical energy [...]the mechanical energy extractable [...]is restricted to a certain fixed proportion of the energy or power contained in the air stream. [78, p. 81]

The aerodynamics of a wind turbine is not straightforward. The air-flows at the rotor surface exhibit phenomena that are rarely seen in other aerodynamic fields. Nevertheless, Betz showed that the fundamental laws of conservation of mass and energy allowed no more than 59.3%[18] of the kinetic energy of the wind to be captured. So only at a certain ratio between the flow velocity of air in front of the converter and the flow velocity behind the converter could an optimal power extraction be realized. This is referred to as *Betz's Elementary Momentum Theory*. In other words, he figured out that the maximum possible energy to be derived from a wind engine is only 59.3% of the kinetic energy in wind, this is referred to as *Betz's Law* [21]. This maximum theoretical efficiency n max (also called power coefficient) of a wind turbine is the ratio of maximum power obtained from the wind to the total power available in the wind, which is the maximum fraction of the power in a wind stream that can be extracted. He pointed out that wind turbines can never be better than this maximum power coefficient. This Betz' law limit can be approached by modern turbine designs and may reach 70% to 80% of this theoretical limit of 59.3%. Mathematically, the *power coefficient* $C_p$ is derived from *power output from wind machine* divided by the *power available in wind*. Betz's Law, applied in a different way, specifies the power coefficient directly as a function of the *velocity ratio* $v_2/v_1$, which is shown in the right part of Figure 3.7 on the next page. The left side shows a decrease in the flow velocity behind the wind energy converter with a widening of the cross-section on account of the extracted energy at the cost of the kinetic energy contained in the wind stream.

[18]original value is 16/27

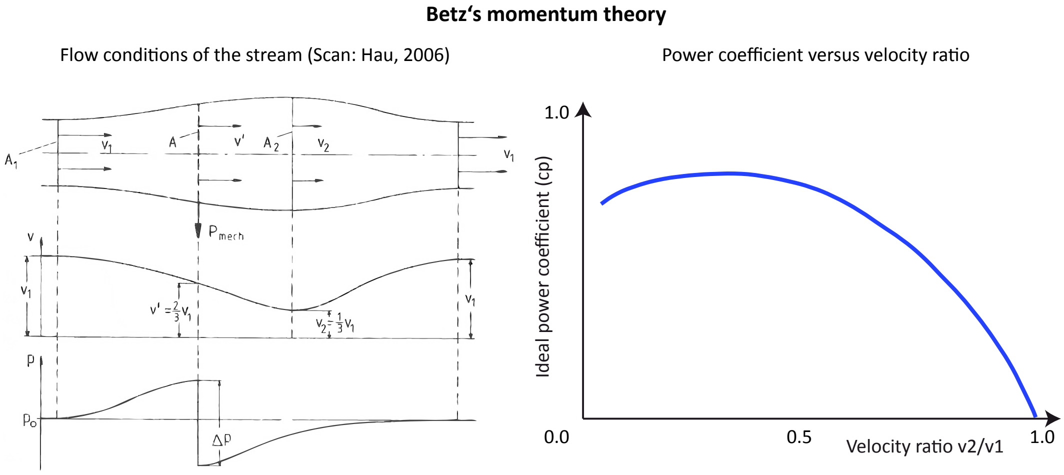



Figure 3.7.: Left-hand side: Flow conditions through an disk-shaped energy converter; Right-hand side: Power coefficient as function of the flow velocity ratio of the flow before and after energy converter

After the wind power is transformed into a mechanical rotation, it is converted into electrical power by an electric generator, a device that converts mechanical energy into electrical energy. An alternator is the focal point for all preceding components in the functional chain and more important for a wind turbine than the rotor mover. Basically any generator can be used to generate power. Currently, wind turbines have three-phase alternating current (AC) generators installed. Figure 3.8 gives an overview of the mechanical–electrical functional chain in a wind turbine. The effectiveness of today's

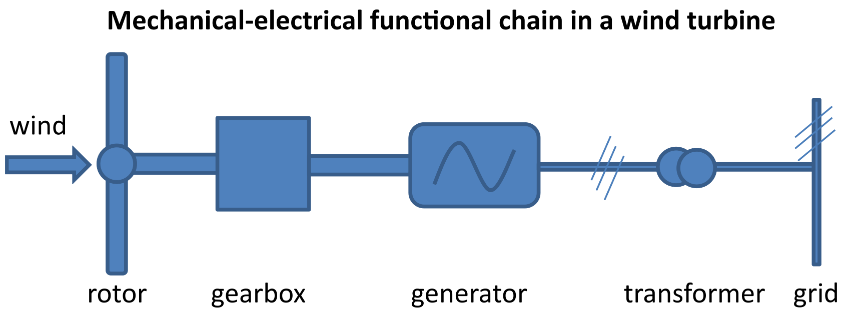



Figure 3.8.: Mechanical–electrical functional chain in a wind turbine

asynchronous alternators is about 90%, depending on the extent to which copper and iron are lost by friction. References and studies:

- Hau Erich, Wind Turbines Chapter 4 [78, pp. 81-86]
- The Lanchester–Betz–Joukowsky limit, article [96]

### 3.3.2. Design and construction of modern wind turbines

The concept of wind turbines is ancient and the technology has been widely disseminated both domestically and commercially. Nonetheless, the production of a wind turbine is still a challenge. Today wind turbine manufacturers have to consider the following points with regard to current wind technology:

- Specifications, such as frequency, voltage or harmonic content have to be adequate for standard electricity generation
- Variability of wind – there can be severe turbulences, low and high wind sites (wind speeds from 5 m/s to 70 m/s)
- Ability to compete economically with other energy sources
- Mechanical fatigue and stall
- Aerodynamic performance
- Impacts on the environmental, i.e. acoustic performance, visual disturbance
- Grid compatibility
- Offshore generation as a viable future development

A modern power–generating wind turbine has the function to generate high quality, network frequency electricity and is required to work unattended, with low maintenance and continuously for over 20 years. Anyway, each wind turbine must function as an automatically controlled independent mini-power station requiring less attendance than other power stations to operate in an economical way. The use of microprocessors to control the wind turbines has played a decisive role in making wind technology cost effective, and to maintain grid compatibility [14, Part: Technology]. Based on these facts, the trend will be to have large offshore wind turbines situated far from local habitation to reduce the effects on the local environment[19] whereas on the other hand smaller installations with short towers and smaller rotor diameters are employed on sites where the wind reaches extreme speeds. Acoustic performance can be achieved by regulating the tip speed, which requires careful attention to mechanical and aerodynamic engineering details. The trend is to maximize performance without aggravating loads.

#### 3.3.2.1. Concept of wind energy converters – design styles

The most obvious characteristic of the wind rotor is the position of its axis of rotation. According to Hau

> the aerodynamic function of the rotor is characterized by the way the wind energy converter captures its power; either exclusively from the aerodynamic drag of the air stream acting on the rotor surfaces, or it is able to utilize the

[19] designs for offshore foundations, maintenance, rotor technology and low mass nacelle arrangements

aerodynamic drag lift created by the flow against suitably shaped surfaces [78, p. 67].

It is thus possible and necessary to distinguish between *drag-type-rotors* and rotors using the *aerodynamic lift*, because, if the energy converter uses the aerodynamic drag, the achievable power output is not the same as when the converter uses the aerodynamic lift. The difference between the two maximum power coefficients is about 0.2 (see Figure 3.13 on page 59).

Rotors with a vertical axis rotation are the oldest design. They can be found on railroad carriages as ventilators, for instance. Darrieus developed a concept of a rotor, *the Darrieus-rotor* that effectively utilizes the aerodynamic lift in 1925. Vertical axis turbines typically have two or three blades, are simply designed and there is the possibility that the mechanical and electrical components, such as gearbox or generator, are constructed at ground level. The disadvantages are a low tip speed ratio (see 3.3.2.3 on page 57), problems to self-start and the impracticality to control output or speed by pitching the rotor blades. Furthermore, the cost of a three bladed H-rotor cannot compete with horizontal-axis rotors. Nevertheless, the vertical axis technology is uneconomic (despite the potentially lower installation costs) for the use of electricity production because the best design has a maximum power coefficient of 0.25[20]

On the other hand horizontal-axis rotors are the dominant design in the world. The *propeller designs* have advantageous features and are the reason why almost all wind turbine manufacturers make use of this technology. The advantages are the possibility to pitch the rotor blades to control speed and power output to avoid fatigue or overspeed or to aerodynamically optimize the blade. Figure 3.9 on the next page shows both design types and the basics of aerodynamic drag and lift. References: [60, pp. 14–16; 78, pp. 68–89]

It has been just shown that the rotor as an energy converter plays an important role in the chain of functional elements of a wind turbine. As the first element in the chain, its aerodynamic and dynamic properties have a decisive influence on the entire system. The following discussion is concerned with structures of wind turbines and the basic characteristics of the rotor blades, their design and aerodynamic design features.

#### 3.3.2.2. Structure of modern wind turbines

Modern wind turbines are designed to exploit the wind energy that exists at a location. Aerodynamic modelling is used to determine the optimum tower height, control systems, number of blades and blade shape. Figure 3.10 on page 55 shows a typical structure of a horizontal-axis wind turbine which is widely in use nowadays. A wind turbine consists of two main subsystems, the rotor nacelle assembly and the support structure, which has many components (see Figure 3.11 on page 56): [54, Appendix A; 14, Technology]

[20]whereas a modern wind turbine with horizontal-axes rotors has about 0.45

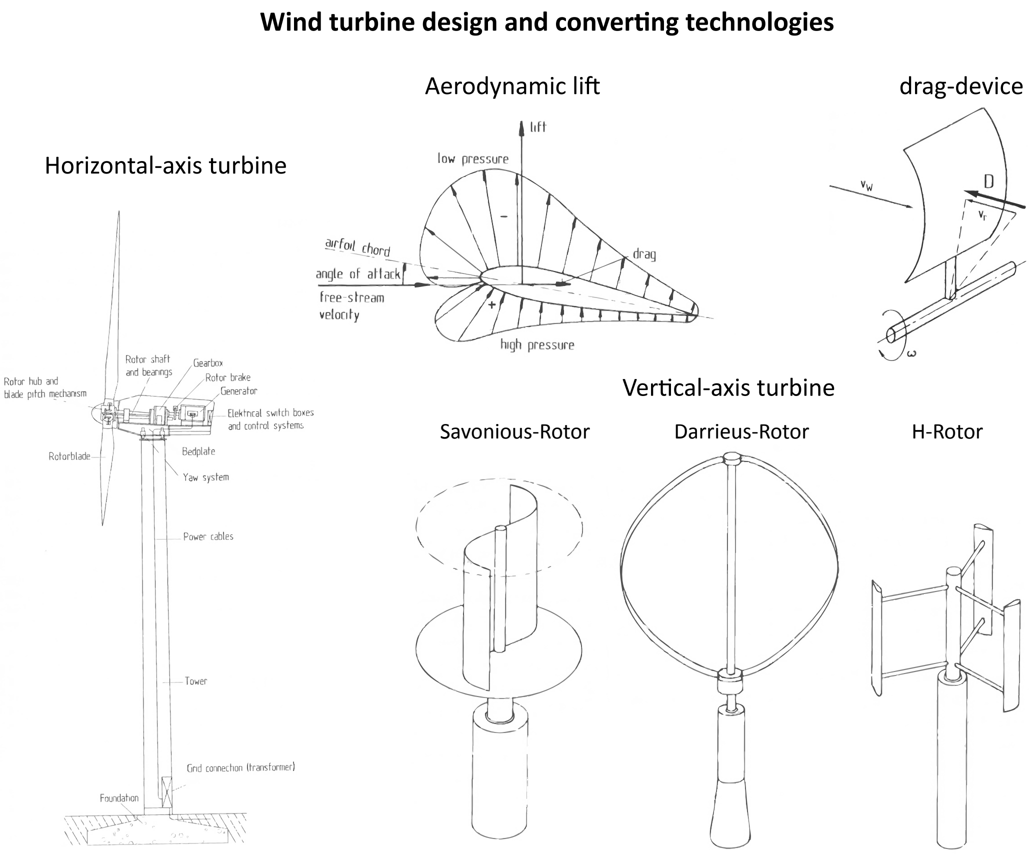



Figure 3.9.: Wind turbine design and converting technologies (Scans from Hau, 2006, p.68-89)

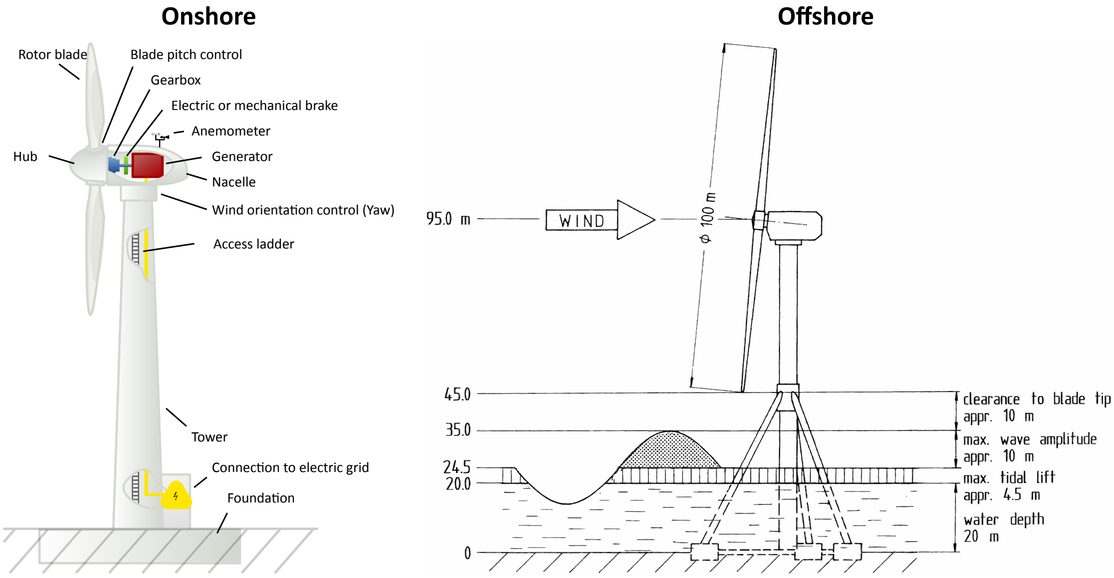



Figure 3.10.: Wind turbine structure of onshore and offshore wind power plants [17; 78, p. 635]

**Rotor nacelle assembly (RNA):** The RNA is the heart of a wind turbine and includes the majority of the components. It converts the kinetic energy of the wind into electrical energy. The RNA is grouped into rotor and drive train. The rotor includes the blades, the hub, and pitch control components. The drive train includes shafts, bearings, gearbox (if any), couplings, mechanical brake, and generator. Other components include the bedplate, yaw bearing and yaw drive, oil cooling system, climate control, other electrical components and parts of the control system.

**Rotor:** The rotor blades are the major component of the rotor, oriented to operate upwind of the tower. The blades have a special airfoil, can be pitched to achieve a maximum of power output and reduce noise. The laminates are primarily fibre glass with some carbon fibre for additional strength, and bound by polyester or epoxy. The root of the blade is comprised of steel and bolted to the hub.

**Drive train:** The drive train consists of a number of components, including shafts, couplings, a gearbox, a generator, and a brake.

**Shafts:** Shafts transmit the torque from the rotor to the gearbox or directly to the generator (when gearless). It carries all the weight of the rotor.

**Gearbox:** A gearbox (if used) increases the speed of the shaft that drives the generator, because conventional generators are designed to turn at higher speeds than that of wind turbine rotors. They are typically of the parallel shaft or planetary type.

**Brake:** A mechanical brake is used to stop and park the rotor under all foreseeable conditions. It can be placed on the low speed or the high speed side of the gearbox. On the high speed side, a robust torque is required but, as the torque must then pass through the gearbox that may lead to premature failure of the gearbox.

**Generator:** The magnetic field (either by using electromagnets or with permanent magnets) of the generator induces electricity. The majority of utility scale wind turbines today use wound rotor induction generators, which can function over a relatively wide range of speeds.

**Yaw system:** The yaw system facilitates orienting the RNA into the wind as the wind direction changes[21].

**Control system:** A control system ensures the proper operation of the turbine at all times. Firstly, it monitors the external conditions and the operating parameters of the turbine. Furthermore, the dynamic control system ensures smooth operation while pitching blades, for instance.

**Support structure – tower and foundation:** The tower is normally constructed of tapered steel tubes, which are bolted together on site to form a single structure. The foundation is constructed mainly of reinforced concrete, and on rocks the wind turbine is attached to the rock with rods grouted into pre-drilled holes.

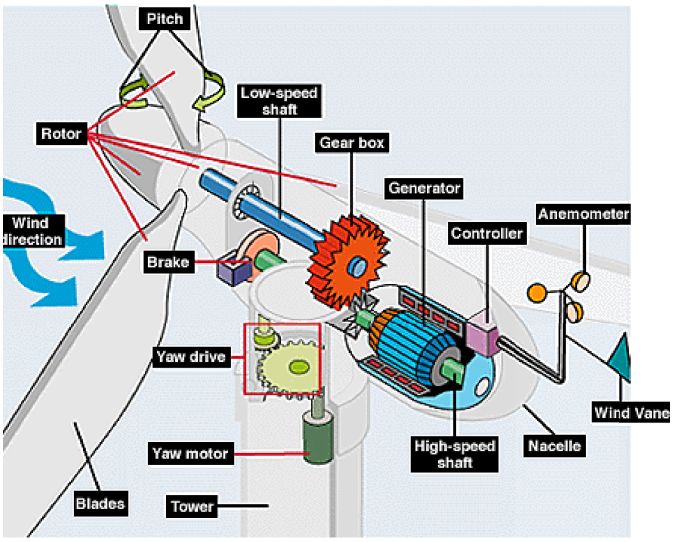



Figure 3.11.: Nacelle of a wind turbine [45]

[21] including an outside perimeter

#### 3.3.2.3. Rotor aerodynamics

Hau mentions clearly

> that the capability of the rotor to convert a maximum proportion of the wind power flowing through it is converted[22] into mechanical energy is obviously the direct result of its aerodynamic properties, which, in turn, largely determine the overall efficiency of the energy system It is this efficiency of the energy collector which is of prime importance with regard to the overall economics of the system. [78, p. 91]

Aerodynamic properties are an important factor to avoid poor torque characteristics or critical flow separation of the rotor blades. Whenever a blade is designed some corrections are always necessary to find the ideal relationship between the shape, number of blades or its airfoil to be sure of the best aerodynamic properties. To determine the power curve of a rotor blade, the following assumptions have to be considered: taking a rotoring wake into consideration when a real rotor operates, the power coefficient of the turbine has to be smaller than the value according to Betz's Law[23] [78, pp. 92 sq.]. Some of the energy in the wind will go into that rotation and will not be available for conversion into mechanical power. The power coefficient becomes now dependent on the ratio between the energy components from the rotating motion (tangential velocity of the rotor blade tip) and the translated motion of the air stream (speed of wind). This ratio is called *tip speed ratio*. The power coefficient is a function of the tip speed ratio. Additionally, besides the wake rotation, the geometry of the rotor blade influences the power coefficient. The aerodynamic properties caused by the blade airfoil have to be considered and determined[24]. This results in an *induced drag*, which decreases the power coefficient[25]. Figure 3.12 on the following page represents first of all the ideal power coefficient by Betz's momentum theory, secondly the results of taking the rotor wakes into consideration (here the coefficient becomes a function of the tip speed ratio) and, thirdly, the introduction of the aerodynamic forces acting on the rotor blades (aerodynamic drag)[26] [78, p. 98]. Apart from the rotor power, the behaviour of the *torque* is also a significant parameter which characterizes the rotor performance. Power and torque curves are the characteristic features of each rotor configuration. The following parameters are dependent on the two curves, including important aerodynamic design feature on the rotor blades:

- Rotor design (Dutch windmill vs. two–bladed rotor)
- Number of rotor blades

[22] Hau wrote [. . . ]wind energy flowing through its swept into [. . . ], but this is grammatically wrong. Hau meant converted instead of swept

[23] Betz's original analysis was based on the fundamental principles of fluid mechanics including linear momentum theory

[24] method is called the *blade element or strip theory*

[25] detailed derivation see [78, pp. 92 sqq.]

[26] considering that several simplifications in the theories limit their validity to a disc-shaped wind-energy converter

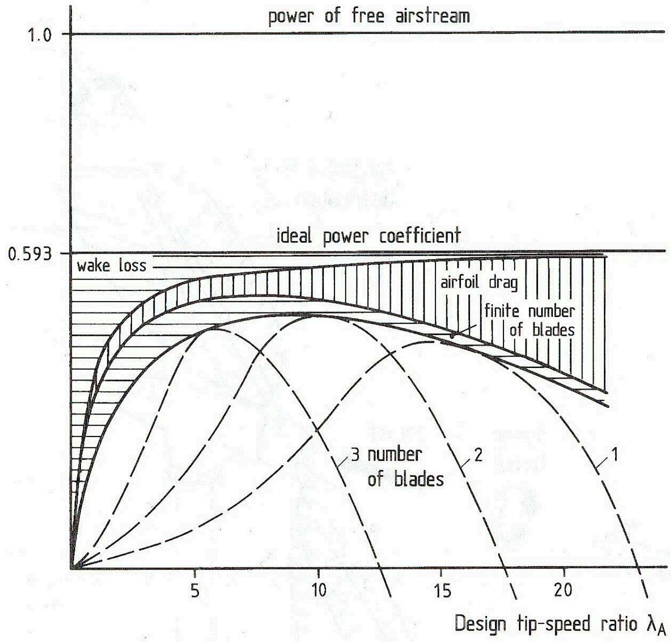



Figure 3.12.: Rotor power curve of various theoretical approaches (Scan from Hau, 2006, p98)

- Shape of rotor
- Rotor blade twist
- Blade airfoil
- Blade thickness
- Design of tip speed ratio of rotor
- Power control (blade pitching, passive and active stall control, turning out of wind) more infos see [78, pp. 102–116]

Only the number of blades and design types are discussed in this thesis because these are the factors which give rise to negative effects, such as noise, visual intrusion or flickering shadow (for detailed information see [78, pp. 120–142]). The number of blades is important because that determines the efficiency of power output (see Figure 3.13 on the next page). Three-bladed rotors have the best power coefficient and a tip speed ratio that does not produce such a disturbing noise as other rotors[27]. Three-bladed rotors are currently used by many operators, as four blades would be too expensive to manufacture, if the cost-benefit ratio os considered, and increase the power output to a very small degree only (more infos see [8, Part: number of blades]).

[27]Higher tip speeds result in higher noise levels and require stronger blades owing to the strong centrifugal forces

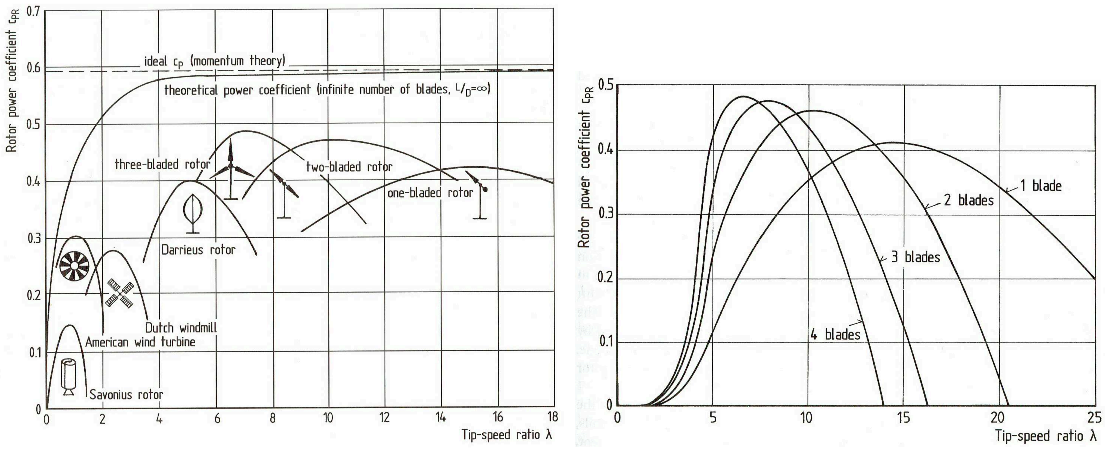



Figure 3.13.: Power coefficient: Different blade designs and number of rotor blades (Scans from Hau, 2006, p.101 and p.121)

The possibility to control the operation process is very important because the power output increases with an optimal adjustment of the properties of the rotors. This can be achieved by either pitching the blades or by stalling them[28], to limit power, on the one hand, and to increase power output, on the other hand, (see also *energy yield* in the next part 3.3.3 on the following page). To summarize, the speed and torque must be controlled because it is necessary:

- to optimize the aerodynamic efficiency of the rotor in light winds
- to keep the generator within its speed and torque limits
- to keep the rotor and hub within their centrifugal force limits
- to keep the rotor and tower within their strength limits and to survive much higher wind loads
- to enable maintenance
- to reduce noise[29] [171]

[28] function and detailed description in [78, pp. 102-116]

[29] "It is generally understood that noise increases with higher tip speeds of the blade. To increase the tip speed without increasing the noise level would allow reduction of the torque into the gearbox and generator and reduce overall structural loads, thereby reducing costs. The reduction of noise is closely linked with the detailed aerodynamics of the blades, and, in particular, with those factors that reduce abrupt stalling. The inability to predict stalling restricts the development of effective aerodynamic concepts" [162]

### 3.3.3. Power output and wind

#### 3.3.3.1. Wind and factors affecting the location of a wind turbine

As the planet Earth is continually spinning from west to east it is pulling the atmosphere with it – this explains why there is always air in motion. Then because of the differential heating of Earth's surface by the rays of the sun, zones of high and low pressure develop which also create currents of air. These are the origins of the winds on the planet Earth. The following influences, with regard to wind and insofar as it relates to wind turbine operation should be mentioned:

- Geostrophic wind[30]
- Atmospheric boundary layer meteorology
- Variation of wind speed with height
- Surface roughness and turbulence

The upper atmosphere winds mostly impinge on wind turbines. They are the source of most of the energy that can be generated. The energy in the upper atmosphere is transferred down closer to the surface via a variety of mechanisms, most notably turbulence, which is generated mechanically via surface roughness, and thermally via the rising of warm air and the falling of cooler air.

Wind has the characteristic to be variable, both temporal (short term, diurnal or seasonal) and spatial (from one location to another). The variability of wind is shown in Figure 3.14 on the next page [111; 167, p. 3]. We can see that the highest wind speeds are measured in winter. The progress of the curves show significantly that the variability of wind correlates with the demand for electricity (more demand and wind available in winter). It is also necessary to consider local air circulations between land and water, for instance, which are used in coastal areas, such as in Denmark and in Northern Germany, shown in Figure 3.15 on the facing page.

[30] is the wind in the upper atmosphere, which results from the combined effects of the pressure gradient and the earth's rotation via the Coriolis force

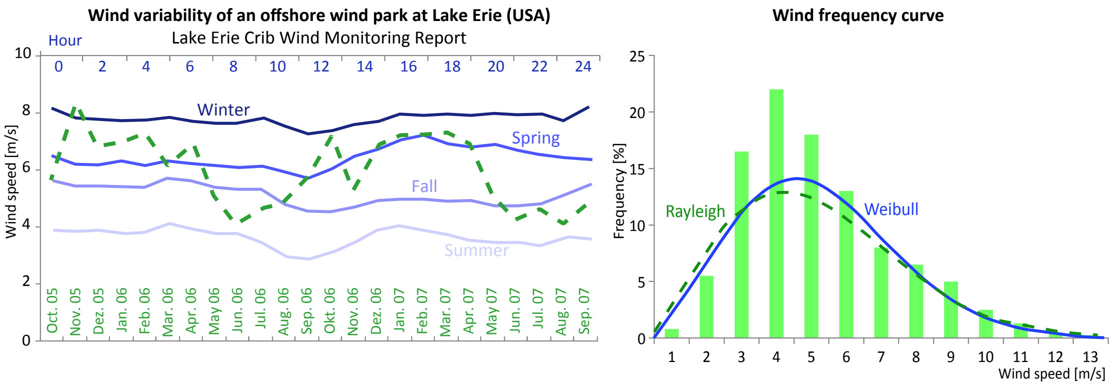



Figure 3.14.: Variability of wind

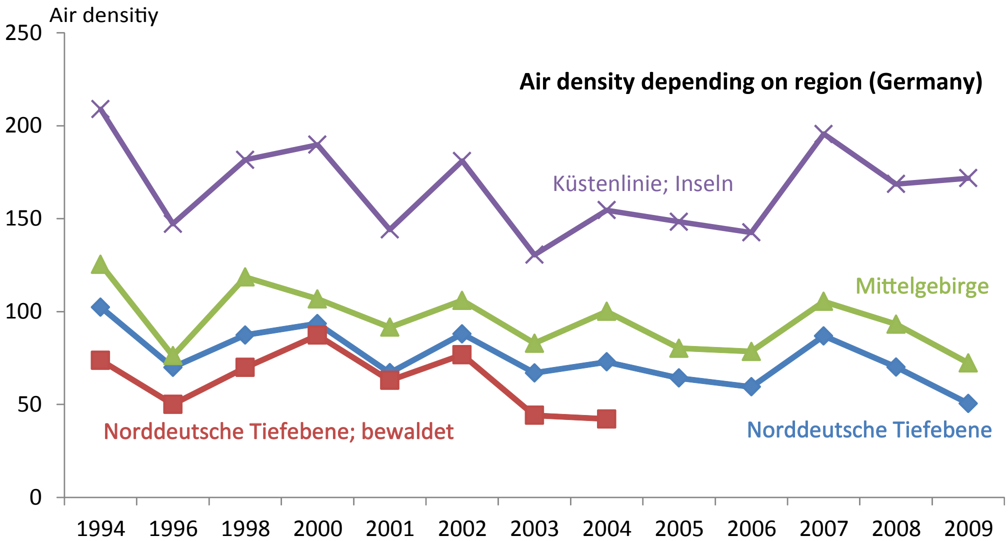



Figure 3.15.: Wind speeds in several locations

A look at the spatial component of wind shows that it would seem reasonable to set up wind turbines only in regions with sufficient wind conditions. The *Roadmap 2050*, an initiative of the European Climate Foundation (ECF), shows applications related to renewable energies all over Europe, shown in Figure A.3 on page 173 in the appendix chapter. It shows clearly that wind power plants are useful only at some specific locations to achieve a well-balanced cost-benefit-ratio[31]. Wind has also the ability to increase the higher the altitude [167]. This is the reason why larger wind turbines are the future trend as they will have higher power outputs. To guarantee economic and ecological efficiency, the following *location factors* are important (consider Figure 3.16 on the following page [60, pp. 22 sqq.; 14, Section Technology]:

[31]that means an environmental sustainable result, too

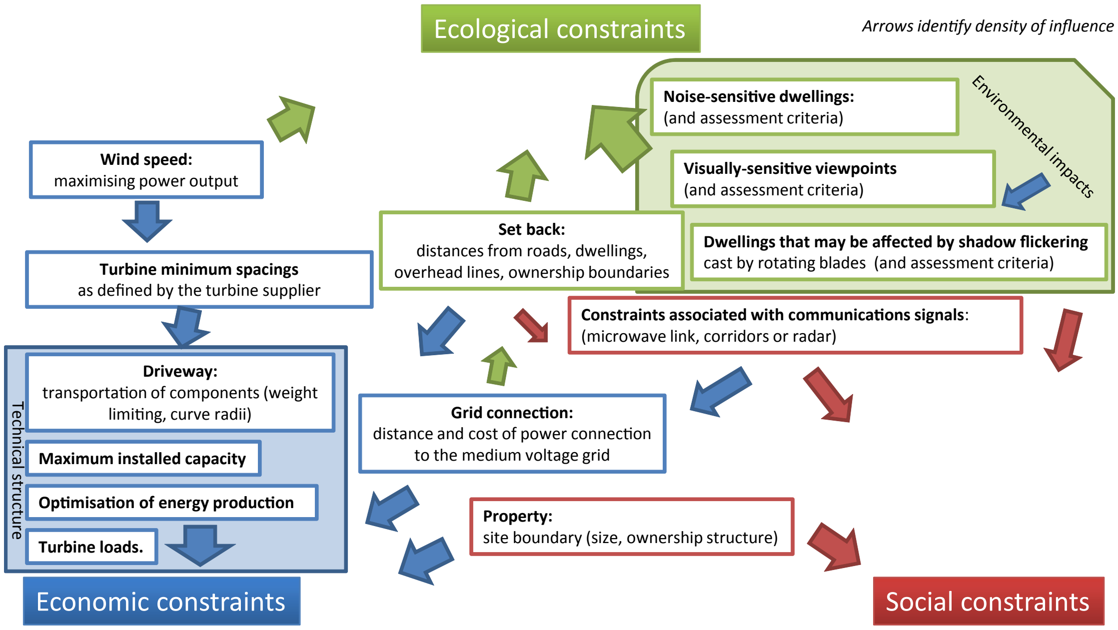



Figure 3.16.: Factors affecting the location of a wind turbine

### 3.3.3.2. Power output

**Power curve** All in all, the power output of a wind turbine depends, from a manufacturer's point of view, primarily on the design of the rotor blades, assuming that wind is constantly available. Therefore the concept of a wind turbine (size and performance) has to be assessed in accordance with its rotor diameter[32] and not to its rated power. To determine the result of the technical characteristics or performance of a wind turbine, including wind data, a *power curve* is often used. The power curve describes the performance of a wind turbine and is the basis for the *energy yield* to be expected under given wind conditions[33]. It is also "the most important testimony for the performance of the wind turbine from the point of view of the operator." [78, p. 485] Figure 3.17 on the next page shows the electrical power output versus wind speed, which is referred to as the power curve. No power is produced below the cut-in speed. Between cut-in and rated wind speed the power increases significantly with wind speed. Above the rated speed the power produced is constant regardless of the wind speed. If above the cut-out speed is exceeded, the turbine is shut down (automatically by the use of brakes and a power control system).

In the next Figure 3.18 on the facing page power losses are shown during the whole operation process, caused by several factors, which are not mentioned here and can be looked up precisely in *Hau Erich's Wind Turbines, Chapter 14* [78, pp. 485-494].

[32] with a given diameter the design is aimed at maximizing the power output
[33] it is the turbine's official certificate of performance, guaranteed by the manufacturer

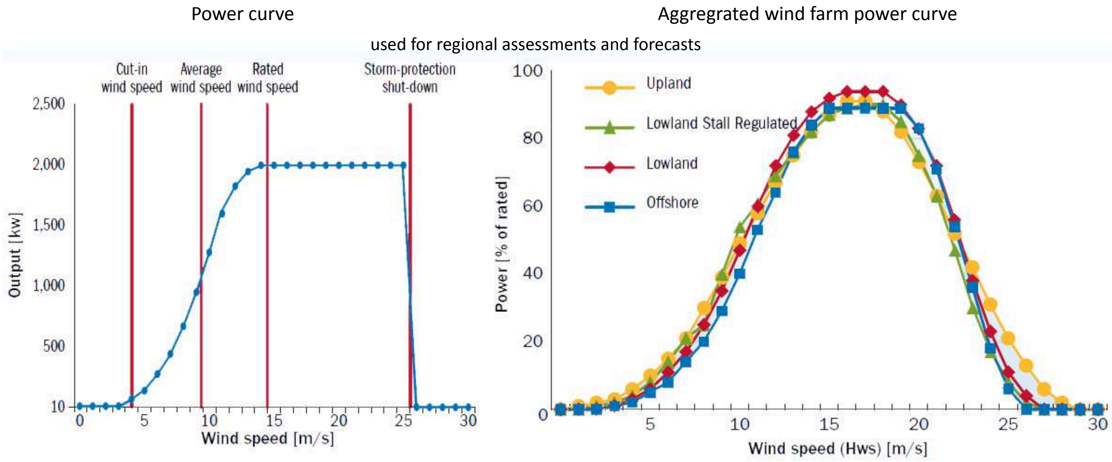



Figure 3.17.: Power curve of a wind turbine [57, p. 41]

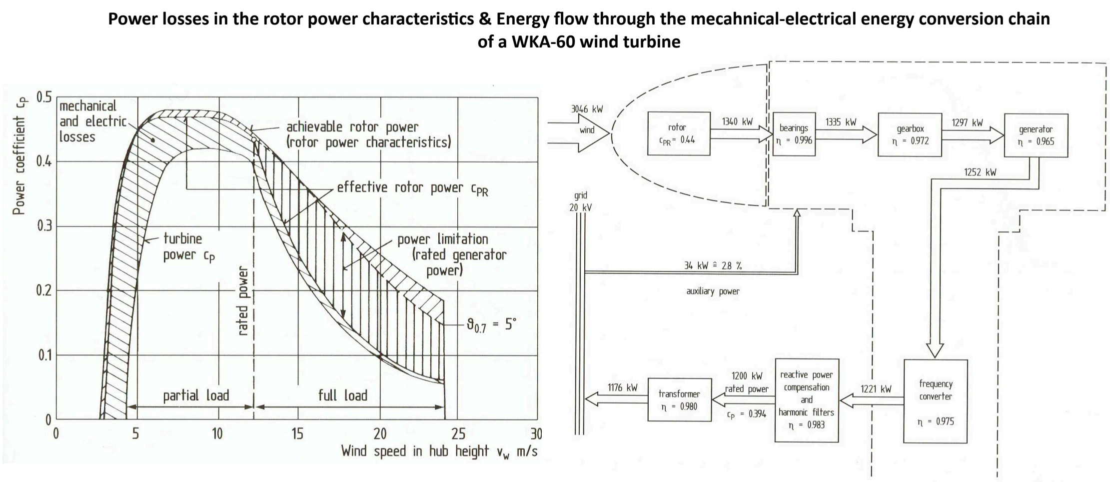



Figure 3.18.: Left-hand side: Energy flow of the mechanical-electrical conversion; Right-hand side: Power losses (Scans from Hau, 2006, p.488, p.489)

**Energy yield** The energy yield requires both the power curve and the frequency distribution of the wind and is the product of rated power and usage time, as it is given in Figure 3.19. To reach a maximum of power output, as already mentioned in an ear-

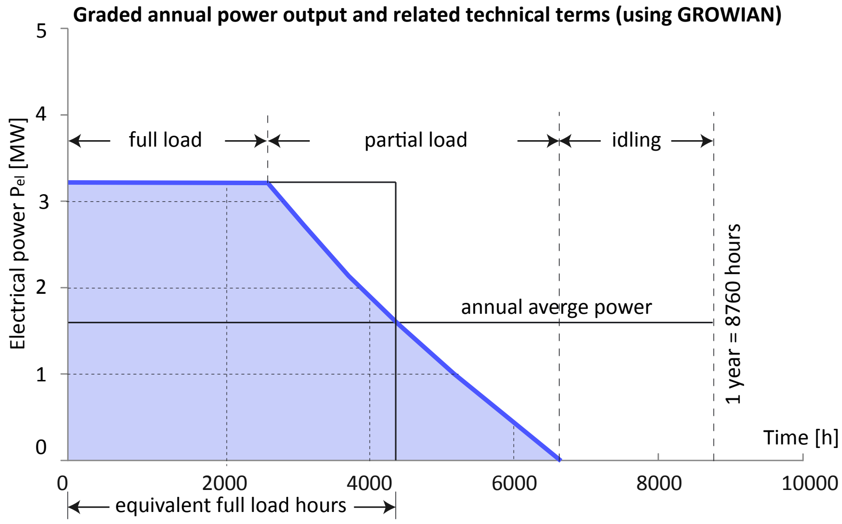



Figure 3.19.: Frequency distribution and normalized power curve lead to the graded annual power output [78, pp. 504-505]

lier part, power control and technology innovations are an important factor[34] in these days. Pitching and high performance generators guarantee an almost smooth power output with variable speed operation, which is shown in Figure A.4 on page 174 [78, pp. 523 sq.]. To summarize again, the major influences on the power curve and the energy yield (which will not be discussed in detail, but only mentioned in this thesis) are:

- Rotor diameter (rotor blades)
- Rotor power coefficient (rotor blades)
- Wind regime on site (environmental conditions)
- Air density (environmental conditions)
- Turbulence (environmental conditions and blade design)
- Optimal rotor speed and variable rotor speed operation (blade design, power control and environmental conditions)
- Rotor hub height (structure, blade design)
- Power control (blade design and software)

[34] software and hardware technology improves rapidly

- Installed generator power (design and structure)
- Operational wind speed range (environmental condition)

References: [78, pp. 485-522; 57, pp. 35-54; 54, Appendix A; 49]

## 3.4. Wind turbine costs

The cost structure of planning a wind turbine is not that easy as one might think. Because of the enormous cost, the vast majority of commercial wind farms have been funded through project finance [35]. This section discusses and reflects the cost structure and not the whole process of wind farm development from a financial point of view. A major question is whether the manufacturing costs are so high that the generation becomes uneconomical [78, pp. 704 sq.]. Before the costs can be determined, the following costs have to be known [78, pp. 703–750]:

**Manufacturing costs** are the costs of the product itself. These are the costs of components and their manufacture. The production environment has also a bearing on the costs. Certain components, such as blades, become cheaper when produced in larger numbers (economies of scale) [78, p. 714]. A typical cost breakdown of manufacturing costs into the main subsystems and components is shown in 3.20 [78, p. 711].

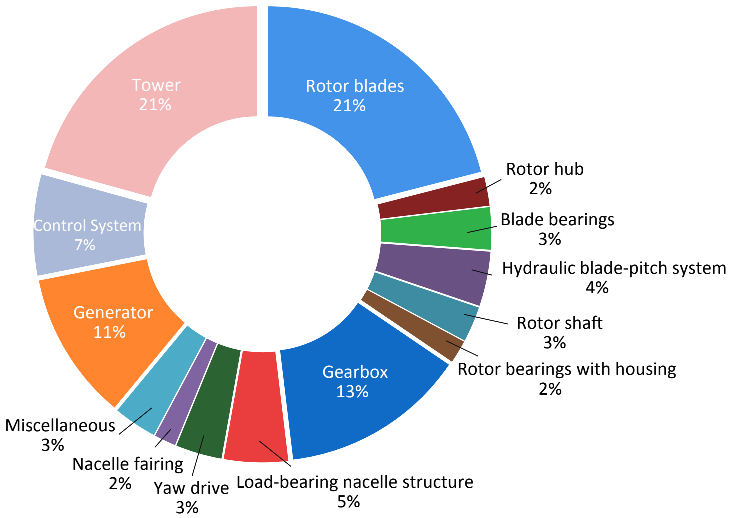



Figure 3.20.: Cost breakdown of a 1.5 MW wind tubine

**Development costs** in the sense of research and technology innovation [78, p. 732]

**Investment costs or installed costs** include *wind turbine costs* and *site related costs* for determining its economic viability. “The realization of a project frequently spans a period of several years from the first idea to the day of starting operation and, therefore, firstly entails considerable planning costs which are frequently underestimated at first glance.” [78, p. 733] For instance, planning activities include a wind resource assessment, geological studies, noise emission or shadow casting assessment. Further parameters of

[35]a project loan backed by the cash flow of the specific project

influence which belong to site-related costs are cabling and grid connection, foundation and financing costs. All of these costs can be summarized in the *total investment costs*, shown in Figure 3.21 [78, pp. 748 sqq.].

| | | Cost $US | Proportion % |
|---|---|---|---|
| **Wind park** | | | |
| 120 wind turbines, rated power | 2.5 MW | | |
| Rotor diameter | 80 m | | |
| Hub height | 70 m | | |
| Distance from land | approx. 30 km | | |
| Depth of water | 12–17 m | | |
| Mean wind speed at hub height | 9.0 m/s | | |
| **Wind turbines** | | | |
| Single ex-works price incl. erection | 1 950 000 $US | | |
| | 120 units | 234 000 000 | 54.4 |
| **Foundations** (tripod/steel tube) | | | |
| Production cost per unit | 350 000 $US | | |
| Transport and erection per unit | 350 000 $US | | |
| | 120 units | 84 000 000 | 19.55 |
| **Electrical infrastructure** | | | |
| Internal power system (24 kV), 85 km cable run (260 $US/m) | | 22 100 000 | |
| Offshore substation (24/110 kV), include erection | | 18 000 000 | |
| 30 km 110 kV marine cable run (460 $US/m) | | 13 000 000 | |
| 30 km 110 kV overhead line on land (400 $US/m) | | 12 000 000 | |
| Substation on land (110 kV/220 kV) | | 6 000 000 | |
| | Total | 71 000 000 | 16.73 |
| **Remaining infrastructure and logistics** | | | |
| Maintenance ship, pontoons etc. | | 5 000 000 | |
| Operations building | | 1 000 000 | |
| Remote monitoring, measuring and control | | 2 000 000 | |
| Anemometer system (4 masts 70-m high) | | 1 800 000 | |
| | Total | 9 800 000 | 2.28 |
| **Project development** | | | |
| Technical planning and project management | | 15 000 000 | |
| Geological, traffic engineering and environmental investigations | | 10 000 000 | |
| Other investigations, permits | | 5 000 000 | |
| | Total | 30 000 000 | 6.98 |
| **Technical investment costs** | | 429 700 000 | 100 |
| **Specific investment costs** | | 1432 $US/kW | |

Figure 3.21.: Total costs of a large offshore wind park (Scan from Hau, 2006, p.748

**Annual costs** or operation and maintenance costs have to be considered, too. Although wind turbines hardly consume any[36] fuel. Nevertheless, maintenance and repairs cause recurring operational costs. Often an operating wind turbine stops working owing to technical breakdowns or failures [78, pp. 695-701]. Typical annual costs are repairs, maintenance, insurances[37], land leasing, taxes or administration costs [78, pp. 742-750].

[36]wind turbines need energy from the grid system for some operational phases
[37]liability insurance, insurance against machine break, loss-of-profit insurance

**Dynamic calculation of economic viability** An economic point of view is essential to carry out a successful cost assessment. The utilization of a wind farm has to fulfil the expectation of cost effectiveness and economic viability. Therefore, often a cost per unit (e.g. euro cent per kilowatt hour) is calculated to compare it with other energy systems. The financing aspects of an investment project are only realistic by inclusion of these costs per unit.

The estimation of the cost of electricity and a repayment period is as important as the previously mentioned cost calculation methods. The *static* calculation of the achievable power-generation costs should mark the beginning of every analysis of an investment project which is going to be carried out. One key question that is always posed is the amount that wind energy costs and the period of repayment. The result of calculations to find the cost of generating electricity using wind turbines, taking into consideration the repayment periods of, in general, 10 or 20 years, are measured in a currency unit per kilowatt hour[38] (see Figure 3.22 [78, pp. 758 sqq.]).

| | |
|---|---|
| **Investment costs** | |
| $US Ex-works price of the wind turbine | 1 400 000 $US |
| Planning, infrastructure and financing, (30 % of ex-factory price) | 420 000 $US |
| Total investments costs | 1 820 000 $US |
| **Annual costs** | |
| Maintenance and repairs, insurance, land lease | 56 000 $US |
| (4 % of ex-factory price) | |
| Service of capital (6 % interest p.a.) | |
| – 10 years (ave. annuity 13.59 %) | 247 738 $US |
| – 20 years (ave. annuity 8.72 %) | 158 704 $US |
| **Site** | |
| Mean annual wind speed at 30 m height | 5.50 m/s |
| Roughness length $z_0$ | 0.1 m |
| Mean wind speed at hub height (80 m) | 6.50 m/s |
| **Annual energy yield** | |
| at 98 % technical availability | 3 500 000 kWh |
| **Specific investment costs** with respect to annual energy yield | 0.52 $US/kWh |
| **Power-generation costs** | |
| – with repayment in 10 years | 0.087 $US/kWh |
| – with repayment in 20 years | 0.061 $US/kWh |

Figure 3.22.: Power-generation cost of a 1.5 MW wind turbine with 70 m diameter, 30 m height and mean wind velocity of 5.5 m/s (Scan from Hau, 2006, p.758)

A dynamic calculation method conveys not only a static picture of the economics. A long-term investment requires the anticipated development of certain economic conditions in the investment period. Such elements are the general rate of inflation rate

[38]typical power-generation costs with repayment in 20 years, and with wind speeds at 7 metres per second, were 5 euro cents per kilowatt hour [78, p. 759]

and the increase in electricity prices. A calculation method that considers a dynamic development is based on the *present-value* or *cash-value* method [169]. This method has

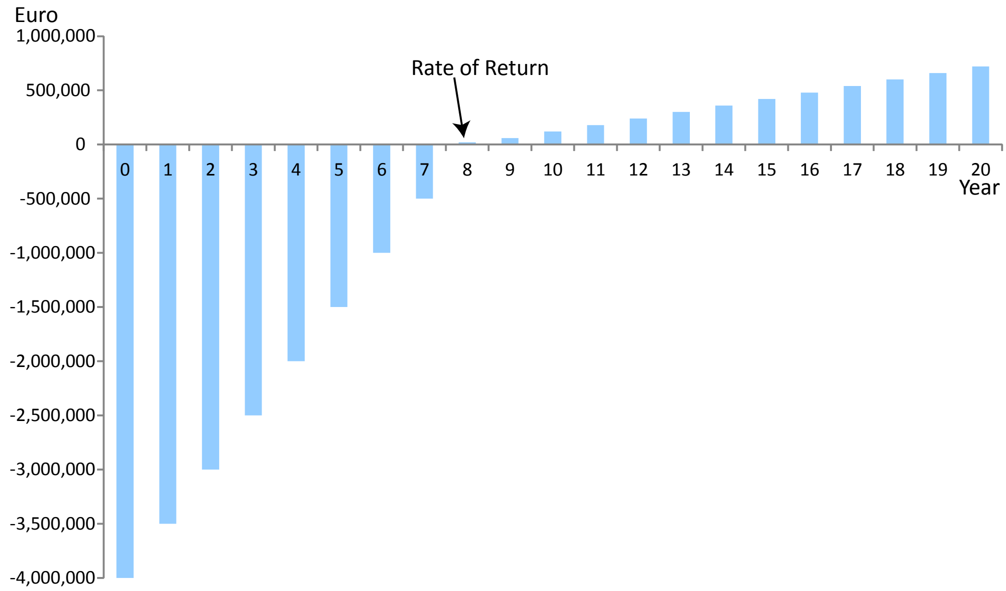



Figure 3.23.: Evolution of the net present value of a wind turbine (schematic)

the characteristic that costs and incomes at different times of the payment flows are taken into account. All flows for every year (point of time) are considered, regardless of whether the money has been or will be paid or received in the past or in the future. To ensure payment flows at a common reference time, all payments are discounted[39]. Discounting is to be understood as calculating what the present value of a payment is worth in the future. The discount rate in energy projects will not be discussed in detail in this thesis (more infos: [104, pp. 31-35; 128; 76, pp. 101-118]). The sum of all present values (all incomes and investments over the whole period) is referred to as the *net present value*. It provides an idea of the profitability of a project. When the *internal rate of return*[40] is reached, a project is profitable. A cost-benefit-analysis is often made to calculate the net present value to see if an investment is profitable over the entire period of time. Figure 3.23 shows the evolution of the net present value with its single present values. [169; 76; 78, pp. 703-774]

[39]the discount rate is a very essential factor – the entire profit of a project also depends on the choice of the discount rate! Some economists argue that the discount rate for environmental goods should be negative, because the value of clean air increases (with increasing air pollution) in the future, for instance

[40]when the net present value becomes equal to zero

# 4. Social costs of wind energy in the energy industry

That the generation of electricity using wind turbines has some effects on the environment has been discussed already, but the number and degree of these impacts, as compared with other technologies in which biomass or natural gas is used to generate energy, has not yet been definitely clarified. Analyses of the economics of wind energy showed that the electricity generated with wind turbines is increasingly competitive with conventional power plants, although under the present market conditions, the gulf that still exists before wind energy can become at least an equal among the other competitors, if not to surpass them, has to be bridged by economic support instruments such as feed-in tariffs (eco-power tax) and tradeable green certificates. This means that wind energy and other renewable energy sources have environmental benefits compared with conventional electricity-generating technologies. These benefits may not be fully reflected in electricity market prices, and it does not matter if the consumed electricity originates from renewable energy sources with less environmental impact or fossil fuels with much pollution. The major question is, are externalities included in the price mechanisms and do electricity market prices give an appropriate representation of the full costs of generating electricity to society? It is not easy to answer this question. The price of electricity, as it will be compensated in the electricity bill, usually depends on the marginal cost of production[1]. Externalities are included only in the eco-power tax, but, in actual fact, this tax is not used to compensate for the impacts made on the environment. The tax is used to adjust the high private costs of renewable energy to make it competitive (e.g. photovoltaic or solar power) to conventional technologies[2]. Consider the average electricity market price of 3 euro cents/kWh; this covers only the private costs of conventional power plants, but both the external costs (see cost analysis in the next parts) or costs of the renewable electricity generation have to be considered, too. [52; 1; 104, pp. 130–139].

In the next sections the amount of the social costs of wind energy are outlined in comparison with other electricity-generating technologies, from two points of view. First of all, an analysis of the quantities of externalities of other energy systems is carried out and then compared with wind energy (the number and extent of externalities are compared) to estimate the hidden benefits or damage of electricity generation, which has been considered in a full cost assessment. Secondly, it is interesting to know what the full costs of different energy systems are, nowadays, and what they are likely to be in the future. The full costs (or social costs) of electricity generation determine the relevancy

[1]including energy generation, infrastructure, maintenance costs, etc.
[2]Infos related to electricity prices and taxes see: [51; 53]

of impacts of wind power all over the electricity market. Both internal and external costs need to be taken into account to establish a consistent and fair comparison of the different electricity-generating technologies.

## 4.1. Full costs of electricity generation

To take all costs into account, the newest results of a study, published by the European Union, the *ExternE project* (External Costs of Energy) will be discussed. The study has been funded by the European Commission DG Research (European Research Network) since 1991. The scope of the ExternE project is to value the external costs of both production and consumption. Such evaluations have been applied mainly to energy-related activities. Through the ExternE project great progress has been made in the analysis of environmental costs (socio-environmental damages must first be estimated and monetized) over the past 20 years. More than 50 research teams in over 20 countries were involved and a lot of studies were applied to develop the methodology.

> The effects of energy conversion are physically, environmentally and socially complex and difficult to estimate, and involve very large, sometimes ultimately unresolvable, uncertainties, unpredictability and differences of opinion. Despite these difficulties, ExternE has become a recognized source for the method and results of externality estimation. [55]

The estimation of external costs is also used in other applications, such as in cost-benefit analysis. Therefore, it is an important task [76]. Since 1995, many projects using the ExternE methodology have been started and finalized, whereas only the results from the project *CASES*[3] are presented. Some important projects using the ExternE methodology are *CASES (2006–2009)*, *NEEDS (2004-2008)*, *NewExt (2001–2004)* and *ExternE-Pol (2003–2005)*. A view of all current and past projects is listed on the ExternE webpage [55, Projects]

The objectives of CASES can be described as follows [104, Introduction]:

- to compile a complete and coherent assessment of both external and internal costs of electricity generation for different electricity-generating technologies at the national level for the EU27 countries and non-EU countries under well-defined energy scenarios until 2030
- to improve the efficiency of energy use by evaluating policy options
- to disseminate research findings to energy sector producers and users as well as the policy-making community

For this thesis, the consideration of full costs shows perfectly the efficiency of electricity generation from firstly, an economic and, secondly, ecological and social point of view. Not only externalities, but also private costs are compared[4]. Furthermore, the

[3] Cost Assessment for Sustainable Energy Systems
[4] representing the economic point of view

profitability of an energy-generating technology can be realized.

### 4.1.1. Methodology

CASES uses the life-cycle inventory estimation, as described in subsection 2.5.2 on page 36, and a framework provided by the ExternE Methodology. This framework transforms negative impacts of electricity generators that are expressed in different units into a common untit[5]. This bottom-up approach characterizes the stages of the fuel cycle of the electricity generation technology and identifies fuel chain burdens[6]. After the definition of the impact categories and externalities, the impacts of the activity are estimated in physical units, independent of their number, type or size. After describing this so-called *accounting framework*, the impacts are selected and only their effects are calculated for the final analysis. Afterwards, the impacts are monetized to provide external costs in euro cents/kWh generated electricity. Furthermore, uncertainties are assessed and a sensitivity analysis is carried out followed by an analysis of the results. The *impact pathway approach*, developed by ExternE, is used to quantify environmental impacts. Particularized, it "[. . . ]proceeds to establish the effects and spatial distribution of the burdens to see their final impact on health and the environment[7]." [9] In welfare theory, damages represent welfare losses for the people. If market prices cannot be used for evaluation, there is only the possibility to evaluate a willingness to pay. Figure 4.1 on the following page represents the impact pathway approach (IPA). The first step is the specification of the relevant technologies and emissions of a pollutant, for instance, the number of kilograms of emitted oxides of nitrogen that are emitted by a power plant at a specific location. To include exposures via the food chain or the pollution in air, water and soil, an atmospheric dispersion model was developed to calculate the concentrations of the pollutants in all affected regions. In a further step exposure-response models[8] are used to calculate the cumulated exposure from increased concentration levels, followed by the calculation of impacts (damage in physical units). Finally, the impacts are valuated in monetary terms to obtain the external costs per unit of emission[9]. The normalization of all negative environmental effects is essential to be able to compare different energy-generating technologies and this can be a currency per unit or just in so-called eco-points[10]. EcoSense (Figure 4.1 on the next page) is a model that allows complex analyses of external costs. It is a software tool that has been developed during the last ten years by the EU research effort. EcoSense models the pathway of emissions, as it is described in the impact pathway approach, by assessing complex environmental issues (air pollutants can damage a number of different receptors) in terms of external costs of

[5] i.e. euro cent per kilowatt hour

[6] burden is anything that could cause an impact of whatever kind

[7] i.e. damages depend on meteorological conditions or population distribution

[8] compiled and critically reviewed by expert groups

[9] damages per functional unit are interesting, e.g. euro cents/kWh

[10] the unit milli-person equivalents is often used in normalized LCA results. It is 1/1000 of an average European's allocated emission [100]

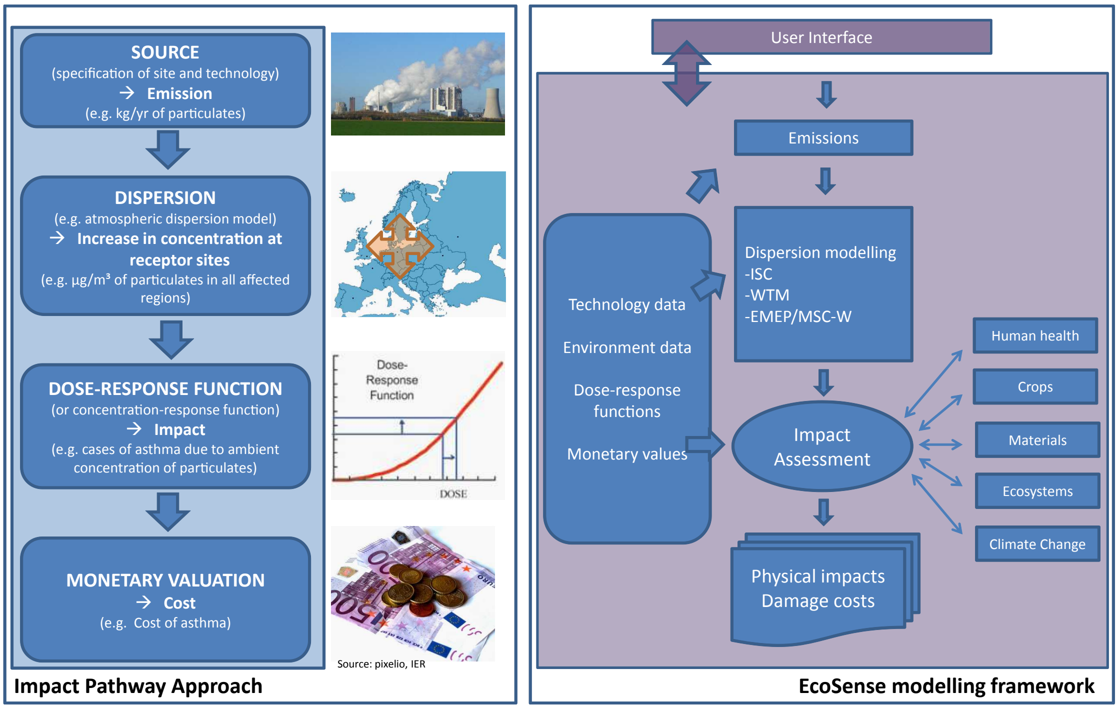



Figure 4.1.: Left-hand side: Impact Pathway Approach; Right-hand side: EcoSense model

electricity-generating systems[11]. It also provides the relevant data and models required for an integrated impact assessment related to airborne pollutants [104, pp. 3 sqq.; 23, pp. 1 sqq.; 55; 11; 9].

The aim of every evaluation is to cover all the relevant external effects. This is hardly possible, so there are still gaps and uncertainties. For instance, events with less probability to occur (nuclear accidents) are often not accounted for in an analysis and not included in an assessment [6].

The ExternE project covers a wide range of impacts taking into consideration the entire life cycle compared to other LCA: [104, pp. 20-31; 23, pp. 1-6]

- Environmental impacts: discharging either substances (e.g. fine particles) or energy (noise, radiation, heat) into air, soil and water.
- Global warming impacts: avoidance cost approach and estimation of quantifiable damage.
- Accidents: public and occupational accident risks (calculating the damage and by multiplying the damage with the probability of the accidents). A method for

[11] e.g. to calculate the external costs of a given conventional power plant portfolio as well as the avoided external costs of wind energy

addressing so-called Damocles-risks (high impacts with low probability) has still to be developed.

- Energy security: changes in availability and prices of energy carriers.

However, impacts on employment[12] (change of the distribution of working places cause local effects) and depletion of non-renewable resources has not been considered yet.

In the EcoSense model, some externalities of energy production are also missing. The reader will probably notice that it is often the same categories are not included in the evaluation process, because they are not easy to quantify or are of only minor relevance. These omitted values are: [104, pp. 35-76; 61]

- Land use-change and biodiversity
- Biodiversity losses caused by acidification and eutrophication
- Visual intrusion of wind, hydro-electric-power and overhead transmission lines
- Emissions of greenhouse gases
- Risk of nuclear proliferation and terrorism
- Risk prevention and the handling of Damocles risks[13]

In general, the most important emissions concerning the fuel-based generation of electricity are $CO_2$, $SO_2$, $NO_x$ and also $PM10$[14]. Wind energy operates almost emission-neutral for which reason economists often talk about the benefits of wind energy, which are that harmful emissions are avoided and external costs from fossil fuel-based electricity generation [5].

- $CO_2$: no opportunity to reduce carbon dioxide emissions by using filters
- $SO_2$: emission depends on the sulphur content of the input fuel; it is reduced by filtering the exhaust gas and by converting it into elementary sulphur. Lignite has a rather high sulphur content, followed by oil, anthracite (hard coal) and gas (almost sulphur-free)
- $NO_x$: unrelated to input fuel and formed from the nitrogen in air during combustion, reduced by choosing a lower combustion temperature or denitrifying the exhaust gas

The impact inventory is the major influencing variable in a life-cycle analysis. It covers all the inputs and outputs, and should include all indirect life-cycle-branches from *cradle-to-grave*. "The estimated difference in the simulated air quality situation between the

[12] not seen as external cost according to economic theory, but argument in every investment theory [55]
[13] impacts with low probability
[14] particulate matter up to 10 micrometres in size

case and the reference situation is combined with exposure response functions to derive differences in physical impacts on public health, crops and building materials[15]." [55, Methodology]

> The main categories are human health (fatal and non-fatal effects), effects on crops and materials. Moreover, damages caused by global warming instigated by greenhouse gases have been assessed on a global level within ExternE. However, the range of uncertainty is much higher for global warming impacts than for other damages. In addition to the damage cost estimates, for impacts on ecosystems and global warming, where damage cost estimates show large uncertainty ranges, marginal and total avoidance costs to reach agreed environmental aims are calculated as an alternative second best approach. The costs for ecosystems are based on the concept of Eco-indicator99 (Potentially Disappeared Fraction (PDF)). The PDF can be interpreted as the fraction of a species that has a high probability of no occurrence in a region owing to unfavourable conditions as a consequence of acidification and eutrophication [55, Damages assessed].

CASES includes the following damages to be assessed and included in the analysis (Figure 4.2 on the facing page) [55].

[15] to remind: dispersion models are used to calculate the damage of transformed and transported air pollutants hundreds of kilometres away from source

| Impact Category | Pollutant / Burden | Effects |
|---|---|---|
| Human Health – mortality | PM10a), PM2.5b), $SO_2$, $O_3$ | Reduction in life expectancy due to short and long time exposure |
| | Heavy Metal (HM), Benzene, Benzo-[a]-pyrene1,3-butadiene Diesel particles, radionuclides | Reduction in life expectancy due to short and long time exposure |
| | Accident risk | Fatality risk from traffic and workplace accidents |
| | Noise | Reduction in life expectancy due to long time exposure |
| Human Health – morbidity | PM10, PM2.5, $O_3$, $SO_2$ | Respiratory hospital admissions |
| | PM10, PM2.5, $O_3$ | Restricted activity days |
| | PM10, PM2.5, CO | Congestive heart failure |
| | Benzene, Benzo-[a]-pyrene1,3-butadiene, Diesel particles, radionuclides, Heavy Metal (HM) | Cancer risk (non-fatal)Osteroporosia, ataxia, renal dysfunction |
| | PM10, PM2.5 | Cerebrovascular hospital admissions, Cases of chronic bronchitis, Cases of chronic cough in children, Cough in asthmatics, Lower respiratory symptoms |
| | Mercury | Loss of IQ of children |
| | $O_3$ | Asthma attacksSymptom days |
| | Noise | Myocardial infarction, Angina pectoris, Hypertension, Sleep disturbance |
| | Accident risk | Risk of injuries from traffic and workplace accidents |
| Building Material | $SO_2$, Acid deposition | Ageing of galvanised steel, limestone, mortar, sand-stone, paint, rendering, and zinc for utilitarian buildings |
| | Combustion particles | Soiling of buildings |
| Crops | $NO_x$, $SO_2$ | Yield change for wheat, barley, rye, oats, potato, sugar beet |
| | $O_3$ | Yield change for wheat, barley, rye, oats, potato, rice, tobacco, sunflower seed |
| | Acid deposition | Increased need for liming |
| | N, S deposition | Fertilising effects |
| Global Warming | $CO_2$, $CH_4$, $N_2O$ | World-wide effects on mortality, morbidity, coastal impacts, agriculture, energy demand, and economic impacts due to temperature change and sea level rise |
| Amenity losses | Noise | Amenity losses due to noise exposure |
| Ecosystems | Acid deposition, nitrogen deposition, $SO_2$, $NO_x$, $NH_3$ | Acidity and eutrophication, 'PDF' of species |
| Land use Change | | 'PDF' of species |

Figure 4.2.: Damages assessed in the analysis

A list with the whole CASES inventory can be downloaded from the CASES webpage [146]. Excursion: inventory for LCA see: [135, pp. 54-65]

### 4.1.2. Results

In this subsection some results provided by CASES, a project that uses the ExternE methodology, are described. The part 4.1.2.1 presents the private costs of electricity-generating technologies and divides them into their subcategories. In Part 4.1.2.2 on page 81 external cost structures of typical power plants are analyzed and compared with wind energy and the major impact categories are presented. This is essential, because economic activities are often calculated or valued without externalities. Finally, the private and external costs together are what are referred to as social costs, which is shown in part 4.1.2.3 on page 85.

In CASES, a wide set of power plant technologies have been analyzed. In these sections the set has been reduced to a smaller, but expressive range of electricity-generating technologies:

1. Anthracite (hard coal) (and CHP technology) and lignite
2. Natural gas (and CHP technology)
3. Heavy oil
4. Biomass as CHP technology
5. Wind onshore and offshore
6. Solar (open space)
7. Hydro-electric-power
8. Nuclear power[16]

Table A.5 on page 175 with technology data for each power plant[17] is presented in A on page 175 in the appendix [146].

#### 4.1.2.1. Private costs

Often, only the economic point of view in cost assessments is analyzed. So, regularly, renewable energy is seen as an economically inefficient and expensive technology, and its benefits as a clean technology (less environmental pollution) are simply disregarded. A coal or gas power plant works more efficiently and saves a lot of money, compared with an expensive (i.e. with marginal costs) wind power plant with lower power output.

Business administration uses investment appraisal, which is a preliminary stage to the internal investment appraisal which does not include externalities[18] [168]. The methodology of CASES is to find the private costs as a summation of a subset of costs, which are

[16] a few externalities, e.g. accident risks have been excluded in a number of analyses
[17] capacity, lifetime, full load hours, efficiency
[18] firms to not have to pay for polluting the environment

*investment costs*, *operation and maintenance costs*, *fuel costs*, *$CO_2$-transport and storage costs*, as well as *backup costs* for renewable energy sources. In Figure 4.3, it can be seen that the electricity which is generated in conventional power plants is much cheaper than the electricity generated from most of the renewable energy sources. However, wind

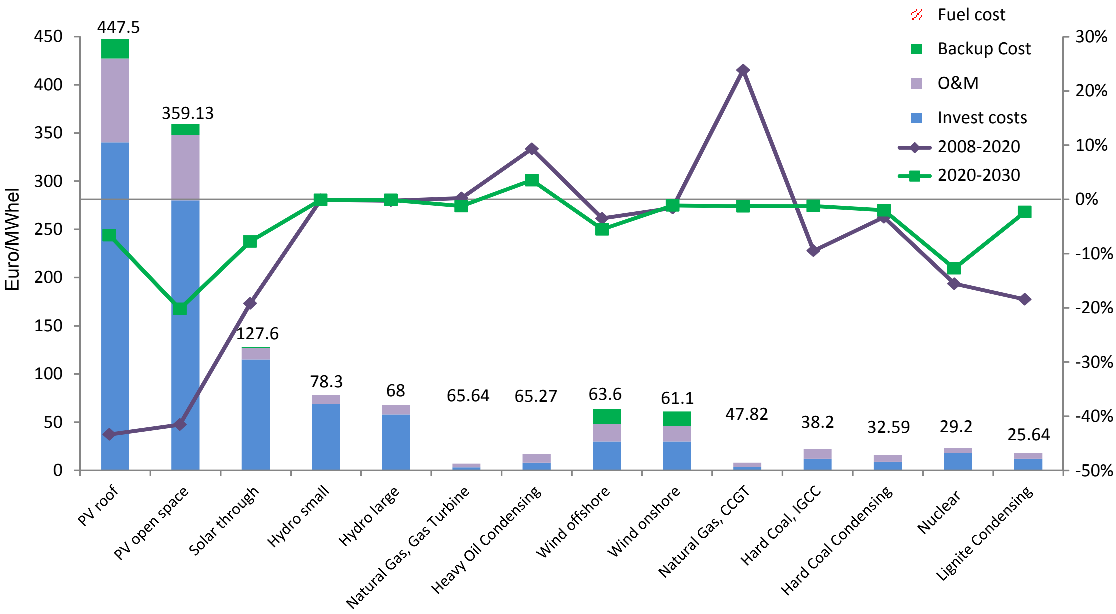



Figure 4.3.: Private cost of conventional and renewable electricity-generating technology (2008) and shifts from 2008–2020 and 2020–2030

power does compete with gas and oil power plants. Lignite plants have the lowest specific private costs per MWh electricity generated, whereas especially natural gas power plants and oil power plants, with their low investment and operating costs, have a very high share of fuel costs. A natural gas power plant can provide electricity in base and in peak loads with acceptable production costs. Renewable energy shows higher private costs, which are a result of the shorter lifetime and lower full loading hours as a consequence of volatile generating processes. Hydro-electric-power has a maximum lifetime of 30 years, whereas a wind turbine can function for approximately 20 years with full loading hours of 2,700 hours for onshore, and 4,100 hours for offshore plants. Offshore power plants have higher investment costs (4100 EUR/kW) than onshore plants (2600 EUR/kW), but in offshore areas wind speeds are higher and with fewer turbulences. Solar-generating technologies, with a low net efficiency of 15%, have developed into a mature technology with the acceptable costs of 127 EUR/MWh in 2008, and the costs are expected to decrease in future[19] to the estimated 94 EUR/MWh. It can be seen that the costs per generated power (e.g. kilowatt hours per year) vary enormously. This depends on the efficiency of each technology. For instance, a comparison of offshore wind power with photovoltaics shows big differences in the diagram of the private costs (64 EUR/MWh

[19]calculated for 2020 and 2030 with a discount rate of 5%

for wind and 447 EUR/MWh for PV) for 2008. Wind energy is the cheapest renewable technology at present, and it will be also in the future. The shift of private costs from 2005 to 2020, and 2020 to 2030 was analyzed: Here it can be seen that private costs for some renewable energy sources, PV and solar, will become less in the future. It is unlikely that the private costs of conventional plants, such as those based on coal or gas, will be reduced very much, if at all, because of the increasing fuel costs to be expected in the future.

Renewable energy sources do not need any fuel, and so their investment costs will decrease until 2030. Oil power plants may even have a positive shift (as a consequence of high oil prices in future), although an assumed discount rate of 5%[20]. Private costs are calculated using the average levelled generating costs methodology [104, p. 140]. [104, pp. 122-139]

The *Sustainable Development Commission* reported the effect of the discount rate on the costs of electricity generation in the United Kingdom. They presented the generation costs for wind and gas power plants with two test discount rates, the difference between the two technologies with a discount rate of 5% is only 0.3 p/kWh (wind: 2.4 p/kWh, gas: 2.1 p/kWh), whereas the gap between wind and gas widens to 0.9 p/kWh (wind: 3.2 p/kWh gas: 2.3 p/kWh) with a discount rate of 10% [165, pp. 27 sq.]. The Commission also compared different calculations (different discount rates, life time, etc.) of generation costs and summarized these. The result is a range of electricity generation costs from 2.65 p/kWh up to 3.3 p/kWh for onshore, and 3.2 p/kWh to 5.7 p/kWh for offshore plants [165, p. 30]. An important effect on private costs is shown by the wind speed available for the generation: An increase in wind speed of 1 m/s can reduce generation costs by around 25% [165, p. 29].

A very interesting issue is the estimated additional cost, in total, of adding specified amounts of renewable energy to an electricity network. This so-called *system cost* depends on the estimated cost of wind power (higher installed cost and network upgrades) and the benefits (reduced conventional fuel use, less pollution/emissions). It is referred to as the *net additional cost* of electricity from the whole system when a certain percentage of wind power plants is added. Dale et al. evaluated the net additional cost of wind power by assuming it will make up 20% of the total UK electricity output by 2020 (full table in [165, p. 32]). They calculated a total extra cost of 0.3 p/kWh, which is equal to 5% increase on the current average domestic consumer electricity bill (6.0 p/kWh) in the UK [165, p. 32].

If the gas price is considered versus the net additional costs, it can be seen that when the gas price increases, the net additional cost of wind energy applications decreases. The progression of the lines which are almost linear show, in comparison the extra cost to the consumer of electricity with a 7.5% share of wind-generated electricity by 2010, and a 20% share of the same by 2020. With gas at 40p/therm. the extra cost would be 0.009p/kWh and 0.03 p/kWh, respectively, for the 20% share of the wind scenario

[20] the extreme increase of the CCGT gas turbine is related to the application of a CO2 capturing filter in future

[165, p. 33]. With regard to only the generating costs, this shows clearly that wind is competitive on the electricity market (see Figure 4.13 on page 91.

#### 4.1.2.2. External costs

The external costs of electricity-generating technologies are calculated using the methodology described in the previous subsection 4.1.1 on page 73. The average size of the release values per unit of the emission are multiplied by the quantity of the emissions per unit of the electricity generated (kg/kWh) [104, p. 141]. All of the impact categories are principally air pollutants, formaldehyde, some heavy metals and a set of radionuclides for the assessment of human health and effects on environment. All types of external costs are calculated in $Euro_{2000}$, which means that the values are actualized to 2005 using the average *EU Harmonized Indices of Consumer Prices*[21]. The external costs for each kWh electricity generated are subdivided into the four life-cycle stages *construction*, *fuel supply*, *operation* and *dismantling*[22]. To obtain the external costs, "[...]the marginal value per unit of emission is multiplied by the quantity of pollutants emitted at each production stage, per unit of electricity." [104, p. 142] Although the costs of damage caused by emissions of pollutants into the air, soil and water are included, some components are missing. As already mentioned, these are nuclear accidents and risk assessment[23], the cost of acidification of the aquatic environment and visual impacts [104, pp. 143–144]. Figure 4.4 on the next page shows how much the external costs are for a selection of power plants divided into a set of impact categories. Conventional power plants, such as those using hard coal, lignite, oil and gas, have high external costs (20 times higher than the average of those for renewable energy sources) whereas the costs of nearly every renewable technology (except solar open space) varies from 0.01 euro cents/kWh (hydro-electric-power larger 100MW) to 0.1 euro cents/kWh (wind). The highest impact shares in the power plant selection come within *human health* and *climate change*, as can be seen in Figure 4.4 on the following page. Nuclear power plants do not really reflect marginal external costs as they might be in reality, as accidents and risks are not included[24]. It is also interesting that biomass straw (counted in the study as CHP) has just as high external costs as gas turbines. The next Figure 4.5 on page 83 shows a list of all major pollutants for different electricity-generating technologies. It can be seen that conventional power plants emit primarily $CO_2$, $SO_2$ and $NO_x$ whereas renewable energy sources generate fewer emissions. The aggregation as a percentage value shows a different characteristic for each pollutant: Some renewable energy sources partially emit particles (particle pollution). Wind emits mainly $NO_x$, $SO_2$ and *Other pollutants*[25] and biomass plants produce more $NH_3$, for instance. It should not be forgotten that the absolute values (external costs) of renewable energy sources are many

[21] using a coefficient of 1.1095 calculated by using the HICOs from 2001-2005

[22] starting with a chain analysis, material and energy demand, waste and release of emissions, quantified in the LCA inventory

[23] an accident or war caused by nuclear weapons could cost billions of euro

[24] an accident can cost billions of euros, as in the recent case of Fukushima, Japan in 2011

[25] Other pollutants are: Arsenic, Cadmium, Chromium, Lead, Mercury and Nickel

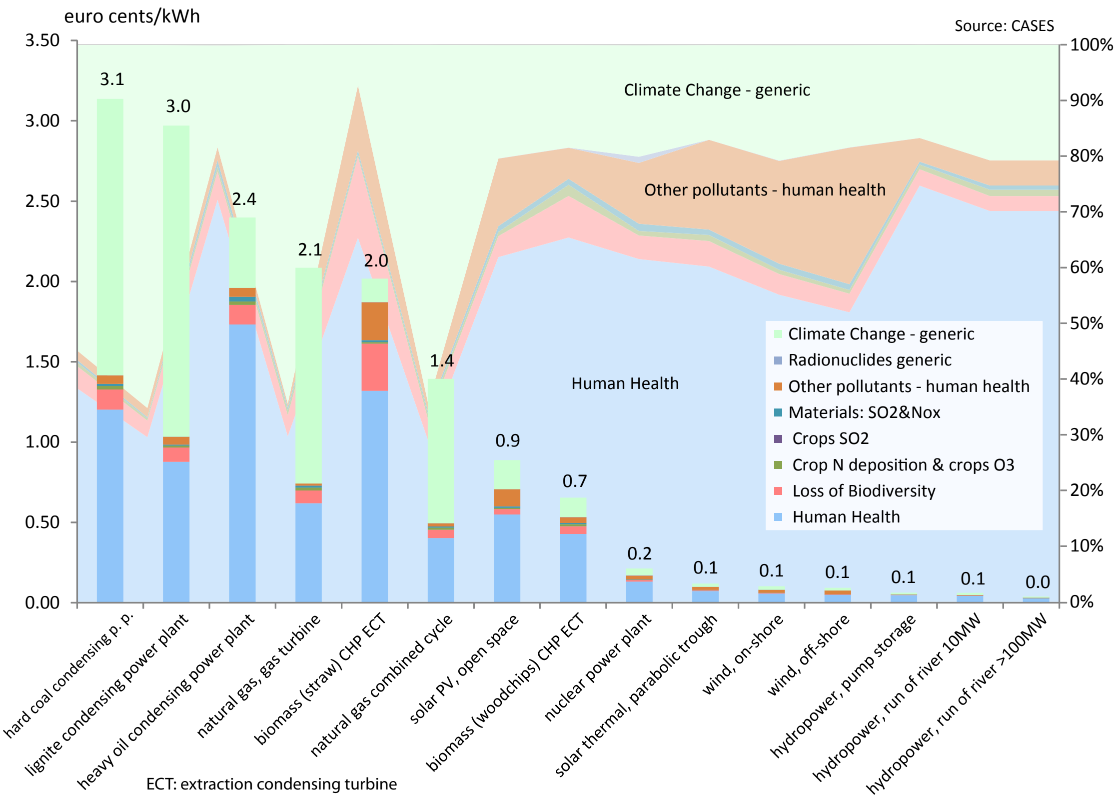



Figure 4.4.: EU27 - 2005–2010: Amount of external costs by impact categories

times lower than those of conventional electricity-generating technologies. If a look is taken at the external costs, with regard to the life-cycle stages, the shares of conventional power plants consist mainly of external costs in the fuel and operation cycle. Otherwise, external costs caused by renewable energy sources, such as wind, solar or hydro-electric-power can be accounted for the construction and operation phases, respectively. During the operation period, wind turbines show some of the same emissions that are emitted by conventional power plants, because some times a mix of energy is used from other sources which may include fossil fuel. This electricity consumption is responsible for sulphur dioxide as well as carbon dioxide pollution in the operation cycle[26]. This is presented in Figure 4.6 on the facing page. Detailed analyses for wind power are presented in section 5.2 on page 97. In Figure 4.7 on page 84 a further interesting view is given. It shows the amount (in g) of the most important emissions concerning the fuel-based electricity generation, which are $CO_2$, $SO_2$, $NO_x$ and $PM10$. Carbon dioxide is presented in an extra diagram (see Figure 4.8 on page 85) because of its high values in comparison to the other pollutants. Wind energy again has the fewest negative effects of all power plants, followed by hydro-electric-power. Solar energy emits more pollutants than the other renewable energy sources. Natural gas emits large quantities of carbon monoxide.

[26]Many studies do not take into consideration, which results in fewer impacts in the operation process

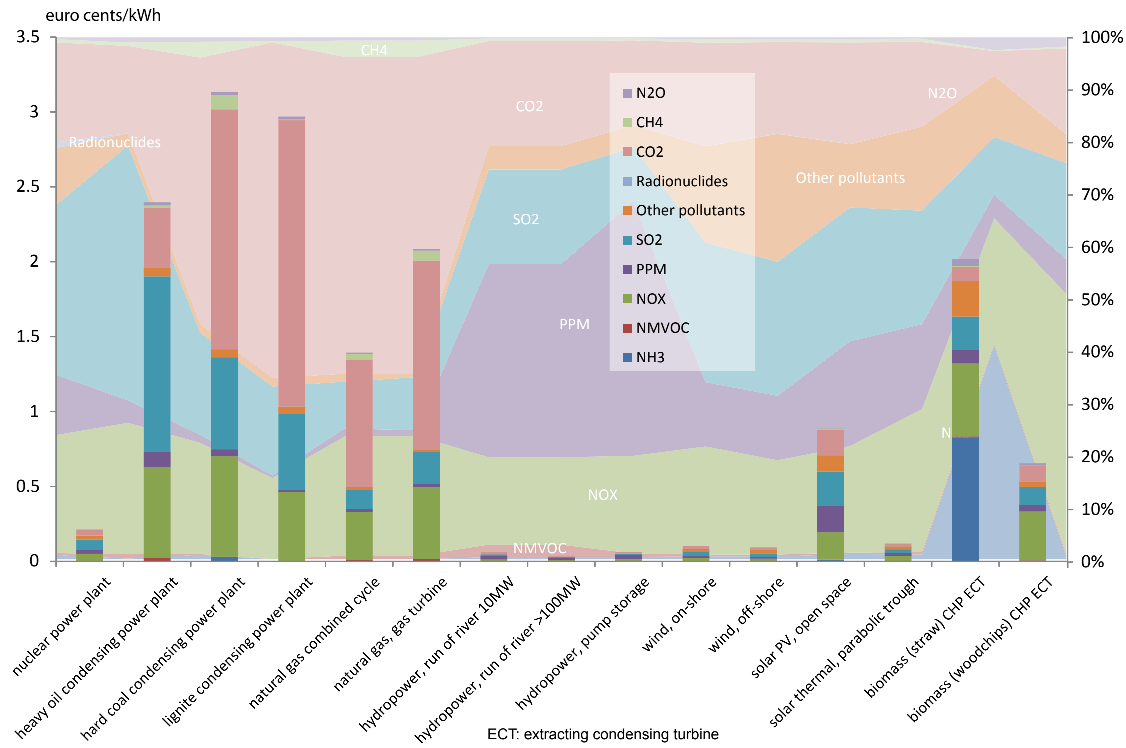



Figure 4.5.: EU27 - 2005–2010: Amount of external costs by pollutants (in euro cent/kWh and cumulative effect

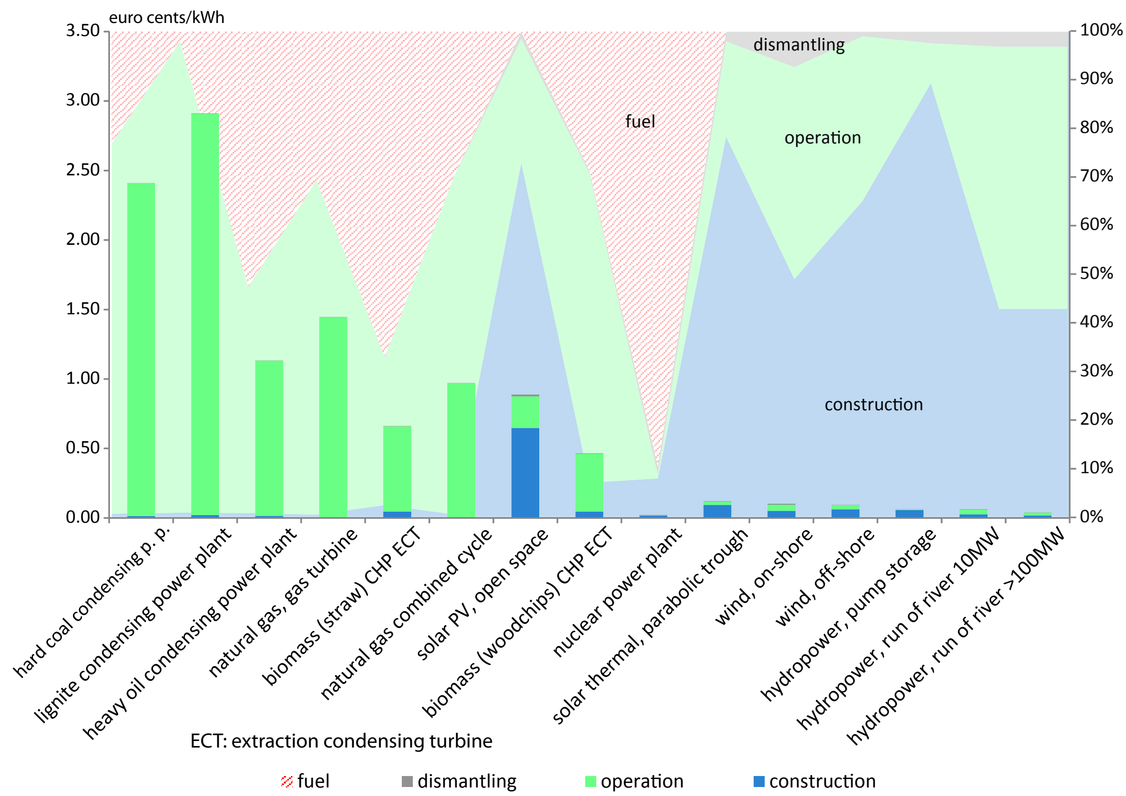





Figure 4.6.: External cost by live-cycle stages absolute (euro cent/kWh) and relative (per cent)

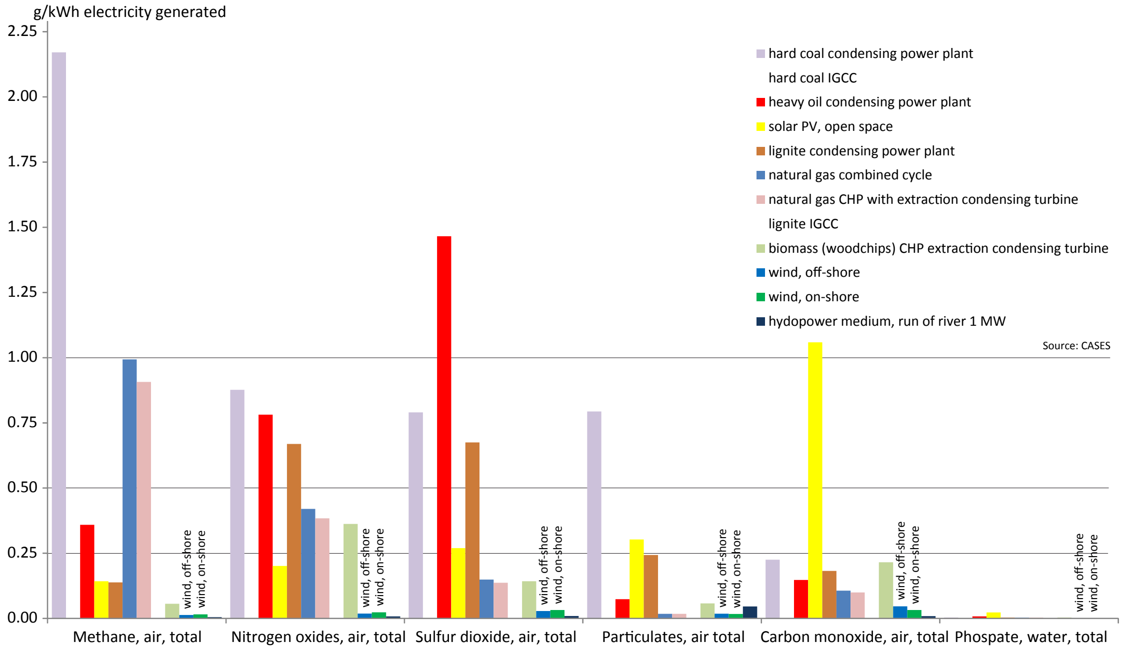



Figure 4.7.: CASES: Inventory selection of air and water pollutants for 2007

The emissions of conventional power plants are caused mainly by the burning of (fossil) fuels. It can be seen clearly that the negative effects on humans impacts are caused primarily by thermal power plants. The carbon dioxide diagram proves that, too. Conventional power plants are responsible for the emission of great quantities of pollutants. Biomass has the highest output of $CO_2$. Figure 4.8 on the facing page shows clearly that conventional technology in the future (CO2-capturing filters, ICGG) can decrease the emission of $CO_2$. Combined heat and power technology reduces $CO_2$ to some extent. Since wind energy has fewer impacts on the environment than other electricity-generating technologies, the environmental effects of wind energy are discussed in more detail in the next Chapter 5 on page 93.

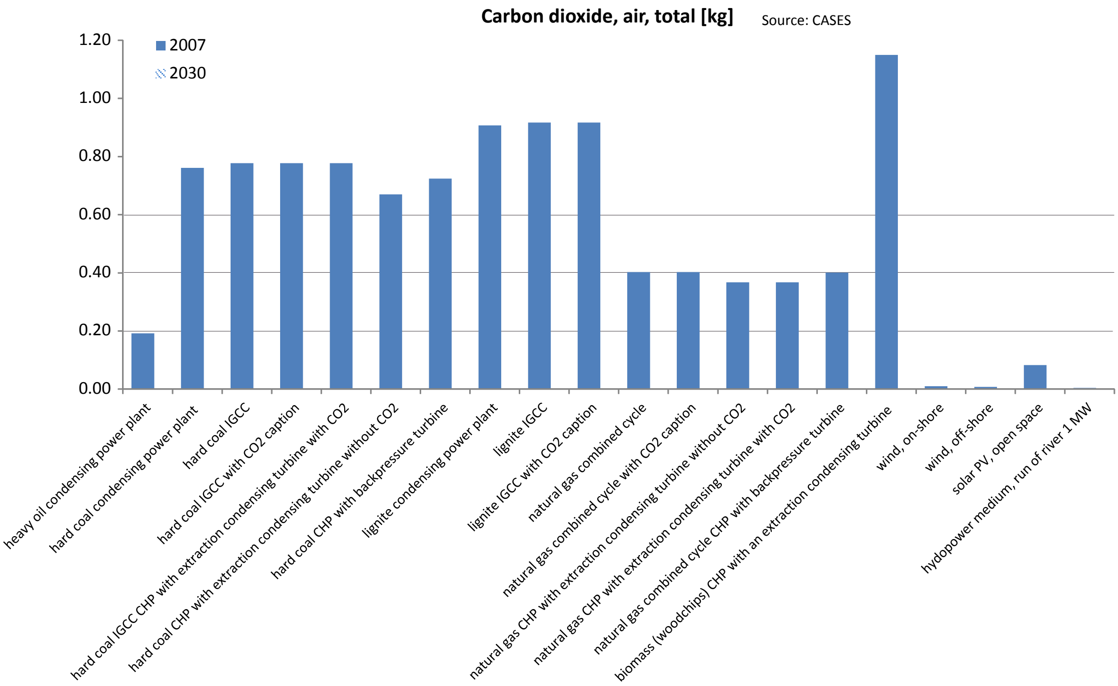



Figure 4.8.: Inventory: Carbon Dioxide change from 2007-2030

#### 4.1.2.3. Social costs

One of the major objectives of the project CASES was the evaluation of full costs. By adding all of the external costs to the private costs, the amount of the social costs of electricity generation are obtained and expressed in euro cent per kilowatt hour. The results for the period 2005–2010 are shown in Figure 4.9 on the following page. The accurate values for 2005–2010, as well as projections to 2020 and 2030 are presented in Figure 4.10 on page 87. Whereas conventional power plants were thought of as an economic efficient set of technologies as far as their private costs were concerned, the aggregation of external costs changed the situation. Renewable energy sources are not the most expensive technologies any longer. Even wind energy costs less than that produced in hard coal or natural gas power plants. The use of wind power has developed to become a relatively inexpensive and sustainable technology with social and environmental advantages (with the full costs of 6.2 euro cents per produced kilowatt-hour – compared with natural gas whose full costs are 6.6 euro cents/kWh). Nevertheless, CHP's efficiency will increase in the next few decades because the combined heat-and- power producing cycle makes use of the emitted heat produced in the generation of electricity. Photovoltaics cannot compete with all the other technologies because their full costs are much higher than the electricity market prices, which is why photovoltaics require subsidies, for example eco-power taxes. If an eco-power tax is a correct solution, is not discussed in this thesis[...]. Figure 4.9 on the following page also shows the average market prices traded at the energy exchange for 2011 (ranging from 3.0 cents/kWh to 7.0 cents/kWh) and the

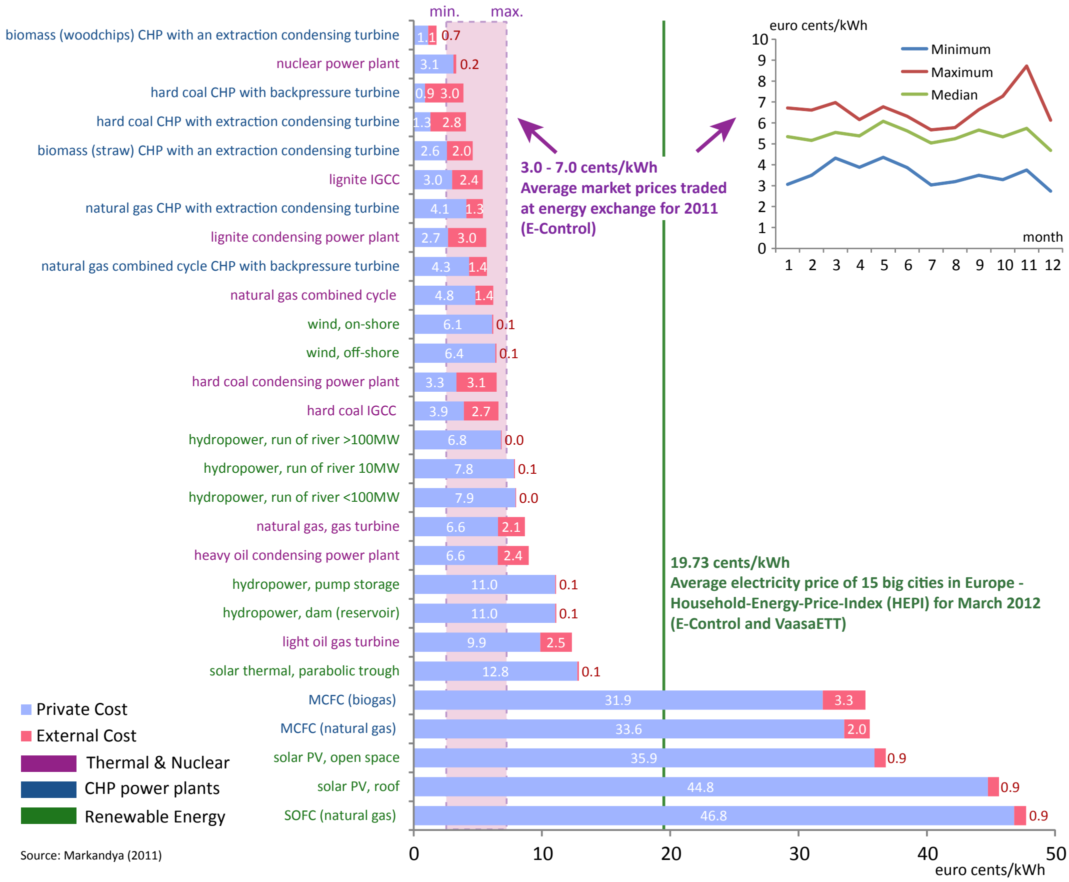



Figure 4.9.: Social cost of electricity-generating technologies 2005-2010

average electricity price for consumers of 19,73 cents/kWh. The former shows clearly that wind energy is situated in the range of prices traded at the energy exchange (the same is the case for hydro-electric-power). There are only a few electricity-generating technologies that exceed the electricity price for consumers: PV, SOFC, and MCFC. All of the other power plants have full costs beneath 19.72 cents/kWh and are thus highly competitive on the market. All in all, if all costs (total costs) are considered to the electricity-generating process, renewable energy, especially wind energy gains increasing acceptance in the electricity industry. In other words, "the benefits of wind energy are avoided emissions and avoided external costs as compared with conventional, mainly fossil-fuel based, electricity generation." [5] Wind energy has less impacts compared to all other technologies, but how much is the hazard potential and how do impacts develop on a site? This is discussed in more detail in the next two chapters.

| Source: CASES, ExternE | Data in euro cents/kWh | 2005-2010 | | | 2020 | | | 2030 | | | Change 2005-2020 | | | Change 2020-2030 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | T.Ext | T.Priv | Full | T.Ext | T.Priv | Full | T.Ext | T.Priv | Full | T.Ext | T.Priv | Full | T.Ext | T.Priv | Full |
| CHP | natural gas CHP with extraction condensing turbine without CO2 capture | 1.28 | 4.12 | 5.39 | 1.35 | 4.37 | 5.72 | 1.77 | 4.40 | 6.17 | 6% | 6% | 6% | 31% | 1% | 8% |
| | natural gas CHP with extraction condensing turbine with CO2 capture | 1.28 | 4.12 | 5.39 | 0.85 | 6.37 | 7.22 | 1.04 | 6.32 | 7.36 | -33% | 55% | 34% | 23% | -1% | 2% |
| | hard coal CHP with extraction condensing turbine without CO2 capture | 2.76 | 1.31 | 4.07 | 2.98 | 1.34 | 4.31 | 3.82 | 1.39 | 5.21 | 8% | 2% | 6% | 28% | 4% | 21% |
| | hard coal CHP with extraction condensing turbine with CO2 capture | 2.76 | 1.31 | 4.07 | 1.13 | 3.12 | 4.26 | 1.40 | 3.09 | 4.48 | -59% | 139% | 5% | 23% | -1% | 5% |
| | natural gas combined cycle CHP with backpressure turbine | 1.39 | 4.31 | 5.71 | 1.57 | 4.27 | 5.83 | 2.06 | 4.24 | 6.31 | 13% | -1% | 2% | 32% | -1% | 8% |
| | hard coal CHP with backpressure turbine | 2.99 | 0.89 | 3.88 | 3.28 | 0.91 | 4.19 | 4.21 | 1.04 | 5.25 | 10% | 2% | 8% | 28% | 15% | 25% |
| | biomass (straw) CHP with an extraction condensing turbine | 2.02 | 2.59 | 4.61 | 2.19 | 2.18 | 4.37 | 2.62 | 2.18 | 4.80 | 8% | -16% | -5% | 20% | 0% | 10% |
| | biomass (woodchips) CHP with an extraction condensing turbine | 0.65 | 1.13 | 1.79 | 0.82 | 0.98 | 1.80 | 0.99 | 0.98 | 1.97 | 25% | -14% | 1% | 21% | 0% | 10% |
| | MCFC (natural gas) | 2.00 | 33.55 | 35.55 | 2.43 | 13.34 | 15.77 | 2.65 | 7.26 | 9.91 | 22% | -60% | -56% | 9% | -46% | -37% |
| | SOFC (natural gas) | 0.94 | 46.80 | 47.73 | 0.99 | 11.55 | 12.54 | 1.23 | 7.02 | 8.25 | 5% | -75% | -74% | 25% | -39% | -34% |
| | MCFC (biogas) | 3.33 | 31.88 | 35.21 | 4.03 | 13.23 | 17.26 | 4.39 | 6.36 | 10.75 | 21% | -59% | -51% | 9% | -52% | -38% |
| Thermal & Nuclear | nuclear power plant | 0.21 | 3.10 | 3.32 | 0.14 | 2.62 | 2.76 | 0.11 | 2.28 | 2.40 | -34% | -16% | -17% | -19% | -13% | -13% |
| | heavy oil condensing power plant | 2.40 | 6.57 | 8.96 | 3.00 | 7.19 | 10.19 | 3.64 | 7.46 | 11.10 | 25% | 10% | 14% | 22% | 4% | 9% |
| | light oil gas turbine | 2.47 | 9.87 | 12.34 | 2.93 | 10.08 | 13.01 | 3.68 | 10.34 | 14.03 | 19% | 2% | 5% | 26% | 3% | 8% |
| | hard coal condensing power plant | 3.14 | 3.33 | 6.47 | 3.30 | 3.23 | 6.52 | 4.14 | 3.16 | 7.30 | 5% | -3% | 1% | 26% | -2% | 12% |
| | hard coal IGCC without CO2 capture | 2.70 | 3.91 | 6.61 | 2.48 | 3.54 | 6.03 | 3.27 | 3.50 | 6.77 | -8% | -9% | -9% | 32% | -1% | 12% |
| | hard coal IGCC with CO2 capture | 2.70 | 3.91 | 6.61 | 1.47 | 4.20 | 5.66 | 1.79 | 4.16 | 5.95 | -46% | 7% | -14% | 22% | -1% | 5% |
| | lignite condensing power plant | 2.97 | 2.68 | 5.65 | 2.97 | 2.18 | 5.15 | 3.94 | 2.14 | 6.07 | 0% | -19% | -9% | 33% | -2% | 18% |
| | lignite IGCC without CO2 capture | 2.38 | 3.00 | 5.38 | 2.13 | 2.83 | 4.96 | 2.91 | 2.77 | 5.68 | -10% | -6% | -8% | 36% | -2% | 15% |
| | lignite IGCC with CO2 capture | 2.38 | 3.00 | 5.38 | 0.76 | 3.39 | 4.15 | 0.94 | 3.34 | 4.28 | -68% | 13% | -23% | 24% | -1% | 3% |
| | natural gas combined cycle without CO2 capture | 1.39 | 4.81 | 6.20 | 1.45 | 4.58 | 6.04 | 1.90 | 4.54 | 6.43 | 4% | -5% | -3% | 30% | -1% | 7% |
| | natural gas combined cycle with CO2 capture | 1.39 | 4.81 | 6.20 | 0.92 | 5.98 | 6.90 | 1.12 | 5.91 | 7.03 | -34% | 24% | 11% | 22% | -1% | 2% |
| | natural gas. gas turbine | 2.08 | 6.58 | 8.66 | 2.29 | 6.60 | 8.89 | 2.95 | 6.53 | 9.48 | 10% | 0% | 3% | 29% | -1% | 7% |
| Renewable Energy | hydropower, run of river 10MW | 0.06 | 7.83 | 7.90 | 0.07 | 7.83 | 7.91 | 0.09 | 7.83 | 7.92 | 17% | 0% | 0% | 23% | 0% | 0% |
| | hydropower, run of river <100MW | 0.04 | 7.93 | 7.98 | 0.05 | 6.80 | 6.85 | 0.06 | 6.80 | 6.86 | 17% | -14% | -14% | 23% | 0% | 0% |
| | hydropower, run of river >100MW | 0.04 | 6.81 | 6.85 | 0.05 | 6.80 | 6.85 | 0.06 | 6.80 | 6.86 | 17% | 0% | 0% | 23% | 0% | 0% |
| | hydropower, dam (reservoir) | 0.08 | 11.04 | 11.12 | 0.09 | 11.04 | 11.13 | 0.11 | 11.04 | 11.15 | 18% | 0% | 0% | 22% | 0% | 0% |
| | hydropower, pump storage | 0.06 | 11.04 | 11.10 | 0.07 | 11.04 | 11.11 | 0.09 | 11.04 | 11.13 | 19% | 0% | 0% | 22% | 0% | 0% |
| | wind on-shore | 0.10 | 6.11 | 6.21 | 0.07 | 6.02 | 6.09 | 0.07 | 5.96 | 6.03 | -30% | -1% | -2% | 5% | -1% | -1% |
| | wind off-shore | 0.09 | 6.36 | 6.46 | 0.07 | 6.14 | 6.21 | 0.07 | 5.81 | 5.88 | -26% | -3% | -4% | 7% | -5% | -5% |
| | solar PV roof | 0.87 | 44.76 | 45.63 | 0.80 | 25.14 | 25.94 | 0.91 | 23.48 | 24.39 | -8% | -44% | -43% | 13% | -7% | -6% |
| | solar PV open space | 0.89 | 35.91 | 36.80 | 0.82 | 20.83 | 21.65 | 0.93 | 16.58 | 17.51 | -8% | -42% | -41% | 13% | -20% | -19% |
| | solar thermal parabolic trough | 0.12 | 12.76 | 12.88 | 0.11 | 10.30 | 10.41 | 0.11 | 9.50 | 9.61 | -5% | -19% | -19% | -3% | -8% | -8% |

Figure 4.10.: Social costs of electricity-generating technologies

## 4.2. On the comparison of different research findings

In general, the fossil-fuel cycle of electricity generation demonstrates the highest values of external effects and external costs (hard coal, lignite, peat, oil and gas), of which gas is the least damaging. In the ExternE studies, nuclear and renewable energy are shown to have the lowest externalities or cause the least damage, respectively. But what results do other research findings offer concerning the costs of electricity generation? Several studies have been carried out by different institutions and companies in order to quantify the environmental effects of energy systems. However, the ExternE framework is one of the latest and largest research works that have been carried out for the whole of Europe, yet. After widespread research in the relevant literature, the author came to the decision that the ExternE approach delivers high-quality results with its assumptions, (dispersion-) models and data inventories to a considerable extent. Other studies concentrate on an improved impact assessment for a small selection of power plants, for instance. LCAs are often carried out on energy technologies. Their focus depends on the author and his interests as represented within these studies. The range of inputs and outputs disperses, too. Ottinger et al. specialized in the assessment of severe accidents related to nuclear power plants [9]. Vestas concentrates on life-cycle-assessments on onshore and offshore wind turbines, sometimes compared with analyzed environmental impacts produced by average European electricity, using data from the Danish method for environmental design of industrial products (EDIP) database. But this is only used to see the order of magnitude in the differences of environmental impacts [7; 145], shown in Figure 4.11. Another aspect is that some analyses do not focus on the whole cause-and-effect chain. Vestas focuses only on the so-called *midpoints*, whereas ExternE calculates impacts on category *end-points* (see again Figure 2.15 on page 41).

> This means that they aggregate data on emissions (the starting points in the cause-effect chain) and characterize their potential impacts in various categories (e.g. global warming, acidification, etc.), but do not go as far as to assess the endpoints, such as loss of biodiversity, damage to human health, etc. caused by these impacts. As such, the impact assessment results that were obtained are relative expressions and do not predict impacts on category end-points, the exceeding of thresholds, safety margins or risks [65, p. 35].

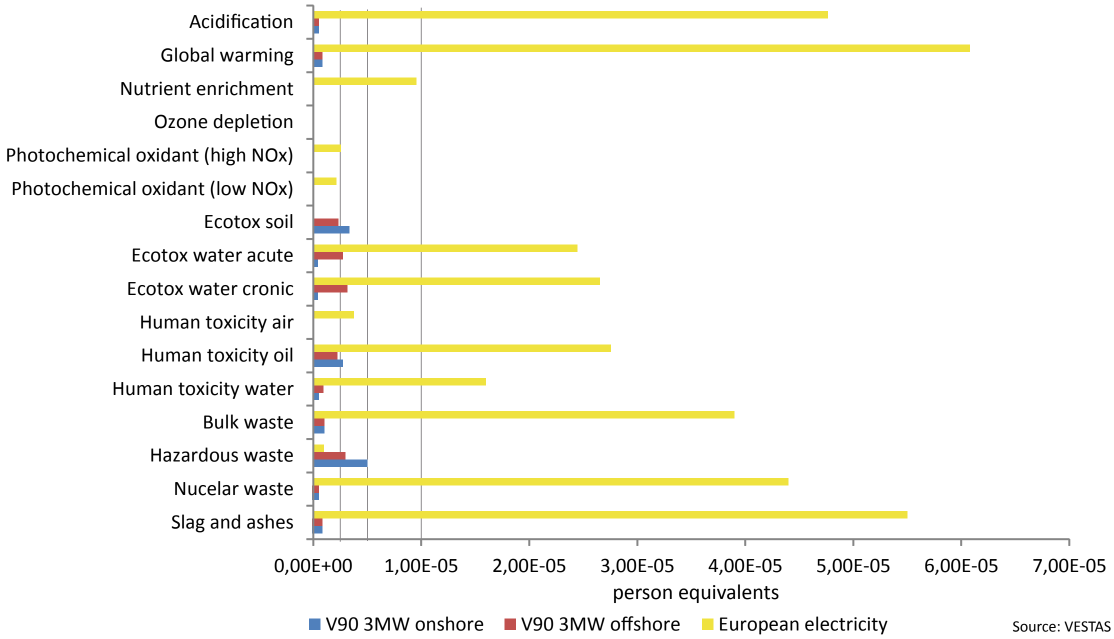



Figure 4.11.: Comparison of 1 kWh from V90-3.0 offshore, V90-3.0 onshore and European electricity

It is not easy to aggregate the results of different projects into one uniform unit, because each project uses different units, inventory inputs, models or assumptions. The transformation of different units is also very complicated, especially if currency units are

to be compared with eco-points or person equivalents. There is hardly any correlation or identifiable methods to convert eco-points into a currency unit, for instance. The simplest way to compare results is the use of eco-points or currency units (e.g. euro cents/kWh). An interesting presentation by Bras compared three well-documented and tested single score methods, the *Eco-Points method*, the *Environmental Priority System* and the *Eco-Indicator (95 & 99)* [29].
To compare different studies is a very complicated matter, because there are such a lot of factors (inputs, models, etc.) that vary from each other: [94, pp. 16-18; 55, FAQ]

- Discount rate
- Time frame
- Inventory (impacts included)
- Cost of climate change diverge from 5 $EUR/t_{CO2}$ to 300 $EUR/t_{CO2}$
- Type of equity weighting[27]
- Cost assessment: avoidance cost or willingness to pay
- Top down approach versus bottom up approach
- date of the study (up-to-dateness of technology developments)

The authors of studies always mention that there are some missing values in the assessment of the external costs of electricity-generating technologies. These impacts are often hard to assess, as shown in the matrix by Downing u. Watkiss (non-market impacts and socially contingent). For wind energy, these are impacts related often to visual intrusion (scenery, flickering), noise or effects on wildlife [94, pp. 18, 33].

## 4.3. The benefits of wind energy

It has been mentioned more than once in this thesis that wind turbines do have a benefit. But what does this actually mean? In a comparison of renewable energy with conventional electricity-generating technologies, it can be seen that former do not pollute the environment in the same way or to the same extent (if there are any emissions at all) as the latter. The most essential emissions concerning the fuel-based electricity generation are $CO_2$, $SO_2$, $NO_x$ and also $PM10$. Environmental benefits of wind electricity can be assessed in terms of avoided emissions compared to other alternative electricity generation technologies. Figure 4.7 on page 84 already showed that wind energy has less emissions compared to fuel-based electricity generation. To quantify the benefits of wind energy, the author subtracted the emissions from each power plant with the averaged emissions of an onshore and offshore wind power plant. The following emissions are considered from the CASES life-cycle inventory table [146]:

[27] the practice of assigning different values to currencies according to factors such as geographical location and climate [37]

- Carbon dioxide, air, total [g]
- Carbon monoxide, air, total [mg]
- Methane, air, total [mg]
- Nitrogen oxides, air, total [mg]
- NMVOC, unspecified origin, air, total [mg]
- Particulates, air total [mg]
- Sulphur dioxide, air, total [mg]
- Nitrate water, total [mg]
- Phosphate, water, total [mg]

Figure 4.12 on the facing page presents the benefits of wind energy (of relevant polluters) compared to other power plant technologies per kWh generated electricity. In other words, the emissions avoided by using wind farms to produce electricity instead of other technologies are shown. It can be seen that the traditional conventional power plants (using lignite, hard coal, gas), and also those plants with an extraction condensing turbine, IGCC or CHP emit very large quantities of pollutants in almost all emission categories. A comparison of electricity generation with wind turbines with other renewable energy systems shows very different results. Solar or biomass have more emission than wind power, hydro-electric-power has fewer impacts than wind (the difference between hydro-electric-power and wind is so small that it is negligible).

If the effect of including the social cost of carbon into estimates for the net system cost of wind energy (in this thesis introduced in part 4.1.2.1 on page 78) is taken into consideration, it will show decreasing system costs with regard to wind energy at 20% of the total output scenario[28]. Benefits would occur starting at a gas price of 30p/therm with costs of £19 per ton of released $CO_2$. For £38 per ton of discharged $CO_2$, benefits would occur starting at a gas price of 23p/therm [165, p. 36]. This is shown in Figure 4.13 on the facing page.

Another interesting result is presented in Figure 4.14 on page 92: Results are translated from Figure 4.10 on page 87 into comparative statistics of different sources of energy to obtain a view on how many times do private, external and full costs of the other power plants differ from wind energy. It can be seen that with regard to external costs only hydro-electric-power has fewer costs than wind power plants. The external costs (T.Ext.) of typical conventional power plants are about 14 to 30 times higher than wind power plants, and are expected to increase by 2020. In contrast, the private costs of wind energy are more expensive.

[28] in the report by the *Sustainable Development Commission*

| amount per kWh electricity generated | Carbon dioxide air, total [g] | Carbon monoxide, air. total [mg] | Methane air, total [mg] | Nitrogen oxides, air, total [mg] | NMVOC unspecified origin, air, total [mg] | Particulates air, total [mg] | Sulfur dioxide air, total [mg] | Nitrate water, total [mg] | Phospate water, total [mg] |
|---|---|---|---|---|---|---|---|---|---|
| wind on-shore | 9.78 | 32.57 | 15.83 | 23.55 | 4.18 | 17.24 | 32.46 | 1.33 | 0.78 |
| wind off-shore | 7.90 | 46.55 | 13.08 | 18.82 | 3.59 | 18.07 | 28.48 | 1.10 | 1.13 |
| *Wind average* | *8.84* | *39.56* | *14.45* | *21.19* | *3.89* | *17.66* | *30.47* | *1.22* | *0.96* |
| **Benefits of wind energy: Gap of emissions related to wind energy in the period 2005-2010 (CASES) - Calculation: Specific power plant minus wind average** | | | | | | | | | |
| nuclear power plant | 10.95 | -16.82 | 16.74 | 32.58 | 4.62 | 8.12 | 51.86 | -0.06 | -0.47 |
| heavy oil condensing power plant | 182.93 | 107.96 | 344.54 | 760.32 | 221.24 | 56.21 | 1,435.26 | 1.26 | 7.13 |
| light oil gas turbine | 414.30 | 149.50 | 410.33 | 630.05 | 274.70 | 62.77 | 959.85 | 0.85 | 1.31 |
| hard coal condensing power plant | 752.25 | 185.64 | 2,156.56 | 855.45 | 45.21 | 776.23 | 759.99 | 0.29 | 2.62 |
| hard coal IGCC | 768.70 | 118.13 | 2,205.00 | 495.86 | 39.46 | 766.78 | 439.27 | 0.31 | 2.73 |
| lignite condensing power plant | 898.50 | 142.78 | 123.73 | 648.22 | 6.10 | 225.70 | 644.66 | -0.37 | 2.36 |
| lignite IGCC | 908.48 | -23.43 | 124.56 | 210.71 | 6.01 | 194.29 | 248.35 | -0.37 | 2.28 |
| natural gas combined cycle | 393.57 | 67.22 | 979.19 | 399.10 | 101.85 | 0.27 | 118.65 | -0.55 | 2.16 |
| natural gas. gas turbine | 591.87 | 116.21 | 1,483.59 | 611.55 | 149.03 | 2.05 | 224.94 | -1.09 | 0.31 |
| hydopower small. run of river 200kW | -2.92 | -26.86 | -7.43 | -9.76 | 12.72 | 46.78 | -17.28 | -1.18 | 0.03 |
| hydopower large. run of river 50MW | -5.04 | -31.39 | -9.94 | -13.84 | 6.79 | 23.77 | -21.99 | -1.19 | -0.32 |
| hydopower. pump storage | -3.93 | -28.30 | -9.04 | -8.13 | 0.51 | 68.81 | -22.76 | -1.19 | -0.64 |
| solar PV roof | 74.59 | 763.29 | 130.32 | 171.92 | 26.31 | 197.30 | 292.19 | 1.93 | 14.28 |
| solar PV open space | 74.17 | 1,019.43 | 128.23 | 180.13 | 26.07 | 285.05 | 239.28 | 1.49 | 22.21 |
| solar thermal. parabolic trough | 0.53 | 36.38 | 3.68 | 15.35 | 2.57 | 9.83 | 0.46 | -1.05 | 0.85 |
| natural gas CHP ECT | 358.56 | 60.42 | 892.62 | 362.96 | 92.71 | 0.11 | 106.55 | -0.60 | 1.95 |
| hard coal CHP ECT | 661.23 | 158.21 | 1,896.96 | 750.56 | 39.30 | 681.16 | 665.33 | 0.11 | 2.18 |
| hard coal CHP backpressure turbine | 715.34 | 175.35 | 2,051.10 | 813.14 | 42.83 | 738.07 | 721.70 | 0.22 | 2.46 |
| biomass (woodchips) CHP ECT | 1,140.75 | 175.86 | 41.87 | 341.39 | 26.60 | 40.12 | 112.08 | -0.63 | 2.35 |
| MCFC (natural gas) | 136.48 | 337.57 | 1,956.15 | 590.41 | 250.78 | 129.54 | 894.35 | -0.38 | 3.15 |
| SOFC (natural gas) | 94.18 | 153.65 | 1,988.09 | 292.00 | 202.07 | 21.65 | 291.97 | -1.00 | 1.33 |
| MCFC (biogas) | 308.48 | 385.86 | 457.50 | 776.90 | 101.67 | 384.29 | 1,629.13 | 3.83 | 8.24 |

ECT: extraction condensing turbine
Source: CASES

Figure 4.12.: Emissions of relevant pollutants along the whole life cycle and benefits of wind versus other electricity-generating technologies

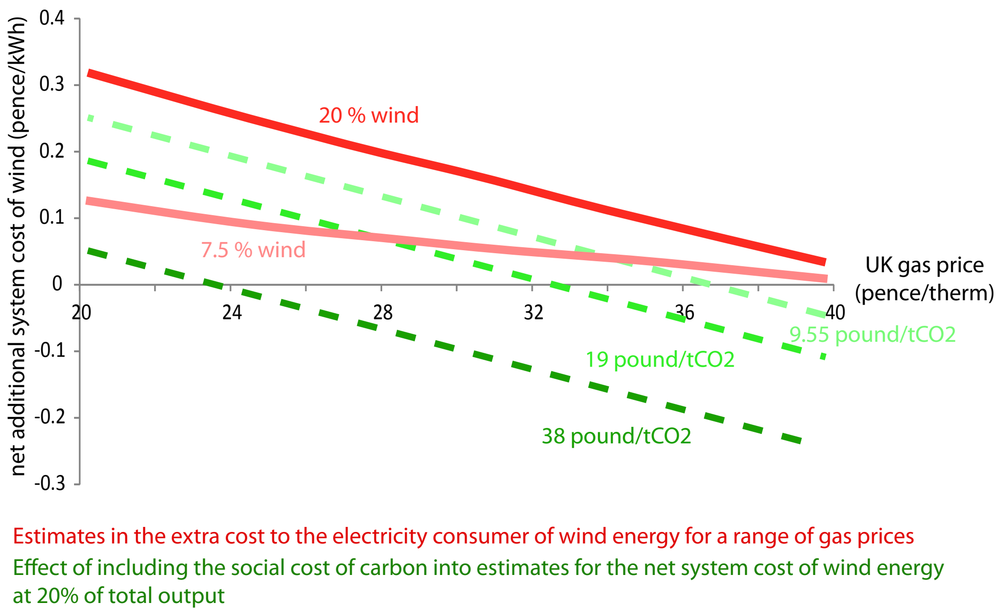



Figure 4.13.: Net additional generation cost of wind energy versus gas prices

Every value beneath 1 (T.Priv and Full) means that wind is more expensive when measured against the specific given factor 1[29]. For instance, an anthracite (hard coal) CHP power plant(value 0.2) is 5 times cheaper than wind energy with regard to the private costs and approximately two-thirds cheaper with regard to the full costs, but has 28 times more emissions with regard to the external costs. All in all, wind energy has few external costs but with regard to full costs it is more expensive than conventional electricity-generating technologies, except the natural gas turbine cycle and oil power plants[30].

| | | 2005-2010 | | | 2020 | | |
|---|---|---|---|---|---|---|---|
| | | T.Ext | T.Priv | Full | T.Ext | T.Priv | Full |
| CHP | natural gas CHP extraction condensing turbine no CO2 capture | 13.0 | 0.7 | 0.9 | 19.2 | 0.7 | 0.9 |
| | natural gas CHP extraction condensing turbine w ith CO2 capture | 13.0 | 0.7 | 0.9 | 12.1 | 1.0 | 1.2 |
| | hard coal CHP extraction condensing turbine no CO2 capture | 28.1 | 0.2 | 0.6 | 42.3 | 0.2 | 0.7 |
| | hard coal CHP extraction condensing turbine CO2 capture | 28.1 | 0.2 | 0.6 | 16.1 | 0.5 | 0.7 |
| | natural gas combined cycle CHP w ith backpressure turbine | 14.2 | 0.7 | 0.9 | 22.3 | 0.7 | 0.9 |
| | hard coal CHP w ith backpressure turbine | 30.5 | 0.1 | 0.6 | 46.6 | 0.1 | 0.7 |
| | biomass (straw ) CHP w ith an extraction condensing turbine | 20.6 | 0.4 | 0.7 | 31.1 | 0.4 | 0.7 |
| | biomass (w oodchips) CHP w ith an extraction condensing turbine | 6.7 | 0.2 | 0.3 | 11.6 | 0.2 | 0.3 |
| | MCFC (natural gas) | 20.3 | 5.4 | 5.6 | 34.5 | 2.2 | 2.6 |
| | SOFC (natural gas) | 9.5 | 7.5 | 7.5 | 14.0 | 1.9 | 2.0 |
| | MCFC (biogas) | 33.9 | 5.1 | 5.6 | 57.2 | 2.2 | 2.8 |
| Thermal & Nuclear | nuclear pow er plant | 2.2 | 0.5 | 0.5 | 2.0 | 0.4 | 0.4 |
| | heavy oil condensing pow er plant | 24.4 | 1.1 | 1.4 | 42.6 | 1.2 | 1.7 |
| | light oil gas turbine | 25.1 | 1.6 | 1.9 | 41.6 | 1.7 | 2.1 |
| | hard coal condensing pow er plant | 32.0 | 0.5 | 1.0 | 46.8 | 0.5 | 1.1 |
| | hard coal IGCC w ithout CO2 capture | 27.5 | 0.6 | 1.0 | 35.3 | 0.6 | 1.0 |
| | hard coal IGCC w ith CO2 capture | 27.5 | 0.6 | 1.0 | 20.8 | 0.7 | 0.9 |
| | lignite condensing pow er plant | 30.3 | 0.4 | 0.9 | 42.2 | 0.4 | 0.8 |
| | lignite IGCC w ithout CO2 capture | 24.3 | 0.5 | 0.8 | 30.3 | 0.5 | 0.8 |
| | lignite IGCC w ith CO2 capture | 24.3 | 0.5 | 0.8 | 10.8 | 0.6 | 0.7 |
| | natural gas combined cycle w ithout CO2 capture | 14.2 | 0.8 | 1.0 | 20.7 | 0.8 | 1.0 |
| | natural gas combined cycle w ith CO2 capture | 14.2 | 0.8 | 1.0 | 13.1 | 1.0 | 1.1 |
| | natural gas. gas turbine | 21.2 | 1.1 | 1.4 | 32.5 | 1.1 | 1.4 |
| Renewable Energy | hydropow er, run of river 10MW | 0.6 | 1.3 | 1.2 | 1.0 | 1.3 | 1.3 |
| | hydropow er, run of river <100MW | 0.4 | 1.3 | 1.3 | 0.7 | 1.1 | 1.1 |
| | hydropow er, run of river >100MW | 0.4 | 1.1 | 1.1 | 0.7 | 1.1 | 1.1 |
| | hydropow er, dam (reservoir) | 0.8 | 1.8 | 1.8 | 1.3 | 1.8 | 1.8 |
| | hydropow er, pump storage | 0.6 | 1.8 | 1.8 | 1.1 | 1.8 | 1.8 |
| | w ind, on-shore | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| | w ind, off-shore | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| | solar PV, roof | 8.9 | 7.2 | 7.2 | 11.4 | 4.1 | 4.2 |
| | solar PV, open space | 9.0 | 5.8 | 5.8 | 11.7 | 3.4 | 3.5 |
| | solar thermal, parabolic trough | 1.2 | 2.0 | 2.0 | 1.6 | 1.7 | 1.7 |

Figure 4.14.: Factors affecting costs and external benefits of wind energy

[29] factor 1 is wind power and the frequency of how often the costs exceed those of conventional power plants is expressed in relation to this factor

[30] wind competes with natural gas turbines and hydro-electric-power

# 5. The effects of wind turbines on the environment

The amount of external costs of wind energy compared with other electricity-generating technologies is discussed in chapter 4 on page 71. The impact pathway approach represents an advanced model for evaluating the costs of electricity based on a life-cycle assessment. The results of many studies show that wind energy has only a relatively low level of greenhouse gas emissions and thus greatly reduces air pollution[1]. Furthermore, wind turbines do not need any kind of fuel and so there are no environmental risks in connection with the entire business of using some kind of fuel[2]. Wind energy has the least external costs compared with other technologies. These environmental benefits of wind-generated electricity can be assessed in terms of avoided emissions (see 4.3 on page 89). Although wind energy is a clean technology (on account of the avoidance of emissions), it is not totally free of impacts on the environment and on human health. The construction and operation of wind turbines can have negative effects on the local environment. These are seen as site-related effects, which have to be considered before a project is started[3].

The most commonly discussed environmental effects of wind energy are visual intrusion, noise, indirect pollution in the process of manufacturing the turbines, land use, impacts on wildlife including birds as well as marine life. Although the environmental effects of wind power are fewer than those of conventional power plants, those that do exist have to be acknowledged, nonetheless. This chapter discusses and analyzes all the environmental concerns in the process of the entire life cycle of a wind turbine.

At first, a set of all the relevant impacts is introduced which is related to wind energy. In 5.2 on page 97, research that was carried out on life-cycle evaluation on onshore and offshore wind turbines is discussed, and the results are compared with other electricity-generating technologies[4] to understand more fully the environmentally relevant flows of energy and materials[5] (i.e. energy demand, material resources, wastes and emissions). The purpose of this section is to achieve a greater understanding of the effects on environment of the different phases of wind plant installations provided by the LCA methodology. Section 5.2 on page 97 enumerates and describes negative effects based on the site of a wind turbine (usually those impacts occurring in the operation stage). These

[1] these items are currently the main environmental problems discussed all over the world

[2] exploration, extraction, transport, shipment, processing or disposal of fuel

[3] and significant for spatial planning aims

[4] amount, level of detail and set of impacts assessed

[5] following an attributional approach, which focuses on quantifying the relevant environmental flows related to the wind power plant itself

site-related impacts are not generic issues[6] as they are identified usually by LCA and are not easy to quantify. They usually have to be determined in *Environmental Impact Assessments (EIA)* or *Strategic Environmental Assessments (SEA)*, qualitatively.

## 5.1. Impact overview

Figure 5.1 on page 96 is the result of widespread research. The idea is a complete list of all impacts related to the life cycle of a wind turbine, divided into two major impact categories. The first category deals with a so-called attributional approach[7]. The negative effects of wind energy are associated with the demand of material, resources and energy inputs and their release into the environment, considering all the stages of a wind turbine's lifespan based on the resource demand. This can result in several consequences, such as global warming, morbidity and mortality, as well as restrictions of land use, for example, the depletion of resources, degradation and destruction. The second impact category focuses on site-related issues. These are issues that concern the physical and social environment of humans, fauna and flora. Local influences on the environment are commonly caused by the operation of a power plant and are difficult to evaluate. A wind turbine has only a relatively low level of emissions – from resource and energy demand – which could be quantified and monetized into external costs, unlike the pollutants emitted by conventional power plants. For the latter there are still many research findings available. When a wind turbine operates it causes some effects on a neighbouring population (in both villages and animal habitats). It causes disturbances, such as visual intrusion, noise, restrictions on wildlife with regard to their way of life, or a barrier for migrating birds. Moreover, the presence of a wind turbine affects the local employment situation, land rights in correlation with the zoning plan, or the destruction of a cultural heritage site, which are sub-categorized as social impacts. A wind turbine can also have an effect on security (system failures, accidents) and economic and fiscal issues that have, to some extent, no connection with emissions. The difference between the two categories is that the first one is identified by the material and energy flows of resources, and the second one focuses on the effects allocated to the presence of the wind turbine at a specific location. The assessment of the first category is implemented commonly by LCA[8] whereas the assessment of impacts of the second category seems to be a difficult process (subjective, non-market values, etc.). A lot of software packages offer LCA, but many of them provide only a basic set of relevant guidelines in the database inventories, which are required for an ISO-certified implementation. Databases used in LCA software include *Ecoinvent*, *Gabi-Database*, *US LCI Database* or *European LCD* [134]. Some relevant negative effects of wind energy do not have to be included in an ISO-based implementation. Noise, for instance, was included in an ISO-based LCA and has subsequently been added to commercial software packages. Visual intrusion and other

[6] activities such as energy, materials or waste discharged into the environment

[7] an attributional approach focuses on quantifying the relevant environmental flows related to the wind power plant itself and describes the potential impacts of the power plant [65, p. 33]

[8] LCA is an widespread field of research

site-related impacts are still missing. These missing components bother the residents of a community and require significant consideration in EIAs [135, pp. 9–22].

Additionally, the author included the life-cycle stages extraction, construction, operation and dismantling in the illustration and assigned important relations between stages and impact categories for a better understanding. It is interesting that a lot of negative effects related to the operation of a wind turbine are not included in a life-cycle analysis. In an EIA or SEA these impacts are often assessed only qualitatively, which, however, is better than no treatment at all.

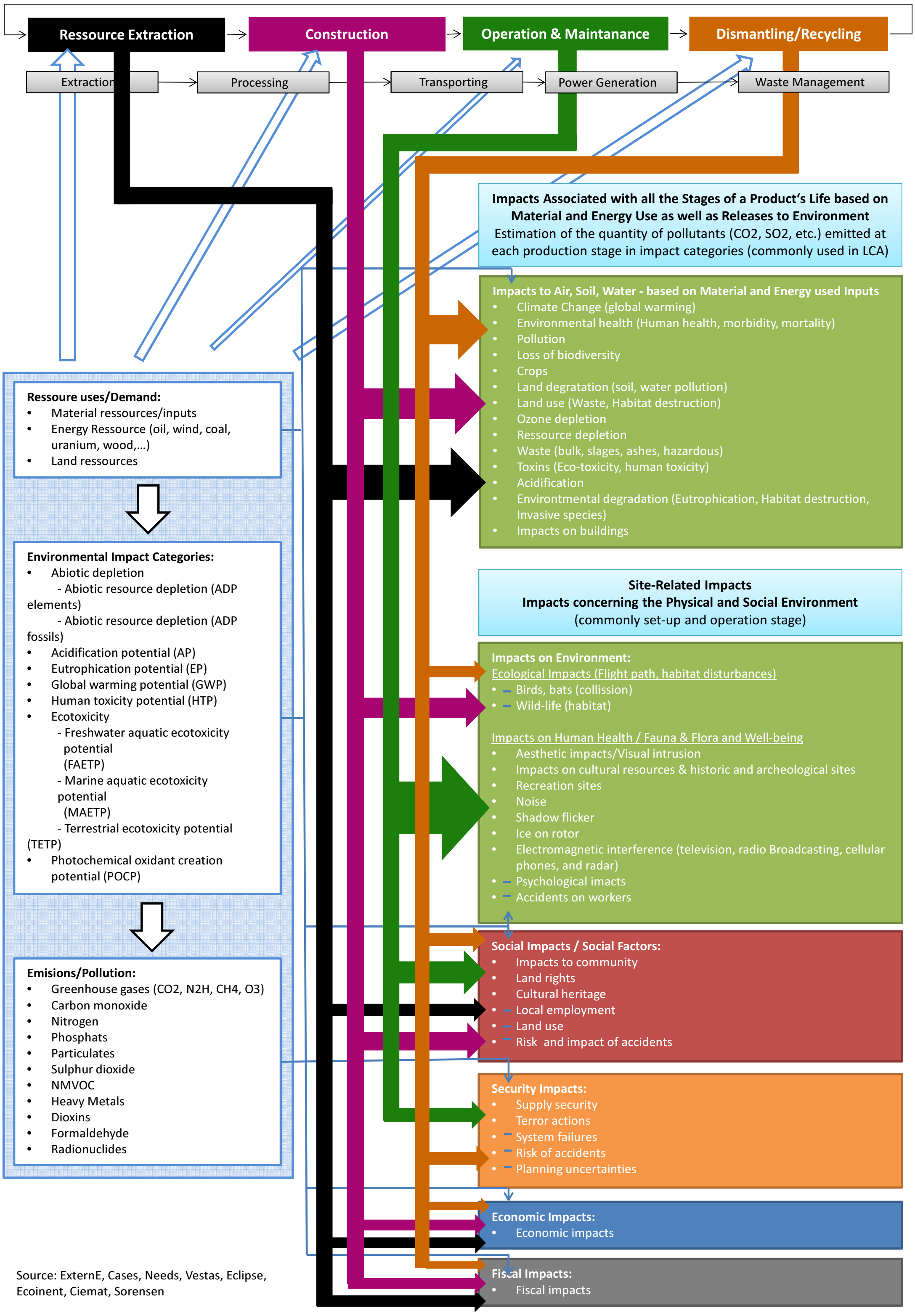



Figure 5.1.: View on impacts of wind energy

## 5.2. Life-cycle assessment on wind turbines - literature research and comparison

In this section, the negative environmental effects of wind energy are discussed in a more detailed fashion. Section 4 on page 71 already compared wind energy to other electricity-generating technologies. The external costs of wind are more or less negligible. Nevertheless, a close look at the externalities of wind power plants is taken, and the different results of the life-cycle approaches of impact assessment are discussed. To understand the full LCA process, it is recommended to review 2.5.2.2 on page 38).

### 5.2.1. The LCA concept on wind turbines

As already mentioned theoretically, a life-cycle assessment starts with the definition of a scope and a goal. The typical scope of a wind plant LCA is shown in Figure 5.2 on the following page. It includes all the components of the wind plant, which are referred to as from the *cradle-to-grave*, from the extraction of the raw materials, the manufacturing process, transport to the site, erection, putting into operation, the period of operation and the dismantling phase (when parts of the components are returned for new processing). Not to be forgotten:

> An LCA considers not only the direct emissions from wind farm construction, operation and dismantling, but also the environmental burdens and resources requirement associated with the entire lifetime of all the relevant upstream and downstream processes within the energy chain. [14]

The LCA stages of a wind turbine project carried out/conducted by VESTAS consists of the following components [143]:

- Manufacturing includes the production and transport of raw materials and the manufacture of wind plant components (foundations, towers, nacelles, blades, cables and the transformer station)[9]

- Wind plant set-up includes the transport of wind plant components to the construction site and construction work (e.g. provision of roads, working areas, turning areas, processes associated with laying the foundations, erecting the turbines, laying internal cables, installing/erecting the transformer station and connecting to the existing grid[10])

- Operation is the performance of the wind turbine plant including the change of oil, lubrication and renovation/replacement of worn parts (e.g. the gearbox) over the lifetime of the wind plant. Transport to and from the turbines for operation and maintenance purposes is included in this phase.

[9] The transport of raw materials to the specific production sites is not included within the scope of this study

[10] some of these activities are not included in this study

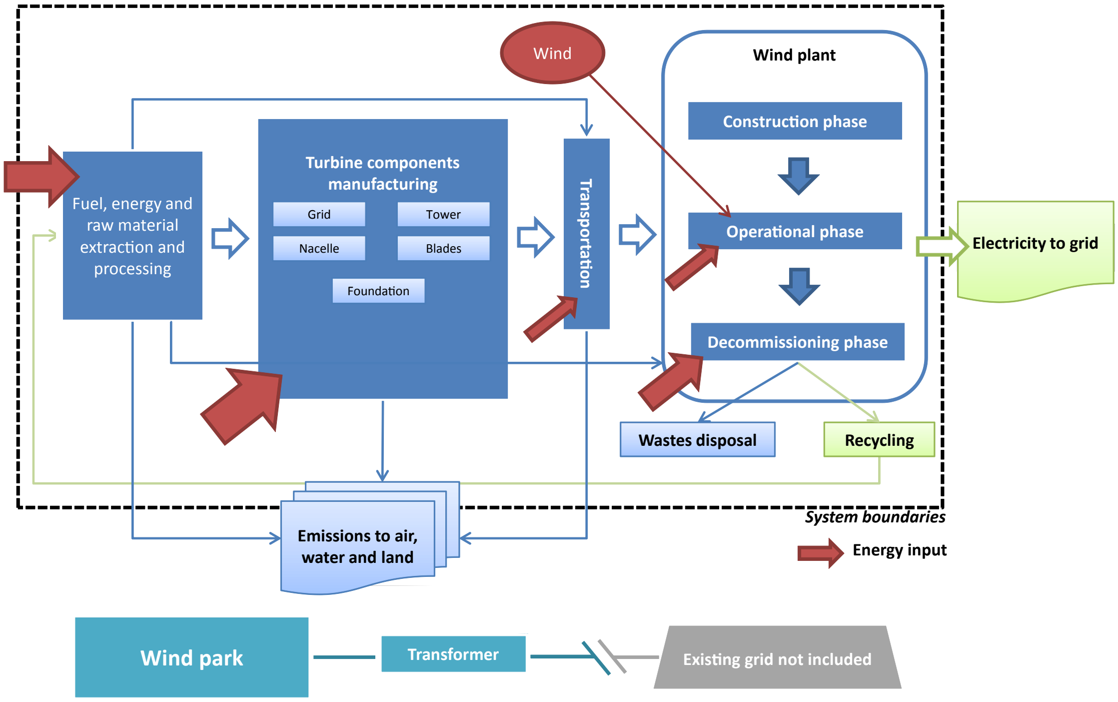



Figure 5.2.: Impacts of wind energy

- Termination (end-of-life) involves the dismantling of the wind turbine plant , the waste management of materials (recycling, incineration with energy recovery or by deposition in landfill sites)

Previous LCAs of wind turbines show that the most significant environmental impacts arise during the manufacturing (construction) phase and the dismantling of the turbine. Hence, a precise data collection is necessary including cranes, on-site vehicles and generators, as well as the transport of turbine components. Many LCA software packages deliver only the life-cylce inventory (i.e. amount of materials in kg), a view of primary data from the supplier and secondary data (to fill the gaps) might be significant. For instance, primary data for VESTAS wind components consist of (taken from a recent study on a V90 2 MW turbine [65]):

- Materials composition and manufacturing process
- Utilities and material consumption (site preparation, operation and maintenance)
- Material composition of larger purchased components (generator, gearbox, transformer, etc.)
- Transport of components to the erection site (fuel and vehicle utilization data from suppliers)

- Electrical losses in the entire power plant.

Secondary data is used to account for background processes such as [11].:

- Country-specific electricity grid mix information
- Production of primary materials and their transport (also manufacturing processes for smaller standard purchased items)
- End-of-life processes (landfill, incineration and recycling of steel)

The relevant inputs and outputs of a system throughout its life cycle (materials, energy used, etc.), the so-called *life-cycle inventory* or *bill of materials*, is appended in almost every study and therefore not presented in further detail in this thesis[12]. The main components of a wind turbine and its related additives[13] are primarily steel, plastic, copper, fibre glass, concrete, aluminium and electronics [142, p. 16]. This leads to the conclusion that most of the impacts are related, first and foremost, to the extraction and manufacturing processes required to construct the wind turbine (energy requirements, destruction of land, etc.) and, secondly, there is also the possibility to re-utilize most of the components on account of the high degree of recyclability (see 5.2.2). The impact categories that are selected for analysis, often differ from each other and may depend on the desired results of the analysis or the intentions of the contracting partner. Nevertheless, an impact category (regarding Figure 2.15 on page 41) is a composition of inventory items[14], which arise in consequence of activities carried out by humans[15], often bundled into environmental effects, such as human health/toxicity, acidification, eutrophication, global warming potential, and so on (see also Figure 5.1 on page 96).

### 5.2.2. The results of life-cycle assessments

Many LCA studies have been carried out and, after reviewing a large number of these studies, it became clear that a comparison is very difficult to make on account of the many different assumptions, models, inventories or types of wind turbines (including technical data) that have to be taken into consideration. Furthermore, a uniform unit has to be found to be able to compare different research findings. The results of the LCA on wind-energy projects are discussed in the following text. The following studies were investigated:

- VESTAS (10 studies by a wind turbine manufacturer, unit is person equivalents)
- CASES, ECLIPSE, NEEDS (detailed frameworks by the European Union, in euro cent/kWh)

[11]Secondary data includes secondary sources from industry association: Worldsteel, Plastics Europe or European Aluminium Assciation
[12]full LCAs can be studied in [4; 135]
[13]Internal cables, transformer station and external cables to a wind farm
[14]emissions/pollutants
[15]e.g. the production of a wind park is related to processes, such as extraction, construction, etc. that give rise to emissions

- Ecoinvent database (using eco-points as unit)
- Other studies by different institutions

To make a quantitative comparison of emissions (e.g. kg, g) is possible despite some uncertainties owing to the different assumptions that have been made in the assessment process. The results, which differ from one study to another, may also be an indication that, in some of these studies, certain variables were included or not, respectively (and how the relevant literature diverges).

Figure 5.3 shows emissions from the production of 1 kWh electricity by both onshore and offshore wind farms throughout the entire life cycle of a wind turbine. The bars show the variability of the results when several wind farm configurations are considered in an elaboration. It can be realized that the values of each emission vary (e.g. sulphur dioxide from 22.5 to 41.4 mg/kWh), but taken altogether, the values converge at an appropriate rate. The main outcome of the reviewed studies (apart from CASES) is

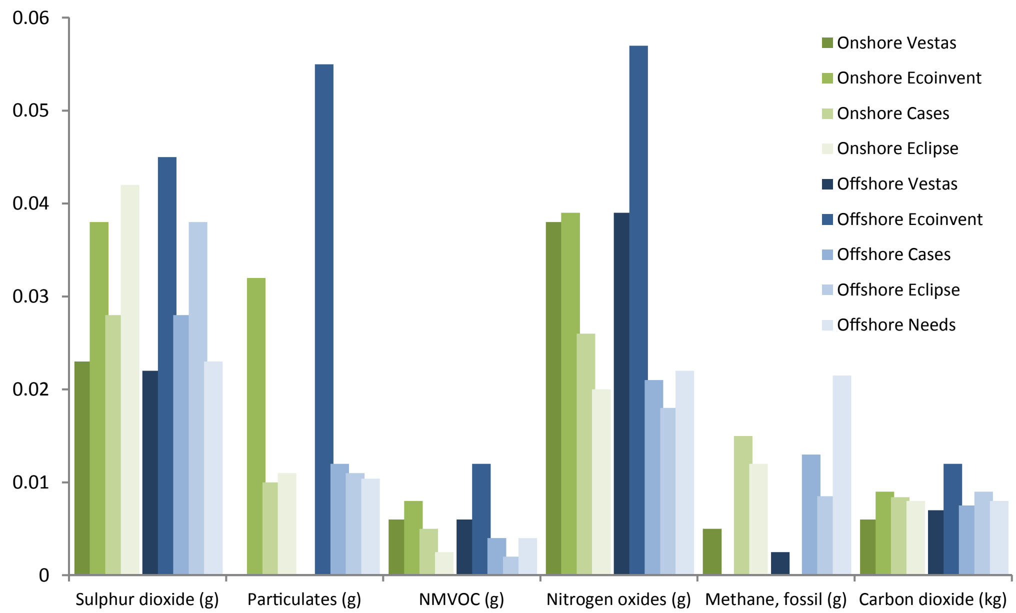



Figure 5.3.: Emissions from the production of 1 kWh in onshore and offshore wind farms throughout the whole life cycle

that the construction phase (extraction, manufacturing, set-up, transport) is the main contributor to the emissions. The operational phase and the discontinuation of a wind farm makes little impact on the environment, which is often confirmed in many studies. A major problem that arises in the energy production phase is how assumptions are selected. Many manufacturers argue that the *net energy generated*[16] during operation by wind turbines is clean because there are no emissions discharged from the turbine.

[16]energy consumption and generation altogether

Another view is concerned with the required domestic consumption of electricity that is used to start/stop the turbine, during operation, which is taken from a mix of different energy sources (including electricity generated from fossil fuels). According to the *Institut für Energiewirtschaft und Rationelle Energieanwendung*[17], an institute contributing to CASES, this internal energy demand leads to high emission values in the operation stage. These are the typical emissions caused by conventional electricity-generating technologies[18], especially sulphur dioxide. This draws attention to a very important aspect. The results will probably differ on account of the mix of different energy sources that a country uses. Unfortunately, there is no data available to investigate this concern. Thus, results from CASES for EU-27 are presented (Figure 5.4 on the next page) because nearly all the other values are quite similar to the results from other studies [146; 147; 104]. Studies conducted by Vestas, a big manufacturer of wind turbines, show that during the operation phase there is practically no emission. Manufacturers who carry out LCAs often also illustrate a positive dismantling process with less energy consumption in strategically well-chosen categories, as it can be seen in every report published by Vestas, for instance [156]. A report issued by *Austrian Verbund* and the *Austrian Umweltbundesamt*, who investigated energy flows, such as energy consumption or payback time, states that there is only low energy consumption during operation [73].

With regard to Figure 5.4 on the following page, it is shown that wind energy does have some effects on the environment. However, if it is compared with a modern natural gas power plant with low external costs or a solar PV (open space), the generation of electricity by wind turbines has hardly an impact on the environment. If the external costs of wind energy are analyzed, it can be seen that the construction phase incurs the highest amounts of money. This is because more energy is required for the extraction, manufacture and the preparation processes. However, the operation stage has, atypically, a high level of emissions throughout the entire life cycle. This is related to additional energy consumption during operation, mostly from a conventional mix of different energy sources[19], which emits higher pollutants ($SO_2$, $NO_x$, $CO_2$). The dismantling stage requires some energy as well as land[20].

Three reports are compared:[21] Vestas transforms emissions into impact categories that, first of all, cannot be understood very well and secondly, make it difficult to compare with alternative electricity-generating technologies [65, pp. 76 sq.]. Martinez and the results from Eclipse present the values either as eco-points or as pollutants: Figure 5.5 on page 103, shows, with regard to different impact categories, the extent to which each of the main components of the wind turbine (i.e. the manufacturing stage and the foundation and rotor in the manufacturing stage) contribute to the emissions. This is shown on the left-hand side of Figure 5.5 on page 103. Transport activities during the construction phase are only relevant in the case of $NO_x$ and $NMVOC$ emissions.

[17] via mail correspondency
[18] $CO_2$, $SO_2$, $PM10$, $NMVOC$ or $CH_4$
[19] coal, gas, nuclear, etc.
[20] landfill, disposal leads to devaluation of soil, water or air
[21] Martinez, Eclipse, Vestas (all studies available)

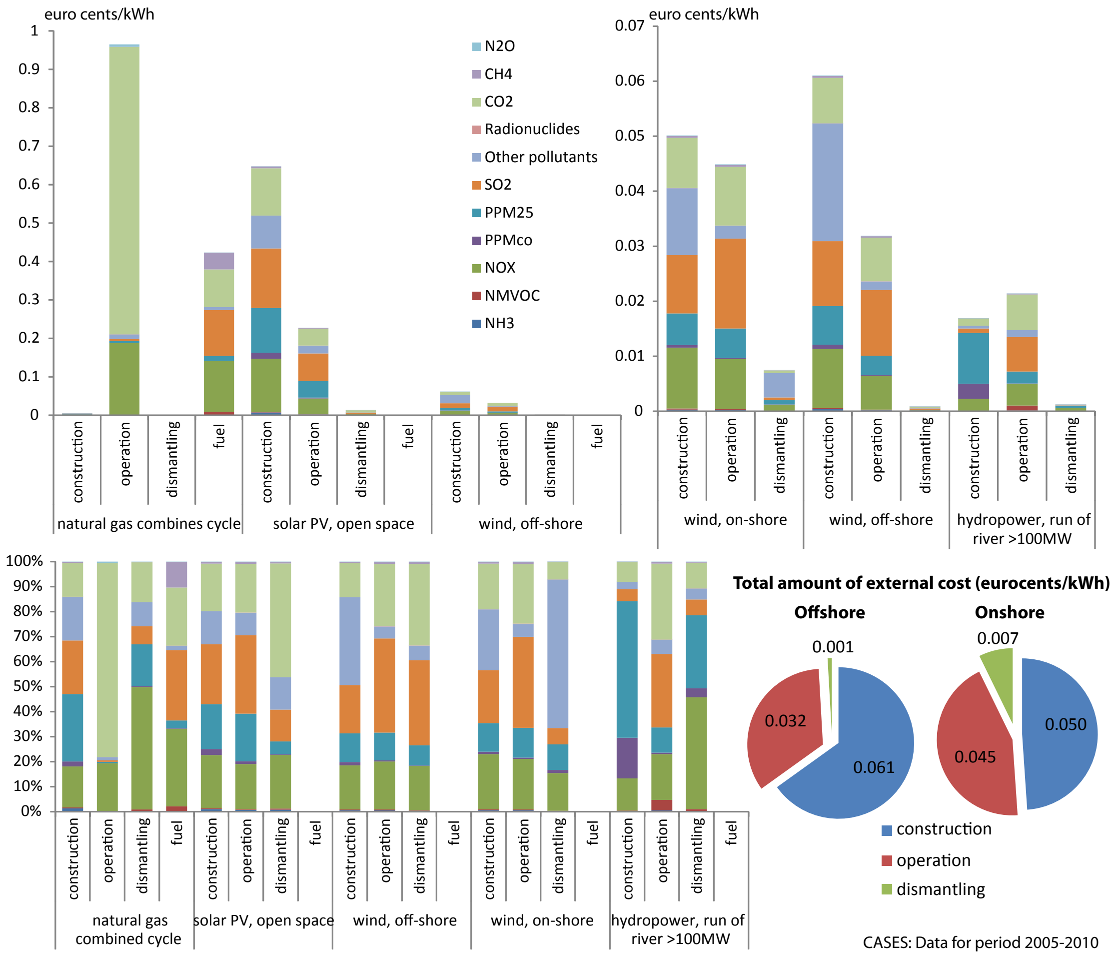



Figure 5.4.: CASES: External cost and most important emissions by stages

The right-hand side of Figure 5.5 on the next page shows the great extent to which the foundation of the wind turbine contributes to the emissions produced in the construction phase. For example, most of the impact on the environment caused by the foundations is centred on the respiratory inorganics category[22]. This impact on the environment is basically, a consequence of the processes involved in making cement. [58; 105]. Looking at the results from Eclipse, the tower and nacelle (of an onshore wind facility) contribute just as much as the foundation or the connection to the grid. The table of emissions shows that, in comparison, the construction of the rotor blades emit far less (see ECLIPSE in [10]).

[22]Infos to eco-point categories see [72]

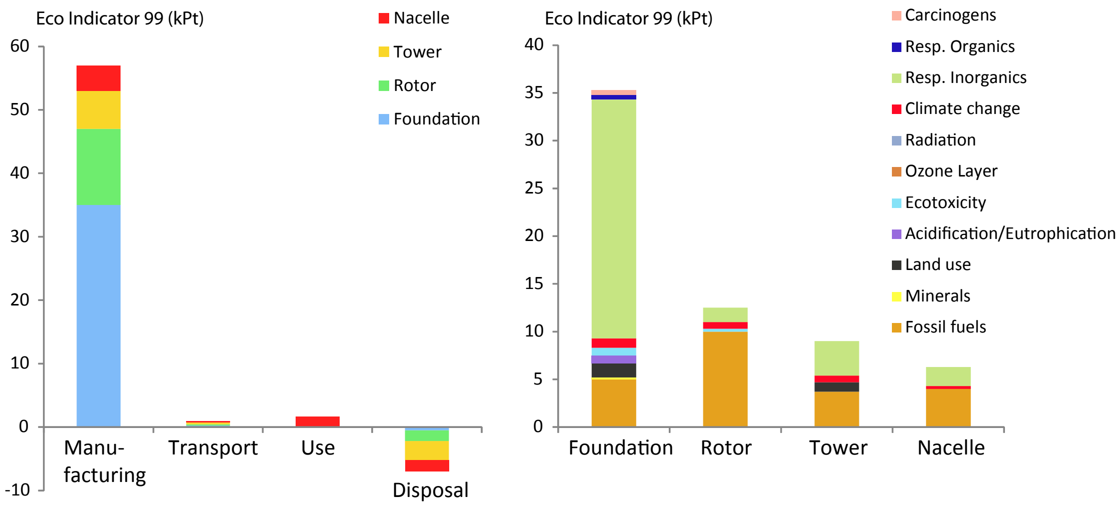



Figure 5.5.: Left-hand side: Component's share in the different life-cylce stages; Right-hand side: Contribution of the components of the construction phase to the different emissions

### 5.2.3. Onshore versus offshore

Figure 5.4 on the facing page has shown already the cost structure of emissions for onshore and offshore wind turbines. The total external cost of an onshore wind power plant is about 0.1 euro cents/kWhel and 0.09 euro cents/kWhel for an offshore facility. This is quite interesting because offshore plants actually seem to be more efficient at sea because there is generally more wind with greater velocity and the wind turbines have larger rotor blades[23] [78, pp. 615 sqq.]. The construction phase of offshore plants incurs higher external costs than onshore plants. This is attributable to an expensive installation process at sea, such as the set-up of the foundation under water[24], for instance. The difference between on-land and offshore in the construction phase is the category *other pollutants* which consists of Cadmium, Arsenic, Nickel, Lead, Mercury, Chromium and Formaldehyde (for the cable installations), according to CASES [147]. The external costs for dismantling are higher for offshore power plants on account of the additional labour it requires. Unfortunately, CASES did not include site-related impacts on the environment in the LCA, and so no potential threats were seen to marine creatures, although some possible hazards are described in the next Chapter 5.3 on page 111. The biggest differences over the total emissions are caused by $NO_x$, $CO_2$, $SO_2$ and *Other pollutants* (see also figure 5.6 on the following page). A study carried out by Vestas compared two 2 MW wind turbines in 2006, one of which was offshore and the other onshore. The LCA showed that

> [...]environmental impacts per kWh electricity generated by the two wind

[23] if a look is taken at the costs per kilowatt hour of generated electricity
[24] there are three types of foundation: *gravity-type with cassons*, *monopile* and *tripod* [78, pp. 637 sq.]

| | wind, on-shore | | | wind, off-shore | | | Difference | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| eurocents/kWh | construction | operation | dismantling | construction | operation | dismantling | construction | operation | dismantling | total |
| NOX | 1,11E-02 | 9,07E-03 | 1,12E-03 | 1,07E-02 | 6,11E-03 | 1,49E-04 | 3,26E-04 | 2,96E-03 | 9,73E-04 | 4,26E-03 |
| CO2 | 9,14E-03 | 1,07E-02 | 5,11E-04 | 8,25E-03 | 7,93E-03 | 2,73E-04 | 8,87E-04 | 2,74E-03 | 2,39E-04 | 3,87E-03 |
| SO2 | 1,06E-02 | 1,63E-02 | 4,85E-04 | 1,18E-02 | 1,20E-02 | 2,85E-04 | -1,19E-03 | 4,35E-03 | 2,00E-04 | 3,36E-03 |
| PPM25 | 5,74E-03 | 5,34E-03 | 7,61E-04 | 7,00E-03 | 3,54E-03 | 6,79E-05 | -1,26E-03 | 1,80E-03 | 6,93E-04 | 1,23E-03 |
| CH4 | 3,31E-04 | 3,55E-04 | 1,42E-05 | 3,31E-04 | 2,42E-04 | 5,95E-06 | -3,93E-07 | 1,14E-04 | 8,30E-06 | 1,22E-04 |
| NMVOC | 1,90E-04 | 1,59E-04 | 1,99E-05 | 1,99E-04 | 1,17E-04 | 1,39E-06 | -8,19E-06 | 4,18E-05 | 1,85E-05 | 5,22E-05 |
| N2O | 9,44E-05 | 1,13E-04 | 5,06E-06 | 8,81E-05 | 7,40E-05 | 2,32E-06 | 6,28E-06 | 3,86E-05 | 2,74E-06 | 4,76E-05 |
| NH3 | 3,11E-04 | 2,59E-04 | 8,91E-06 | 3,70E-04 | 1,70E-04 | 3,37E-06 | -5,94E-05 | 8,88E-05 | 5,54E-06 | 3,49E-05 |
| Radionuclides | 2,20E-05 | 4,68E-05 | 1,32E-06 | 2,02E-05 | 3,06E-05 | 8,66E-07 | 1,80E-06 | 1,63E-05 | 4,49E-07 | 1,85E-05 |
| PPMco | 4,70E-04 | 2,19E-04 | 9,21E-05 | 8,10E-04 | 1,44E-04 | 1,01E-06 | -3,40E-04 | 7,50E-05 | 9,11E-05 | -1,74E-04 |
| Other pollutants | 1,22E-02 | 2,34E-03 | 4,42E-03 | 2,14E-02 | 1,54E-03 | 4,87E-05 | -9,26E-03 | 8,01E-04 | 4,37E-03 | -4,09E-03 |

red: higher value for offshore; green: higher value for onshore

CASES: Data for period 2005-2010

Figure 5.6.: External cost and most significant emissions by stages

> power plants are close to being identical within the expected uncertainties of the results. Resource consumption by the offshore wind power plant is significantly higher than for the onshore wind power plant. However, increased electricity generation by the offshore wind turbines outweighs the increased resource consumption. [145, p. 46]

Conclusion: Offshore power plants have more effects on water while onshore facilities have more effects on soil. Pollution to air seems to be the same. The V90-offshore turbine that was analyzed during operation showed high values according to the EDIP ecotox water potential[25]. If onshore wind turbines were to have a higher energy yield (approximately one third less full load hours than offshore plants, by reason of adverse wind conditions), they would fare better regarding emissions produced in the life cycle.

A LCA of an 150 MW offshore wind farm at Nysted/Roedsand (Denmark) compared environmental effect potentials that are caused by 1 kWh of electricity production delivered to the grid with a 600 kW wind turbine on land[26]. The results were normalized in accordance with the EDIP method and presented in milli-person equivalents. The great improvements of the offshore wind farm "can be explained, in part, by the extra production capacity expected to better wind conditions at sea, as well as electronic regulation and control of the offshore wind turbine facilitating better use of high wind speeds." [100, p. 10] The design of the offshore plants has also reduced the impact potentials, particularly in the hazardous waste category[27]. The transmission system, which is also included, accounts for 30% of the global warming contribution and 15–20% for the other categories [100].

In the *ExternE National Implementation Project*, a LCA for Denmark's electricity-generating technologies was carried out, using the *EcoSense Model* from 1999. External costs were calculated for onshore and offshore wind farms in which with the following impacts were assessed:

- Emissions related to material production, accidents

[25] refers to impacts of toxic substances on marine ecosystems (i.e. zinc is discharged from the offshore cables during the operation stage)

[26] a typical wind turbine of Danish electricity (2001) used for a comparison

[27] tower design and shape, less steel and concrete (foundation) used, refined aerodynamic shape

- Site-related impacts caused by noise, visual intrusion, and negative effects on birds and shells
- For offshore wind farms the impacts on fish and interference with electromagnetic communication systems

The results for an onland wind farm range from 0.8–1.2 mECU/kWh and for an offshore wind farm from 1.0–1.6 mECU/kWh[28]. Table 5.1 shows that most of the emissions are $CO_2$, $NO_x$ and $SO_2$ and mostly related to material production (energy requirements, etc.). Offshore wind turbines cause more damage than onshore wind turbines. The reason for this is the amount of materials used for the foundation and sea cables. Site-related impacts are very low and range from 0.01 mECU/kWh (offshore) to 0.19 mECU/kWh (onshore), whereas the damage caused by onshore wind turbines which is related to noise and visual intrusion is much greater. Table 5.2 shows that the emissions generated by electricity are represented to a high percentage in all three relevant emission categories (from 78% to 97%) [125].

Table 5.1.: External costs related to an onshore wind farm and a wind farm on land

| | **Offshore mECU/kWh** | **Onshore mECU/kWh** |
|---|---|---|
| Power generation (noise, visibility, bird accidents, accidents) | 0.01 | 0.19 |
| Other fuel cycle stages (material production) | 0.66–3.64 | 0.40–2.36 |
| Total | 0.67–3.65 | 0.59–2.55 |

Table 5.2.: Emissions from production of onshore and land-based wind farms, divided into those from the electricity, heat and transportation sectors

| | **SO2 (ton)** | **Nox (ton)** | **CO2 (ton)** |
|---|---|---|---|
| Offshore | 6.9 | 12.8 | 4,132 |
| Onshore | 8.7 | 13.6 | 3,838 |
| Electricity emissions | 83% | 78% | 97% |
| Heat emissions | 9% | 6% | 1% |
| Transport emissions | 7% | 16% | 9% |

### 5.2.4. Significant analyses

**Servicing transport scenarios:** Vestas analyzed the servicing process during operation at Horns Rev offshore wind farm (three transport scenarios) and concluded that boats have very little impacts on the environment, whereas the increased use of more helicopters for maintenance has more negative effects on the environmental profile than the current scenario[29]. But the amount is still insignificantly small compared with the effects on the environment that are caused during other life-cylce stages [144, p. 37].

[28] large interval owing to very large uncertainties in the monetization of CO2
[29] the current scenario consists of the share 1 time boat and 4 times helicopter

**Distance to grid:** The distance of the wind plant from the existing grid varies from site to site. It may be assumed that the further the distance it is to the grid, the longer the cabling that is required. This results in more losses with regard to the distribution of electricity. Vestas analyzed a doubling of distance from 50 km (base scenario) to 100 km to the grid and found that a plant located 100 km from the existing grid does not have a significant effect on the environment. There is an increase of 3% to 5% with regard to the impacts on the environment, and the losses doubled from 3% to 6%[30] [143, p. 54].

**Size of turbine:** Jungbluth et al. showed that there is a significant difference with regard to the effects on the environment when the capacity of wind turbines increased or decreased, respectively. He analyzed 5 Swiss installations with a capacity range from 30 kW (Simplon) to 800 kW (Mont Crosin). The impacts of the smallest turbine is three times larger than the 600 kW and 800 kW turbines[31] [58, p. 13]. Tremeac compared a 250 W with a 4.5 MW wind turbine and drew the conclusion that the poorer results of the 250 W wind turbine are caused mainly by the small amount of electricity produced [151].

**Electricity source:** The entire manufacturing process was analyzed in which it was assumed that it took place in three different countries: in Germany, Denmark and China, with different combinations of mixed energy sources. Most production facilities are, increasingly, being exported to Asian countries with lower labour costs than in Europe. The product is the same, but not the emissions, which vary according to the mix of different energy sources. Denmark has a larger share of wind power plants. China's source of energy is derived from power stations using coal. The analyses showed that China has both quantitatively and qualitatively the most impacts, followed by Denmark and Germany. The results are shown in Table 5.3. The payback time for a 2 MW-geared turbine for the entire life cycle doubled from 1.15 years to 2.36 years, and, as a consequence, the $CO_2$ emissions doubled accordingly[73].

Table 5.3.: Results for different manufacturing locations

| | Units | **Germany** | **Denmark** | **China** |
|---|---|---|---|---|
| Total CO2e | t | 2074 | 2782 | 4584 |
| Total cumulative energy requirements | GWh | 6.90 | 8.06 | 14.1 |
| Energy payback time | yr | 1.15 | 1.35 | 2.36 |
| CO2e | g/kWh | 17.35 | 23.26 | 38.33 |

**Lifetime:** Vestas delivered a report in which onshore and offshore wind turbines were compared with each other. For a V90-3.0 MW turbine, a lifetime of 30 years was

[30] accounting for the increased quantity of transmission cabling required

[31] the greatest difference between the smallest and biggest turbines which were analyzed with regard to impacts in the following category: land use, resp. inorganics, fossil fuels and minerals, sorted descending

predicted for an offshore plant[32] and 20 years for the same onshore system. Operation and servicing were not taken into account being of little significance [145]. The results clearly show that

> the total lifetime of the wind power plant is decisive for the environmental impacts of 1 kWh electricity generated by the wind power plant. [...]the lifetime is just as important as the production of the wind power plants as both results are in direct linear changes in the effects on the environment, calculated per kWh generated by the wind power plants. In an assumed lifetime of thirty years for the offshore turbines, this period is reduced by approximately 30%, on account of the environmental impacts. This is not the case with the 20-year lifetime of the turbines. [145, p. 43]

**Recycling:** The recycling of materials is extremely important after a product is no longer in use. Most of the components of wind turbines can be recycled after they are dismantled. Considering the typical materials used for a wind turbine, about 80% have been calculated to be recyclable[33]. Nearly all the large metal components are primarily mono-material (e.g. gears, transformers, tower sections, etc.) and 98% of which can be recycled. Cables are to 95% recyclable. Aluminium, Copper and steel are to 90% recyclable, and the rest is deposited into landfills. Polymers are to 50% and lubricants are to 100% incinerated. With regard to the components of a wind turbine, 87% of the the nacelle, with a share of 32% by weight can be recycled, as well as 38% of the rotor (20% share of the weight) and 97% of the tower (46% share of the weight) [143, p. 21; 143, p. 48; 64, p. 31].

**Rare earth elements:** Rare earth elements are naturally occurring elements that, once mined and processed, can be used in a variety of industrial applications[34]. Rare earth elements for wind turbines are used in the magnets found in the tower or in the permanent-magnet generators[35] to increase the performance of generators[36] instead of other resources (steel, composite structural materials, etc.). Using 14 kg of rare earth elements in a V112 reduces 8.0 tonnes of $CO_2$ equivalents over the entire life cycle. The two types, conventional geared drive train and direct-drive (without a gearbox, but 10 times more elements than a conventional drive train) use rare earth elements. An essential but extraneous aspect is the origin of the resource. Many suppliers hire children for less money which is against the law in many countries. Manufacturers have to consider this carefully [118]. Further information, especially the application or prices, are presented in a conference paper of the Oeko-Institut (Germany) [33].

[32] offshore wind turbines can technically operate up to 30 years

[33] specific to the turbine itself and excludes the foundations, the site parts and other components of the wind plant

[34] permanent magnets in wind turbines, components for computer/high tech hardware

[35] found in newer models, such as the V112-3.0MW

[36] more efficient and grid compatible

### 5.2.5. Payback time and energy-yield ratio

"The energy balance is an assessment of the relation between the energy consumption of the product and the energy production throughout the lifetime of the turbine." [14] The *payback time* is a term used to measure the net energy value of an energy system. It is the energy requirement for the whole life cycle of the wind power plant (or other device) divided by the total electrical energy output from the wind plant over the whole lifespan. In other words, the energy payback time means the length of time that a device will take to produce the same amount of energy that was used to make it. It can also be used to mean how long the plant has to operate to generate the amount of energy that was required during its entire life. Payback time can be used in both energy and economic terms. The latter asks how long it takes to pay back the costs in monetary terms, for instance [65, pp. 62 sq.; 73, pp. 3 sq.; 14].

*payback time = total cumulative energy requirements divided by the total annual energy generated by the turbine*[37].

The *energy-yield ratio* or *energy-payback ratio* is evaluated to determine the impact of a wind turbine's rated output on its energy yield. The question posed is how often (in times) the used energy for the life cycle can be aggregated until it reaches the total energy generated [48].

*energy-yield-ratio = net annual energy output * wind turbine service life / sum of initial and recurring embodied energy requirements*

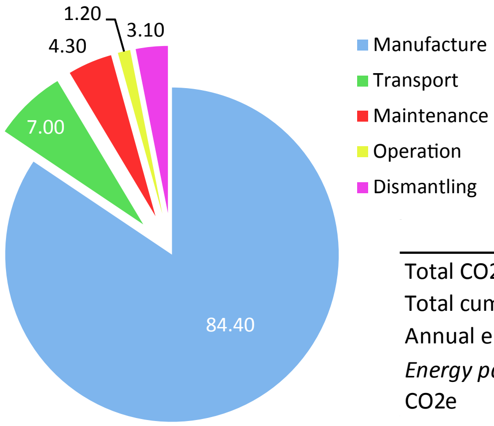
Generally, a wind turbine's energy payback time is about 4–7 months, with regard to a lifetime of 20 to 25 years. A study carried out by the *Austrian Verbund* and *Austrian Umweltbundesamt* calculated the energy payback time of two wind turbines. The first of these is a 2.0 MW-geared turbine[38] and the second one is a 1.8 MW-gearless[39] turbine. Figure 5.7 on the facing page shows the total life-cycle cumulative energy requirements share in relation to the values obtained for the entire life cycle of both turbines. The payback time for both turbines is 7.7 and 7.8 months, respectively. The difference between the two turbines is small, although the gearless turbine has fewer energy requirements[40]. The largest cumulative energy requirements contribution comes from the manufacturing stage here the operation has the smallest share [73]. Vestas carried out LCAs for nearly every wind turbine in their portfolio. Table 5.4 on the next page shows the payback times of different wind turbines. The difference between onshore and offshore is the larger grid transmission and steel consumption for the foundations in

[37] where the total cumulative energy requirements comprises energy for production, transport, maintenance and decommissioning

[38] 3 blades, large rotor, wind speed 7.4m/s

[39] 3 blades, pitch controlled, no gearbox and less rotating, rotor directly connected to the generator shaft, wind speed 6 m/s

[40] the 2 MW turbine is in a better location with stronger and more constant winds. Moreover, it has a more powerful engine




| | | 2.0MW-geared | 1.8MW-gearess |
|---|---|---|---|
| Total CO2e | t | 1164 | 578 |
| Total cumulative energy | GWh | 3.91 | 2.11 |
| Annual energy generated | GWh | 5.98 | 3.27 |
| *Energy payback time* | *year* | *0.65* | *0.64* |
| CO2e | g/kWh | 9.73 | 8.82 |

Figure 5.7.: Cumulative energy requirements share and values for the entire life cycle of a 1.8MW and 2.0MW wind turbine

an offshore scheme. For the V80 turbine, in Horns Rev, the payback time is about 9.0 months and in Tjaereborg, an onshore wind farm, the energy payback period is about 7.7 months [4]. The different wind speeds at a specific location (and possible energy-yield) are decisive for the payback time. The results of the energy-yield-ratio (EYR) for a 3.0

Table 5.4.: Payback time of different wind turbines by VESTAS

| | **Payback time [month]** | **Study from** |
|---|---|---|
| V90 2MW gridstreamer[1] | 7.0 (high wind)–11.0 (low wind) | 2011 |
| V100 | 9.0 (high wind)–11.0 (low wind) | 2011 |
| V90 3 MW onshore | 6.8 | 2006 |
| V90 3 MW offshore | 6.6 | 2006 |
| V82 1.65MW | 7.2 | 2006 |
| V80 2MW gridstreamer | 8.0 | 2011 |
| V80 2MW wind farm offshore | 7.7–9.0 | 2004 |

MW wind turbine, compared with an 850 kW turbine, are shown in the next figure 5.8 on the following page. In this study the EYR ranges from 21 for the 850 kW turbine to 23 for the 3.0 MW turbine[41]. With a longer lifetime of 30 years, the EYR increases to 32 and 35, respectively.

> Whilst the larger 3.0 MW system has been shown to provide a higher EYR, the 11% increase is not considered to be significant. Therefore the size of a wind turbine may have little influence on its potential energy yield. The energy yield of these turbines may vary with the recovery of energy from the re-use or recycling of components and materials [43, p. 2659].

Denholm compared the energy-payback ratio of a set of electricity-generating technologies and found that wind (here with no storage[42]) has the best EYR, which is about 27.

[41] over a 20 year period
[42] The study analyzed renewable energy storage systems

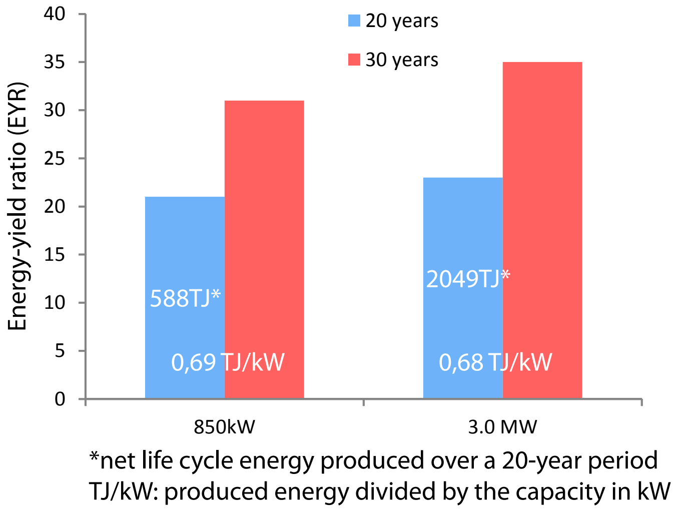



Figure 5.8.: Energy-yield ratio of a 850 kW and 3 MW wind turbine

A gas turbine has an energy-payback ratio of only 4 as can be seen in Figure 5.9 [48, pp. 43 sq.]. Zauner et al. (*Austrian Verbund Renewable Power*) calculated the energy

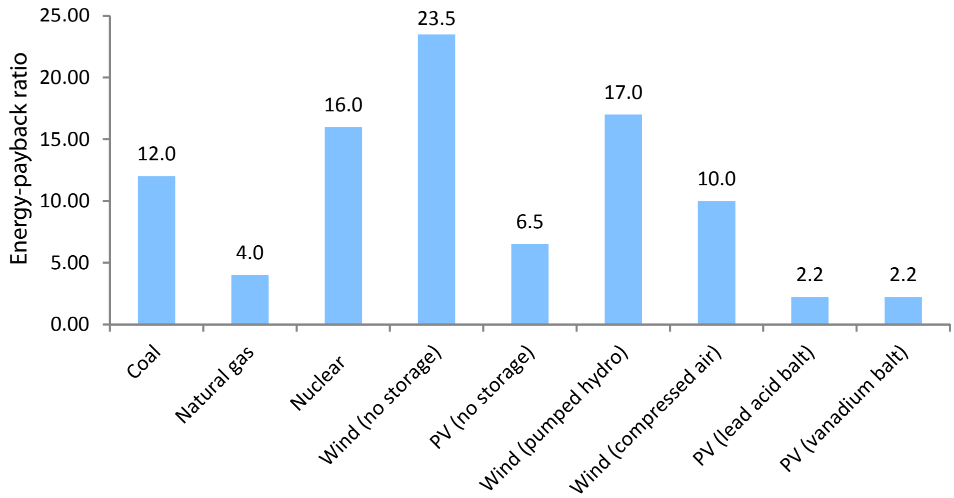



Figure 5.9.: Energy-payback ratio of different electricity-generating technologies

payback time for different energy sources. It is shown that wind and hydro-electric-power are still the most advantageous sources of energy (especially with regard to $CO_2$ emissions) with a payback time of approximately 12 months[43]. Nuclear power has the longest payback time of up to 3.16 years and CHP becomes more attractive with 1.12 years. The payback time for photovoltaics ranges between 1.31 and 1.57 years [73].

[43]the highest value compared to other studies

## 5.3. Site-related effects on physical and social environment

Site-related impacts of wind energy are concerns related to the site of an operating wind turbine. Figure 5.1 on page 96 reflects all environmental effects caused by wind energy. In this section, the most important issues, which usually take place during the operation of a wind turbine are discussed in some detail, and, in particular, the effects of visual intrusion and noise, two of the most disturbing features for some people.[44]. Negative effects on birds or other wildlife are also discussed, but only in general to provide a general view based on the relevant literature. Site-related effects are often difficult to evaluate. However, these *missing impacts* in an evaluation have to be included and discussed in an *Environmental Impact Assessment (EIA)*.

### 5.3.1. Environmental and social effects

The following discusses effects on human health and well-being, as well as on fauna and flora:

- Visual intrusion
- Noise
- Effects on fauna (wildlife, bird-life) and flora
- Electromagnetic interferences
- Land use
- Effects on cultural and recreational sites

#### 5.3.1.1. Visual intrusion

**Aesthetic impacts:** The *European Landscape Convention* defines landscape as an area, the character of which is the result of the interaction of natural and/or human factors. It changes over time on account of human and ecological development. The perception of landscape is subjective and depends on the attitude of the people. There will always be people who are against the installation of wind turbines in a specific area, regardless of whether the design or mitigation measures can minimize the effect of visual impacts. Therefore, Hau points out that of "[...]all the effects on the environment caused by wind turbines, their visual impact on the landscape is the most difficult factor to assess." [78, p. 558]

Visual impacts are important environmental issues in determining wind farm application related to the perception of the landscape. Visual intrusion is subjective and changes over time and in accordance with location. The problem with wind farm developments is the expanding wind energy utilization (planning large wind farms). The

[44] The most commonly discussed impacts on people are caused by noise and visual intrusion, which are both products of modern technology [14]

problem concerning visual effects on the landscape is the large number of wind turbines which are seen as dominant points in the landscape. For that reason it might be recommendable to put fewer and larger turbines instead of numerous, smaller wind turbines in an area, to make them more acceptable [78, pp. 558 sq.; 165, p. 55]. The visual impact depends either on the extent of visibility (where it is seen) or the nature of visibility (how it appears within these views) [165, pp. 52 sqq.]. The design and model of a wind turbine has an influence on the environment. The following characteristics of wind farms have the potential to cause certain visual effects on landscape:

- The turbine itself, such as size, layout, height, material and colour
- Location and number of turbines
- Access and site tracks
- Substation buildings
- Compounds
- Grid connection and transmission line
- Anemometer masts
- Navigational visibility, markings and lights

Offshore wind farms involve several additional elements:

- Transportation and maintenance boats
- Road access and access requirements to the coast
- Piers, Slipway or port used by boats or heliports

Another characteristic or benefit of a wind farm is that it is not permanent, so after the turbines have been dismantled and removed, the landscape can return to its original condition [165]. Offshore wind power plants are mostly bigger than the installations on-land. However, the visual impact is lower on account of the greater distance from the coastline. But coastal landscapes are often unique and most valued by humans, so careful treatment is required. Visibility assessment includes the extent of visibility over the main coastline and land activities[45]. The curvature of the earth and lighting conditions (weather, lights on turbine) are relevant, too. Changes in the intensity of lighting and the weather also alter the impact that is made as well as visual aesthetics. The distance between the observer and the wind farm has the strongest influence on how it is perceived and thus on the strength of the visual impact.

[45] recreational activities, coastal populations, main road, rail and footpath

The *Swedish National Board of Energy* conducted a study with questions on the visual impacts of large wind turbines[46] and found that the visual impact is determined by three factors:

- A psychological factor: the attitude to wind applications and what the observer associates with these
- The kind of landscape: influences differ from the topology and environment, whether it is an open landscape or in an area with trees and buildings
- The size of the wind turbine

The distance is quite an important factor as it contributes to the degree to which the turbines are a visual disturbance. Most wind farm installations would be accepted as long as the distance between the turbine is between the order of 8 to 10 rotor diameters [56]. Stanton summarized the techniques commonly used to evaluate visual impacts: [138]

- Zones of theoretical visibility (ZTV) are the limits of visibility of the plant defined by maps or viewsheds (totally or partially seen as determined by the topography)
- Photographs record the baseline visual resource
- Diagrams provide a technical indication of the shape, positioning and scale
- Photomontages, such as photos, videos for future developments with installed wind farms

Visual impacts decrease with distance. For that reason the University of Newcastle defined 4 zones of visibility, ranging from visually dominant (up to 2 km), intrusive (1–4.5 km) noticeable (2–8 km) to indiscernible (over 7 km distance). These zones are used as planning guidelines in the UK. Bishop analyzed visual impacts in relation to the distance under different weather conditions. For all different atmospheric conditions the visual impact decreases with distance (see Figure 5.10 on the next page) [26]. A further study based on the Nord Hoyle wind farm[47] showed that visual impacts decreased with distance with a large variety of atmospheric and lighting conditions. The major findings of Bishop and Miller show that distance and contrast are very good predictors of perceived impact: Wind turbines painted white or grey will be only a minor issue for discussion because their lightness (of colour) tends to dominate over colour differences. "[...]the impact level of contrast caused by wind turbines increases the greater the contrast with the surroundings[48]. The authors also mentioned that the contrast level declines with distance." [121, p. 2428] [26]. A reduction of visual impacts can be accomplished when the turbine is made green at the base and gradually changes to grey at the top. Consequently, the wind turbine blends in with the environment (e.g. a skyline in the background) which, however, still causes the death of birds [20].

[46] using photomontages, besides other methods
[47] 7 km off the coast
[48] the contrast level also differs under different conditions see table 10 in Saidur (2011) [121, p. 2429]

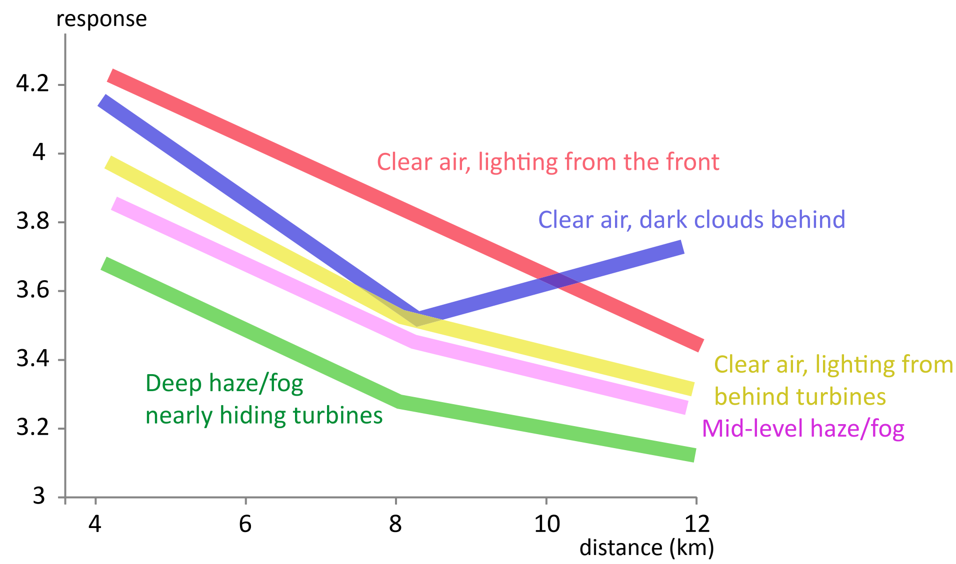



Figure 5.10.: Acceptance of wind turbines with increasing distance (in km). The five lines represent different atmospheric conditions

**Mitigation and minimization:** To decrease the visual intrusion by wind power projects, the layout of the wind farm and its relationship to the topology (form) of the landscape is of great importance. However, siting is limited for technical, practical and economic reasons, such as the grid connection, access, turbulence, wind speed, land ownership and so on. The projects that are accepted by communities are those where a proper look has been taken at a specific location to impart a positive visual image [165, pp. 52 sqq.]. Many tools are available to analyze issues with regard to visibility (e.g. GIS software allows some surface analyses). Lists of potential mitigation measures are also available. To mitigate or minimize visual impacts, the following considerations have to be taken into account: [138; 165; 79; 32]

- Similar size and type of turbines on a wind farm
- Colour: neutral and anti-reflective paint for towers and blades – light grey, beige and white
- Rotor: three blades and rotating in the same direction
- Low number of large turbines is preferable to many smaller wind turbines
- Flat landscapes fit well with turbine distribution in rows.
- The design of the wind farm is in accordance with the characteristics of the site and with respect for the surrounding landscape
- Minimum distance from dwellings

- Underground cables
- Lights for low-altitude flight (only for more exposed towers)
- Number of wind turbines and their orientation
- Minimized areas of visibility from many important points of view

Despite a deliberate planning stage with mitigation of the visual effects, an opposition to wind farms is encountered mainly during the planning phase. Wind farm projects are accepted mostly after commissioning. Wind turbines can be a tourist attraction, too. Only a few visitors react negatively to their appearance.

**Shadow flickering:** Wind shadows that the wind turbine casts over the surroundings when the sun shines, are produced in two ways: either a shadow flickers because it is caused by the moving blades or there is a so-called *disco effect* when therays of the sun reflect on the corpus of the wind turbine. The flickering shadow changes when the light intensity increases or decreases, and then the shadows are cast on the ground or stationary objects. Reflections can be minimized by coating the turbine with a material having poorer reflection properties. Because of the rotation of the earth, the shadow stays only a short period of time at any particular point[49]. Furthermore, the shadow of a wind turbine is confined to the immediate vicinity of the turbine. Admittedly, this shadow can be annoying under certain conditions. It has to be distinguished between a turning rotor and a rotor standing still. The latter casts a long shadow only when the sun sets and the distance to the wind turbine is close. When the wind facility is operating, the rotor blades cut through the sunlight at three times the frequency of the rotation of the rotor and produce an unpleasant flickering stroboscopic effect to residents (disturbance to people inside buildings). This effect can lead to a pulsating light level especially in rooms which are naturally lit. Such environmental effects are only acceptable within certain limits. Although the flickering shadow or variation in light at frequencies of 2.5–3 Hz can cause an anomalous EEG (electroencephalogram) reaction in some persons, this happens in only a few cases. With increasing hub-heights, shadows can stretch over a considerable distance when the sun has reached a certain position in the sky.

In 1999, a study by the State of Schleswig-Holstein in Germany developed a calculation of the astronomically possible times when shadows are cast for a particular wind park configuration and immission points. A limit of 30 hours (30 minutes per day) annually for a shadow that is cast at an *immission point* was recommended. In practice, the possible time when a shadow is cast is reduced by the prevailing weather conditions from 6 to 9 hours spread over a year[50]. There are still other solutions to mitigate the effect of flickering shadows: there is a module that works as an automatic shadow cut-out system. It is programmed with the astronomically possible shadow-casting times,

[49] called the immission point

[50] the effective shadow period is reduced to 20% to 30% of the astronomically possible maximum period of Central European latitudes

and it switches off the turbine with the aid of a light sensor as soon as the weather situation allows a shadow to be cast on a critical point. Another effect could be an unpleasant flashing effect when the sunlight is strongly reflected. This can be reduced by a non-reflecting coating. All in all, when the wind turbines are at an appropriate distance from a residential area, the minimal shadow times are statistically very low. The loss in energy yield is also negligible if it has to be shut down[51]. [78, pp. 549–552; 121; 155]

#### 5.3.1.2. Noise

There is a discussion still going on whether wind turbines have any negative effects on the health on humans and animals, or not. There are many studies with a wide range of different assumptions, statements and findings. It seems almost as if could depend on the contractor (the interested party) whether wind turbines have negative effects or not. The following summarizes the most important findings of research. This section is split into two main parts: the first is an analysis of the production of noise and vibration by wind turbines and health impacts of noise and vibration.

Firstly of all, the perception of noise depends on a person's hearing acuity and tolerance for, or dislike of, a particular kind of noise. Wind turbines typically generate a mechanical tonal noise caused by the gearbox, the generator and an aerodynamic broadband noise caused by the rotation of the blades in interaction with the wind [3, p. 8]. The noise generated by the wind turbine depends either on the type of design (tip speed ratio, rotor diameter, stall or pitch regulation control, upwind and downwind turbines) or the site (placement of the turbine, surrounding terrain[52], atmospheric conditions[53]) [78, pp. 541 sq.; 54, pp. 53 sq.]. At night the noise intensity from wind turbines is perceived to increase owing to the stable atmosphere and the deeper sounds generated by humans [54, p. 53]. Before a look is taken at the specific measurements of wind turbines, the basic acoustic terms are discussed briefly. Besides broadband (typically *swishing*) and tonal noise (typically is a *hum*) wind turbines also generate pulsing low-frequency (i.e. not or barely audible) sounds, which seem to annoy people most [164]. While human beings perceive a frequency range from only 20 Hz to 20 kHz, wind turbines generate noise containing frequency components from 20 Hz to 3.6 kHz[54] as shown in Figure 5.11 on the facing page. The low frequency ranges from 20 Hz to 200 Hz, whereas infrasound is less than 16 Hz. Noise is described in terms of *sound pressure levels* at the location of a receptor[55] typically expressed in dB(A), whereas A describes a corrected or *A-weighted* frequency content adjusted to the sensitivity of the human ear[56].

[51] worst case is 2% of the annual energy yield
[52] reflection from hillsides
[53] wind, temperature gradients, atmospheric absorption
[54] varying with wind speed, blade pitch and blade speed
[55] note that the *sound power level* describes the source of sound
[56] especially the G-weighted values focus on low frequency, which can be interesting for noise analyses of wind turbines [123] [54, p. 124]

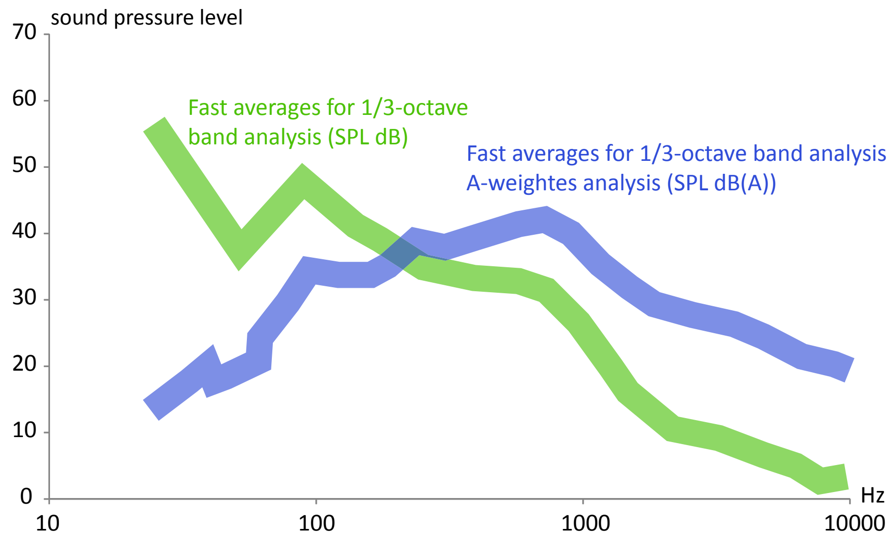



Figure 5.11.: Frequency content of typical wind turbine measurement (averages for 1/3-octave band and A-weighted analysis

Usually, modern wind turbines create a sound power level, depending on the details of the design and the rated power of the turbine, of 80–105 dB(A) (see also Table 5.5 and [78, p. 545; 54, AD9]). The perceived sound pressure level at a distance of 40 metres is around 40–60 dB(A)[57]. The sound pressure level decreases rapidly with increasing distance, as can be seen in Figure 5.12 on the following page [78, pp. 544 sq.]. Within a distance of 400 metres the decibel level decreases to 40 dB(A) which is below the level associated with annoyance in many epidemiological studies [54]. The sound pressure level

Table 5.5.: Sound power level in dB(A) from various wind turbines

| Model | Turbine size | Estimated sound power |
|---|---|---|
| Southwest Windpower Whisper H400 | 900 W | 86 dB(A) |
| Bergey Excel BW03 | 10 kW | 96 dB(A) |
| Medium-sized (40m rotor diameter) | 500 kW | 98 dB(A) |
| Vestas V80 (80m rotor diameter) | 1.8 MW | 98–109 dB(A) |
| Enercon E112 (100–120m rotor d.) | 4.5 MW | 107 dB(A) |

is primarily a function of the distance. The following factors contribute to how sound propagates and is attenuated:

- Distance
- Wind direction
- Building material absorption

[57] Alberts measured a level at 58–60 dB(A) at the base of a 1.8 MW turbine [3, p. 9]

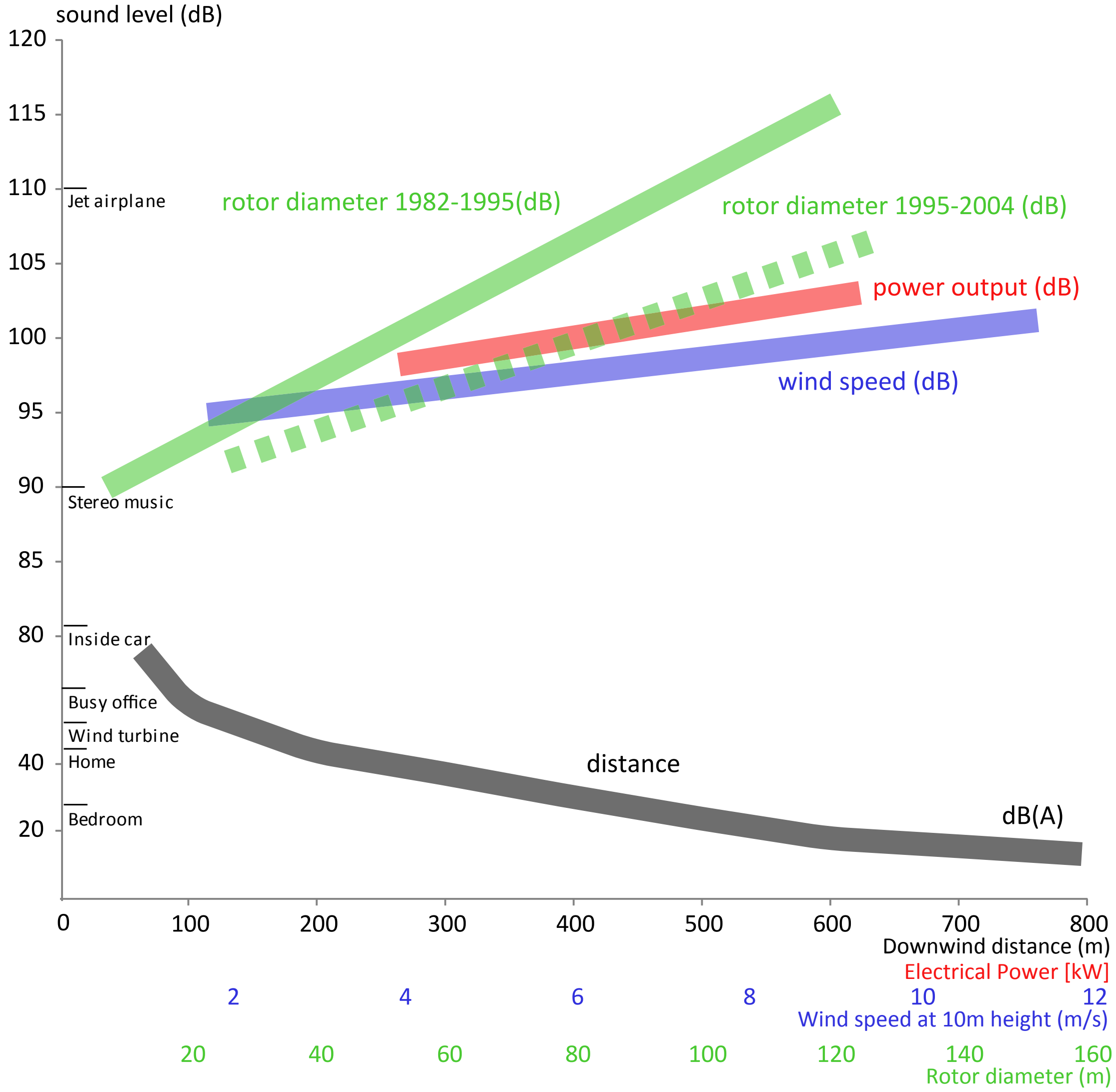



Figure 5.12.: Sound pressure level of a Tacke TW600 related to distance, wind speed, electrical power and rotor diameter

An interesting observation is the progression of frequency attenuation shown in Figure 5.13. It is known that low frequencies travel further than high frequencies. For example, an 8 kHz tonal sound will be attenuated (reduced in volume) about 40 dB per kilometre, whereas by comparison, a 4 kHz tonal sound will be attenuated to only about 20 dB per kilometre.

> For broadband noise, such as wind turbines produce, the low frequency components may travel further than the higher frequency components. Since low-frequency noise is particularly annoying to most people, it is important to specify limits for low frequency noise. [3, p. 15]

The direction of the wind influences sound propagation. Downwind, the sound volume will increase for a time before decreasing, whereas upwind, sound volumes decrease very quickly [3].

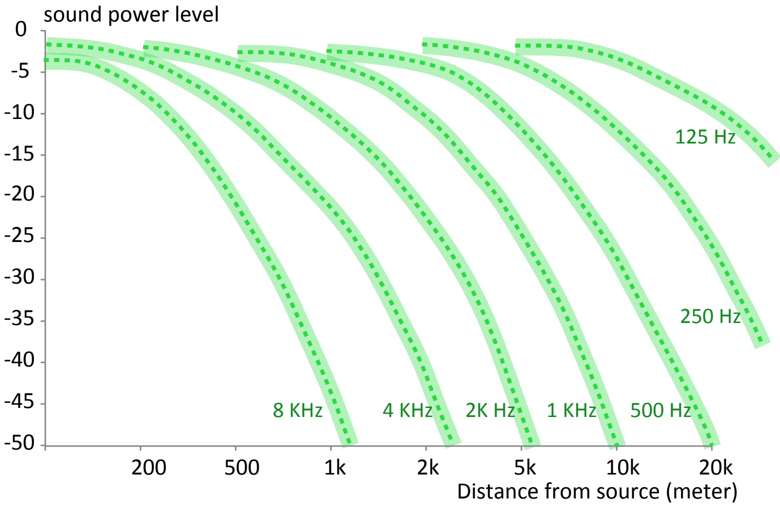



Figure 5.13.: Frequency attenuation

Compared to other noise sources, the sound pressure level of an operating wind turbine is silent (Table 5.6 on page 121[58]) [3, p. 5]. According to the *Health Study Expert Panel* (2012)

> [. . . ]infrasound refers to vibrations with frequencies below 20 Hz. Infrasound at amplitudes over 100–110 dB can be heard and felt. Research has shown that vibrations below these amplitudes are not felt. The highest infrasound levels that have been measured near turbines and reported in the literature near turbines are under 90 dB at 5 Hz and lower at higher frequencies for locations as close as 100 metres. [54, p. 54]

[58]Source: American Wind Energy Association

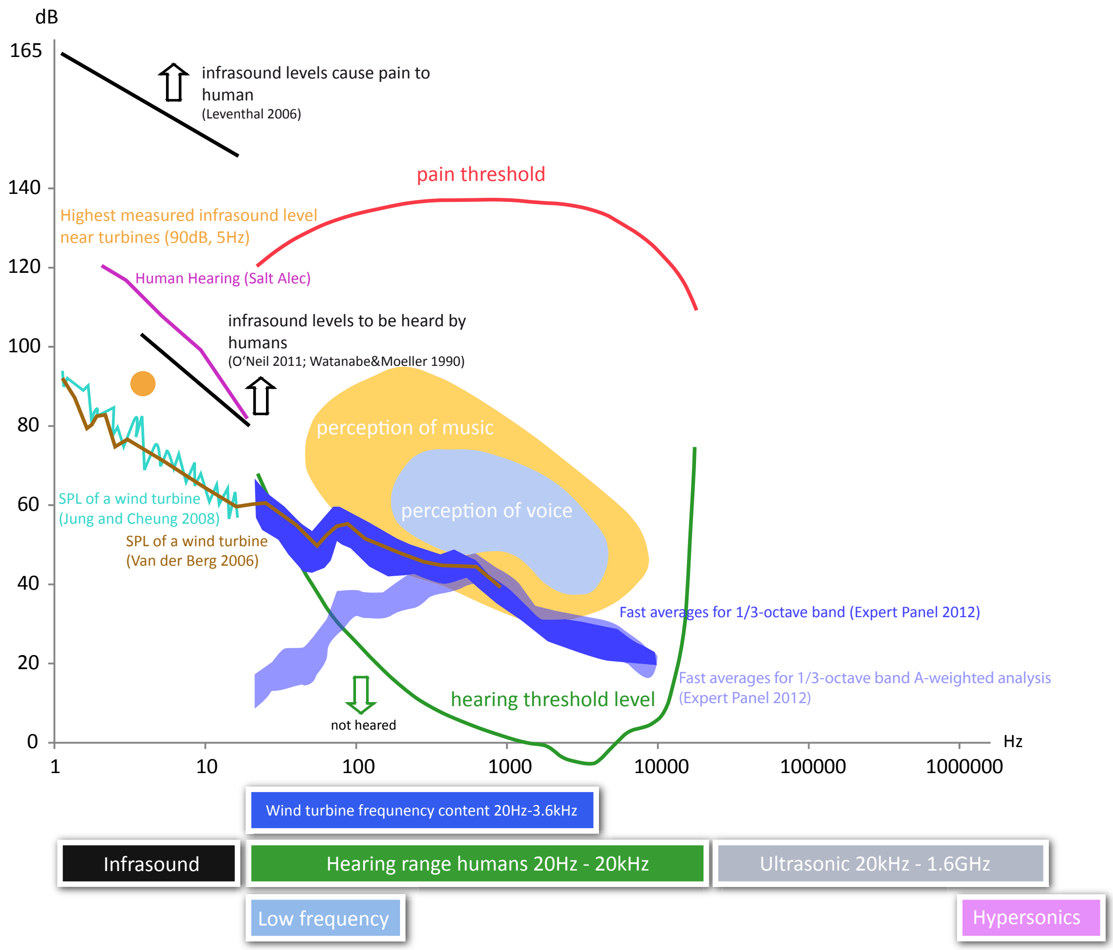



Figure 5.14.: Frequency bands and thresholds

Furthermore, *the Health Study Expert Panel* points out that pressure waves can cause vibration in another structure or substance that has the ability to receive the waves. Generally, low frequency vibration on organisms is not well understood. But Pierpont (2006) is sure that some people feel disturbing amounts of vibration, pulsation or the beats of the blades from wind turbines, even if they do not hear or see them. The perception of unwanted sounds is highly variable among humans [114]. Figure 5.14 shows different bands of frequencies related to thresholds for humans, and the measurements made by different authors [122; 3, AD-7; 99; 54, p. 10].

> In the infrasonic range, the amplitude of the sound must be very high for it to be audible to humans. For instance, the hearing threshold below 20 Hz requires that the amplitude be above 80 dB for it to be heard, and at 5 Hz it has to be above 103 dB. This gives little room between the audible and the pain values for the infrasound range: 165 dB at 2 Hz and 145 dB at 20 Hz cause pain. [54, p. 10]

Table 5.6.: The decibel scale

| Type of Source | Decibel |
|---:|---|
| Jet airplane | 150 dB(A) |
| Industrial | 110 dB(A) |
| Stereo music | 90 dB(A) |
| Inside car | 80 dB(A) |
| Busy office | 65 dB(A) |
| Home | 55 dB(A) |
| Small wind turbine | 55 dB(A) |
| Bedroom | 35 dB(A) |
| Whispering | 25 dB(A) |
| Falling leaves | 15 dB(A) |

It has been shown that excessive exposure to noise can cause severe health problems. The most common effects include hearing loss or sleep disturbances [3]. The expertise of the *Health Study Expert Panel* worked out a lot of epidemiologic studies and came to the following results regarding health, the effects of noise and vibration (primarily from onshore wind turbines). Marine animals could be affected by the underwater noise generated during the construction and operation of wind turbines. This is discussed in the next part 5.3.1.3 on the following page:

1. Most literature relates to annoyance, reported by afflicted persons, which depends on the attitude held towards wind turbine projects

2. Hearing loss caused by wind turbines is not possible because the sound pressure at the base of a turbine is approximately 50 dB and according to Sengpiel, a person can be exposed for about 16 hours to 82 dB before there is any hearing damage [131].

3. Sleep disruption:

   a) It has not been sufficiently quantified to confirm whether particular sound-pressure thresholds emitted by wind turbines cause sleep disruption, or not. It is, however, possible. “A very loud wind turbine could cause disrupted sleep, particularly in vulnerable populations, at a certain distance, while it is not likely that a very quiet wind turbine would disrupt even the lightest of sleepers at that same distance.” [54, ES6] Nonetheless, there is evidence that disrupted sleep can adversely affect the mood, health and well-being and cognitive functioning of an individual.

   b) A study reports that only 10% of the test persons were awakened when the noise level was only 40–45 dB, whereas a noise level of 60 dB woke 90% of them after they had fallen asleep, and it was noted that 55 dB can affect the REM cycles [3, p. 12].

4. There are no scientific demonstrations to show that infrasound of wind turbines have a directly impact on the vestibular system. Infrasound levels near wind turbines (i.e. as close as 68 metres) are well below that required for non-auditory

perception (i.e. there is no feeling of vibration in the body or pressure in the region of the chest).

a) Structural vibrations in other applications have been shown to lead to feelings of uneasiness and general annoyance, but not from modern wind turbines

b) It is unlikely that seismic measurements will show vibration issuing from the wind turbines

c) A mechanism between the vestibular system and infrasound[59] has been proposed, but not fully understood or explained. Wind turbines create high levels of infrasound that can be sensed by the OHC, but there is no evidence to demonstrate any influence of wind turbine-generated infrasound on vestibular-mediated effects on the brain.

5. There is no evidence for a set of health effects emanating, from exposure to wind turbines, that could be characterized as a *Wind Turbine Syndrome*

6. No association could be found between noise from wind turbines and measured degrees of psychological distress, mental health problems or disease.

7. There has been no study as yet to provide any epidemiological evidence that pain and stiffness, diabetes, high blood pressure, tinnitus, hearing impairment, cardiovascular disease, and headaches or migraine have any connection with the operation of wind turbines.

8. To guarantee less impacts, a sound pressure level of 35 dB should not exceeded. That would correspond to a distance of 500 metres between the wind turbine and an individual.

By contrast, a lot of web blogs exist in which comments have been made regarding the noise of wind turbines and the impacts these (may) have on humans. Many of the editors seem to exaggerate and list ailments, such as insomnia, sleep disturbances or high blood pressure as the negative effects of operating wind turbines [119]. The stories that have been investigated reveal that about 90% of the people suffering from disturbances or certain ailments live or spend their lives in the vicinity of a wind facility. Studies that focus on the effects of noise on human health show clearly that a short distance to wind turbines can, indeed, have an impact on health. As already mentioned, it may also be the case that some people simply have a negative psychological attitude towards wind turbines, because they associate them with negative experiences or other incidents.

#### 5.3.1.3. Effects on fauna and flora

Impacts on wildlife can be categorized as being either direct or indirect. A direct effect is the mortality of birds through from collisions with the blades of wind turbines. Some of the indirect effects are avoidance, displacement or habitat disruption. Researchers

[59] via the outer hair cells (OHC) in the inner ear

have found that the impacts, especially those on wildlife, are smaller compared to those emanating through other sources of energy [59]. According to the available evidence and from scientific investigation wind power plants do not contribute to a significant reduction of the bird populations. The consequences of climate change are a much greater threat to wildlife [121].

**Birds:** Birds, in particularly, may be negatively affected by the presence of wind turbines. Most of the investigation and monitoring that have been carried out have focused only on the negative effects on birds. Wind farms may represent a risk to those birds which live permanently in the surrounding area (resident birds) as well as to those which migrate (migratory birds). It is difficult to reach a clear conclusion because the effects on birds are very specific to the site of the wind farm, and also vary according to the species they belong to. Site-related factors are the landscape topography, wind farm layout, season, species and types of resident or migratory birds in the area, for instance [102]. The birds have the following risks [133; 50; 25]:

- To collide with the blades and towers of the wind turbine causing injury or death
- Disturbance of the habitat
- Interference in the movements of birds with regard to feeding, the winter months, breeding and moulting, which might incur additional flights (birds avoid the wind turbines) and thus also require more energy
- Loss or reduction of habitats

Although birds are the largest group of victims which might be killed in a collision with the blades or tower of wind turbines, the mortality rate is, in fact, very low and can be regarded as negligible compared with the danger to birds on account of other human activities. The death of 20 birds have been counted as consequence of wind turbines, and of 2,000 killed by hunters. Many birds have been killed in collisions with vehicles or by transmission lines. Table 5.7 on the next page shows the leading human-related causes of bird deaths in the United States [121; 136].

"In Tarifa, the two main reasons were that the wind farms were installed in topographical bottlenecks, where large numbers of migrating and local birds fly at the same time through mountain passes, and the use of wind by soaring birds to gain lift over ridges" [121] [50; 16]. Of almost 1,000 wind turbines, the mortality rate lies between 0.1 to 0.6 collisions per turbine and year[60], according to a study in Navarra [63]. Drewitt's findings reflect a mortality rate ranging from 0.01 to 23 per turbine, per year. Counting the offshore environment is more difficult because fewer carcasses can be found. A thermal imaging monitor at Nysted reported that only 0.02% of birds collided with wind turbines.

[60] raptors affected by 78.2% during the spring months, followed by migrant passerines in the post breeding migration period, which is September and October

Table 5.7.: Causes of avian mortality in the United States (2009)

| **Source** | **Estimated mortality (thousands)** |
|---:|:---:|
| Wind turbines | 20 |
| Aircraft | 80 |
| Nuclear power plants | 330 |
| Large Communications Towers | 6,8 |
| Communication towers (cellular, radio, microwave) | 4,000–50,000 |
| Fossil fuel power plants | 14 |
| Cars, trucks | 50,000–100,000 |
| Agriculture | 67 |
| Pesticide use | 72 |
| Building windows | 97,000–976,000 |
| Domestic cats | 100 |
| Hunting | 100 |
| Feral cats | 110 |
| Transmission Lines (conventional powerplants) | 175 |

The following factors affect avian mortality:

- Weather
- Lighting: disorientation in poor weather and foggy nights – birds are attracted by the light emitted by wind power plants
- Tower design: older turbines often have lower hub heights and higher rotor spins or seem to offer nesting possibilities for some birds [59]
- The height of flight

According to Gregory et al., 45 fatalities occurred when the weather was a factor. This is related to lower flight altitudes of birds during heavy overcast skies with high winds, low clouds and rain [87]. According to many studies birds, some birds quickly learn to identify wind turbines and fly around them. This was mostly observed in relation to local birds [74; 30]. Migratory birds with no local experience may be harmed through wind turbines although they rarely fly below an altitude of 200 metres. A monitoring of *golden plover* and *curlew* showed that 90% of these species keep a sufficient distance away from the wind turbines. [30]. Birds flying near a wind turbine adjust their flight pattern and height. Few birds have put themselves at the risk of a collision with rotors [121]. In other words, birds also have to expend a significant amount of extra energy to fly around the obstacle. Offshore wind farms can be quite large and can replace essential habitats from seabirds (seabirds have restricted areas in which they can successfully feed) [133]. Handke found that for some species (singing birds) no displacement effects have been recorded. A relocation of resting birds was on the one hand validated, although it was also monitored that many species frequent areas near wind turbines on the other hand. This could belong to other influencing parameters such as tradition, biotope structure, food availability or other general disturbances [74].

**Wildlife:** A study made by the *Institut für Wildtierforschung an der Tierärztlichen Hochschule Hannover* investigated how wildlife (especially rabbit, roe deer, fox and partridge) use the space in areas with and without wind turbines, and found that the presence of wind facilities did not lead to any annoyance. In some cases, even more animals could be observed in the vicinity of the wind turbines. The project team came to the conclusion that wind turbines do not seem to be a source of disturbance and do not induce wildlife of emigration of wildlife[61] [39].

A problem for wildlife could likely be if a wind facility were to be installed near the habitats or breeding places of wildlife, it is very likely that that could be a real problem for these animals (just imagine a situation in which someone builds a big house in front of your observation terrace or your property is expropriated for other projects [62]). If wildlife cannot access their habitats anymore, relocation will be the consequence [30; 102]. Although some species can be displaced from their original habitat during construction of the wind turbine, in most cases, they return during the operational phase[63][113].

Another negative effect on animals is attributable to the noise and vibration emitted by wind turbines, which is an increasing problem of the offshore wind farms. The risk of accidents owing to ice falling off the rotors near onshore wind farms must be considered, too.

**Marine animals:**

> From an ecological point of view, shallow waters are usually places of great ecological value and are important habitats for breeding, resting and migratory seabirds. Close participation and good communication between the countries involved in the new developments are essential to reduce the impacts from several wind farms in the same area have on the environment [12].

Marine animals can be disturbed by offshore wind farms. The most relevant magnitude of influence is noise, vibration and the electromagnetic field caused by power lines. The noise level depends on the construction and operation stages and the parameters of a wind turbine (foundation, rated power, material) as well as the depth of water at the site and on the construction period [92]. During the construction period, the peak noise of a pile hammering could be as much as 190 dB to 260 dB. Subsequently, fish and the other marine animals (mammals, benthos) avoid the area for the duration of the construction phase, i.e. they leave the area for a temporary period only. Salmon and cod show significant avoidance behaviour: 1.4 km and 5.5 km, respectively [150]. When an offshore wind turbine is in operation the noise it makes is not heard so distinctly under water. There are also some species of marine animals which sensitive to the electromagnetic

[61] One problem for partridges was pointed out in relation to the problem that the foundation could become an ecological trap when the grass is mown near the supply infrastructure of wind turbines (road that leads to wind turbine)

[62] or gentrification is also always connected with relocation

[63] exclusions while other species may appear in the breeding period

fields that are created by buried underwater cables, although, according to Greenpeace, the influence of magnetic fields used in marine wind farms, is small or zero [67]. In the area of the Nysted wind farm some impacts on fish behaviour have been recorded, but no correlation could be established [110]. Species with electro-sensitive organs could be attracted by electro-magnetic fields that are generated by the submarine cables. Some experimental analyses on benthic organisms have been carried out. Even after several weeks, no differences in survival between the experimental and control populations could be found. For instance mussels living under the static magnetic field did not show any significant differences. Koeller comes to the decision that benthic organisms do not seem to be influenced by orientation, movement or physiology [92]. Most of the experience in this matter, comes from several years of monitoring three wind farms in Denmark (Middelgrunden, Horns Rev and Nysted), which were installed from 2001 to 2003.

**Local climate:** Scientists have found that a particularly large number of wind turbines in an area could influence the local climate caused by the energy losses of wind converted into kinetic energy by the rotors. In Inner Mongolia (Xilingo League) the precipitation data, that was collected there, showed that there has been an unprecedented drought since 2005, especially in wind turbine areas [35]. An experiment was made in which two general circulation models simulated an induced climate change on a continental scale, which showed that a minor effect on the global average surface temperature could result. The climate could be changed by mixing the air up and down at long distances thus, intensifying local moisture evaporation as a consequence of the turbulence in the wake of the turbines (the direction of the high-speed wind could be changed). Another possibility is to use giant wind turbines, which increase the surface temperatures at night and have a cooling effect in the daytime [89; 24; 98]. The German *Max-Planck-Institut* found that wind turbines could have an influence on the global climate if the amount of installed wind capacity reaches the current electricity demand (85 times that of the current wind turbine capacity) all over the world [107].

To mitigate or prevent impacts on fauna and flora, the following list was compiled [121; 50; 98; 63]:

- Continue to study effects as now more and more wind farms will be constructed in the next few decades
- Further research and proper optimization should be carried out
- Avoiding important zones of conservation and sensitivity in order to protect habitats
- Implementation of environmental monitoring programs before, during and after construction of wind turbine to evaluate their impacts. A tool for mitigating conflicts between wind farms and birds is the *Wind Farm Sensitivity Index*, developed by Garthe and Hüppop[64]. It might be useful in Strategic Environmental Impact assessments [66]

[64] here specialized on seabirds

- by siting turbines in such a way that avoids alignment perpendicular to the main flight paths (by providing corridors between clusters of wind turbines, if necessary, or increasing the visibility of the rotor)
- by better visibility of the overhead cables using by deflectors to avoid areas with high concentrations of birds
- by environmental training of site personnel, as well as the presence of a biologist or ecologist when construction is carried out in vulnerable locations
- by the relocation of those currently installed turbines which have given grounds to conflict among the local population and wind farm owners
- by stopping operation during peak migration periods or when a hazard is detected
- by the use of special technology to avoid collisions: Avian radars detect birds in the area and stop if there is potential danger or reduce the rotor speed in critical periods

Generally, almost any kind of restriction of living space would probably have some effects on the fauna and flora. There will always be some conflict between undisturbed Nature and the requirements of a technical civilization (e.g. urbanization). The effects on flora can be summarized as the destruction and loss of vegetation (especially the loss of protected, i.e. endangered plant species).

#### 5.3.1.4. Electromagnetic interference

Wind energy projects can have negative effects, related to several telecommunication facilities, on human activities. There are many devices that generate electromagnetic disturbances, which can interfere with the normal operation of other systems[65]. An electromagnetic disturbance can be an interruption, obstruction, degradation or limitation of the effective performance of an electronic device or electrical equipment. Either of these can cause a communication path, which should be a straight-line, to be deviated if the electromagnetic waves are blocked by an obstacle or refracted.

Wind turbines[66] can disrupt electromagnetic signals. This can be attributed to two causes. First of all, the disturbances caused by the rotating rotor blades when the turbine is positioned in line with the receiver (direct) and, secondly, indirect influences by reflecting the direct signal and producing an unwanted signal[67] [78, pp. 553–555; 164]. Electromagnetic disturbances are often related to the following telecommunications, navigation and radar services:

- Television (50 MHz–1 GHz)

[65] e.g. power and communication networks, electrified railways or computer networks
[66] investigations carried out with the experimental NASA MOD turbines
[67] ghost images and flickering when the turbine is operating

- Radio broadcasting (1.5 MHz AM and 100 MHz FM)
- Fixed radio links (3–60 GHz)
- Mobile phones (1 or 2 GHz)
- Radar

The interferences depend either on the concept of the wind turbines, mainly on the design of the rotor blades[68], or the topography of the site. Rotor blades made of steel cause the highest interference, glass-fibre or wood is less disturbing, although during standstill there are also some perceptive influences. Sengupta and Senior summarize the factors of influence related to wind turbines as follows [132]:

- Location of the wind turbine between receiver and transmitter
- Characteristics of the rotor blades
- Characteristics of the receiver
- Signal frequency
- Radio wave propagation in the local atmosphere

The disturbances to television can be solved mainly by a simple installation of technical equipment (additional transmitter masts) [148]. Furthermore, the digital or satellite transmission of television programmes continues to increase rapidly and will replace terrestrial television in the very near future. Radio transmissions are also not disturbed very much and only within tens of metres [164]. The performance of fixed radio links can be influenced by a wind turbine not "[...]only if it is within the line of sight of the link but also if it is within a certain lateral distance of the link, known as the *Fresnel Zone*[69]." [164, p. 171] The degree of interference experienced with regard to mobile radio services is usually negligible and depends on the topography and position of the mobile receiver. The effects are restricted to the quality of communication [148; 164, p. 171]. All in all, electromagnetic disturbance in communication systems is negligible because it can be avoided by careful wind farm design [165].

That wind turbines can cause interference when radar is used is still a problem as no solution has been found yet [164, pp. 171 sq.]. A masking[70], clutter[71], scattering, refraction or false returns[72] can be possible effects the wind turbine has which disturb radar control:

[68] The electrical system is not usually a problem for telecommunications (e.g. generator), because interference can be eliminated with proper nacelle insulation and good maintenance

[69] this area is around and between the transmitter and receiver and depends on transmission frequency, distance between them and local atmospheric conditions

[70] An aircraft can be masked by reflecting or deflecting the returns when the aircraft is flying in the shadow of wind turbines, which prevents it from being detected

[71] Radar clutter is an effect when radar performance may be adversely affected by unwanted returns in certain geographical areas, or under particular meteorological conditions

[72] Wind turbine blades reflect or refract radar waves in the atmosphere

- Multiple, false radar returns are displayed to the radar operator
- The position of the aircraft is recorded at an incorrect location
- Loss of information
- Marine radars, navigation and communications are not significantly affected when a certain distance to wind farms is kept [81]

A table A.6 on page 176 in appendix shows effects and mitigation measures according to different types of radar [13].

#### 5.3.1.5. Land use

The planning process of a wind power project is very complex and there are a lot of requirements and impact statements. Many countries require an *Environmental Impact Assessment* or a *Strategic Environmental Assessment*. EIA and SEA are statements that try to assess both the positive and negative impacts that are possible, and which a proposed project may have on the environment, consisting of the environmental, social and economic aspects. They help decision-makers to decide carefully whether to proceed with a project or not [38]. In some countries land-use plans are zoning special areas of reservation for wind energy projects (legal framework for Austria see [112] or [139]). Although the generation of electricity by wind turbines in the operation process has fewer emissions which cause health problems to creatures, the planning as a whole, requires special attention to be paid to the interests of nature reserves, the surrounding zones, the habitats of endangered flora and fauna, and the conservation of Nature as a whole.[73]. An important new concern has been raised in the EU concerning peat lands. Peat lands cover only 3% of the world's surface, but store the equivalent of 75% of all atmospheric carbon [14].

Another issue is the interaction between tourism and wind energy. In 2008 a review of 40 studies by the Scottish Government came to the conclusion that the strongest opposition is experienced at the planning stage. Acceptance grows over time, whereas a significant number of people see a loss of scenic value when a wind farm is installed. There is also no evidence to suggest any serious negative effects on tourism[74] [14].

To discuss the land-use requirements of wind turbines, it is necessary to distinguish between two issues: Either, if only the area used for the foundation is to be considered, or the whole of the area around, i.e. the safety zone – should the rotor blades fly off. The latter can be neglected, because this argument must be opposed rigorously as it would lead to extensive safety zones alongside every road or flight corridor, for instance.

Hau mentions a figure by Jensch (1987) that shows the installed power in relation to land-use requirements. Wind power demands less area (related to installed power) than

[73] e.g. Natura2000, FFH or Ramsar sites by EU directive

[74] Tourist interests must be considered and tourist organizations should be allowed to make suggestions as part of the planning procedure with an analysis

other renewable energy sources and competes with a coal power plant. If a look is taken at the annual, energy output in relation to the total area of land that is required, a wind turbine with 500 kW yields a value of 11.7 $MWh/m^2$, while a coal-fired power plant with 750 MW has a characteristic value of 15–20 $MWh/m^2$ [78, pp. 556 sq.; 85].

#### 5.3.1.6. Effects on cultural and recreational sites

Recreation and a wind facility either fit together or not. Whereas a wind turbine can lead to positive effects for tourism, direct and indirect negative effects cannot be excluded either. A positive influence could be to create a connection to tourism services, such as centres for visitors and open access for additional opportunities. A direct effect can result when recreational activities require a rerouting around the wind facility. An indirect effect includes an aesthetic disturbance, which affects the recreational experience. An assessment of recreational issues is often identified by recreational uses. Recreational surveys are conducted by developers to determine recreational uses. In the United States the *U.S. Forest Service* provided a ranking of recreational facilities that may need to be adopted by the States or local communities. Sensitivity levels are often identified to assess aesthetic and recreational impacts [164, pp. 153 sq.].

Cultural places, such as historic, sacred and archaeological sites have to be regarded as sites to be treated with especial care and respect . Direct effects from wind projects can easily be avoided in most instances if important historic sites are well documented and rated according to their significance. It is difficult to assess the loss of a historical site accurately, because not everyone values such a site to the same degree. Inventories are required in most States owing to the lack of knowledge pertaining to archaeological and sacred sites, for instance.

> Good descriptive documentation will identify the particular values involved and the extent to which the context or setting contributes to the structure or landscape and in what way. Generally, the documentation of historic sites offers useful guidance to the value of the surrounding landscape to the interpretation of the resource, although the final determination probably should be done by experts. [164, p. 156]

Cultural recreation is essential, nowadays. People expect not only to see pre-revolutionary structures but also want to experience life as it was in those times. It is essential that developers of wind farm projects show consideration for vulnerable areas, and that the appropriate authority (at the local or national level) follow the guidelines to be found in well-founded documentary reports, besides gaining public approval in an EIA. The determination of the individual welfare function (a procedure to find out and to evaluate individual preferences) reflects the estimation of a public good revealed in surveys. With these assumptions it is possible to construct a social welfare function simply by summing up all the individual utility functions [126]. The main references of this part were provided by the *Committee on Environmental Impacts of Wind-Energy Projects and National Academies Press (U.S.)*

### 5.3.2. Security effects of wind power

In this part the following impacts of wind turbines on security are discussed briefly:

- Risk of accidents (Maintenance, air traffic, icing)
- System failures
- Ensuring the supply security
- Terror actions
- Planning uncertainties

#### 5.3.2.1. Risk of accidents

Two safety aspects have to be considered: first of all, the so-called functional dependability of the wind turbine itself as an unmanned system. During service and repair work only humans are affected in any way, whether positively or negatively. Secondly, a functional failure of the turbine can pose a threat to the surrounding area. Despite the low safety hazards of current wind turbine technology (as it consumes no fuel and does not pollute during normal operation) there are still accidents in connection with the construction, operation and maintenance. Some interesting *tables of accidents* show that there have been at least 40 fatalities or injuries (falls or caught in machinery) of workers attributed to the wind power life cycle of thousands of industrial-sized wind turbines [69; 70]. Another risk that may cause negative impacts on human beings is ice in winter. Despite the poor aerodynamic properties of ice and the loss of up to 30% of the annual energy delivery it can cause, ice can be hurled away by the rotating rotor over distances of several hundred metres. Seifert et al. recommend that the safety distance should be 1.5 times the sum of the height of the tower and rotor diameter [130; 157]. Modern turbines detect ice formation and shut down automatically, and some manufacturers offer de-icing systems on the rotor blades as an optional extra [78, p. 693]. Although it is highly improbable that a rotor could fly off. Hau discusses such an accident (flight path and distance) and comes to the conclusion that wind power technology can be regarded as absolutely safe and as the least dangerous form of energy generation technology, especially when compared with nuclear power, for instance [78, pp. 534 sq.]. The impacts of an aeroplane crashing into a wind turbine is negligible and comparable to the same risk as crashing into a high building or a chimney. Gipe estimates in his book *Wind Energy Comes of Age* that the mortality rate on account of wind power generation of electricity in the period from 1980–1994 was 0.4 deaths per terawatt hour, and at the end 2000 it was 0.15 deaths per TWh, a decline attributed to greater total cumulative generation [68].

#### 5.3.2.2. System failures

Besides the risk that rotor blades might fly off, a brake might fail and cause a fire, or the turbine might spin freely until it disintegrates. The danger of fire is that it cannot be extinguished because of the height of the plant, and so, sometimes it has to be left to burn itself out. This can cause toxic fumes or secondary fires that burns hundreds of acres of vegetation. New wind turbines have automatic fire extinguishing systems (FIREX) [42; 108]. Such a fire could raise the costs to millions of euros if the losses are considered, because these include the landscape, fauna, flora, costs of evacuation and reconstruction costs or even the deaths of individuals[75]. Apart from such accidents, the probability of which is extremely low, quite a few minor failures can, nonetheless, occur. Often some damage occurs in the gearboxes or generators, and climatic conditions are also responsible for some failures. A wind turbine in the mountains has twice as many failures as a wind turbine situated on the coastline (grid, ice, storm, lightning). This, and other kinds of failures are monitored by the *Fraunhofer Institute (IWE)* and provide a general idea of the reliability of a wind turbine. [84]. Hau writes on the causes of damage and repair risks in his book *Wind Turbines* [78, pp. 695 sqq.].

#### 5.3.2.3. Supply security, terror actions and planning uncertainties

These days, the installation of new, especially decentralized power-generating technologies, such as biomass, wind power or PV could be accelerated if there were not the problem of an overloaded grid. Over the past few years, the media have issued warnings that there will be grid bottlenecks that force network operators to disconnect more and more of their power plants. The German *Bundesnetzagentur* reported that the power loss of overload increased by 70% in 2011. Wind turbines had to be disconnected from the grid because the wirings were not sufficient [28]. *Ecofys Germany* reported that an amount between 72 GWh and 150 GWh were lost as a consequence of grid bottlenecks in Germany in 2010. These are between 0.2% and 0.4% of the electricity fed into the grid generated by wind power, which is an increase by approximately 45% from 2009 to 2010 [27].

As terror actions can be neglected (no serious literature or report has been found on this issue, yet) as a source of social impacts, it is, at present, the uncertainties in the planning process that can cause more impacts, especially with regard to the costs for the owner or firm managing the wind turbines (not discussed here but for more information look up the term *wind power forecasting*). Axel and Gerdes showed that there "exists a large potential of uncertainty regarding the energy production of wind farms. A minimization of financial risk involved in a wind farm already starts in the planning phase by performing high quality wind measurements at the wind farm location." [15, p. 35] Planning uncertainties or causes for unsatisfactory energy production can be an insufficient wind resource assessment, differences in annual wind potentials or a discrepancy between the actual and guaranteed wind power curves [15]. Non-professional planning of a wind farm could lead to increased private costs for the investor.

[75] for an assessment using the substitute-cost method can be used (see previous Chapter 2.5.1 on page 33)

### 5.3.3. Economic and fiscal effects of wind power plants

Wind energy projects can have positive and negative economic and fiscal effects on the local, regional and national levels. At this point a brief discussion follows on lease and easement arrangements, property values, employment and public revenues. A wind energy project generates (like other industries) a tax income for the local government. However, the high income for some communities[76] may also lead to some expenditures that are expected to make a project possible. The costs for infrastructure accessing the services can be expensive, too. From a private economics point of view, a positive effect can be an additional income for a landowner by leasing his land. Property is rarely purchased in fee. The lease payment to a landowner has been estimated to be around 3,000 dollar per year for a single wind turbine, according to the *American Wind Energy Association (AWEA)* in 2006. However, a positive effect is guaranteed only if the financial and other contractual terms are fair. Guidelines have been developed by associations[77], that ensure and clarify fair businesses [109].

The discussion on whether wind energy projects depreciate property values, or not, is still not resolved. It is very difficult to calculate the effects of wind energy projects on property values. Sterzinger et al. and Hoen found no statistical effects of changes in property values over a three year period within a distance of 5 miles to ten wind energy projects. In contrast, a further analysis found negative effects, especially on non-farm properties [34; 80; 140]. The problem is that property values are affected by many variables. Isolating the impacts of one variable is extremely difficult, and forecasts, too [164, p. 164]. Considering employment and secondary economic effects, it is obvious that wind power, used to generate electricity gives rise to employment opportunities. Every stage of the life cycle of a wind turbine offers employment, to scientists and technologists, manufacturers, technicians, to those workers who construct ,assemble and, later, dismantle the wind turbine, as well those who create the requisite infrastructure, logistics, transport and, last but not least, all those involved in the financial, technical, environmental, marketing and social management. The *AWEA* figured out that every megawatt installed wind capacity creates (directly and indirectly) about 60 person-years of employment and 15 to 19 jobs [164]. Models for assessing the secondary economic impacts are not well suited generally, but have been available for some time. *JEDI*, an input-output model developed for the *National Renewable Energy Laboratory* calculates the direct, indirect and induced economic benefits from new wind energy facilities. Such models

> can improve an understanding of the economic impacts of new energy facilities, especially when these impacts are considered at the macro-level[...]One NREL report concluded that these facilities have a large direct impact on the economies of rural communities, especially those with a few other supporting industries[...] [164, p. 167]

[76] according to AWEA a 240 MW of wind capacity produced 2 million dollar annually tax income to counties for instance

[77] e.g. the *Wind Easement Work Group of Windustry in Minnesota*

# 6. Summary

The generation of electricity by means of wind turbines is increasing rapidly. In the last five years the amount of wind turbines has doubled. The annual growth of capacity of wind turbines was about 27% in 2009 with a market penetration of 2.5% of the worldwide electricity demand, and is expected to reach 3.4% by 2013 and 8% by 2018.

The social costs of wind energy can be determined as the sum of private costs and external costs. Private costs can be described as the costs internal to the production of goods or a service and reflect the costs the buyer pays to the seller. External costs are expressed in monetary units of an externality. In other words, it is the amount or price that has to be included into the usage of an activity to create an efficient situation on a market from a welfare-economic point of view. Externalities and public goods are two reasons for market failure. An externality is a cost or benefit that is not transmitted through prices, and is incurred by a party who did not agree to this action[1]. Public goods are defined as commodities that allow for a collective consumption with the specific properties of non-exclusion and non-rivalry.

Environment has the following characteristics: it functions in a similar way to an economic good and has the properties of a public good. An environmental good (i.e. landscape, clean air, etc.) is often used by many people and can be consumed or contributed to the satisfaction of their needs directly as well as indirectly. But public goods are often overused, and environmental goods are often polluted by the activity of the people. An internalization of inefficiencies (e.g. polluted air) is an important task, but there is a great lack of knowledge with regard to their worth. Hence, evaluation methods have to be used to value or monetize externalities. This is often effected by expressing a willingness to pay by either using a dollar-based, or non-dollar based, measurement. For the latter, it is more difficult as no market prices are available. An evaluation of the negative environmental effects of energy systems with regard to their full life cycle is possible with a method referred to as *life-cycle analysis*. It is an ISO-implemented technique that allows the assessment of environmental effects that come about in all the stages of the lifespan of a product from *cradle-to-grave*. LCA takes into account all materials and energy flows, from the extraction of the materials, the construction and operation phases of a product, right up to their dismantling. Especially designed for electricity-generating technologies, a LCA can be applied to determine the impacts of material and energy flows. A LCA also normalizes and monetizes the impact categories from the inventory. This is essential if some technologies have to be compared. Monetization is often a difficult step because it requires a serious framework of evaluation that is comprehensible for experts, as well as for decision-makers. Scientists should pay

[1]In this thesis the focus is on the negative technological externalities

careful attention and be accurate in the evaluation process. The typical life-cycle steps of a LCA on wind turbines are extraction, construction (manufacture, transport and setup), operation and the dismantling period.

The physical fundamentals of a wind turbine show that wind speed and the rotor blade design influence most of all the power output and energy yield. According to Betz's law, the maximum possible energy to be derived from a wind turbine is only 59.3% of the kinetic energy in wind. Modern wind turbine designs reach up to 80% of this theoretical limit and have a horizontal-axis turbine. However, this is possible only by using a wind turbine with aerodynamic lift, as a drag-type rotor has a maximum power coefficient of 0.25. Nowadays, typical wind turbines consist of three blades (horizontal-axis) and are about 100 metres high. The average power output is 2–3 MW with a lifetime of 20–25 years. Offshore wind turbines are larger and have a greater power output on account of the better wind conditions at sea. The main components of a modern wind turbine are the rotor nacelle assembly (RNA), which consists of the main energy converting components (rotor, drive train, shafts, brake, generator, yaw and control system) as well as the support structure (tower, foundation). From a technical point of view, a high power coefficient depends on the aerodynamic properties of the blades. The following parameters are important: Rotor design, the number of blades, shape of the rotor, the rotor blade twist, blade airfoil and thickness.

Which factors have to be considered depends on the location. The best wind conditions can be found on coastlines and at sea. The lowlands have at least suitable wind conditions in comparison with those on the coastlines. In the winter months, the wind speeds are twice as high as in the summer. The most common wind speeds range from 4 to 8 m/s, and the best power output can be achieved with wind speeds varying from 12 to 25 m/s. With a normal wind speed, approximately 60% of the power output can be reached. With 8,760 hours in a year, a modern wind turbine has about 2,800 (onshore) to 3,800 (offshore) full load hours and about 4,000–5,000 hours of operation[2]. Losses on account of the location are greater than the losses as a result of mechanical-electrical conversion: Of the 1,340 kW of kinetic energy from the rotors, only 180 kW are lost (generator, bearings or the frequency converter). Rotors with three blades have the best power coefficient and a tip speed ratio that produces a less disturbing noise level. In conclusion, the location and efficiency of a wind turbine depends on the following factors:

- Hazards to environment that affect dwellings (noise, visual-dissatisfaction with the view)
- Proximity to a grid connection
- Property
- Set back (distance to road, grid, etc.)

[2] values depend mainly on location, wind speeds as well as wind turbine design

- The technical structure of wind turbines and driveway to destination (transport)
- Wind speed

Electricity generated by wind power is regarded as sustainable electricity. However, from a life-cycle perspective, wind turbines also consume resources and cause emissions, primarily during the manufacture and disposal stages. The results of LCA on wind turbines show that the construction phase produces the most negative effects on the environment by consuming energy in the extraction phase, in the manufacturing and assembling processes. Compared with the external costs of a gas or coal turbine, these are almost negligible. The operation stage requires some electricity, but the localized negative influences depend on the mix of different energy sources (renewable and/or conventional electricity sources). The comparison of an onshore and an offshore wind turbine shows that offshore plants have more negative effects on water, and the onshore plants on soil, with the same level of air pollution. The higher external costs of onshore plants are accounted for by the fewer full load hours and lower wind speeds on site. The transport process has a small, but critical influence. Using boats instead of helicopters to maintain offshore wind farms, reduces pollution. A doubling of the distance to the grid does not have a significant effect on the environment. The size of the turbines have the greatest effect: the environmental effects of a small wind turbine (30kW) is three times greater than that of a larger wind turbine (800kW), which depends, however, on the lower power output of the small turbine. Choosing a renewable mix of energy for the construction of a wind turbine, reduces payback time (by half) and environmental pollution enormously. The lifetime also decides whether a wind turbine is competitive[3] or not. A lifetime of 20 years gurantees an unbelievably short *energy payback time* of 5–8 months with a *energy payback ratio* of 22, and increasing competitiveness in the market which, however is still dominated by conventional power plants. The dismantling stage of a modern wind turbine allows a recycling of nearly 80% (steel, copper, cables). A higher amount of recycling results in a better environmental profile.

The impact overview provides an insight into all the effects of wind energy on our environment and on the organisms living on earth. Therefore, site-related effects also have to be taken into account, which is rarely carried out in life-cycle analyses. The most essential site-specific influences of wind energy are visual intrusion and noise. Aesthetic aspects are difficult to assess because they are very subjective and change over time and location. Economists have found that visual impacts decrease with distance. Further factors of influence are certain atmospheric conditions and the contrast between wind turbines and landscape. The visual disturbance of wind turbines depends on their number and size as well. Lower numbers are preferred with a similar size and design. The flickering shadow of wind turbines is negligible with regard to the minimum distance regulations to dwellings required by law. It is evident that the noise of wind turbines within a close distance can have a negative effect on human health, especially if someone were to reside in the immediate vicinity of an operating wind turbine. As yet, there

[3]both economically and ecologically in comparison with other electricity-generating technologies

have been no reports of alarming negative influences within a minimum distance to an operating wind turbine. Nevertheless, some people feel a disturbing amount of vibration, pulsation or beats from the rotoring blades, even if they do not hear or see them. There are only a few negative effects to fauna and flora if wind energy is compared with other human activities on Earth.

An analysis of the costs of a wind turbine shows:

- The most expensive components are the tower, the gearbox, the rotor blades and the generator
- 75% of the amount is spent on the turbine itself, whereas the remaining support structure (infrastructur, project development) is less expensive (electrical infrastructure and connection to grid is the main part of this 25% share)
- Considering a normal energy yield, the average power generation costs of a wind turbine in Europe (onshore and offshore) vary from 6–8 euro cents/kWh
- An increase in wind speed of 1 m/s can reduce generation costs by around 25%.

An analysis of the private costs shows that wind (62 euro/MWhel) is the cheapest renewable energy source, as it ranks before gas and oil power plants (66 euro/MWh). It is, however, more expensive than coal (38 euro/MWhel) or nuclear power plants. The external costs of wind energy are very low compared with other electricity-generating technologies and range from 0.08–0.1 euro cents/kWhel, whereas a coal power plant has about 3 euro cents/kWhel. With regard to the social costs of electricty, the ranking[4] of power plants changes again. Wind energy competes absolutely with conventional power plants (without CHP) with social costs of 6.3 euro cents/kWhel compared to 5.3–8.8 euro cents/kWhel from coal, gas or oil facilities. It can be seen that the energy balance of wind power is very positive. The so-called benefits of wind energy show the advantage of this technology. Whereas wind energy is currently more expensive than conventional power plants with regard to private costs, an anthracite (hard coal) power plant is about 6 times cheaper than wind power. It is also two-thirds cheaper with regard to full costs, but, and this is the final finding, it has 28 times more emissions with regard to external costs. In other words, conventional power plants have higher external costs than renewable energy sources.

Overall, a comparison of wind energy with conventional technologies draws attention to the environmental advantages of wind energy. The reduction of emissions can be obtained by producing electricity with wind or hydro-electric-power instead of using conventional technologies, such as the fossil fuels, namely, coal, oil and gas-driven power plants.

[4]which power plant the lowest social costs has

# 7. Conclusion

## 7.1. Findings

The annual growth of capacity of wind turbines was about 27% in 2009 with a market penetration of 2.5% of the worldwide electricity demand, and is expected to reach 3.4% by 2013 and 8% by 2018. Although wind turbines seem to have a positive effect on the climate there are a few environmental issues with regard to the usage of wind energy for the generation of electricity. These external costs of wind power have to be localized and compared with other (e.g. conventional) electricity-generating technologies. Furthermore, the social costs of electricity generation were evaluated and analyzed, which consist of private costs and external costs. The aim was to provide a general view of all the relevant environmental issues related to the utilization of wind energy. This belongs to the evaluation of private and external costs[1] (identifying the benefits of wind power), as well as a significant description of negative effects on the environment as a consequence of using wind turbines. The *life-cycle assessment*, an ISO-implemented technique that allows the assessment (analysis and monetization) of environmental effects (all materials and energy flows) that occur in all the stages of a product's lifespan from the cradle (extraction of materials) to the grave (dismantling), was introduced. It was shown that LCA evaluates only the most essential pollutants with regard to a basic set of impact categories for a widespread set of energy systems. A detailed assessment of all the negative environmental effects on wind power was not possible owing to difficulties concerning the evaluation of some environmental issues which, first of all, exhibit a very complex structure and secondly, are non-monetary and are problematic to quantify. After a study of the relevant literature, it was obvious that there are some site-related effects caused by the operation of wind turbines at a specific location, such as visual intrusion, noise or negative effects on wildlife, which were not taken into consideration in many assessment frameworks. These essential site-related effects of wind turbines have to be discussed and dealt with in accordance with seriously treated planning processes. Wind power is clean, free (wind has no costs), inexhaustible and does not need any fuel. It produces smaller quantities of the conventional pollutants, and their benefits show the ecological advantages of this technology. All in all, a comparison of wind energy with conventional technologies draws attention to the environmental advantages of wind energy. Emission reductions can be obtained by producing electricity with wind or hydro-electric-power instead of using conventional technologies such as fossil fuel power plants. The most essential findings with regard to the problems stated in this thesis are shown in the following enumerations.

[1] using the ExternE methodology

### 7.1.1. Wind turbine characteristics

#### Physics and the location of wind turbines

- The wind speed and the rotor blade design influence most of all the power output and energy yield of a wind turbine
- The maximum possible energy to be derived from a wind turbine is only 59.3% of the kinetic energy in wind for horizontal-axis turbines (using aerodynamic lift) and 20.3% for vertical-axis turbines (using a drag-type rotor).
- Modern wind turbine designs reach up to 80% of this theoretical limit and have a horizontal-axis turbine with a three-bladed rotor. They are about 100 metres high and have a power output of 2–4 MW.
- The average full load hours of wind turbines range between 2,800 hours for onshore and 3800 hours for offshore power plants[2]
- Three-bladed rotors achieve the best power coefficient in a horizontal-axis turbine design and produce a less disturbing level of noise.
- The main components of a modern wind turbine are the rotor nacelle assembly (RNA), which consists of the main energy converting components (rotor, drive train, shafts, brake, generator, yaw and control system) as well as the support structure (tower, foundation).
- The following technical parameters are essential for a high power coefficient: Rotor design, number of blades, shape of rotor, rotor blade twist, blade airfoil and thickness, design of tip speed ratio of the rotor and the power control (blade pitching, passive and active stall control, turning out of wind)
- Computerized control of wind turbines can optimize their lifetime and energy yield (torque, force, strength limits, noise reduction, automated shut down on failures and hazards)
- A consideration of factors that depend on location, the best wind conditions can be found on the coastline and at sea. The lowlands have less suitable wind conditions in comparison with coastlines. Average wind speeds range from 4 to 8 m/s.
- Wind speeds are twice as high in winter as in summer.
- The best power output can be achieved with wind speeds varying from 12 to 25 m/s, whereas with normal wind speeds only 60% of the power output can be reached.
- Few power losses are to be detected as a result of mechanical-electrical conversion.
- The location and efficiency of a wind farm project depends on:

[2] the full load hours depend on the efficiency of the wind turbine, topography and wind speeds

  - Hazards to environment that affect dwellings (noise, visual-sensitive viewpoints)
  - Proximity to grid for connection
  - Property rights
  - Set back (distance to road, grid, etc.)
  - Technical structure of wind turbines and driveway to destination (transport)
  - Wind speed

#### Cost structure of wind turbines

- The most expensive components are the tower, the gearbox, the rotor blades and the generator.
- 75% of the amount is spend on the turbine itself, whereas the remaining supporting structure (infrastructure, project development) is less expensive (electrical infrastructure and connection to grid is the main part of this 25% share).
- With regard to a normal energy yield, the average power generation costs of a wind turbine in Europe (onshore and offshore) vary from 6–8 euro cents/kWh.
- An increase in wind speed of 1 m/s can reduce generation costs by around 25%.

### 7.1.2. Wind turbines and life-cycle assessment

- *Life-cycle assessment* is a powerful method to analyze and monetize environmental effects of energy systems (e.g. electricity-generating technologies) that occur in all the stages of a product's lifespan from *cradle-to-grave*. A LCA takes into account all materials and energy flows from the entire life-cycle of a product's activities.
- The ExternE methodology provides a detailed assessment framework to analyze and monetize the full costs of a large set of electricity-generating technologies
- The evaluation of all environmental effects of wind power demands also an assessment of environmental issues which are difficult to assess and problematic to quantify (non-monetary values; e.g. visual intrusion)
- An interpretation and a sensitivity analysis after a LCA is essential to provide comprehensible results for experts as well as decision makers

#### Full cost assessment of electricity-generating technologies

- An analysis of the private costs shows that wind (62 euro/MWhel) is the cheapest renewable energy source, but, ranked before gas and oil power plants (66 euro/MWh), a slighty more expensive than coal (38 euro/MWhel) or nuclear power plants.

- The external costs of wind energy are very low compared with other electricity-generating technologies and range from 0.08–0.1 euro cents/kWhel, whereas a coal power plant has about 3 euro cents/kWhel.

- A consideration of the social costs of electricity generation changes the ranking of power plants with regard to their effectiveness from an economical and ecological point of view. Wind energy competes absolutely with conventional power plants (without CHP) with social costs of 6.3 euro cents/kWhel, compared with the social costs from coal, gas or oil facilities, which range from 5.3–8.8 euro cents/kWhel.

- The energy balance of wind power is very positive. These so-called benefits of wind energy show that it is cheaper than conventional power plants with regard to the social costs. A wind power plant has about 28 times fewer emissions compared with a conventional coal power plant.

### Evaluation of environmental effects of wind turbines

- Wind turbines consume resources and cause emissions, primarily during the production and disposal stages.

- The construction of wind turbines is the most polluting phase, depending on the materials used and the mix of energy sources to produce electricity. Compared with conventional power plants, the externalities of wind power are negligible.

- The most destructive emissions of wind turbines are $CO_2$, $NO_x$, $PM10$ and so-called *Other pollutants* which consist of Cadmium, Arsenic, Nickel, Lead, Mercury, Chromium and Formaldehyde.

- The operational phase generally has few emissions, but requires some electricity. The localized negative effects depend on the mix of energy sources (renewable or conventional electricity sources). Choosing renewable energy sources in the mix of energy for the construction of a wind turbine reduces payback time (by half) and environmental pollution enormously.

- The dismantling stage of a modern wind turbine allows a recycling of nearly 80% (steel, copper, cables) of all components. A higher amount of recycling results in a better environmental profile.

- The size of a wind turbine (rotor) has the greatest effects with regard to environmental issues. The environmental performance of a small 30 kW wind turbine is three times greater than an 800 kW wind turbine (mainly owing to the lower power output of the small wind turbine).

- Offshore and onshore wind turbines have almost the same emissions. Offshore wind farms benefit from better wind conditions and higher full load hours, but the construction has more effects on the environment.

- A doubling of the distance to the grid does not have a significant effect on the environmental.

- The average lifetime of a wind turbine ranges from 20 years (onshore) to 30 years (offshore).

- The *energy-payback time* of a modern wind turbine is about 5–8 months, depending on the *power output* (technical design) and *energy yield* (wind speeds at a specific location) of the wind turbine.

- A wind turbine has an *energy-payback ratio* of 22, whereas conventional power plants have an energy payback ratio ranging from only 4 (gas turbine) to 14 (coal and nuclear power).

- Site-related effects on living organisms (visual disturbances, noise, effects on wildlife) are not assessed in many LCA owing to the fact that their evaluation or monetization, respectively, might be impossible.

### 7.1.3. Environmental effects of wind turbines

- An overview on all negative effects of wind energy is very helpful and can be used for the treatment of environmental issues (which are difficult to assess) in an *Environmental Impact Assessment.* An EIA is a significant statement to mitigate environmental effects on living organism with regard to all kinds of projects to be planned in the future.

- An opposition to wind farms is mainly encountered during the planning phase. Therefore, a consideration of all site-related effects is essential during the planning process of a wind farm project. Wind farm projects are accepted mostly after commissioning.

- The most essential site-specific influences of wind energy are visual intrusion (i.e. it is an eyesore for some, and flickering shadows are annoying) and noise:
  - Aesthetic aspects are difficult to assess because they are perceived subjectively and change over time and location.
  - Visual intrusion decreases with the distance and under certain atmospheric conditions (weather, contrast between wind turbine and landscape).
  - Wind turbines can cause a noise within a close distance (in the direct surrounding of an operating wind turbine) and that can have negative effects on human health (headaches, migraine, high blood pressure). Within a minimum distance, no negative influences have been reported.
  - The flickering shadow of wind turbines is negligible as a minimum distance to dwellings is required by law.

- Birds showed avoidance behaviour, which reduces the risk of collision with wind turbines. Birds even change altitude when passing wind farms to avoid a collision with the rotating blades.

- The monitoring of wildlife at a specific location in the vicinity of a wind farm is an essential task. It helps to mitigate negative effects on fauna as well as flora or aquatic organisms.

- There are only a few negative effects to fauna and flora, if wind energy is compared with other human activities.

- Tourism is hardly affected by wind turbines.

- The size and number of wind turbines at a specific location are the most essential factors of influence with regard to negative environmental effects to living organism.

## 7.2. Discussion

There are a lot of methods of assessment that allow an adequate internalization of externalities. But some externalities are still difficult to assess. The major problem is a correct evaluation method and a way to monetize externalities to integrate them into the market system. Furthermore, an evaluation of some environmental effects of electricity-generating technologies involves some difficulties, because they are often both non-monetary and problematic to quantify. There are also external effects that exhibit a very complex structure, such as aesthetic effects caused by wind turbines in operation, for instance. But which effects are relevant and should be evaluated? Who decides this and how far does it make it sense to assess impact categories that are difficult to quantify?

For energy systems, the life-cycle analysis method was developed to assess environmental effects that occur in all the stages of a product's lifespan. However, the last step of a LCA (the monetization) requires an adequate set of evaluation methods, or at least a way to normalize all impact categories for a comparison with other energy technologies. This is very complicated and widespread, often an underestimated field of research, which requires both knowledge and long-time experience. Often a LCA provides only a basic analysis (presenting a life-cycle inventory in impact categories, such as human health, toxicity or damage to the ecosystem) without a method of monetization. Otherwise, this could be a problem for decision-makers if they try to value and classify the results without an interpretation or available background knowledge of the entire analyzing process. Otherwise, a LCA was developed for identifying materials and the flows of energy systems and not for a full cost assessment.

Since the most harmful emissions concerning the fuel-based electricity generation are $CO_2$, $SO_2$, $NO_x$ and $PM10$, wind power presents only a small amount of these pollutants. However, the real problems concerning wind power are operational effects which are often discussed and cause problems. Unfortunately, the ExternE methodology[3] does not specialize in the evaluation of negative external effects of wind energy in detail. So a detailed assessment framework still has to be designed for wind turbines, which also considers the site-related effects of wind power. And this does not have to be within the scope of a LCA, but can be carried out in another assessment framework. However, these missing values should be treated in an *Environmental Impact Assessment (EIA)*. But is it sufficient, necessary or useful to treat such effects? How far does it make sense to develop a detailed evaluation framework that considers all negative externalities, although some are not essential being only very small quantities?

Although an EIA is a powerful policy framework[4] it is essential to include limited results from the LCA framework into an EIA and to combine the inputs for a well-founded sensitivity report and interpretation, instead of searching for a complicated tool that allows the exact expression of a willingness to pay for the evaluation of a landscape with wind turbines. Therefore, a view of all environmental effects related to wind power is necessary. Every effect has to be mentioned and described, as well as the significance of the effects that have to be evaluated. Even if some effects are not easy to quantify, they should not be neglected. Since the measurement of the negative effects of offshore wind farms to marine creatures is very difficult and has not been explored in detail yet, widespread monitoring is the best way to improve and enlarge an adequate inside into the situation. This has to be carried out for all items that are currently difficult to evaluate. In contrast, effects on environment, such as visual intrusion do not cause impacts on health, the typical pollutants emitted by the burning of fossil-fuels as it is takes place in conventional power plants have a large impact on the environment and all living organisms. The evaluation of visual intrusion makes absolutely sense, but is it not more essential to reduce or limit hazards that cause mortality, morbidity or loss of biodiversity in vulnerable locations?

Wind power has many benefits (they emit less conventional pollutants) compared with conventional power plants. The negative site-related effects that ensue during the operation of the wind turbines is often a matter for discussion. However, no-one ever talks about the site-related effects or hazards, visual intrusion or effects to fauna or flora with regard to an anthracite power plant, although the mining of coal, for instance, has countless times more negative effects on biodiversity or human health (compared with wind power). All in all, the burning of fossil fuels to produce electricity has by far more negative influences. Humans still try, nonetheless, to prove that the low external costs of wind energy destroy the habitats of wildlife. Again: How far does this make sense? It is important to realize that wildlife is probably more endangered by climate warming or environmental pollution than by the presence of wind turbines. If negative effects of wind turbines have to be estimated, all the effects have to be considered. Site-related impacts of wind energy, which are more difficult to evaluate, require more extensive surveys or public participation. A systematic approach to the evaluation of visual intrusion, for

[3]was developed to compare a wide set of electricity-generating technologies
[4]an inclusion of all environmental effects of wind energy makes sense

instance, (general participation, workshops, etc.) has to be defined and carried out at the same time as analyses of energy and material flows (commonly carried out in a LCA). A weighting for all the effects of wind turbines on the environment has to be defined with the aim to limit or avoid the most hazardous impact categories, especially pollutants. It is essential to integrate local, regional and national planning authorities as well as organizations and communities of interest to achieve the best solution for a sustainable wind turbine development. Moreover, these suggestions are addressed to all planning activities and are not restricted to wind turbine projects.

Generally, it has to be considered that an evaluation tool is always a model, which does not reflect reality to 100%. An evaluation has the purpose to help decision-makers to carry out their function to the best of their abilities and does not replace an expert panel. An expertise is always essential and necessary to support decision-makers. Values that are hard to quantify have to be considered in sensitivity analyses. It is always better to have fundamentals of a result, instead of having nothing or only insufficient coherences (Fritsch).

### 7.2.1. General topics of discussion:

**Life-cylce assessment:** However, the framework of a life-cycle analysis, whether it makes sense or not, has to be challenged. For instance, an ISO certification does not mean that the consultant's work ensures the quality of the data. Decision-makers have to be advised carefully by experts. The author also warns against considering only a few environmental issues in a LCA (e.g. human health or energy impacts). To find out whether the effects of an energy technology have to be given attention or not, all effects have to be more or less fully assessed or interpreted. Furthermore, impacts are treated differently in each country, so some high amounts of pollution are exported to other countries that care less about them. Another important task is the estimation of impacts in different units. Using normalized values is clearly a way to cheat because only the consultant, who writes a LCA software tool, knows the exchange rates. Secondly, eco-points are not different from monetary currencies. Politicians could be influenced by the consultant's weighting of the numbers.

**Dynamic calculation methods – the discounting:** To obtain a *net present value* of a project, all periods of time have to be discounted (humans discount future values to obtain a present value). But the discount rate is a very important and powerful value. It decides the value of future values of a project. This can be risky, because environmental goods are not less valuable in future as they might be for an economic good. By contrast, the worth of the environment (e.g. clean air) increases in future with regard to increasing pollution (clean air is limited).

**Lifetime of a wind turbine:** The manufacture of a wind turbine is an essential part in the business of utilizing wind power to meet energy requirements. Thus, the following factors are important and should be considered:

- Types of materials used and their origin (including energy consumption for extraction)
- Location of manufacture: the use of an energy mix (of renewable or conventional energy source), what is the distance from manufacture to the site
- Transport: types of vehicles and distance

Using only renewable energy for construction and transport could minimize external costs. Wind turbines require some energy during operation. If this energy were not from a conventional mix of energy sources, the effects on the environment would be minimized.

**Environmental effects of wind turbines:** The discussion on whether wind turbines destroy the landscape or not (often the individual, subjective scenery) is more or less superfluous, if one considers the other negative sources of impacts, such as transmission lines or the smokestack of a gas power plant, which have much the same disturbing character. Besides, the mortality rate of birds caused by transmission lines is much higher than that caused by the rotating blades of a wind turbine. Yet, the existence of transmission lines from a centralized coal power plant to all consumers over a large grid network is rarely discussed or challenged by the residents of a region. Some site-related effects on fauna and flora have still to be analyzed and investigated in more detail. It is therefore important to create a comprehensive monitoring framework. For instance, after seven years of monitoring Horns Rev and Nysted wind farms some minor effects were registered on bird populations. Visual eyesore have to be considered, but insofar as it makes sense. A disturbance of health caused by a visual perception of wind turbines is not known so far.

# 8. Glossary

- CHP: Combined heat and power
- CO2: Carbon dioxide
- Environmental impacts: environmental effects, a negative effect caused by an activity
- EUR: Euro
- Euro cent/kWhel: Euro cent per kilowatt hour electricity generated
- EYR: energy yield ratio
- GHz: Giga hertz
- GWh: Gigawatt hour
- h/a: hours per year
- Hydro power: hydro-electric-power
- Hz: Hertz
- IGCC: Integrated gasification combined cycle
- Impact: in this thesis, a negative influence that is caused by an activity (e.g. operation of a power plant)
- IPA: impact pathway approach
- kg: Kilogramm
- kHz Kilo hertz
- kW: Kilowatt
- kWh: kilowatt hour
- LCA: Life-cycle-assessment
- LCI: Life-cycle inventory
- MCFC: Molten-carbonate fuel cells

- m/s: meter per second
- MWh: Megawatt hour
- NOx: Nitrogen oxide
- MW Megawatt
- p/kWh: pence per kilowatt hour
- PM: Partigulates
- PV: Photovoltaic
- SO2: Sulphur oxide
- SOFC: A solid oxide fuel cell
- SPL: Sound pressure level
- t: Ton

# List of Figures

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# A. Appendix

## Wind turbine – characteristics

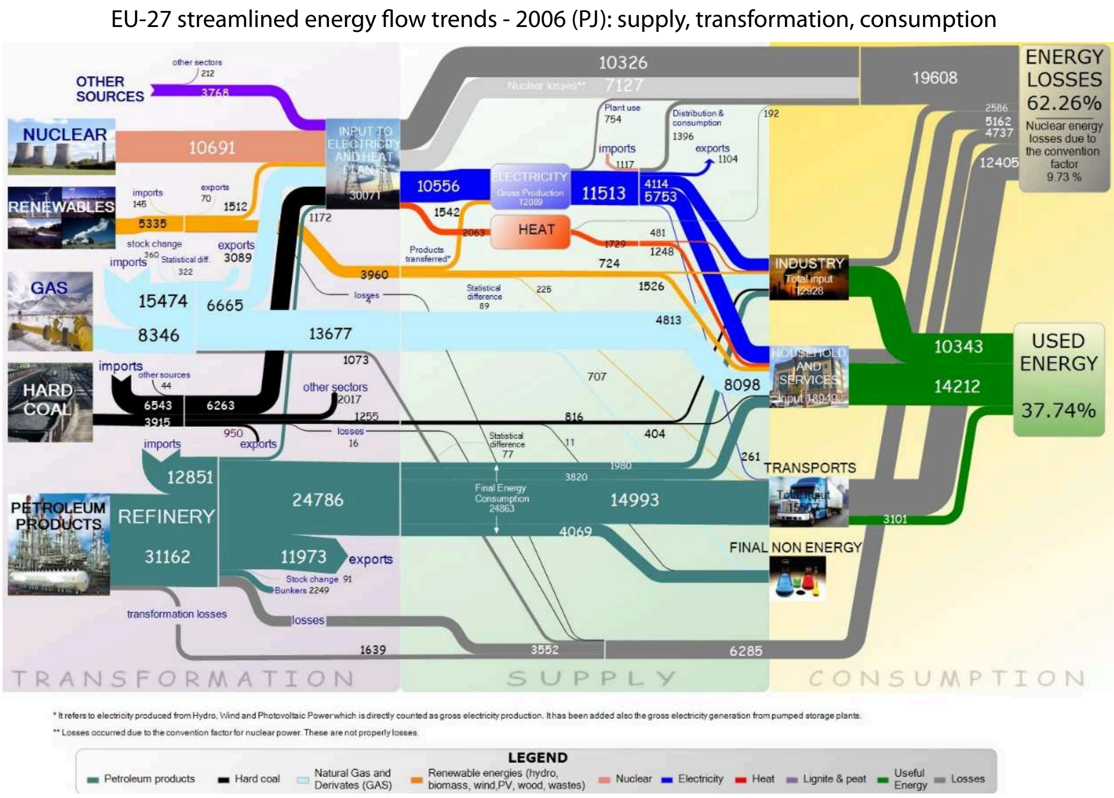



Figure A.1.: EU-27 streamlined energy flow trends - 2006 (PJ)

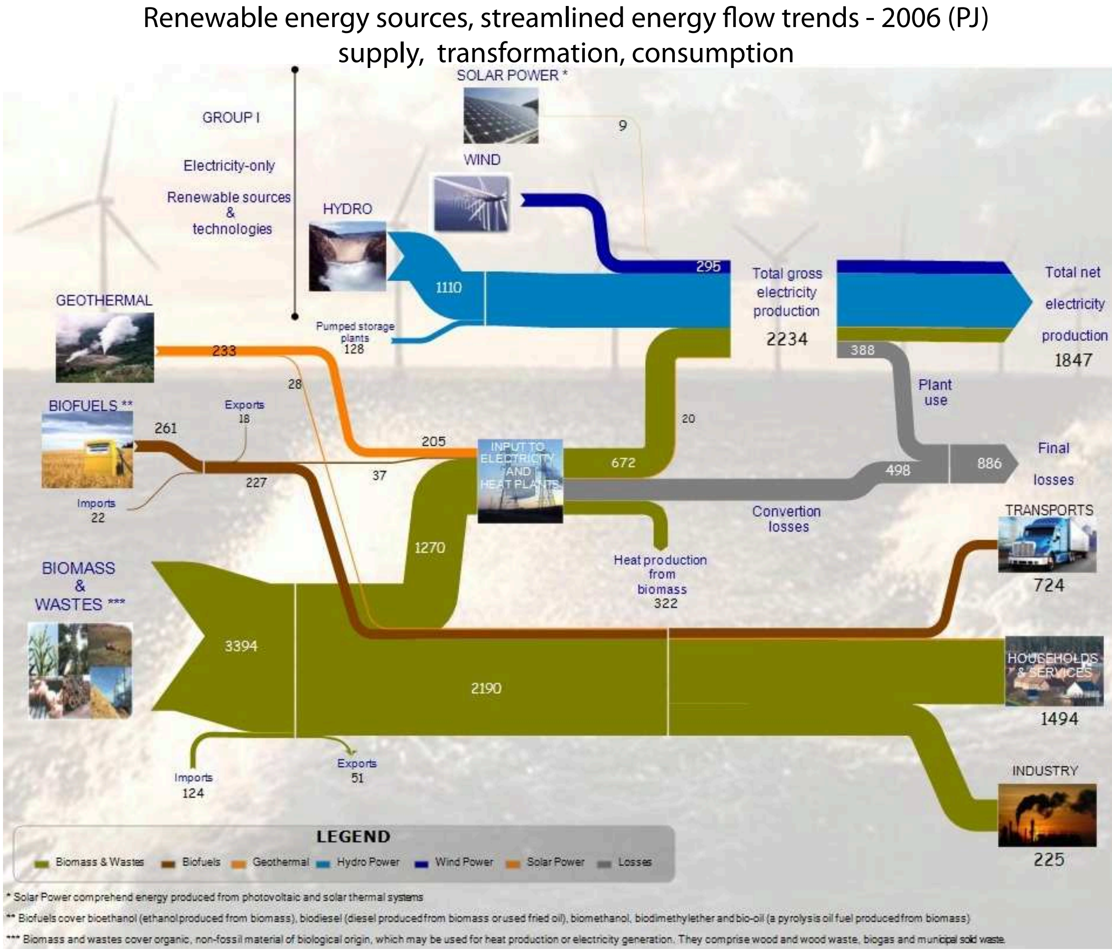



Figure A.2.: Renewable energy sources, streamlined energy flow trends - 2006 (PJ)

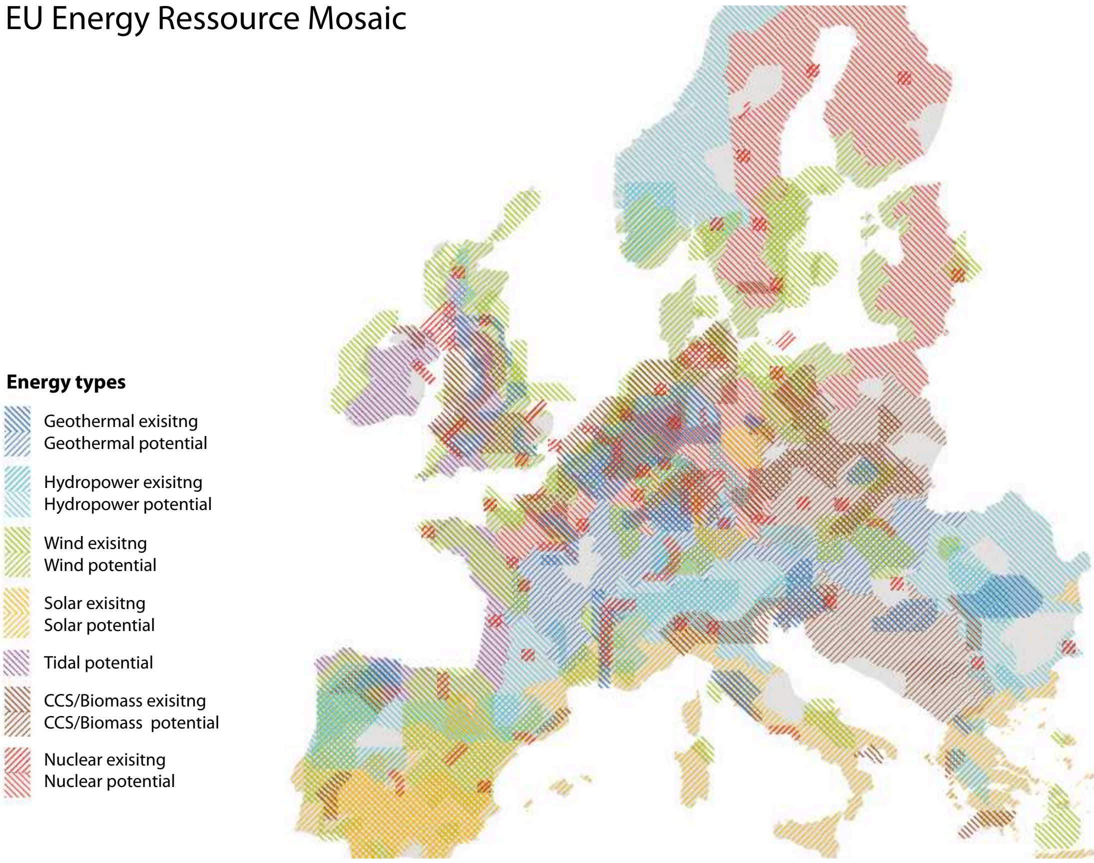
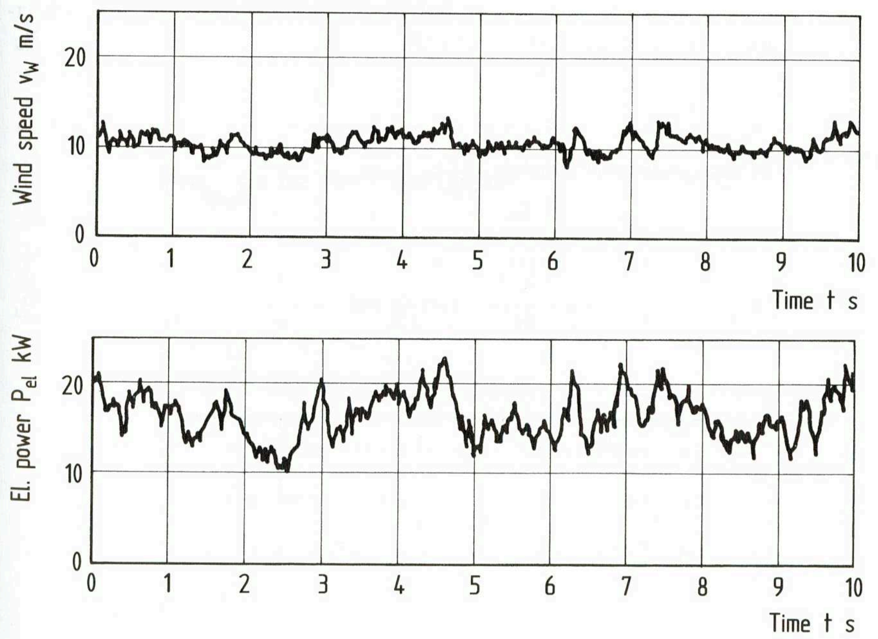



Figure A.3.: EU Energy Ressource Mosaic – overlay of current energy use and those regions with the highest energy potential

Electrical power output of a small wind turbine with fixed blade pitch angle and a grid.coupled induction generator




Electrical power output of the WKA-60 wind turbine with blade pitch control and variable speed generator system (speed variation +-15%,

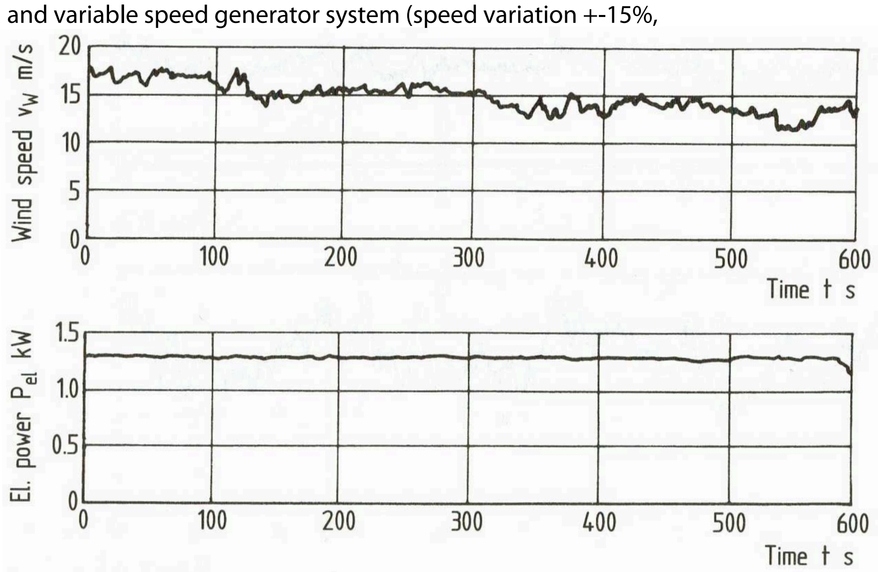



Figure A.4.: Uniformity of the power output

# Energy-generating technologies

## Technology Data

| | | | 2007 | | 2020 | | 2030 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **type of power plant** | **energy carrier** | **technology of electricity generation** | **net el. capacity** | **el. efficiency** | **net el. capacity** | **el. efficiency** | **net el. capacity** | **el. efficiency** | **full load hours** | **technical life time** |
| | | | **[MW]** | **[%]** | **[MW]** | **[%]** | **[MW]** | **[%]** | **[h/a]** | **[a]** |
| nuclear power plant | nuclear power | PWR (Pressurized Water Reactor) | 1300 | 33 | 1300 | 35 | 1300 | 36 | 7500 | 60 |
| fossil fired power plant | heavy fuel oil | condensing | 350 | 43 | 350 | 43 | 350 | 43 | 7500 | 35 |
| | light oil | gas turbine | 50 | 36 | 50 | 38 | 50 | 38 | 7500 | 35 |
| | hard coal | condensing | 600 | 46 | 600 | 50 | 600 | 52 | 7500 | 35 |
| | | IGCC | 450 | 45 | 450 | 54 | 450 | 54.4 | 7500 | 35 |
| | | IGCC with CO2 capture | | | 450 | 48 | 450 | 48.5 | 7500 | 35 |
| | lignite | condensing | 965 | 44.5 | 965 | 50 | 965 | 50 | 7500 | 35 |
| | | IGCC | 450 | 44 | 450 | 52 | 450 | 52.5 | 7500 | 35 |
| | | IGCC with CO2 capture | | | 450 | 46 | 450 | 46.5 | 7500 | 35 |
| | natural gas | combined cycle (CC) | 1000 | 57.5 | 1000 | 62 | 1000 | 63 | 7500 | 35 |
| | | CC with CO2 capture | | | 1000 | 56 | 1000 | 57 | 7500 | 35 |
| | | gas turbine | 50 | 38 | 50 | 39 | 50 | 40 | 7500 | 35 |
| electricity generation based on renewables | hydro | run of river | 0.2 | 85 | 0.2 | 85 | 0.2 | 85 | 5000 | 70 |
| | | | 1 | 85 | 1 | 85 | 1 | 85 | 5000 | 70 |
| | | | 50 | 85 | 50 | 85 | 50 | 85 | 5000 | 70 |
| | | dam | 1000 | 83 | 1000 | 83 | 1000 | 83 | 3000 | 120 |
| | | pump storage | 500 | 72 | 500 | 72 | 500 | 72 | 3000 | 120 |
| | wind | on-shore | 2 | 100 | 12 | 100 | 22.7 | 100 | 2628 | 20 |
| | | off-shore | 2 | 100 | 12 | 100 | 22.7 | 100 | 4044 | 20 |
| | PV | poly cristalline, roof | 0.00312 | 13.5 | 0.00312 | 19.3 | 0.00312 | 21.8 | 1070 | 25 |
| | | poly cristalline, open space | 0.00312 | 13.5 | 0.00312 | 19.3 | 0.00312 | 21.8 | 1070 | 25 |
| | solar thermal | solar trough | 80 | 13,2 | 80 | 15 | 80 | 17 | 1900 | 40 |
| CHP with an extraction condensing turbine | natural gas | combined cycle | 200 | 47 | 200 | 47 | 200 | 47 | 7500 | 35 |
| | | Combined cycle with CO2 capture | 200 | 41 | 200 | 41 | 200 | 41 | 7500 | 35 |
| | hard coal | condensing | 500 | 37 | 500 | 37 | 500 | 37 | 7500 | 35 |
| | | IGCC with CO2 capture | 450 | 36 | 450 | 36 | 450 | 36 | 7500 | 35 |
| CHP back pressure turbine | natural gas | combined cycle | 200 | 46.5 | 200 | 46.5 | 200 | 46.5 | 7500 | 35 |
| | hard coal | CHP back pressure | 200 | 38 | 200 | 38 | 200 | 38 | 7500 | 35 |
| Biomass CHP with an extraction condensing turbine | straw | extraction condensing turbine | 6.1 | 19.5 | 6.1 | 19.5 | 6.1 | 19.5 | 7500 | 30 |
| | wood chips | extraction condensing turbine | 6.1 | 19.5 | 6.1 | 19.5 | 6.1 | 19.5 | 7500 | 30 |
| fuel cells | natural gas | MCFC | 0.25 | 50 | 0.25 | 50 | 0.25 | 50 | 7500 | 7 |
| | | SOFC | 0,2 | 56 | 0,2 | 56 | 0,2 | 56 | 7500 | 7 |
| | biogas | MCFC | 0.25 | 50 | 0.25 | 50 | 0.25 | 50 | 7500 | 7 |

Figure A.5.: Technology data of electricity-generating technologies

# Environmental effects of wind energy

## Noise

Table A.1.: ISO 1996-1971 Recommendations for Community Noise Limits in dB(A)

| Dsitrict type | Daytime Limit | Evening Limit (7-11pm) | Night Limit (11pm-7am) |
|---:|:---:|:---:|:---:|
| Rural | 35 | 30 | 25 |
| Suburban | 40 | 35 | 30 |
| Urban residential | 45 | 40 | 35 |
| Urban mixed | 50 | 45 | 40 |

## Radar Interference

| Systems | Air traffic control | | Meteorological control | Air defence | |
|---|---|---|---|---|---|
| Mission | Control of arrival, departure and transit invicinity of airport and transit over the country | | Weather forecasting; very important toaviation safety | Detect and identify aircraft approaching, leaving or flying over the territory of a country | |
| Types | Primary radar | Secondary surveillance radar | Weather radar Wind profile radar | Ground based radars | Airborne radars |
| Wind turbines'effects | False radar responses or returns | Masking genuine aircraftreturns; reflection from windturbines could cause misidentification or mislocation of aircraft | Reflection | Highly complex andnot completely understood | Highly complex andnot completelyunderstood |
| Mitigation measures at the beginning of project planning | Ensuring location in area with low aircraft traffic; ensuring location not inline of sight ofany aircraft radar | Avoiding close vicinity to radars; minimum safe distance between wind farm sand these types of radars not defined | Avoiding wind farm installation at 10 km or less of radar facility | Minister of Defence of UK does not permit any wind farm located at less than 74 km from an air defence radar, unless developers can demonstrate no interferences with the defence radar | Moving the location of wind farm or adjusting the configuration of turbines to avoid interference; providing alternative site for the affected radar; contribute to investment in additional or improved radar system |

Figure A.6.: Effects and Mitigation Measures by Radar Types