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Leveraging the competitive advantages of end-of-life underground coal mines to maximise the creation of green and quality jobs

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Summary

As part of the RFCS-funded EU-project GreenJOBS: "Leveraging the competitive advantages of end-of-life underground coal mines to maximize the creation of green and quality jobs", Deliverable 2.3 dealt with the integration of wind power. One focus was to illuminate wind power in former mining regions and the associated potential and challenges from a socio-economic as well as a technical perspective.

The state of research shows that the wind energy sector is constantly growing and therefore has a positive influence on the European economy. In concrete terms, this is reflected in economic growth and the creation of sustainable jobs. As a result, wind energy is particularly popular in research and the optimization of associated processes is constantly being promoted. This includes not only the technology that is used, but also the characterization and distribution of wind energy. In order to undertake the integration and installation, the associated advantages and disadvantages of this resource are of importance: clean energy, low operating and efficiency costs, as well as high market potential, saving water and creating jobs. The disadvantages in turn are ranging from the specific local conditions, nature and animal protection, the shadow flicker phenomenon and the reliability of the wind resource itself. Apart from that, the demand for rare earths for the production of wind turbines is rising and exceeding existing reserves, while imports and dependencies increase to meet climate goals and a green transition. For the proper utilization in former mining regions, the formal participation of citizens in regions affected by former mining is guaranteed by Europe-wide standards, the planning and approval of such processes are laid down in law. For example, the following aspects must be considered: avifaunistic assessment, noise assessment, shadow assessment, turbulence assessment and geotechnical report. In the further approach, the report shows a site demo installation based on the investigation of the economic, employment-related and general technical requirements of wind energy on heaps in the German Ruhr area. Another feature is the consideration of employment effects related to wind energy. The entire value chain of projects for the installation and use of wind power includes: extraction and processing of raw materials, associated equipment construction and logistics, but also the project planning and installation. In any case the maintenance and operation, energy delivery, repowering and, after the end of the term, decommissioning and subsequent recycling is needed. Finally, some successful application examples for wind turbines on heaps follow, both in former and still active mining locations. Some of these post-mining examples can be found in Germany, such as the Hoppenbruch heap in the city of Herten in the Ruhr area.

This report forms a wide range of analysis factors for the application and further development of wind energy for Europe and uses a wide variety of examples. One of these many examples shows that the European heaps largely have one thing in common. Their material is often too soft to withstand a superstructure and as a result requires soil improvement and support structures to ensure buildability of wind turbines.

1 Introduction

This report focuses on the overarching topic of "Deploying wind power". This is part of the work package Nº 2 for further processing of the funded EU project GreenJOBS under the consortium leadership of the Universidad de Oviedo (UNIOVI).

Together with colleagues from Główny Instytut Górnictwa (GIG), Magellan & Barents, S.L. (M&B), Weglokoks Kraj Sp. z o.o. (WEGLO), Hulleras del Norte, S.A. (HUNOSA) and Premogovnik Velenje d.o.o. (PV) the work package Nº 2 was edited in different sub-topics. The goal here is the detailed consideration of energy amplification technologies as well as energy utilization technologies and green hydrogen. Since the authors from DMT-THGA dealt with the field of wind power, the following conditions applied: On the one hand, the most common units on the market with regard to wind power should be selected. On the other hand, it is then necessary to present the technical conditions required for this and to identify the associated costs and possible operating restrictions. Ultimately, an accurate analysis of the potential for creating new jobs can be made.

Using the methods of the input-output matrix and the employment factor methods, the potential to be exploited for the creation of new jobs in the course of renewable energies is to be determined. Therefore, the question arises to what extent renewable energies can influence employment, both the net and the gross effects. The first method, the input-output model, uses an analysis of economic activities to determine the influence of investments on economic sectors and to classify the employment effects in relation to supply and demand. In this way, the multiplier effect can be recorded, which, in addition to direct employment, also provides information about indirect and induced employment. The second methodology, the employment factor, focuses on the general potential for job creation, where an analysis using the input-output method is ineffective. The combination of these two methods enables the multiplication of the respective level of activities within the renewable energy value chain. For this purpose, the relevant factors for employment are included, which are determined individually in the consideration of a single renewable energy technology (here wind power). While it is important to note that these factor methodologies only include direct effects, not net effects. Nevertheless, in this case, they are more transparent in their presentation and the resulting results.

The specific analysis of wind power is then assigned to the DMT-THGA as a sub-task (2.1) within the work package. In addition to the overarching goals mentioned, it is important to create an overview of the following aspects: costs, operational restrictions, technical requirements and employment potential. Based on the German experience, the analysis focuses, among other things, on the following analysis points:

a) Efficiency in %
b) Minimum load of the device in %

c) Efficiency at minimum load in %
d) The ramp-up limit for units per unit per minute in %
e) The ramp-down limit for units per unit per minute in %
f) Unit size in MW
g) Operating and maintenance costs in € per MWh
h) Availability of the unit when analysing investments
i) The maximum contribution to the upward reserve from available generation in the Shipping method in %
j) Maintenance and operating costs per year in € per MW
k) Investment costs in € per MW
l) Start-up costs in € per MW
m) The lifetime of the units in years
n) Energy consumption
o) Reduction of CO_2 emissions due to the installation of the new equipment in tons per year
p) Job creation potential per installed MW for both commissioning and operation (GreenJOBS, 2022)

The authors of this report divided the chapters for a better overview of the different analysing aspects. Therefore, first an introduction to the topic of "Wind power globally and in Europe" is given. The sub-chapters deal with the topics of "Tackling of the general raw material-, environmental- and recycling- problems of wind energy" and "Special possibilities and problems of wind power in mining areas" in more detail here. Afterwards, the sequel to "Opportunities for jobs and growth by wind energy in European coal regions" follows. Finally, the chapter "Geotechnical requirements of the (mining) terrain for deploying wind power" adds the technical perspective before a conclusion is given.

2 State of the art of “technology”

Wind power is the production of electric energy by using the kinetic energy of airflows. The wind is a free, abundant and clean energy source used to generate electricity and one of the fastest growing renewable energy technologies.

Capacity developments

The amount of global installed wind-generation capacity (onshore and offshore) has increased by a factor of almost 75 in the past two decades, according to IRENA, the International Renewable Agency, from the amount of 7.5 Gigawatts in 1997 to some 564 Gigawatts in 2018 and much more in the years thereafter. The Global Wind Report of GWEC (Global Wind Energy Council) recorded a global cumulative wind power capacity in 2021 of 837 GW.

According to Eurostat, wind power accounted for one-third of the total electricity generated from renewable sources in the EU in 2020, which made up 37% of gross electricity production in the European Union. However, the expanding wind sector is also a significant contributor to the European economy now, boosting growth and creating sustainable jobs. According to the sectoral association WindEurope, it provided between 240,000 and 300,000 jobs in the EU in 2020 (of which about 62,000 were in the offshore wind industry, the rest of around 200,000 jobs were provided by onshore wind power installations). Furthermore, wind energy can be key to the future perspectives of coal regions in transition and support them in cutting power sector emissions by half in 2030.

The wind has been used as a source of energy in agriculture, transport, trade and later in industry for thousands of years. As the European Commission DG Energy states also modern wind turbines work on some relatively simple principles: The wind makes their blades spin, creating kinetic energy. A generator then converts this kinetic in electric energy. Due to the location, there are single stand-alone units, small groups of wind power stations or wind farms as larger groups that can cover several square kilometers of land or sea to harness either onshore or offshore wind. Continued improvements in manufacturing and turbine design combined with improved capacity factors (more MWh of electricity generated per MW of wind turbines installed) have enabled impressive economic progress. Thanks to better localisation and/or more performant turbines and repowering as well as the economies of scale in the process of expansion and considerable technological development, the costs of wind power have driven down and reaffirmed its position as a key driver of the energy transition.

Due to EUROSERV’ERs Wind Energy Barometer March 2022, there had been an estimated electricity production of 384.9 TWh from wind power in the EU (of 27 in 2021). This was a production of 12.5 TWh less than in 2020 although capacities were enlarged, because the wind power generation is weather-dependent and in contrast to 2020 many European countries had poor winds (especially Germany).

The cumulative wind power capacity installed in the EU at the end of 2021 was 187.8 GW (of which had been an offshore capacity of 15.1 GW and an onshore capacity of 172.6 GW). Roughly, one-third of the European wind power capacity is based in Germany and roughly, the half is installed in the two Member States Germany and Spain, followed by France, Sweden and Italy with also five-digit-MW-capacities. Four-digit-MW-capacities are now installed in the Netherlands, Poland, Denmark, Portugal, Belgium, Greece, Ireland, Austria, Finland and Romania. There is no Member State of the EU today without wind power capacity, but all the other ones have installed quite smaller capacities. (Looking only upon offshore capacities, 19% of the total wind power capacity in the EU-27, more than the half is built by German offshore wind farms.)

The additional capacity in 2021 in the EU-27 increased by 11 GW against 2020. This had been an improvement and the fourth best yearly enhancement performance of the last decade, but the pace seems to be still much too low to meet the EU climate targets for 2030. The wind energy industry reckons that in order to achieve the new goal of 40% of renewable energy in final energy consumption in 2030, almost three times as much capacity needs to be installed every year. This is enough reason to inquire and examine the potentials of former or transitioning coal mining areas as locations for new wind power installations.

For a comparison with the world’s Number 1 state in wind energy: China’s installed wind power capacity in 2021 stands at 328.5 GW (including 26.4 GW of offshore capacity), which is 75% more than the capacity of the EU. Wind power output in China for 2021 is estimated at 655.6 TWh, which had been 41% more than in the previous year 2020 (very astonishing with a view to other growth rates in the light of the Corona depression) and far exceeds the total electricity generation of Germany, France or any other European country.

The Wind Energy Barometer 2022 includes a special hint to the current warnings of the European wind industry to the European Commission at the turn of the year 2021. It relates to the critical situation in which the European wind energy supply chain finds itself, and of its harmful consequences for the European Green Deal. The CEOs of the five biggest EU-based wind turbine manufacturers (Enercon, GE Renewable Energy Europe, Nordex, Siemens Gamea Renewable Energy, Vestas Energy System A/S) and the CEO of the association WindEurope sent a joint letter to the President of the European Commission Ursula von der Leyen. This was already before the unfolding of the macroeconomic crisis triggered by the Russian war against Ukraine and all its effects on the energy sector. In this letter, they warned her as mentioned above of the critical situation for the European wind industry and explained that it was rgoing through unprecedented tough times, closing factories and halting investments in the European

Union at the very moment when the industry needed to be expanding. They stated that in the space of two years, the industry had been forced to close turbine and component manufacturing plants in Germany, Spain and Denmark, which are traditional bastions of Europe’s wind industry. They underlined as well that the problem was not a lack of ambition on the part of the Member States, which have all stressed their willingness to develop wind energy, nor the issue of public acceptance. However, the rules and procedures used by the public powers in the EU to authorize wind energy projects are too long and too complex. They feel that the delay and dearth of construction permits available are thwarting the Member States’ climate ambitions. As a result, wind farm developers bid in government auctions at the lowest possible price to secure the small volumes of the permitted projects on offer. This damages the European Union’s supply chain, which is struggling to stick to these cost levels in relation to competitors from third countries. At the same time, the wind industry is hindered by high prices for steel and other raw materials, disrupted supply chains and uncoordinated trade defense measures. The CEOs also point to the fact that the Chinese wind industry enjoys unflagging growth and is installing many more wind farms than in Europe. While the European industry exports 8 billion Euros’ worth of technology and equipment every year, it is losing ground because of the inroads Chinese manufacturers are making in Asia, South America and Africa. Furthermore, China is starting to win orders in Europe.

The CEOs of the European wind industry went on to set out four special action points for the EU: Firstly, to streamline and accelerate the national authorization processes, and the grid investments needed because the grid expansion is a prerequisite for more renewable energy (especially wind power). Secondly, to strengthen the European wind energy industry’s position in government auctions for new wind farms by introducing non-price related criteria. So far, auctions have been awarded based on price only, and as their Chinese competitors position themselves on just and only this criterion, the European bidders are today, and in the near future, in a no-win situation. The new Guidelines on State Aid for Climate, Environmental Protection and Energy defined by the European Commission are a step in the right direction, but should be improved further. They now enable governments to base up to 30% of the score on criteria other than tariff and this reward the added value contributed by the European industry, such as more sustainable and circular-economy-friendly turbines, grid-balancing technologies and providing jobs.

The third point put forward is to discourage national governments from holding negative auctions. Effectively, developers pay the governments for the right to construct a wind farm; however, they should not have to do so unless the market price of electricity is higher than the auction price. Negative auctions incur additional costs for developers that have to be passed on to the consumer if possible, which puts even more pressure on the wind energy supply chain. The fourth and last point raised is the demand for innovation support to ensure that the European Union retains its technological lead in wind energy. And this is not only in the emergence of new technologies such as floating wind turbines in offshore wind farms, but also in gradual improvements to keep Europe's lead in the land-based onshore (and fixed bottom offshore) wind farm sphere.

Besides the own view of the wind industry, a new scientific study on the key factors influencing onshore wind energy development in the Journal *Energy Policy* by Kiunke et al. (2022) confirms by doing a SWOT analysis that complicated and lengthy bureaucratic procedures and (too?) strict environmental protection regulations are the main threats for the development of onshore wind power accompanied by local protests and resistance against wind projects. This study confirms also the well-known strengths and weaknesses of wind energy. The strengths are the very low CO_2 emissions and the increasing competitiveness of wind power in the energy market forced by technological progress in repowering and many suitable locations for wind farms. The weaknesses are impacts on humans and wildlife in the neighbourhood of the installations and limited spatial opportunities for wind energy expansion. At the same time, there are driving priorities in the opportunities for wind energy development as the overall topic of climate change, the political will and incentives to foster wind energy, technological developments in the storage sector (which are essential for the question of security of energy supply by renewables) and national plans for nuclear and/or coal phase out in power generation. It is evident that all these points are as well of high relevance for the future framework of wind projects in coal mining areas and their specific potential and scope for the creation of new jobs and value added.

As announced as their own ambition, the European wind industry players are committed to the vital issue of wind energy's environmental credentials as Wind Energy Barometer 2022 points out. Recently, there are also outstanding technological leaps. Europe's wind energy industry is actively committed to reusing, recycling or recovering 100% of decommissioned blades. In a communiqué released in June 2021, Wind Europe called for a Europe-wide ban on dumping decommissioned wind turbine blades by 2025. A ban of this sort would further speed up the development of sustainable recycling technologies for composite materials. At the same time, the sector has undertaken not to send decommissioned wind turbine blades for dumping to Non-European countries. The communiqué of WindEurope claims that the standard expectancy of a land-based wind farm is about 20-25 years. As it stands, 85-90% of the total mass of a wind turbine can be recycled. There are recycling circuits for most of the components – including steel, cement, copper wire, electronics and gears. However, turbine blades are harder to recycle as they contain complex composite materials, namely a combination of reinforced fibers (generally glass or carbon fiber) and a polymer matrix that enhance blade performance levels by making them lighter and longer.

In September 2021, Siemens Gamea announced its market launch of the first recyclable wind turbine blade for commercial use offshore: the "RecyclableBlade" designed to be recycled at the end of its lifecycle. In March 2022, the ZEBRA consortium (Zero wastE Blade ReseArch), associating the French Research Center IRT Jules Verne and several manufacturers such as Arkema, CANOE, Engie and LM Wind Power (belonging to GE Renewables, Owens Corning and SUEZ, who also announced the production of the first prototype of a 100% recyclable wind turbine. It shall be made of Elium resin, a thermoplastic resin, well known for its recyclable properties.)

According to the Wind Energy Barometer 2022, the current political and economic crisis in Europe caused by the Russian war against Ukraine, the dependency of the EU on fossil fuels supplied by overtly hostile third countries and the resulting energy price hike as well as the climate imperative, may be a catalyst for an accelerated expansion of renewable energies, including wind power in the EU. The development of wind energy and other future-proof options, therefore, is a race against time.

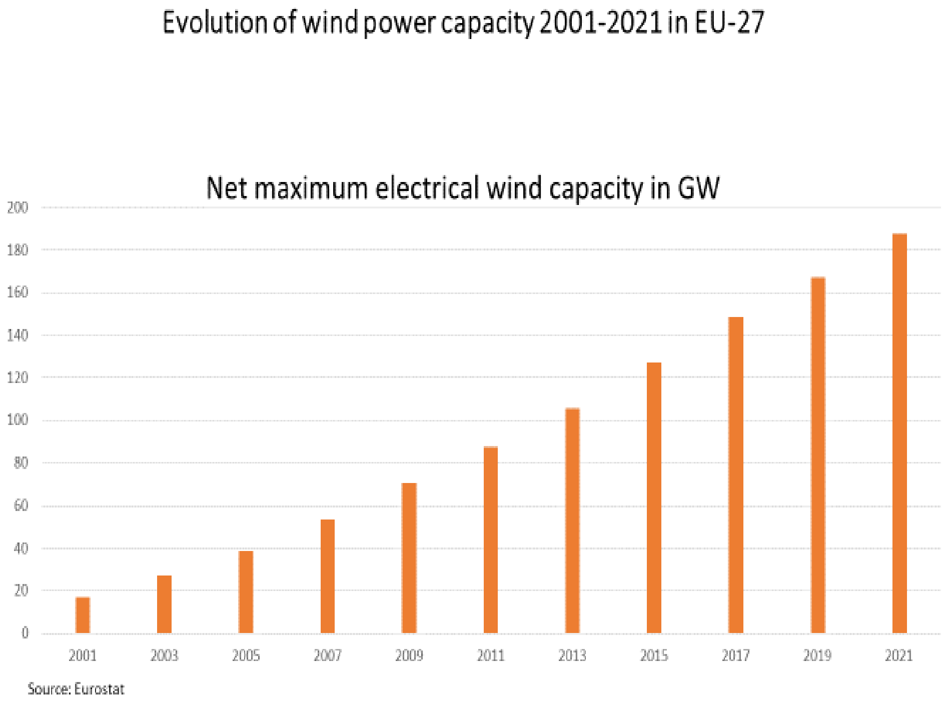
With its “Green Deal for Europe“, the European Union has already outlined its very ambitious vision of a climate-neutral, fair and prosperous European society, with a modern, competitive and resource-efficient economy. To fulfill this ambition, the European Commission published its “Fit for 55” climate and energy policy package in summer 2021, which has presented 12 legislative proposals that affect all the economy’s sectors and aim for not less than a root-and-branch-overhaul of Europe’s economies to achieve at least 55% emissions reduction by 2030 on the way to 100% in 2050.

In spring 2022, the Commission proposed the REPowerEU plan to liberate Europe from its dependency, especially on Russian fossil fuels, and is working since then to finalize and accomplish this plan in cooperation with the Member States. As a matter of urgency, REPowerEU aims to diversify the gas supply for the EU, accelerate the rollout of renewable (“green”) gas to support the increased production of hydrogen and replace the gas used for space heating and generating electricity in the EU. The plan includes provisions for faster rollout of wind and solar power, entailing a 20% increase in the average deployment rate in the EU. The Commission will seek to implement the means to make renewable energy production projects easier all over Europe, focusing on the main obstacles to rolling out these projects, such as the lengthy authorization procedures, the complexity of site selection rules and administrative processes, several grid connection issues and staffing those authorities responsible for assessing permits. The “Fit for 55”-Package follows already the plan to double the European Union’s wind and solar power capacity by 2025 and treble them by 2030 (in relation to 2020). By the end of 2030, this implies the deployment of 480 GW of wind energy capacity in the EU-27.

Table 2-1 shows installed wind power capacity and electricity production from wind power in the EU for the year 2021, whereas the evolution and projection of net maximum electric wind capacity in the EU27 from 2001 to 2021 are given in Figure 2-1.

Table 2-1. Wind power capacity installed and electricity production from wind power in the EU in 2021

Country/EU	Wind power capacity installed (MW)	Of which offshore (MW)	Electricity production from wind power (TWh)	Of which offshore (TWh)
Germany	63865.0	7774.0	113.848	24.374
Spain	27575.1	-	62.009	-
France	18548.0	-	36.800	-
Sweden	12080.0	203.0	27.368	0.629
Italy	11100.0	-	20.778	-
Netherlands	7800.0	2459.5	17.894	7.952
Poland	7116.7	-	15.867	-
Denmark	6995.2	2305.6	16.083	7.593
Portugal	5627.0	25.0	13.147	0.052
Belgium	4740.9	2261.8	11.876	6.926
Greece	4649.1	-	10.483	-
Ireland	4339.0	25.2	9.721	-
Austria	3300.0	-	6.723	-
Finland	3257.0	73.0	8.114	0.299
Romania	3029.0	-	6.576	-
Croatia	990.2	-	2.071	-
Bulgaria	707.0	-	1.403	-
Lithuania	671.0	-	1.362	-
Czechia	339.4	-	602	-
Hungary	329.0	-	640	-
Estonia	320.0	-	800	-
Luxembourg	160.0	-	327	-
Cyprus	157.7	-	240	-
Latvia	77.9	-	156	-
Slovenia	3.3	-	6	-
Slovakia	3.0	-	4	-
Malta	0.1	-	0	-
Total EU-27	**187780.7**	**15127.1**	**384.899**	**47.826**



Source: Eurostat

Figure 2-1. Evolution and projection of net maximum electric wind capacity (in GW) in the EU27 from 2001 to 2021

Each suitable wind energy location will be needed, also the very ones in the former European coal mining regions, using the available relationships between (closed) mines and wind farming. The (optimal) site selection for deploying wind power stations is often discussed by purely economic aspects, including external environmental costs.

An important question in the context of the contribution of wind power to the development and decarbonisation of the energy sector is how to site wind power stations in order to attain deployment targets cost-effectively, as far as possible including energy system costs. In this respect, the energy economic calculus for siting decisions typically involves trade-offs between minimizing the levelised cost of electricity generation and other energy system costs related to the electricity storage or backup and the extension of networks. Such trade-offs have been studied for some single countries, but also the European electricity system (Eriksen et al., 2017; Schlachtberger et al., 2017).

Certainly, these are important economic questions, also for the deployment of wind power in (former) mining terrains. However, it cannot be ignored – in mining terrains or other locations – that the deployment of onshore wind power also causes external environmental costs. These costs are spatially heterogeneous and may thus affect the optimal siting of wind power generation capacities. One important category of external environmental costs is related to local disamenities for residents living near wind turbines, mainly due to noise emissions and annoying visual effects or impairments of housing, nature and leisure qualities near the terrain. No question, local disamenities matter. One study to analyse the effects of trade-off with minimizing electricity costs in Germany has been the paper of Lehmann et al. 2021. This paper has analysed how the presence of local disamenities affects the socially optimal siting of onshore wind power in trade-off with generation costs. The analysis builds on a spatial optimization model using geographical information system (GIS) data for Germany and selected German regions. The results indicate as expected a major spatial trade-off between the goals of minimizing electricity generation and disamenity costs. Considering disamenity costs, they substantially alter and in fact dominate the socially optimal allocation of wind power stations. This is because in Germany, a) the spatial correlation between generation costs and disamenity costs is only moderate positively and b) disamenity costs exhibit a larger spatial heterogeneity than the generation costs. These results are robust to variations in the level and slope of the disamenity cost function of the authors' model. The findings emphasize the geographical sensitivity in the site selection process as well as the political importance of supplementing support schemes for wind power deployment with approaches that specially address local disamenities, e.g. minimum settlement distances (Lehmann et al., 2021).

A similar study by Grimsrud et al. (2021) highlights the conditions for the efficient geographical siting of wind power plants in Norway by accounting for the environmental costs of both wind turbines and the necessary additional grids. By a model, taking account of both production and environmental costs, the paper of Grimsrud et al. (2021) shows that the environmental costs of wind turbines and power lines were crucial to the efficient spatial allocation of wind power. The authors present therefore an economically adequate environmental taxation scheme (based on a detailed numerical energy system model for Norway) for achieving economically efficient spatial distribution of new wind power. The analysis shows too that a given target for wind power production can be achieved by significantly lower cost, by taking into consideration from the start of planning negative environmental costs associated with wind power plants due to the physical characteristics of turbine installations and associated power lines and the geographical siting.

A central implication of these economic studies is that geographical factors are of utmost importance for the socially optimal siting of wind power stations. This statement is including geotechnical and other local requirements, which will be discussed hereafter in a more general view, but also concerning wind power in coal mining terrains, especially on large waste heaps.

A prerequisite is here, as for wind energy in general, that only areas that are identified as priority or legally allowed areas for wind power stations in state regional plans and that withstand detailed examination can be considered as a location where wind turbines are erected. In addition to the required minimum distances to residential areas and transport routes, bodies of water, nature and landscape conservation areas, military bases, airports and listed buildings, the local wind conditions must be right.

Another general question in this context is why wind power stations will not only be located in very windy regions as near the coasts or directly offshore. The answer is that throughout Europe and its Member States – and also in coal regions and at former coal mines – there are locations that are suitable for wind power generation and these should be used as part of a sensible energy transition to accomplish the Green Deal.

Today, technical innovations make it possible for energy production to begin at even lower wind speeds. At wind power stations with newer or even older turbines, it can be observed that the technically more sophisticated new types start-up even at low speeds. This leads to increasing operating hours and even more economic use of wind energy.

If wind energy is generated inland and near the consuming industries and households, this has additional advantages. The electricity does not have to be transported from the very windy regions across the entire country (or even several countries and regions) to the large cities, conurbations and industrial customers. This avoids transmission losses during electricity transport and relieves the grid bottlenecks that are still occurring in the transmission and distribution grids. Finally, weather-related fluctuations are better compensated: Europe- and nationwide expansion will increase the security of supply, as lulls at one location can be partially or totally compensated by the power of wind turbines running at other locations.

Other very important geographical factors for wind energy deployment are the geotechnical requirements. As the wind industry has seen more and more tall towers and turbines in more diverse locations being utilized to harness wind resource at higher elevations (to take advantage of higher wind speeds and reduced turbulence) the towers require larger or more robust foundations to support the wind turbine systems what typically translates to higher capital costs for the projects. Balance of plant (foundation and infrastructure) make up a considerable part of capital costs for utility-scale wind power projects and although there has been a reduction in wind turbine costs over years, construction costs remain relatively high.

Firstly, a thorough geotechnical investigation is necessary to adequately characterize subsurface conditions and risks, but also to facilitate efficient foundation design. During the project-planning phase, a preliminary geotechnical investigation, including geologic reconnaissance, soil borings, geophysical surveys and laboratory testing should be performed across the project site to identify significant geotechnical risks and evaluate the geotechnical feasibility of the proposed development.

Technological and economic basics

Similarly impressive as the capacity development of wind power in the recent past is the technological development of wind energy in the long term. From the start of the very first vertical-axis, wind machines are operating based on drag forces, historically proven by grain machines of the ancient Persians (documented at the Persian-Afghan borders around 200 BC), up to the current time with (horizontal-axis) large-scale wind turbines onshore and offshore for generating electricity, the technological development of wind energy counts thousands of years. From the early and later times of wind energy exploitation onshore used for grinding, to the times that electricity power generation lies on the rotation of huge epoxy-based blades reinforced with carbon fibre including the exploitation of the special offshore potential of wind power, humankind has encountered numerous types of wind machines and designs. They have always found to be an important place in the puzzle of technological development. Not only, but also and considerably European countries played an important role for this evolution. The evolution of the wind power concept throughout this long period may be reflected in the most straightforward way by the fact that we have now entered and developed the time of the fourth-generation wind-power machines as shown in Figure 2-2 (Kaldellis & Zafirakis, 2012).

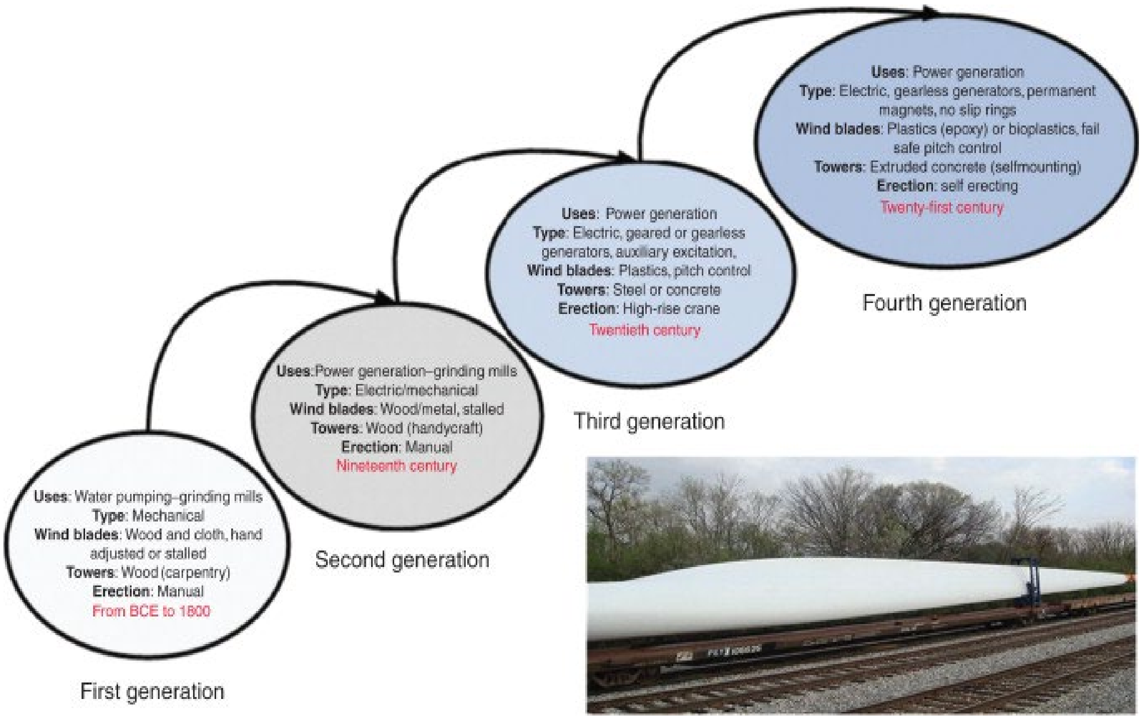


Figure 2-2. Wind power evolution: From the first to the fourth generation of wind power machines (Kaldellis & Zafirakis, 2012)

From the Middle Ages until the Industrial Revolution the horizontal-axis windmills of the Netherlands, other European countries and the Mediterranean for grinding grain and/or water pumping – eventually with connections to mining activities - have literally shaped the landscapes and are still icons of their time (AD around 1300-1875). Further evolution and perfection of these systems was performed in the United States during the second half of the nineteenth century, when over six million small machines with initially wooden towers were used for water pumping. In this context, the first larger wind machine to generate electricity was developed and installed in Cleveland, Ohio, in 1888 (a low-speed and high-solidity wind turbine of 12 kW). A follow-up of 25 kW machines was widespread throughout Denmark during the late stages of World War I. The first wind turbine feeding a local grid to support a 20 MW steam power station was installed in 1931 in Balaklava in Sevastopol on Crimea, then it became part of the USSR (later of Ukraine and is now under Russian occupation). Further development of wind generators in the USA and elsewhere was inspired by the design of airplane propellers and monoplane wings. Subsequent efforts again in Denmark, but also in France, the United Kingdom and Germany during the period between 1935 and 1970, showed that large-scale wind turbines could work (Kaldellis & Zafirakis, 2012).

There had been a lot of experiments and trials with vertical-axis wind turbines, like the “eggbeater windmill” of George Darrieus invented in 1931, and some developments of comparable concepts of wind machines, especially in Europe after World War II: For example, the Gedser mill in Denmark with a 200 kW three-bladed upwind rotor that operated successfully until the early 1960s. The main track has gone to the development of horizontal-axis wind machines (i.e. the shaft of rotation is parallel to the ground) operating on the top of adequately high towers and using a small number of blades (initially two or, today normally the most used concept, three). In Germany, a series of advanced horizontal-axis designs were developed dictating the future horizontal-axis approaches later emerging in the 1970s. One of the most important milestones of wind energy history coincides with the US government`s involvement in wind energy R&D after the oil crisis of 1973. Following this, in the years between 1973 and 1986, the commercial wind turbine market evolved from domestic and agricultural predominance (1-25 kW) to utility-interconnected wind farm applications. The first large-scale wind energy penetration was encountered in California (“California outbreak”), where over 16.000 machines ranging from 20 to 359 kW (a total of 1,7 GW) were installed between 1981 and 1990, as a result of economic incentives given by the US government, such as federal investments and energy credits for private investments.

At the same time in Europe, wind farm installations increased slower, but steadily through the 1980s and 1990s, especially in Northern Europe with excellent wind resources (but still higher cost of electricity in relation to conventional energies) creating a small, but stable market. After 1990, most market activity in the wind sector shifted to Europe and brought wind energy to the front line of the global power scene, with major players from all of the world`s regions, and a tremendous growth. Not only in terms of an expanding market share, but also in terms of technological developments, this brought modern turbines (with average capacities of 2-3 MW and more onshore for new ones) and the era of offshore wind power generation (with giant turbines to date reach

8-10 MW) with it, as well as other innovative clean energy technologies combined with wind energy, took place. The European Union at this point is still at the forefront, but since the last decade the dynamic introduction of the Chinese and meanwhile India and the revival of interest in the United States have much altered-up the recent wind energy market situation (Kaldellis & Zafirakis, 2012).

The three major elements of wind power generation are the turbine type (horizontal/vertical axis), installation characteristics (onshore/offshore and other topographically adjusted specialities) and grid-connectivity (connected/stand-alone). Most large wind turbines used today are the up-wind horizontal-axis turbines with three blades. Most new small wind turbines are also horizontal-axis. Still, there are ongoing experiments and innovative designs for vertical-axis turbines mainly being applied in urban environments, particularly in China.

The technological principles of wind energy are relatively easy. A wind turbine’s blades convert kinetic energy from the movement of air into rotational energy; then a generator converts this rotational energy via electromagnetic induction to electricity. The wind power that is generated by this process is produced proportional to the dimensions of the rotor and to the cubing of the wind speed.

The specific system configuration of a wind power station is determined mainly by the wind conditions (especially wind speed), land availability (or where the plant is sited, for example in a former mining area or otherwise), grid availability, turbine size and height, as well as blade size. There are some peculiarities for vertical-axis turbines used primarily for small generation capacities that could be relevant for former mining sites as well. However, because they have been proofed being more efficient, horizontal-axis turbines are being used commercially all over the world (IEA-ETSAP & IRENA, 2016). Therefore, they are also predominant today, when being constructed on heaps of closed coal mines or in former open-cast territories.

The rotating shaft of a horizontal-axis wind turbine is mounted parallel to the ground and the prevailing wind flow. The turbines can have two types of rotors: up-wind and down-wind. The advantage of up-wind rotors is that they are hardly influenced by the turbulence caused by the tower. However, a yaw mechanism is needed to align with the respectively prevailing wind. Meanwhile down-wind rotors have been emerged in Japan, because they can sufficiently catch winds blowing upwards. This could be a promising technology for improving the stability and safety of floating offshore or swimming wind facilities.

The basic elements of all wind power systems are the tower, the blades, the rotor hub, the rotor shaft, the nacelle, the rotor brake, the gearbox, the generator, the controller, and the transformer (the subsequent descriptions are also based on IEA-ETSAP & IRENA, 2016).

The tower height is determined by the rotor diameter and the wind conditions of the site and reach onshore nowadays heights of 200m and more. Rotor blades, rotor hub and nacelle are elevated and supported by and on the tower. Many wind turbine towers are made from steel tubes, which allow access to the nacelle inside the tower, even with bad weather conditions. Newer tower types include a space frame tower, which improves the logistics of installation and transport. In large wind turbines, the tower contains electric cables, a ladder or a lift for maintenance and visits, and occasionally a control system.

The blades capture and convert the wind’s energy to rotational energy. The number of blades also influences the structure and availability of wind turbines. Because of the better balance of gyroscopic forces and better speed count, most modern wind turbines use three rotor blades; fewer blades would mean slower rotation, requiring more from the gearbox and transmission. Modern blades are typically blade from reinforced fibreglass and are shaped aerodynamically, similar to the profile of aircraft wings. Although carbon fibre-reinforced plastics is a stronger material also in use, the costs remain relatively high, apart from the recycling problems. Smaller blades can be made from laminated wood, which has strength and weight advantages.

The rotor hub transfers the rotational energy to the rotor shaft, which is fixed to the rotor hub. The other end of the rotor shaft is connected to the gearbox, which changes the (low) rotating speed from the blades to a (higher) rotating speed for input to the generator. Direct-drive systems without a gearbox are also available, and their market share has been growing in China, as well as in Europe. Advantages of gearless turbines include their compact structure, lower risk of breakdown and simpler maintenance.

The high-speed rotating shaft connected to the gearbox forces the shaft of the generator to rotate, converting the rotational energy to electricity using electromagnetic induction. Typically, two types of generators are used with wind turbines: induction (or asynchronous) generators, which usually require excitation power from the network; and synchronous generators, which can start in isolation and produce power corresponding directly to rotor speed.

The rotor shaft and the rotor brake, gearbox and generator components are housed within a nacelle. The nacelle is directly connected to the blades at a high elevation and is one of the main structures of the wind-generating system. To rotate the nacelle to align the wind turbine with the direction of the wind, the turbine has a mechanism that is called the yaw system. All modern large turbines are installed with an active yawing system, which is controlled by an electric control system with a wind direction sensor.

The modern wind turbines incorporate such a control system by standard to prevent excessive rotation speeds in high winds, which could otherwise break the blades or other components. The two methods for controlling the speed of the blade or delivering the power output from the blade to the rotating shaft are pitch control and stall control. A pitch control system actively adjusts the angle of the blades to the wind speed. The rotor hub includes a pitch mechanism, and the control system features a break. A stall system decreases the rotational speed by using the aerodynamic effects of the blades when the wind speed is too high, lowering the efficiency to protect the turbine from damage. Besides the controlling function relating to rotating speed and yaw direction, the control system has two other main functions: monitoring and collecting operational data (e.g. weather conditions, or input/output data for the system, including electricity voltage and current, rotating speed, changes of yaw direction, vibration frequency of blade and nacelle) and communicating with the operators.

A transformer is usually placed at ground level and transforms the electricity from the generator to the required voltage of the grid, accompanied with all the necessary grid connections.

In general, a wind power generating facility, which contains a number of wind turbines, is called a "wind farm". The basic elements of the wind farm are not only the wind turbines, but also monitoring facilities, substations and transmission cables.

There is an important physical insight for all wind energy systems to be taken into consideration. Theoretically, when the wind speed is doubled, the wind power increases by a factor of eight – and vice versa, when the wind speed is halved, the wind power will be reduced by a factor of eight (IEA-ETSAP & IRENA, 2016).

Decisive for this phenomenon is the cubic wind power equation (Wind energy I Open Energy Information 2018): $\mathbf{P_{wind} = ½\, \rho\, A\, v^3}$, where

P_{wind} is the resulting *wind power*, ρ (Rho) the *air density,* A the *surface of the blade and* v the *air velocity*.

Explanation:

Wind energy as kinetic energy E_{kin} of the movement of air can physically be described by *air mass* m and the *air velocity* v with the formula: $E_{kin} = ½\, m\, v^2$.

The air mass m is a product of *air density* ρ and *air volume* V: $m = \rho\, V$. Therefore $E_{kin,\, wind} = ½\, V\, \rho\, v^2$.

Looking to a marginal time unit Δt, the air is flowing through the distance $s = v\, \Delta t$. Multiplication of the distance with the blade surface A results in the moved volume $\Delta V = A\, v\, \Delta t$.

Wind power is the wind energy in ratio to the unit of time i.e. $P_{wind} = E_{kin,\, wind} / \Delta t$. Replaced by the former derivation we get: $P_{wind} = \Delta V\, \rho\, v^2 / 2\, \Delta t = 1/2\, \rho\, A\, v^3$, q.e.d.

The conclusion from the wind power equation is that main factors of the power output are the wind speed and the length of the blades, modified by other geographical and technical conditions. Because of this, technological development is driving to ever-higher towers and longer blades.

While a “windy” location is always very important for a wind power station, in cases of “too much” wind or stormy conditions, wind power stations must be switched off for reasons of technical security and prevention of overload. Optimal wind conditions are given by a wind velocity between 12 and 16 m/s. (the specification of the installed or nominal power of a wind turbine always refers to these optimal conditions).

For wind farms, there should be a minimum distance between the single turbines of roughly eightfold of the rotor diameter in the main direction of the wind and of the quadruple perpendicularly to avoid slipstream effects.

However, the effective wind power at a certain location is normally smaller than its potential. With aerodynamic energy loss of 50-60% at the blade and rotor, mechanical loss at the gear, and a further 6% electromechanical loss at the generator, overall *generation efficiency* is typically 30-40% at wind power facilities (IEA-ETSAP & IRENA, 2016).

Moreover, due to the natural volatility of the wind levels, the global average workload or *capacity factor* of a wind power station per year in Europe amounts onshore typically now in a range between 25 to 40 % (inland and coastal areas); offshore more than 40% are possible.

Technological progress has enabled that the Levelized Cost of Electricity (LCOE) for wind power on average has fallen and not increased for a long time, despite fluctuations and eventual increases in some cost components. In some countries, regions or locations where wind conditions are quite good and where conventional electricity generation costs are comparatively high or increased by CO_2 costs, onshore wind power has been cost-competitive with new conventional power plants for years (IEA-ETSAP & IRENA, 2016).

According to the newest IRENA Report on “Renewable Power Generation Costs in 2021” the costs of wind power have been lowered more and more in the last years. The cost of electricity from onshore wind fell by 15% to USD 0.033/kWh, converted in €: 0.28, compared to 2020, although the supply chain challenges and rising commodity prices have yet shown their full impact on project costs. Between 2010 and 2021, the cost of newly commissioned utility-scale wind power onshore facilities fell by 68%, for offshore wind by 60%. Overall, in 2021, the country-level average turbine capacity of onshore wind power turbine capacity ranged from 2.0 MW to 4.3 MW, and rotor diameter from 99 m to 147 m.

Considering the cost developments in wind power as well as the cost reductions of solar power, IRENA has come to the conclusion that the world has witnessed a “seismic shift in the competitiveness of renewable power generation options since 2010” and “almost two-thirds of newly installed renewable power in 2021 had lower costs than the world‘s cheapest coal-fired option in the G-20, confirming the critical role of cost-competitive renewables addressing today’s energy and climate crises”. This general statement includes different developments marked by more modest cost reductions of bioenergy and even global cost increases of hydropower and geothermal energy since 2010 (IRENA, 2022).

Of course, also the cost reductions of wind power were not universal, but as the weighted average total installation costs of onshore wind increased globally to 7 out of the top 25 national in 2021, compared to 2020 and years before. IRENA’s data also suggest that some material cost increases are yet to be passed through into equipment prices and project costs, for example, the prices for commodities like steel, copper or aluminium. If material prices remain elevated, the price pressures in 2022/2023 will be more pronounced and overall costs may rise. On the other side, technology improvements (e.g. larger wind turbines) and improvements in manufacturing and scale will continue.

Since the energy crisis in 2022 and its consequences all over the economies, but also the consequences of the energy transition, for example, by shortages and price hikes of critical raw materials or qualified personal, could change this picture further to a certain degree. Also, a possible normalisation of energy markets after a hypothetical end of the Ukraine war and a (re-)stabilisation of the current turmoils and disruptions in international relations could do a change. For a whole picture of the cost ratios, the total electrical system costs including system services and reserve capacities or storage, that are necessary for times with low or no winds, must be taken into account. Nevertheless, a considerable part of wind power is and will presumably remain cost-competitive against the fossil fuel-based power and this economic development is very sustainable.

IRENA (2022) has presented the globally weighted average total installation cost, capacity factor and levelized cost of electricity (LCOE) trends by each renewable technology 2010 and 2021, whereof the data for wind energy are given in Table 2-2.

Table 2-2. Global weighted average total cost, capacity factor and levelised cost of electricity trends 2010 and 2021 (and rate of change in percent)

	Total installation costs (2021 USD/kW)			**Capacity factor (% of nominal load)**			**LCOE (2021 USD/kWh)**		
	2010	**2021**	**Change in %**	**2010**	**2021**	**Change in %**	**2010**	**2021**	**Change in %**
Wind *onshore*	2042	1325	-35%	27	39	+44%	0.102	0.033	-68%

Wind *offshore*	4876	2858	-41%	38	39	+3%	0.188	0.075	-60%

The fall of LCOE of wind power from 2010 to 2021 occurred as the worldwide cumulative installed capacity of onshore wind grew from 178 to 796 MW (a plus of 432%). The cost reductions for onshore wind were driven by big falls in turbine prices and balanced by plant costs. As the industry scaled-up in manufacturing, average project sizes increased (not only, but notably outside Europe), supply chains became more competitive, and the cost of capital (including a special technology premium for wind power) fell; as well as the higher capacity factors achieved by today's state-of-the-art turbines. Reductions in O&M costs have also occurred as a result of increased competition among operation and maintenance costs (O&M) service providers, greater wind farm operational experience, and improved preventative maintenance programmes. Improvements in technology have resulted in turbines that are more reliable too. This also means increased availability and higher capacity factors. Higher capacity factors mean at the same time that the fixed O&M costs per unit of output have fallen even faster than the fixed O&M costs measured as USD (or €)/kW/year. Therefore, better wind farming or technology developments as higher hub heights, larger turbines and swept blade areas, can achieve higher capacity factors from the same wind site than their less optimal sited or smaller predecessors (IRENA, 2022).

For evaluating the technological and economic developments, it is necessary to get a more differentiated view on the capital cost structure of wind power stations and the weights of the several components.

The main elements of the electricity costs for wind power are the installation and O&M costs. For onshore wind, turbine costs dominate with the tower and the rotor blades accounting for nearly half of the total cost of a turbine. Of course, due to market competition the turbine prices vary as other commodity prices.

Grid connection costs, including electrical work, electricity lines and connection points, vary depending on the site specifics and on the network or regulatory regime.

The main construction cost is for the turbine foundation.

Other capital costs include costs for development, engineering services and licensing. The inquiry of the Wind Power Technology Brief of IEA-ETSAP & IRENA (2016) has presented the capital cost structure for typical onshore and offshore wind power systems as given in Table 2-3.

Table 2-3. Comparison of capital cost breakdown for wind power systems

Cost share of:	**Onshore (%)**	**Offshore (%)**
Wind turbine	64-84	30-50

Grid connection	9-14	15-30
Construction	4-10	15-25
Other capital	4-10	8-30

To reduce the LCOE for wind power, major factors are larger turbines and large-scale installations of wind farms. Because larger turbines harness strong wind at higher altitudes, they produce more electricity per unit of installation area, thereby reducing both the number of turbines and the land area needed per unit of output. Large-scale installation of wind farms increases the economies of scale in manufacturing and reduces costs for transport, installation and O&M. Reducing the weight of rotor blades has a great potential for reducing turbine costs, as do improving the aerodynamic efficiency and material selection. Here, carbon fibre has been and is still a major candidate for reducing weight and increasing aerodynamic efficiency, but it remains expensive. The costs of grid connection depend greatly on the site configuration. For onshore wind, smart integration of decentralised generation into local and regional grids has the potential to lower system costs substantially, reducing the need for larger power networks (IEA-ETSAP & IRENA, 2016).

Besides the development of offshore wind power, the urgent development of more and larger wind power stations and wind farms onshore has reduced the remaining sites with good resource potential, especially in more densely populated areas of Europe (which is a good reason again to explore the potential of former mining areas).

Several efforts have been made to improve the economic efficiency of wind power facilities. Wind farms are being built to maximize energy production and to minimize capital and operating costs, while remaining within the constraints imposed by the site. Once the site constraints are explored, evaluated and defined, “micro-siting” is performed to optimize the layout design of the wind power project. For most projects, the economics depend far more on the fluctuating costs and prices of energy production than on infrastructure costs. Therefore, the dominant parameter for layout designs for both onshore and offshore wind facilities is the maximization of energy production respectively electricity generation.

Certainly, other factors are not irrelevant, for example, whether turbines are located near to one another for ease of maintenance or grid connection. Like most renewable energy sources, wind power is capital-intensive, and reductions (or increases) in capital costs are important, also for wind energy projects. Although continually wind operations have no fuel cost, reducing the O&M costs will be one of the keys to improving the economics of wind power. Some countries have introduced financial support such as feed-in tariffs to secure or enhance revenues and to reduce investor risk. Of course, additional technological innovation and adaptation is the key factor for future wind power development. Although the technology is relatively mature now, further room exists for developments. Pilot facilities are increasingly incorporating energy storage and information technology systems, such as two-way telecommunication between a control center and remote wind plants, to control power output (IEA-ETSAP & IRENA, 2016).

On order of IRENA, the University of Cork/Ireland examined the cost components for onshore wind turbines between 2008 and 2017 to understand the underlying drivers of cost reductions in wind turbines, including an assessment on the cost and intensity of materials and the changing of these factors over time (Elia et al., 2020; IRENA 2022). This analysis is only representative for Europe and markets outside China and India, as these two countries (with one-third of the world population) have very different cost structures, furthermore market conditions and would require a separate analysis. In the case of China, for example, wind turbine prices did not increase, but actually fell in 2021, as developers pressed manufacturers with political backup to lower prices in the face of the end of the hitherto subsidy support.

In general, onshore wind turbine technology has advanced significantly over the reported period. In addition to the technological improvements, total installation costs, O&M costs, and LCOE have been falling for pure economic reasons as economies of scale, increased competitiveness and the growing market maturity of the sector. Wind turbine original equipment manufacturers (OEMs) offer a wide range of designs, catering for different site characteristics (such as different wind speeds, areas for adequate spacing to reduce wake turbulence, and turbulence inducing terrain features), grid accessibility and policy requirements in distinct locations. These variations may also include different land-use and transportation requirements as well as the particular technical and commercial requirements of the developer. This may lead to turning it into a developer for a former coal region.

The use by the OEMs of a series of supply “platforms” that offer different configurations suited to individual sites has also been an important driver of cost reduction and economic optimization of wind projects. The platforms do this by amortising product development costs over a larger number of turbines, while also optimising turbine selection for a particular site, further reducing the LCOE.

Turbines with larger rotor diameters increase energy capture at sites with the same wind speed, and this is especially useful in exploiting marginal locations, for example a coal mining area. In addition, the higher hub heights, that have become common, enable higher wind speeds to be accessed at the same location, while also increasing the range of suitable locations for wind turbines. A taller hub height means an increased distance between the blade tips and the ground, enabling installation also in certain forested or renaturalized areas. These developments yield materially higher capacity factors, given that the power output increases as cubic function of wind speed due to the wind power equation. The higher turbine capacity also enables larger projects to become economically attractive and to be deployed, which reduces the total installation costs for some cost components by the effect of scale economies.

Revising the cost development in the past, it is to register that wind turbine prices fall sweepingly at the end of the 1990s, reached their previous low between 2000 and 2002, followed by a sharp increase in prices in the next period. This was attributed already then in increases in commodity prices (particularly cement, copper, iron and steel) and supply chain bottlenecks. However, this resulted later in improvements in turbine design, with larger and more efficient models introduced to the market. Due to increased government renewable energy policy support for wind deployment, however, this period also coincided with a significant mismatch between higher demand and tight supply, which enabled significantly higher margins for OEMs. Yet, as technological progress went on and the supply chain became deeper and more competitive while manufacturing capacity grew. These are the typical and to be expected trends fostered by market forces in such a constellation. These supply constraints eased and wind turbine prices peaked and began to fall again. Most wind markets experienced their peaks between 2007 and 2010. With greater competition among wind turbine manufacturers, prices and margins have come under increasing pressure. The decline of turbine prices globally (and in Europe) occurred over the last decade despite the increase in rotor diameters, hub heights and nameplate capacities. In addition, price differences between wind turbines with differing rotor diameters narrowed significantly until 2019 for all classes (Class I-III with criterion >100 m or <100 m rotor diameter), but now the gap has started to widen.

Manufacturers’ turbine sales margins have fallen more and more over time, lately with increased commodity costs, which leads to questions about the investment incentives for the next time. Sharper competition is being reinforced by the increased use of competitive procurement processes for wind power and other renewables in a growing number of countries. Sharper competition has also led to more investor acquisitions in the turbine and balance-of-plant sectors and a trend to moving the manufacturing of the equipment to countries with lower manufacturing costs. This sharper competition, however, does not make the sector immune from the impact of supply and demand imbalances as any other market good. This is why the significant growth in the market in the last years and the current supply chain constraints (since 2020 due to COVID 19) saw wind turbine prices tick up (IRENA, 2022). This trend could last for the years to come.

Because of the global availability of the resource, wind power has a huge potential for further development and progress. IEA and IRENA have estimated (in 2016) a global potential of 95 TW or more to be developed onshore (and even a larger resource potential offshore), as well as less of an environmental impact in relation to the fossil alternatives. The further technological and economic development will show how much of this potential can be realised. This must include technological progress in storage systems, new sustainable materials and better digital control technology.

Still, many of the possibilities depend on genuine political factors, not only in the form of financial support schemes (and in the long term by becoming increasingly competitive). As already mentioned as a very recent topic, critical barriers to the rapid expansion of wind power include long and unpredictable waiting times for permitting and authorisation. To reduce such risks, policy makers can introduce (more) appropriate regulatory schemes and set a specific, predictable schedule for the administrative process. An important issue for managing power systems that integrate large amounts of wind energy is the variability of the power output. One way to achieve a higher share of wind power generation in a grid system is to operate wind turbines or wind farms using integrated transmission systems and power output predictions systems, including weather forecasting with already available technologies. The development of standards and certifications help to improve the performance of small wind systems, especially in developing countries or regions.

Special environmental impacts associated with wind power include concerns of noise and visual impact, as well as an impact on migratory species, such as birds and bats. Communication and compromises with the public are key to mitigating these concerns. Developers need to communicate with stakeholders based on proper environmental impact assessments. Proper siting of wind power stations and wind farms can also mitigate visual impacts and impacts on migratory species. Involvement of local communities, particularly through local ownership, is key for high social acceptance (IEA-ETSAP & IRENA, 2016).

Wind energy is and remains a vast and very popular research field. No wonder this has evoked the development of research in all areas regarding wind energy uses, including the resource itself, i.e. the wind and its characterization and distribution as well as the devices for capturing the energy, i.e. the different kinds of wind energy converters and all their components and performance (Sawant et al., 2021). A quite interesting and partially promising newer research line in a relatively early stage could be the development of direct wind-to-heat conversion technologies, may be compressed-based wind thermal conversion, friction-based wind thermal conversion or induction wind thermal conversion. Wind-powered thermal energy systems could substitute any electrical power plant, especially wind parks with storage. Possible applications are heat supply systems for industrial heat processes, space heating, and district heating. The main opportunities are potentially lower capital costs and higher efficiency than electrical wind turbines. The main disadvantage is until now the immaturity of this technology, and it is uncertain if this new technology would survive market competition with established and other new green heat systems (Neumeier et al., 2022). Nevertheless, in terms of new perspectives in coal regions, this kind of development in wind technology is worth a closer look.

3 Features of the implementation of “technology” in a mining area

In addition to the problem and the limited possibility of recycling in relation to wind turbines, this is not the only hurdle. Before a wind turbine can even be used at a location, it must be clarified in advance which location is suitable for it. At a much earlier point, the decisive question arises as to the extent to which criteria must be met in order to set up such a system. Another point of interest is which requirements does a location have to meet in order to offer opportunities and which not in order to avoid problems.

The starting point is always the existing infrastructure of the respective location within the region, regardless of the country. Because the energy infrastructures that are present today primarily emerged in the second half of the 20th century. Therefore, these are now characterized by overload and ending load capacity. In the course of the ever-growing demand for energy and the traditionally available resources, which are limited in their occurrence, this represents a further problem. In this respect, the switch to more environmentally friendly and sustainable energy alternatives is not surprising (Geidl et al., 2007). However, it is a totally different questions as to what extent the available infrastructure and the site-specific conditions allow this. In order to take a closer look at these hurdles, the general advantages and disadvantages of wind energy are first focused on. Then the necessary prerequisites for the implementation and the growing need of wind turbines are analysed.

3.1 Advantages of wind energy

(a) Clean energy: Wind power generation is completely clean and far ahead of traditional generation methods that rely on traditional resources such as oil or coal. As a result, there is no pollution of land, water and soil. Existing dependencies on resource imports can also be reduced in this way, at least for the proportion of traditional resources (Conserve Energy Future, 2023; Office of Energy Efficiency & Renewable Energy, 2023; EWE, 2023; Windkraft-Journal, 2021).

(b) Renewable resource: Wind is not only a freely available resource for everyone; it is also usually infinite depending on the region. Furthermore, the costs for the provision of wind energy are decreasing, so that the costs for purchasing and correspondingly integrating such a system are amortized (Conserve Energy Future, 2023; Office of Energy Efficiency & Renewable Energy, 2023; Windkraft-Journal, 2021).

(c) Operating costs: Aside from the previous point of currently decreasing installation costs, while in general these can cost a lot of money, this is only true for procurement and installation. The energy production itself is close to zero for the entire lifetime of the plant because the operating costs are low and the turbines usually require little maintenance (Conserve Energy Future, 2023; Windkraft-Journal, 2021).

(d) Efficiency (costs): A single wind turbine can supply several households. Depending on the location, it can be very cost-effective for entrepreneurs or private individuals to use the services of a local electricity provider with this energy generation (Conserve Energy Future, 2023; Local Government Association, 2023; Windkraft-Journal, 2021).

(e) Technological advances: Due to advances in technology, prices for providing this energy alternative have fallen by approximately 80% since 1980 and are expected to continue to fall (Conserve Energy Future, 2023; Just Energy, 2023; Windkraft-Journal, 2021).

(f) Developments: In addition, thanks to technological advances, the design is becoming slimmer and thus more attractive to many people whom are landowners considering potentially acquisition such a system for their own property (if the conditions are right). Accordingly, there are now different sizes of turbines, depending on the factory, company or private ownership. Even portable wind turbines are now a topic that can power small devices on the go. Furthermore, with the latest standards, these systems require less maintenance, are quieter and still generate more electricity (Conserve Energy Future, 2023; Wake Prediction Technologies, 2023).

(g) Market potential: Since the use of wind power is potentially possible worldwide, there is also enormous potential here, with researchers classifying this at an estimated 400 terawatts (Conserve Energy Future, 2023).

(h) Wind farms: Due to their design, wind turbines save a relatively large amount of space and can be installed in large numbers on agricultural land, for example. This can be lucrative for farmers, represent an additional income if they make their land available, and take a lease for it (Conserve Energy Future, 2023; Just Energy, 2023; EWE, 2023).

(i) Water savings: Compared to traditional energy production methods, wind power saves enormous amounts of water, in direct comparison namely 500 times more than coal and 600 times more than nuclear power. In addition, no emissions are produced when using the turbines, so that water bodies are spared from pollution compared to conventional generation (Conserve Energy Future, 2023; Local Government Association, 2023).

(j) Job growth: Due to the growing attractiveness of renewable energies, especially wind power, their installation and production as well as advice for interested parties are also increasing. This has another advantage as a consequence: jobs are created and that globally. According to evaluations by IRENA, the degree of employment in wind energy was 1.15 million (10 million for the entire renewable energy sector). China in particular offers an enormous number with 500,000 jobs, followed by Germany with around 150,000 and the USA with up to 100,000 jobs created (Conserve Energy Future, 2023; IRENA & ILO, 2022; EWE, 2023).

This abundance of advantages sometimes also shows the possible potential for the integration of wind turbines on former mine sites and their dumps. However, wind power also faces various disadvantages.

3.2 Disadvantages of wind energy

(a) Competition: Although it is an advantage that wind power has extremely low costs once installed, this also applies to other renewable energy alternatives such as solar projects in a direct comparison. However, depending on the location the wind conditions, the acquisition and amortization are influenced (Office of Energy Efficiency & Renewable Energy, 2023; Conserve Energy Future, 2023).

(b) Location: It is often still the case that the most suitable locations for wind power are preferably remote, making it more difficult to supply the urban areas that, however, primarily need this electricity (Office of Energy Efficiency & Renewable Energy, 2023).

(c) Reliability: Another factor is the wind itself. It forms the necessary basis for being able to generate energy from it. Nevertheless, wind does not always blow and is sometimes unpredictable or constant. Accordingly, the wind can also be absent and with it the generation of wind energy (Conserve Energy Future, 2023; Just Energy, 2023).

(d) Animals: Although wind energy is an environmentally friendly form of electricity generation, it also poses a risk to the animals living in it. Birds in particular can be affected and the rotor blades can become dangerous for them (Conserve Energy Future, 2023; Office of Energy Efficiency & Renewable Energy, 2023; Just Energy, 2023; Local Government Association, 2023).

(e) Disturbance: The systems are relatively loud and generate an average background noise of between 50 and 60 decibels. Especially when it comes to investing in such a system for the country as a private individual, this can be quite disruptive, both for the person himself and for the residents. Another point in this connection is the design of the plants. While some find this appealing, many see it as controversial and detrimental to landscapes (Conserve Energy Future 2023; Office of Energy Efficiency & Renewable Energy, 2023; Just Energy, 2023; Local Government Association, 2023).

(f) Shadow flicker: In addition, the so-called shadow flickering can also occur in this context, from which residents are disturbed by the shadows of rotating leaves. This is due to the rapid and constant changes in light while the system is actively running (Conserve Energy Future, 2023; Local Government Association, 2023).

(g) Contradiction: Depending on the region and the possibilities, the areas for wind turbines are limited or regulations prevent the installation of a system on private property. Therefore, it happens that extra trees are still felled and areas are created in order to build systems on them. This thwarts sustainable and renewable energy production (Conserve Energy Future, 2023).

In the comparison, it can be stated that wind turbines and wind energy themselves have both many advantages and some disadvantages. However, the advantages outweigh the disadvantages and show enormous potential for the future. This factor should also be considered when considering the current disadvantages. Because many of these factors can be eliminated through further technological progress and the adjustment of specifications, regulations and further development. Concrete examples of this would be the design of systems, the generation of disturbing noises, where and when a system can and may be set up and the costs of providing such systems. It becomes more difficult with natural factors such as the wind itself and when it blows, as well as the wildlife, or birds, and the interference of possible collisions.

Based on the overview of wind turbine specific, the possibilities for integrating this renewable energy generation on heaps of former mining sites can now be considered. There are already a number of examples for this. Because closed or abandoned mines are usually found in more remote locations, there is enough space to install wind turbines.

The downside of abandoned mining locations is usually that this remoteness means that there is no connection to the electricity grid. Instead, electricity is generated using diesel generators, although the cost of transporting fuel is also high on average. In this way, renewable alternatives can supplement the unit in order to reduce both the cost of purchasing fuel and the overall electricity costs. Due to this fact, coupled with the closure of more and more mines, experts in this field expect a large increase in the integration of renewable energies at former mine sites (THENERGY, 2023; Igogo et al., 2021).

3.3 Tackling of the general raw material-, environmental- and recycling-problems of wind energy

Both globally, but especially at the European level, the requirements for the energy management situation are clearly defined. The goal is the low-carbon economy with the help of renewable energy alternatives, such as wind power. This has side effects that go along with it. Namely, these are both increased energy efficiency, as well as reduced pollution of the environment from the production of energy, and ultimately the spread to the use of renewable energy. Accordingly, the reduction target of greenhouse gas emissions for the EU in 2020 was already at least 20% less than before (compared to 1990), so that by 2030 the aim is to achieve at least 40% savings. Overall, the share of renewables in total energy consumption has increased by about 32% compared to 1990 (as of 2019) (Ziemba, 2019). However, in order to achieve the further objectives and to be able to expand the development of renewable energies and, in this specific case, of wind energy, there is a great need for raw materials. In order to be able to produce wind turbines at all, raw materials are needed that are only scarce in Europe, hence the dependencies on other countries that can offer this raw material are growing enormously. This development can be critical, because the greater the dependencies become, the more difficult it will be to realistically implement such a goal (Carrara et al., 2020).

Therefore, it is sometimes crucial to look closely at the demand for materials and their composition. Finally, current and future consumption is mainly related to the closed climate targets for 2030 and the targeted climate neutrality by 2050. On the one hand, both the reduction of greenhouse gas emissions to a certain level and the expansion of energy efficiency in times of instability in the energy economy are crucial. Second, other aspects must be included in the holistic view. Namely, material intensity, as well as the lifetime of a power plant and the respective market share for sub-technologies also play a decisive role in the evaluation. Considering the above factors, the respective material requirements are then planned for three different scenarios: low, medium or high demand. With regard to the production of a wind turbine, an increase in demand between 2- 15 times the current demand is likely to be expected, taking into account the climate targets discussed. The structural materials such as plastic, concrete, aluminium, steel, chromium, glass, nickel, iron, copper, molybdenum, zinc, and manganese are particularly affected. In addition, however, smaller metals and rare earths (Neodym, Terbium, Dysprosium and Praseodym) are also required, which are available in high quantities, especially in China. They are used in the turbines combined with permanent magnets. A further distinction is made between wind power, which is integrated onshore or offshore as shown in Figure 2-3. While offshore wind power is expected to experience less fluctuation, onshore wind power is expected to experience an increased rise of material costs. For demand within the EU alone, rare earths are so indispensable to wind power development that demand by 2050 anticipates a 15-fold increase as given in Figure 2-4. Therefore, this would require the current required framework of available rare earths across the entire EU market. It is important to note that this is only the consideration for the EU and does not even include the global demand with growing expansion of renewable alternatives (Carrara et al., 2020).

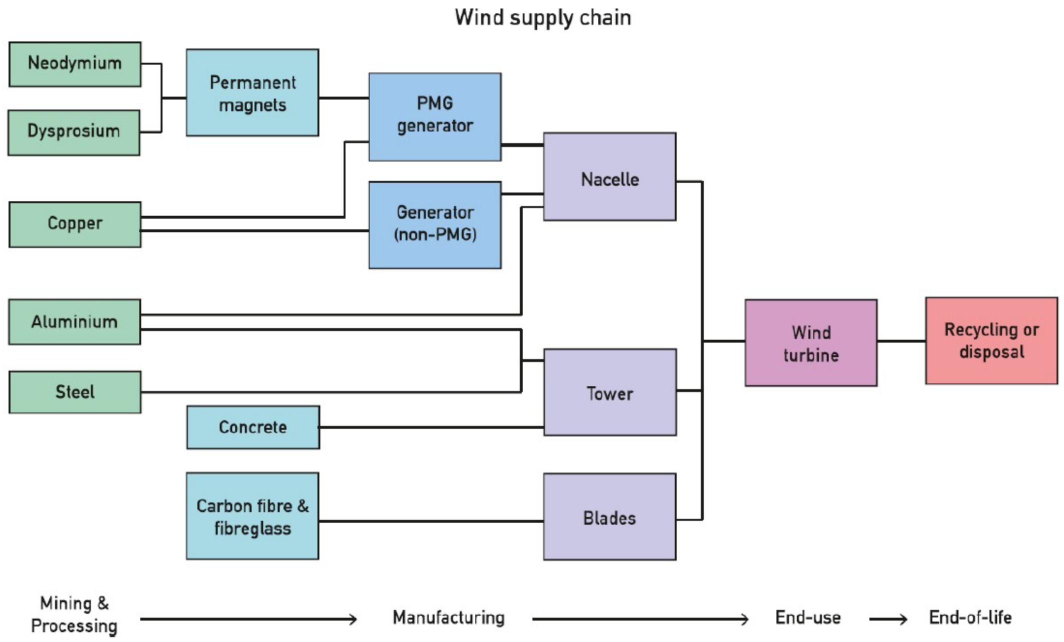


Figure 2-1. Supply chain for wind energy and needed raw materials (Carrara et al., 2020)

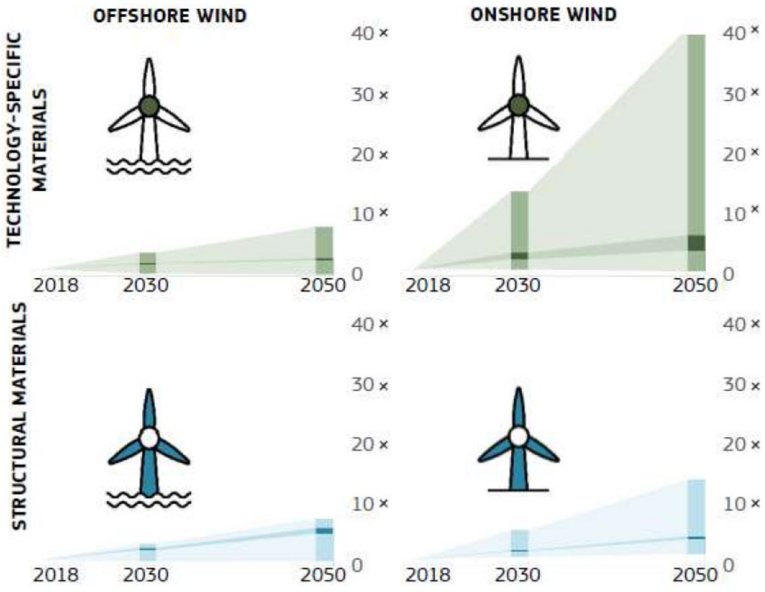


Figure 2-2. Demand of raw materials to be expected with technology-specific materials (rare earths) and structural materials until 2050 (Carrara et al., 2020)

This rapid increase in demand, which is expected to continue at a steady pace, brings with it other aspects to consider: recycling. In recent years, the recycling of components, for example wind turbines, has proved to be so difficult because it was hardly possible, and in some cases still is, to separate the components that are difficult to recycle from the components which can be recycled. The risk is often too great and recycling is simply not possible, so that after an average service life of 20 - 30 years, the wind turbines end up in a designated landfill (U.S. Department of Energy, 2017; Umweltbundesamt, 2020; Jacoby, 2022). This is neither green nor sustainable in the long term. In this respect, a lot of research has been done regarding this subject to develop new approaches for a future handling in the recycling of the used rare earth elements.

However, it can be stated in advance that despite the progress made in recent years, much further development is still needed, as there is still a lack of more environmentally friendly and cheaper, yet efficient technologies in the field of recycling that can be combined with reprocessing (Chen et al., 2019; Paulsen & Enevoldsen, 2021). Here, blade materials are the focus of further research, as they can contribute to improving clean energy from wind by using modified thermoset and thermoplastic resins and natural fibres right from the start. Considering this, a closer look at the material required for a wind turbine can be taken. It is estimated that for every 1 kW of power, approximately 10 kg of blade material is required, so that for a 7.5 MW wind turbine, approximately 75 tons of this material will be needed. Although turbines are in operation for an estimated 20-30 years, some are replaced earlier (after 15 years) due to damage or aging. In China alone, as the most production-intensive country of renewable energies, up to 5700 rotor blades were taken out of service in 2018, and in 2022 this figure will already be 59,000 tons. Due to the further planned increase in the integration of wind energy, another double increase can be expected for the next 5 to 8 years depending on the installed capacity. Accordingly, with the recycling problem mentioned at the beginning, it should become clear what an enormous burden is created here for the environment with the supposedly clean and green energy production itself (Chen et al., 2019). Up to now, turbine blades have mainly been manufactured using thermoset resin matrix composites. These are then reinforced with the aid of fibres, either carbon or glass. This makes recycling difficult here, because the so-called "inherent heterogeneity" of the composites used cannot be melted down and reused (Chen et al., 2019; Paulsen & Enevoldsen, 2021). In most cases, the resin is high quality polyester or epoxy. The recycling here is so complicated because the resin and fibres harden together and can then hardly be separated from each other. In addition, fiberglass is classified as a rather worthless material, making recycling even more unlikely as it is not worth the effort. Additionally, it is essential to understand that a rotor blade consists of approximately 90-93% composite material, while the remaining 10-7% is divided between balsa wood (2%), PVC (2%), metal, paint and a seal (3%). Studies show that 8 - 13.4 tons of composite material are needed for each installed MW wind turbine (Paulsen & Enevoldsen, 2021). Furthermore, the discarded rotor blades are either ultimately disposed of in appropriate landfills or, if possible, incinerated. This precludes recycling and places an additional burden on the environment when the materials are incinerated (Chen et al., 2019).

The handling of thermoset composites already includes various technologies for reprocessing, which can be divided into three areas as shown in Figure 2-5: thermal, chemical and mechanical. In the latter, mechanical recycling, the materials are simply crushed and both fibres and small particles can be extracted from this process. These can then serve as a filler or reinforcer for new material. Nevertheless, this process proves to be detrimental to the structural condition of the fibres, so that they suffer and can only be recovered to a limited extent. On the other hand, the chemical application, as the name suggests, uses chemicals to extract molecules from the resin of the composite material. With the help of the molecules obtained, fibres can then also be regenerated. Another advantage offered by this method is that the heat generated during combustion can be converted and used for other energies. Otherwise, recovered substances can also be used for building materials, such as concrete and cement. Although this procedure is simple, the associated production costs are quite high and the incineration of the waste also pollutes the air with exhaust gases, while the resulting ash also represents an additional burden on the environment. Conversely, this means that it is certainly possible to recover resin and, above all, fibres due to the approach taken, but always at the expense of material damage and environmental pollution (Chen et al., 2019; Paulsen & Enevoldsen, 2021). The thermal method primarily means pyrolysis, also in the form of the so-called microwave pyrolysis and the fluidized bed process. During pyrolysis, the resin matrix in the composite is broken down to yield fibres. For this purpose, inert gas heat is used to generate small molecules. By applying pyrolysis twice and then combining it with an oxidation, it can result in clean fibres. These can then be used for the further production of short fibre composites and are in very good condition. In contrast to pyrolysis, microwave pyrolysis uses microwave radiation to decompose the composites within the matrix. In the fluidized bed process, air is again used to split the matrix into its components by means of an air heat flow, so that the resulting heat and the fibres can both be used as shown in Figure 2-5 (Chen et al., 2021).

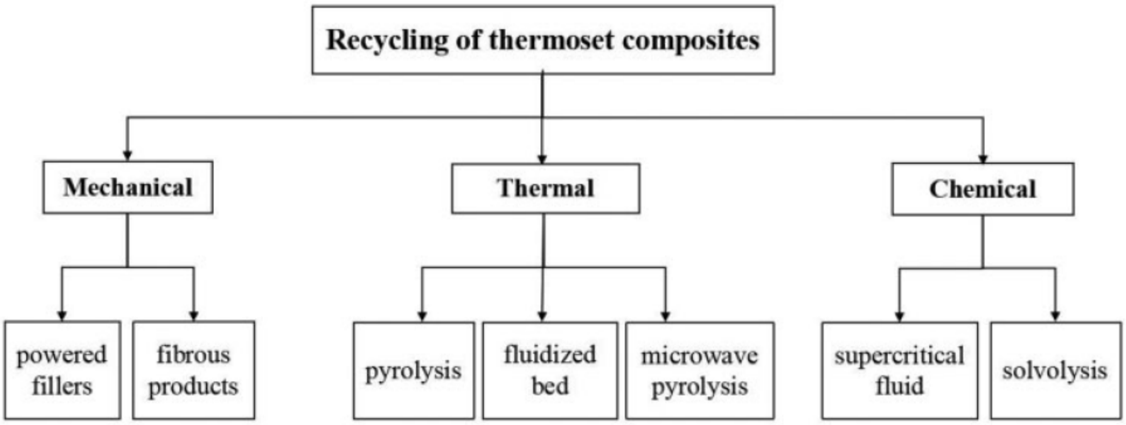


Figure 2-3. Overview of the most common methods for recycling of thermoset composite materials (Chen et al., 2019)

Furthermore, an overview of the previous reuse options for the materials based on the various recycling technologies divided into mechanical, thermal and chemical is given in Table 2-4 according to the results of the study by Chen et al. (2019). What cannot be recycled is going to finally end up as considered waste. The waste hereby produced by each rotor blade at the end of its service life can be broken down into three subcategories. There is general waste for rotor blades taken out of service, as well as production waste - defective blades while still in service or blades used for tests - and finally the waste from the service area, i.e. improved blades or repairs made (Paulsen & Enevoldsen, 2021).

Table 2-1. Overview of the different recycling methods with possible reuse application (Chen et al., 2019)

Method of Recycling	**Reuse and application**
Mechanical recycling	Composites reinforced by recycled fibre; Concrete reinforced
Thermal recycling	**Pyrolysis:** Organic liquid fuel; Pyrolytic gas/oil; Composites reinforced by fibre **Microwave Pyrolysis:** Composites reinforced by fibre **Fluidized bed:** Bulk moulding compound; Electromagnetic shielding material; High-modulus composites
Chemical recycling	Composites reinforced by fibre; Fuel gas

Based on the most common processing methods presented here, the authors Paulsen and Enevoldsen (2021) have created an assessment that compares the amount of waste produced and a cost estimate including the maturity of the respective recycling technology. Other methods that are not given in detail are listed here, but they are not examined in more detail. Ultimately, the comparison of the different approaches shows that mechanical processing represents the most favourable conditions for sufficient use at a commercial scale as given in Figure 2-6 (Paulsen & Enevoldsen, 2021).

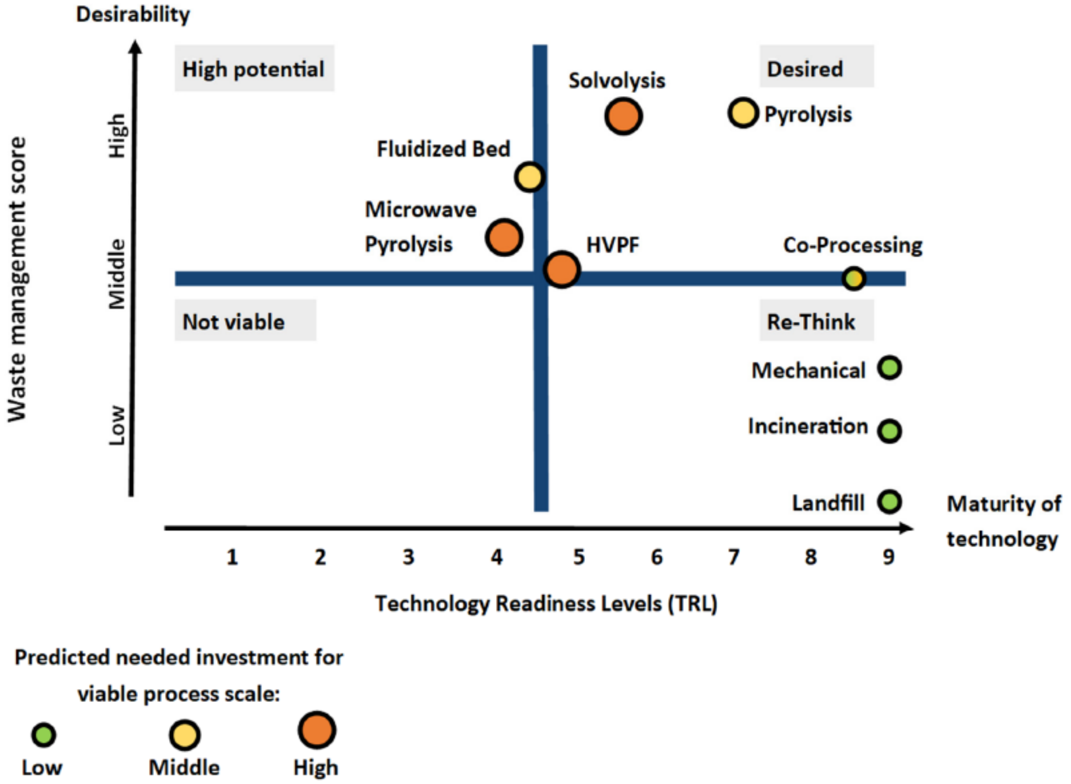


Figure 2-4. The different recycling technologies in comparison regarding technology readiness, investment and waste management (Paulsen & Enevoldsen, 2021)

Nevertheless, it is clear that a transition to green energy can only succeed with the help of renewable energies and, above all, wind energy. This thesis is also supported by previous life cycle assessment (LCA) analyses for wind turbines (analyses the consequences of a product or good over its entire life cycle for the environment). Wind energy has been found to recoup during its life cycle between 23 and 25 times the energy it originally cost to manufacture the turbine. On the other hand, the estimated total damage to the environment is around EUR 500,000 to EUR 1.1 million per system MW installed (without distinguishing between offshore and onshore). In the holistic view of the possible recyclability of a wind turbine, around 86% can be recycled, since the main component is steel. The rest are the materials already explained which prove to be significantly more problematic (Paulsen & Enevoldsen, 2021). According to evaluations and estimates, it can be assumed that around 111.88 MJ/kg are incurred for the production of the required composite material (Paulsen & Enevoldsen, 2021). This specification includes the fabric, resin and fibre production as well as the process for pultrusion (namely the process for the production of fiber-reinforced plastic profiles) and the additives added to the material (Frauenhofer IGCV 2022; Paulsen & Enevoldsen, 2021). Recovering this material through recycling costs only a tenth of the energy required to produce new material. This means a difference of 10-20 times less energy required (Paulsen & Enevoldsen, 2021).

For an evaluation based on this prior knowledge for a suitable recycling method, a comparison was made according to the following aspects: Technology Readiness Level (TRL), Economic Feasibility, Environmental Assessment as well as a possible recyclability of the remaining fibres. From this, it has been concluded that recycling by co-use for the production of cement seems to be the most suitable, based on the TRL. An alternative to this could not be developed, at least in the present study by the authors. Furthermore, the co-processing of cement in production is recognized by the European Commission. An introduction of this methodology is reported to be able to lead to a CO_2 footprint reduction of up to 16% and also in the longer term to change the thinking in the assessment of wind turbines towards a circular economy. Accordingly, this is beneficial to the environment and can be determined here to be not only the most economical, but also the most environmentally friendly process (Paulsen & Enevoldsen, 2021).

4 Identification of the best technology for mining areas: Operational requirements of the selected technology

Recent renewable energy projects provide good reasons for confidence that many former mine sites can be ideal locations for developing alternative energy generation facilities, simply by looking at some of the qualities that made them problematic in the first place in a new light (Whitbread-Abrutat & Coppin, 2012).

Especially mining dumps cover huge areas, and their reclamation has largely been limited to agriculture, forestry, and non-intensive recreation such as parks, green spaces and ecotourism, while it is far more unusual to find the construction of any kind being built on reclaimed mining spoil. It would be reasonable to use these post-mining sites for renewable energy generation, as the Europe's Green Deal strategy involves a number of challenges linked to a need for the European energy sector to undertake action that will result in significantly higher shares of renewable energy sources in an integrated energy system (Resak et al., 2022). Possibilities range from wind, solar photovoltaics (PV), geothermal, hydropower and energy crops to test-beds for a variety of more experimental power generation technologies (Whitbread-Abrutat & Coppin, 2012; Eriksen et al., 2017).

In general, many expert opinions are required by law for the approval of wind energy projects by the appropriate authorities, which serves to protect people, flora and fauna from potentially negative impacts caused by wind turbines or wind farms. The realization of wind power projects is always accompanied by the preparation of these expert opinions. Even before a wind turbine or wind farm is built, the suitability of the site must be determined.

The authorities designate so-called priority areas for the use of wind energy, in which construction and operation are de facto possible without conflict. Nevertheless, there is no guarantee of approval for individual turbines located within these areas. Furthermore, the wind power project must not be opposed by any public concerns (wind-turbine.com, 2015). The formal participation of citizens in the region and near the locations in the planning and approval processes is guaranteed and regulated by law all over Europe. The planning authorities have to protect the interests of all parties involved and ensure that as few conflicts as possible occur. The local people are therefore involved in regional planning by the authorities or have the possibility to do so long before the specific planning of a wind farm or wind power plant (BWE, 2018).

In Germany, wind turbines with a total height of more than 50 meters have been subject to approval since 2005. According to Federal Immission Control Act (BImSchG), the simplified approval procedure is necessary for applications for up to 19 wind turbines which does not require any Environmental Impact Assessment (EIA). Therefore, there is no public participation, nor the procedure is made public. Nevertheless, citizens can raise their objections at any time in the context of legal disputes. The applicant can also voluntarily decide in advance to carry out a so-called formal approval procedure with public participation, which is mandatory anyway for applications for 20 or more turbines. The same conditions apply to the EIA, which must also be carried out if 10 or more hectares of forest must be cleared for the construction of the facilities. If the amount of forest to be cleared is less than 10 hectares but more than 5 hectares, an EIA preliminary assessment is required. This also applies to wind farms with 6 to 19 wind turbines as well as to the expansion of existing wind farms with 20 or more turbines (wind-turbine.com, 2015).

An EIA is an environmental report prepared by the applicant and deals in detail with the central issues such as the effects of the wind turbine on the landscape. These issues generally include

- visual impression on the landscape
- influence on flora and fauna
- shadow cast
- noise emission
- ground heating and drying in the area of underground cables
- ice throw and lightning strikes

In the legal procedure of the planning, the issues of necessary protection can be taken into account by the implementation of standardized distances. The following expert opinions, among others, are generally required in order to prove the harmlessness of wind turbines (wind-turbine.com, 2015):

- Avifaunistic assessment
- Noise assessment
- Shadow assessment
- Turbulence assessment
- Geotechnical report

An avifaunal assessment is required when birds and bats could be exposed to hazards from wind turbines. These serve to analyze, minimize and avoid the risks for species relevant to planning that are at risk of collision.

In order to obtain an approval for a wind power project, it must be proven that the permissible noise immission reference values in the surrounding of wind turbines are not exceeded.

Direct shadowing is a consequence of the operation of wind turbines. Furthermore, behind the turbine, brightness changes are caused, the frequency of which can be approximately between 0.4 and 4 Hz. These fluctuations in brightness can have a disturbing effect on people and even be unacceptable in the case of significant exposure.

The shadow cast by a wind turbine is calculated using the position of the sun. The necessary data are the coordinates of the wind turbine as well as the dimensions of the turbine.

Turbulence assessments are used to estimate the closeness of wind turbines to each other in a wind farm and the required minimum distance.

The location of wind turbines can be significantly influenced, restricted or even prevented by geological factors. In order to find out these factors, site-specific investigations must be carried out. The measures include drilling, probing, taking soil samples, geophysical exploration methods as well as the analyses of the characteristic values in a soil mechanics laboratory. Soil investigations are indispensable for a sufficient design of the foundation and for ensuring the stability of the wind turbines and components. The geotechnical report of these investigations includes a forecast of changes in the properties of soils over time, determines the calculated geotechnical parameters, the partial safety factors for geotechnical calculations and impacts from the ground as well as adopting a ground calculation model, and, finally, includes calculations of bearing capacity, ground subsidence and general stability. It also considers many aspects such as determining the required foundation type (spread- or pile foundation), harmful impacts of groundwater on the constructed object and methods of counteracting these threats, determining the scope of required monitoring of the constructed object, the neighboring objects and the surroundings in order to identify possible threats to the construction (Resak et al., 2022).

Optimized foundation designs can contribute to an overall reduction in technical risks as well as capital costs and would contribute to the advancement of wind energy generation. Locally optimized geotechnical design is an essential component for the design, planning and construction of wind power stations. Wind turbines have specific design requirements, which have to be taken into account to ensure reliable operation of the turbines over a typical design life of 20 to 25 years (or more). For the geotechnical and structural design aspects, it is also important to be adequately synchronized in order to develop at most efficient designs taking into account site-specific geotechnical conditions and potential constraints (Ntambakwa et al., 2016).

A complete geotechnical site investigation is required to finalize the design and provide the necessary geotechnical properties for a detailed design of the foundation at each specific turbine position during the engineering design phase. In-situ and laboratory tests, which are widely used in geotechnical investigations of onshore wind turbine foundations, include (Ntambakwa et al., 2016; Geophysik Ernstson, 2023):

- Soil borings in order to obtain essential subsurface information for project sites by dynamic probing, standard penetration test (SPT) and core drilling

- Cone penetration testing (CPT) in order to either obtain essential subsurface information or supplement traditional soil borings
- Geophysical surveys in order to obtain shear and compression wave velocity profiles of subsurface materials by seismic survey, geoelectric complex resistivity/induce polarization and ground radar
- in-situ measurements (in addition to CPT) in order to characterize the strength and deformation properties of the subsurface deposits by flat plate dilatometer, pressure meter and vane shear
- Groundwater measurements in order to characterize the groundwater conditions and the groundwater level, which are an important part of the design for all geotechnical structures including wind turbines shallow foundation, by observation during soil borings, installation of piezometers/monitoring wells or performing pore pressure dissipation testing during CPT soundings
- Laboratory testing , as given in Table 4-1, in order to estimate the geotechnical soil parameters of collected soil samples

Table 4-1. Typical Laboratory Tests for Wind Turbine Foundation Design (Ntambakwa et al., 2016)

Laboratory Tests	**Soil Properties Measured**
Soil Index Tests	Particle size distribution; Moisture content; Unit weight; Atterberg limits; Expansion/Shrinkage index
Consolidation Tests	Coefficient of consolidation; Max past pressure; Compression/Swelling index
Proctor Compaction Tests	Optimal moisture content; Maximum dry density of backfill material
Direct shear tests, Triaxial Compression Tests	Cohesion and friction angle of granular soils; Undrained shear strength
Soil Chemical Tests	Soil pH; Soluble chloride and soluble sulfate

The geotechnical investigation is also a prerequisite for an evaluation of the geological and geotechnical hazards as well as sufficient mitigation measures. Both geological and geotechnical hazards depend on the region’s geography and subsurface conditions of each project site. Convenient general information can be obtained normally from publicly available resources found in responsible government agencies at regional-, federal- or state levels. However, site-specific information is required to be collected for an adequate evaluation of geological and geotechnical risks at each turbine location and its design. The most common types of geological and geotechnical hazards and their adverse influence on foundation stability are given in Table 4-2.

Table 4-2. Typical Geological Hazards Considered for Wind Power Developments (Ntambakwa et al., 2016)

Hazard	**Typical Effects**	**Potential Mitigation Measures**
Seismic Activity	Strong ground shaking	Evaluate and take into account for turbine tower and foundation design
	Liquefaction Lateral spreading / cyclic mobility	Evaluate and incorporate into design; ground improvement; deep foundations, relocate turbines
Landslides/ Slope Instability	Loss of foundation support Erosion	Evaluate slope stability/pre-existing landslides; install retaining walls; re-grade slopes
Flooding	Backfill erosion / Scour Buoyancy / Global stability Inundation / Infiltration	Evaluate and incorporate into design; utilize erosion control measures; install scour protection; relocate turbines, include adequate drainage provisions
Difficult Soils	Expansive Collapsible Low Strength High Compressibility Constructability issues	Evaluate and incorporate into design; ground improvement; deep foundations, relocate turbines; geotextiles
Karst	Soluble rock Cavity formation Caverns Sinkholes	Appropriate investigation; electrical imaging; review regional geological maps; grouting; ground improvement; deep foundations; relocate turbines

The selection and design of a wind turbine foundation are largely dependent on the specific soil conditions at the proposed turbine site. A thorough subsurface investigation provides reliable geotechnical parameter values for shallow foundation design including the determination of foundation base dimensions, foundation embedment depth and achievable soil unit weight for backfills and spring constants for structural design. The geotechnical parameters are also used in evaluating essential foundation criteria.

The foundation ensures the stability of the wind turbine and transfers all loads coming from the wind rotor and the turbine's own movement to the ground. Gravity base or spread foundations are considered as one of the preferred foundations for onshore wind turbines, due to their simplicity. In the case of soft subsoil, additional pile foundations are used (BWE, 2023). Gravity base foundations generally consist of cylindrical pedestal mounted onto a large reinforced concrete base, with a circular or octagonal or a kind of modular/segmented shape (Ntambakwa et al., 2016). The foundation of onshore wind turbines is usually based on the same principle as the setting up of a parasol by means of a heavy round base as seen in Figure 4-1. This round base is built from concrete reinforced with steel, which on the one hand brings the overall center of gravity of the wind turbine further down in height due to its weight, and on the other hand places the tipping edge sufficiently far from its center of gravity because of its diameter that the wind turbine cannot be overturned by the maximum wind forces acting on it. By adjusting the direction of the rotor axis, the turbine can be turned out of the wind, if necessary, in order to limit the overturning momentum (Bauer, 2017). Typical spread or mat foundation widths are in the order of 15 m to 20 m with a 4,5 m to 5,5 m diameter central pedestal for the foundation connection to the tower. The foundations are typically 2m to 3m thick in the central portions and taper to 1 m or less at the edges. The foundation bases are typically supported at depths ranging from about 1 m to 3 m below the finished ground elevation and backfilled with specific material. This type of foundation relies primarily on massive self-weight and soil overburden/backfill to provide stability against the loads transferred from the turbine tower. The concrete gravity foundation in combination with the soil layers must exhibit competent strength and deformation capacity to resist the loads (Ntambakwa et al., 2016).

Figure 4-1. Foundation of a wind turbine (Max Bögl, 2016)

The following further analyses must be carried out depending on the geotechnical parameters in order to evaluate essential foundation design criteria (Caselowsky, 2008; Svenson, 2010; Ntambakwa et al., 2016):

- Global stability against sliding and overturning
- Soil-bearing capacity
- Allowable foundation uplift/gapping
- Allowable settlement/Differential settlement
- Minimum Foundations Stiffness
- Durability
- Limit State Design Considerations

For shallow depth gravity foundations and other geotechnical requirements, it is necessary to perform global stability analyses under design loading conditions provided by the turbine manufacturer since the consequences of a failure could be dramatic as seen in Figure 4-2. This can be evaluated in order to confirm adequate factors of safety for resistance to overturning and horizontal sliding also under extreme loading conditions.

Figure 4-2. Fallen wind turbine facility (windpark-vechigen, 2023)

For shallow foundation design, it is essential to determine the ultimate and allowable bearing capacity of the foundation support materials within the depth of influence. The evaluation of bearing capacity is usually performed using stress or working stress design approaches. The ultimate bearing capacity of the soil supporting a spread footing is usually determined by bearing capacity factors based on soil properties derived from the results of the geotechnical investigation and appropriate factors of safety. Given that the foundations are subjected to high overturning moments, considerations for load eccentricity have to be incorporated into the bearing capacity evaluations for wind turbine spread foundations.

If the foundation is subject to foundation water pressures, adequate safety against uplift must be provided. A typical requirement for wind turbine foundation design is that the foundation should remain in full contact with the subgrade materials during normal operation. The no-gapping requirement ensures adequate foundation stiffness and limits load cycling, which could contribute to the cyclic degradation of foundation support soils. Foundation gapping could be allowed under extreme loading conditions (infrequent high loads) but should extend no further than the center of the spread foundation width for stability considerations.

Shallow foundation design should incorporate evaluation of both short-term (elastic) and long-term (plastic) settlements. The total settlement is typically calculated for granular soils based on the application of extreme loads, while elastic and long-term consolidation settlement for cohesive soils is calculated under operational (long-term) loading conditions. The assessment of foundation settlement can be based on the results of various in-situ tests (e.g. flat-plate dilatometer, CPT) and laboratory bets (e.g. consolidation testing). Total and differential settlement should be kept at an acceptable level and is an important requirement specified by the turbine manufacturer.

The minimum foundation stiffness, including rotational and translational stiffness, is one of the most important design specifications provided by turbine manufacturers as it forms the basis for estimating the dynamic response of a wind turbine. Overall foundation stiffness is dependent on the soil stiffness and soil-foundation-structure interaction between the concrete footing and subgrade. Considering the finite stiffness of subgrade soil, the foundation stiffness for a shallow foundation is calculated by assuming the right footing on an elastic half-space or a continuum representing the subgrade. The dynamic stiffness of the foundation system is typically evaluated based on strain-constrained dynamic shear modulus values, which can be estimated from shear wave velocity measurements and appropriate modulus reduction factors under operational loading conditions, while the static stiffness is evaluated using a shear modulus value derived from higher strain levels under extreme loading conditions. For foundation designs with relatively thin bases or where deformation of the base or the pedestal is expected to be high, foundation rotational stiffness computations should also consider additional displacement due to deformation of the concrete.

Foundations should be designed with adequate resistance to the deleterious effects of the environment. Soil chemical testing, consisting of measuring soil pH, soluble chlorides and soluble sulfates should be performed as part of the geotechnical investigation in order to determine the potential for concrete sulfate attacks and corrosion risk to buried material. The results of the testing should be appropriately incorporated into the development of the concrete mix design.

When designing structures one has to make sure that all the requirements are fulfilled. Regarding designing of structures, one is talking about different types of limit states such as Ultimate limit state (ULS), Serviceability limit state (SLS). A limit state is reached when a structure is on the verge to exceed a specific requirement. Geotechnical design principles using Limit State Design approaches are well established in some areas globally including Europe where structural and geotechnical design is based on the Eurocodes. Eurocodes are valid for all countries that are members of the European Committee for Standardization. In the scope of the geotechnical design of a wind turbine Eurocode 7 is applied. USL and Load and Resistance Factor Design approaches are well established and widely used for structural design aspects of most structures.

Since wind turbines are rarely built directly on bedrock, in most cases the load-bearing capacity of the soil must be increased by soil improvement measures. The most common methods for this purpose are given in detail below (Keller, 2023).

- Deep soil mixing (DSM): Deep mixing method, also known as wet soil mixing, improves the characteristics of weak soils by mechanically mixing them with cementitious binder slurry.
- Dynamic replacement: This method uses the energy of a falling weight to drive large-diameter granular columns into cohesionless soils and fills.
- Vibro replacement: It involves the construction of load-bearing columns made from gravel or crushed stones with a vibrator to reinforce all soils in the treatment zone and densify surrounding granular soils.
- Vibro compaction: This technique densifies clean, cohesionless granular soils with a downhole vibrator.
- Bored piles: Bored piles are a very effective, state-of-the-art construction element with many applications in foundation and civil engineering. After drilling out of the soil, full-length reinforcing steel is lowered into the hole, which is then filled with concrete.
- Continuous flight auger (CFA) piles: They are a type of bored cast-in-place replacement pile. Reinforcement is placed into the wet concrete after casting, enabling the pile to resist the full range of structural loading.
- Rigid inclusions: This technique uses high deformation modulus columns constructed through compressible soils to reduce settlement and increase bearing capacity. Ground improvement efficiency depends on the stiffness relationship between the soil and the columns. Load from the structure is distributed to the soil and columns via a load transfer platform or rigid foundation.
- Columns with mixed modulus (CMM): CMM is the combination of a rigid inclusion for its lower part with a “supple” inclusion in compacted gravel or crushed stone for the upper part.

- Driven precast piles: They are deep foundation elements installed using impact or vibration hammers to a design depth or resistance.
- Franki piles: This method is also known as pressure-injected footings (PIFS). Franki piles are high-capacity, cast-in-place elements constructed using a drop weight and casing.

Among these, the method of vibro replacement is the most commonly used. In contrast, a foundation with cast-in-situ piles is less economical for most soil conditions at current wind turbine sizes and would only be economical for much larger wind turbines (Bauer, 2017). In Fronhoven, Germany, 18 m deep vibro stone columns (vibro replacement) were implemented on a former brown coal open pit mine area in order to build nine wind turbines up to a height of 143 m. Ground improvement was necessary, since the open pit mine reached depths of up to 100 m and was backfilled using finely-sieved, slightly silty and gravely homogeneous sands. The same method was also applied in Königshovener Höhe in order to build 21 wind turbines with a height of 143 m on a backfilled former brown coal open pit mine area. With the installation of vibro stone columns up to 20 m deep, the homogeneous ground condition could be achieved (Keller, 2019).

Theocharis et al. (2022) investigated the geotechnical aspects of a spoil heap from a surface lignite mine in order to deploy a wind turbine with a shallow foundation. The result was that ground improvement or deep foundations are necessary since a spoil has low stiffness and strength.

5 Demo site installation: Main economic, social and technical characteristics

For investigating the technical, economic and employment characteristics of wind power on waste heaps several expert interviews on this topic in the German Ruhr area were made. In this region some experience has been gained with wind power projects on waste heaps of former coal mines dafter the decline and the phase-out of hard coal production in Germany.

The projects regarded cover typically waste heaps with one to four power stations on a waste heap (depending on the largeness of the heap and its geological and material conditions and other territorial restrictions of the location) and ranging in the performance class of turbines with +/- 3 MW. There are older ones with 2,2 MW and the newest project with 4,5 MW-turbines. The range of the heights of the towers is between 180 m and 207 m, the rotor blade having longitudes of 160 m to 175 m. The turbines on the waste heaps in the Ruhr area have been produced by well-known regional manufacturers of the European wind energy business as ENERCON, SENVION or NORDEX.

The place needed for the installation of a wind turbine on a waste heap is principally the same as the place needed for a wind turbine at a flat land location, i. e. a diameter of +/- 25 m for the foundations of the turbines. Nearby there must be storage areas for the construction operations and interim storages of elements of around 40 x 60 m as well as sufficient transport facilities, also for the blades. A special feature of wind turbines on waste heaps is that they often have to be placed not in the center but near the edges of the heap for stability reasons depending on the materials filled in the heap and its geo-technical characteristics. Moreover, for their stability they need deeper foundations than flat land stations with depths of 15 m to 20 m from the surface to the ground of the foundation and special procedures for soil compaction as vibratory tamping.

The typically calculated lifetime of wind power projects on waste heaps in the Ruhr area is +/- 25 years. Longer lifetimes of 30 years seem possible (not realized until now) by regular maintenance and repowering but shorter lifetimes are to be taken into account as well caused by the material wear and problems for the stability as a result especially of turbulences or extreme weather events and the topographical conditions of the region. The stability has to be examined in intervals of 2-4 years.

The performance of wind turbines on waste heaps is typically better than the performance of comparable turbines at flat land locations because of the greater wind speed in higher height (depending on the special topographical conditions in the region). Therefore, for the wind power projects on waste heaps in the Ruhr area, “reference yields” of 15-20% more wind speed on average in relation to flat land stations in the region are calculated.

It is difficult to get detailed information about the current costs of wind power projects on waste heaps in the Ruhr area for confidential reasons and trade secrets. What is clear: The costs of wind power projects have increased in the last time since 2022 generally, because of the inflation of energy and material prices, construction costs and interest rates for investments. As a result, the cost statistics of 2021 are no more representative.

On the other hand, there are no principal cost differences to the predominant level and structure of installation costs of wind turbines onshore in flatland, but only slightly higher construction costs for the foundation. Consequently, it is not wrong to take the world average data of total installation costs for wind turbines onshore by IRENA for 2021 (in Euro), slightly corrected with a surcharge for construction costs and inflated with the increased rate for the price level of manufacturers (in Germany 17,8% in January 2023). So, a good guess seems to be 1350 €/kw for the total installation costs (including the wind turbine, construction, grid connection and other service and capital costs). In this case for example, the investment would require an amount of capital around 4,1 Mio. € for the installation of a 3 MW turbine on a waste heap.

The assumption of a principal comparability to wind power onshore stations in flatland can be made for operational costs with a deduction for the better workload by greater wind speed. Based on the LCOE data of IRENA, a good guess for current pure operational costs of wind power generation reflecting these assumptions (and changing with fluctuating wind yields) is 3-4 Ct/kWh.

For O & M costs (operation and maintenance) of a wind turbine on a waste heap in the Ruhr area as a whole sum per year, there is business information about a range of 50.000 to 70.000 €.

A more or less difficult approach is the calculation of the employment effects of wind power projects, because for a single wind turbine a lot of people are employed in the planning and construction phase as well in the operation and maintenance phase along the whole value chain, but almost all only part-time and/or with limited work for a special wind power station. According to the employment statistics of the German state agency for wind onshore “Fachagentur Windenergie an Land” (2023), there had been 16,000 employees (full-time job equivalents) all around the wind onshore business in the German country North-Rhine Westphalia (which includes the Ruhr area) in 2019 along the whole value chain from projecting in the beginning to demolition or repowering and other services at the end of the normal lifetime. Exactly 50% of this employment is assigned to the construction of the turbines, 15% is assigned to O & M. With a wind power capacity of 6,174 MW in the same year, this number can be converted to +/- 2.6 full-time jobs per MW on average; an estimate confirmed as quite realistic by business representatives.

Taking this ratio, a single wind turbine of 3 MW would provide for 7.8 jobs, what means approximately 4 jobs by the construction, 3 jobs by several services and only 1 job by O & M activities. A waste heap with a group (or: a small wind park) of four 3 MW-turbines would provide arithmetically for 31.2 jobs. Not included here a very special jobs for researchers in projects, such as Eco-Industrial parks, who do not change the picture.

5.1 Opportunities for jobs and growth by wind energy in European coal regions

Before assessing the possible contribution of wind energy for job creation in coal mining areas and in the special GreenJOBS context, it is meaningful to paint the picture of job opportunities by wind power in the general landscape of the energy transition.

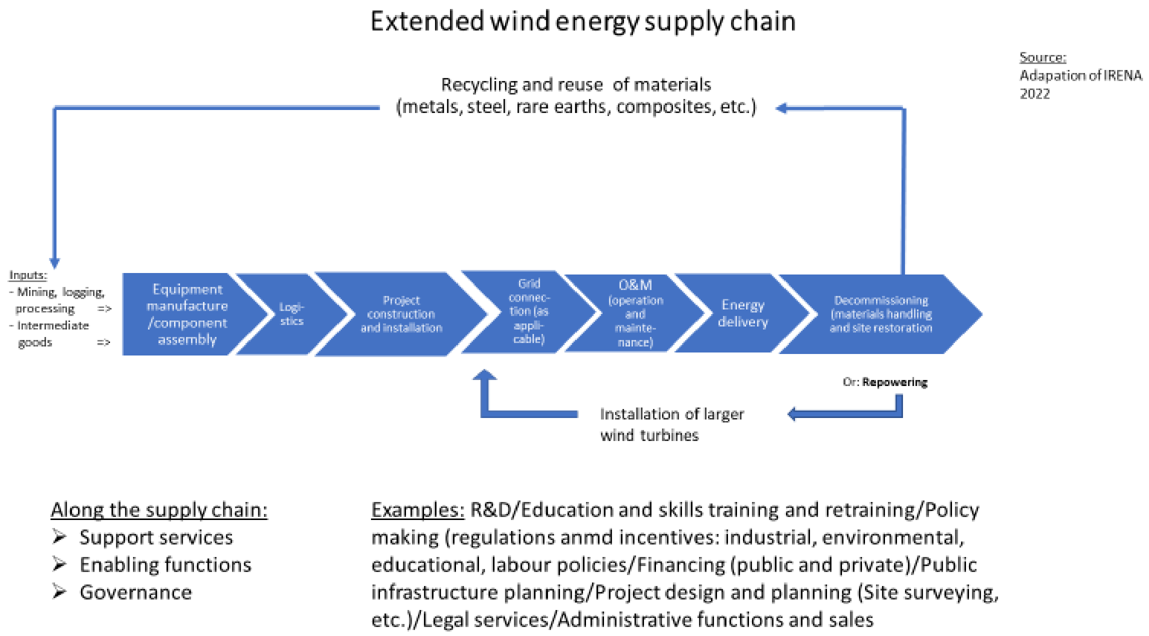
According to the Renewable Energy and Jobs Report – Annual Review 2022 of IRENA in collaboration with the International Labor Organization – the number of people either directly or indirectly employed to the renewable energy sector had been 12.7 million in 2021 worldwide, of which 1.3 million jobs were provided by wind power (IRENA & ILO, 2022).

IRENA & ILO have connected this inventory with the following key observations: At the present, a handful of countries dominate the renewable energy landscape at a global scale, reflecting their strengths in manufacturing, engineering and related services, reaping the majority of jobs. Nevertheless, some component production is shifting from the manufacturing hubs to other countries. In the wind energy sector, the Top 10 countries have 85% of the jobs, thereby China has 48%, but with the European Member States (Germany, Denmark and Spain) under the Top 10, 25% of the global employment relies in Europe (including the UK). Looking upon wind exports, three EU Member States are the leading countries in the world (Germany 30,1%, Denmark 26,3%, Netherlands 13,8%). Meanwhile domestic job creation has more political relevance and awareness. Rising concerns in the context of additional supply chain disruptions, trade disputes and geopolitical rivalries are reinforcing the interest in localization of supply chains, to enhance resilience, domestic value and job creation.

At the same time, decent jobs are essential for the energy transition and its public acceptance. Jobs that pay good wages, adhere to occupational health and safety standards, and provide job security as well as workers' rights, collective bargaining and effective social dialogue. Observance of labor and environmental standards is critical along the renewable energy supply chain (also in wind energy) and its commodities. This includes the mining and processing of metals and other raw materials critical to renewable energy equipment. Industry practices vis-à-vis workers and local communities are receiving greater scrutiny. Once for example, wind turbines reach the end of their life; recycling, remanufacturing and reuse of embedded materials limit waste flows, reduce the extraction of virgin raw materials and offer greater employment opportunities in the circular economy than landfilling or incineration. The continued expansion of decent renewable energy jobs in the wind industry or other sectors requires a comprehensive approach for the political framework comprising policies on deployment, integration and enablement, as well as industrial and energy policies, education and skills training, labor market measures, diversity and inclusion strategies, and regional revitalization and social protection measures (IRENA & ILO, 2022).

Taking this observations into consideration, there are growing employment opportunities (along with challenges to ensure that jobs are decent), also in the upstream portions of the renewable energy and wind energy value chain, as well as in a circular economy approach after projects reach the end of their lives and are decommissioned. In this context, IRENA & ILO (2022) present the “extended renewable value chain”, which applied to wind turbines, as seen in Figure 3-1:

- Providing of inputs by logging, mining or processing of raw materials and/or procurement of all necessary intermediate goods
- Equipment manufacture/component assembly
- Logistics (transport of equipment to project sites, energy delivery from centralized generation, grid feed-in, transmission and distribution)
- Project construction and installation
- Grid connection as applicable (or stand-alone applications)
- Operations and maintenance
- Energy delivery
- Repowering (installation of larger wind turbines at the same location) if possible
- Decommission (materials handling, site restoration)
- Recycling and reuse of materials (such as metals, steel, rare earth, composites, etc.) as far as possible.



Along the supply chain:

- Support services
- Enabling functions
- Governance

Examples: R&D/Education and skills training and retraining/Policy making (regulations anmd incentives: industrial, environmental, educational, labour policies/Financing (public and private)/Public infrastructure planning/Project design and planning (Site surveying, etc.)/Legal services/Administrative functions and sales

Figure 3-1. Extended wind energy supply chain

The Global Wind Energy Council has presented in its Global Wind Report 2022 (GWEC, 2022) a calculation for the workforce and workforce requirements needed for a 50 MW onshore wind project, along the links of the supply chain from project planning to decommission. 144,420 person-days are calculated, of which the largest part (43%) is applicable to operations and maintenance as ongoing work, 30% for installations and grid connections, 17% for procurement and manufacturing, 7% for decommissioning, 2% for project planning and finally 1% for transport. Regarding the skills required for the deployment of wind energy facilities, the GWEC analysis shows that 63% of the workforce requires minimal formal training. Individuals with STEM qualifications, which refers to degrees in fields such as science, technology, engineering and mathematics, are needed in smaller numbers (28%) for onshore wind. Highly qualified non-STEM professionals (such as lawyers, logistic experts, marketing professionals or experts in regulation and standardization) account for roughly 5%, while administrative personnel makes up the smallest share (4%). So, there is a relatively broad spectrum of new job opportunities for all qualification levels and different human resources.

Additionally, the GWEC refers to a case study provided by the US staffing specialist NEC Fircroft about attracting talent into the wind industry, which discusses myths around transitioning from transitional energy to the wind power industry. The results from the study report of NEC Fircroft show for the USA specifically – but most essentials seem to be transferable to the conditions in Europe – that many candidates feel positive about the energy transition and the exciting project it offers, but there are some common misconceptions surrounding moving from traditional energy to a renewable role. One of that is, for example, that the salaries in wind energy are not competitive. However, this is not necessarily the case. More than 75% of respondents, who have transitioned, said that their salary was higher or about the same. Furthermore, many skills are transferable, and the experience especially of engineers from traditional energy projects will be vital to the wind sector. Ambitious wind projects will provide several new jobs and career chances into the latest and greatest technological advances in energy. New and exciting job opportunities will be abundant as companies try to meet the goals of the energy transition. It is also a myth that newer industries may not offer the same stability just because of the energy transition. Big oil, gas and power companies have invested in renewable energy and wind energy is now “front and center”. Projects that will move the needle in sustainability can be groundbreaking and disruptive, but they are surely here to stay. Moreover, there is a societal agreement now that wind energy is at the heart of a just and inclusive transition.

Against this background, there is a need for scaling-up and mobilizing a growing workforce for the wind industry (and other renewable sectors), as well as for targeted education, re- and up-skilling and increased investment in community outreach, recruitment and training to close the skill gaps. GWEC requests that for revitalizing and repurposing the workforce to meet the demands of wind energy growth, policymakers must take responsibility for creating transparent guidance for the job opportunities and proactive frameworks to support this process. In turn, the wind industry must support the shaping and implementation of these frameworks (GWEC, 2022).

Workers from carbon-intensive industries can be part of the solution in addressing the skills gap. Skills and training obtained, for example, by workers in the coal sector can be repurposed and deployed to renewable sectors such as wind power at a variety of points along the value chain. However, a shift to renewables workforce then increases the need for labor mobility, as opposed to merely representing the loss of prevailing jobs in carbon-intensive sectors as coal. Good practices in a just and inclusive transition should include encouraging social dialogue and increased stakeholder engagement, promoting public-private collaboration to generate local value-creation, fostering tailored retraining and reskilling pathways (including re-certification) for workers from carbon-intensive industries (as the coal industry) to the wind industry and also promoting a diverse and inclusive workforce (in all the dimensions of diversity as gender, ethnicity and physical ability). It is vital that the wind sector is publicly recognized as an attractive and welcoming place to work for those of different provenances and career stages. The robustness and pace of the wind industry’s growth will depend on the people who deliver it (GWEC, 2022). None of these insights are wrong for the deployment of wind power in coal regions.

For the capacity factor of onshore wind, the ratio of actual electricity production to the maximum possible electricity production of a power plant, JRC has assumed a European average of 22% (with ranges from 13 to 30% at the country level) based on wind resource measurements for a period of more than 30 years (1986-2018). It considers the current wind portfolio and hourly wind speeds at European hub heights. For the technical lifetime of an onshore wind turbine, JRC has assumed 25 years (Kapetaki et al., 2020).

For the cost trend of wind energy, a special JRC analysis providing CAPEX (Capital Expenditure) values (and assuming OPEX – Operating Expenditures – standardized as 3% of CAPEX, but increasing over the lifetime of the turbines) has formed the basis for three regionally different scenarios from 2020 to 2050 as seen Table 3-1. With scale economies, learning effects and increasing competition (for example by auctions) the CAPEX values of onshore wind power are expected to decrease decade-by-decade (Tsiropoulos et al., 2018).

Table 3-1. CAPEX projection of JRC 2018/2020 for onshore wind energy (EUR2015/kw)

System		**2020**	**2030**	**2040**	**2050**
Low specific capacity, high hub height					
CAPEX	Min	1.670	1.430	1.310	1.230
	Max	1.830	1.800	1.780	1.760
Medium specific capacity, medium hub height					
CAPEX	Min	1.220	1.040	960	900
	Max	1.330	1.320	1.300	1.280
High specific capacity, low hub height					
CAPEX	Min	990	840	770	730
	Max	1.080	1.060	1.050	1.040

For calculating the job opportunities by wind technology, a value chain analysis has been evaluated, assessing the potential jobs created in manufacturing, installation and O&M activities. Furthermore, a special JRC scenario method has been applied to allocate regionally the capacities and employment effects in the coal regions.

The projection has estimated 285,000 wind-related Full-Time Equivalents (FTE) in the EU (still including the UK) by 2015; the year used for calibrating the JRC method, and has assumed growing and scenario-like installation capacity and technology learning as well as constant internal/external manufacturing activity. It implies that European companies will remain the main internal suppliers, keeping their hitherto degree of internalization in the global market. Under these assumptions, the whole wind energy sector could demand around 700,000 jobs by 2050 (Kapetaki et al., 2020). Quite optimistic assumptions can be seen already in 2022; nonetheless, parts of this jobs potential could be realized in EU coal regions.

According to the JRC study 2020, there is a potential of almost 100,000 jobs by wind power in the 31 examined EU “coal regions in transition” as seen in Table 3-2. But, the geographical, technical and economic conditions and circumstances are quite different from coal region to coal region. In addition, it is to underline that these numbers are theoretical potentials, not foreseeable realities (potentials to be developed only under very special favorable conditions).

Table 3-2. Wind-related job potentials in EU coal regions (with exclusion of the UK after BREXIT) (Kapetaki et al., 2020)

Region (European Coal Region in Transition)	EU Member Country	NUTS2 Code	Technical potential of wind (onshore) in the region		Technical potential for wind energy by coal mine reclamation		Average CAPEX needs/GW wind power	Cost/ Job ratio of wind energy investment and O&M	Job creation potential of wind in the region
			GW (power)	GW/year	GW (power)	GW/year	EUR million	EUR million/FTE	FTE
Yugoiztochen	Bulgaria	BG34	7.11	14012	0.12	136.4	468.06	0.57	1409
Yugozapaden	Bulgaria	BG41	3.15	6217	0.05	46.5	501.83	0.57	1511
Severozapad	Czech Republic	CZ04	4.45	8764	0.18	215.5	795.40	1.29	828
Moravskolezsko	Czech Republic	CZ08	4.06	8813	N/A	N/A	235.83	1.43	154
Brandenburg	Germany	DE40	11.43	23666	0.09	136.8	2998.13	0.40	3329
Düsseldorf	Germany	DEA1	0.95	2005	0.03	50.2	1381.25	0.62	3243
Köln	Germany	DEA2	1.23	2569	0.06	89.6	1259.49	0.48	3107
Münster	Germany	DEA3	6.92	14027	N/A	N/A	1385.43	2.89	1440
Saarland	Germany	DEC0	0.10	200	N/A	N/A	264.74	0.04	16307
Dresden	Germany	DED2	2.67	5391	0.04	54.4	567.07	0.43	2128
Leipzig	Germany	DED5	1.78	3511	0.01	18.0	367.71	0.59	1079
Sachsen-Anhalt	Germany	DEE0	13.70	27004	0.03	46.2	2643.01	0.45	5924

Dytiki Macedonia	Greece	EL53	5.58	12262	0.36	245.2	98.81	1.11	151
Peleponnisos	Greece	EL65	27.44	64684	21.7	0.02	31.40	0.92	582
Principado de Asturias	Spain	ES12	7.03	17587	0.00	4.5	173.62	0.39	754
Pais Vasco	Spain	ES21	3.15	7068	0.00	0.7	469.74	0.36	2989
Aragon	Spain	ES24	121.19	280958	0.01	21.5	1521.45	0.56	9673
Castilla y Leon	Spain	ES41	228.19	502125	0.02	24.0	2702.62	0.54	17182
Castilla-La-Mancha	Spain	ES42	154.92	323550	0.01	11.8	1747.190	0.42	11108
Eszak-Magyarorszag	Hungary	HU31	~0	~0	0.03	23.7	20.61	1.57	153
Sardegna	Italy	ITG2	41.94	93388	N/A	N/A	1983.61	0.74	4641
Malopolskie	Poland	PL21	1.23	2512	N/A	N/A	536.30	1.08	862
Slaskie	Poland	PL22	0.30	627	N/A	N/A	807.80	1.11	1298
Wielkopolskie	Poland	PL41	10.40	23752	0.15	565.5	1049.84	1.26	1405
Dolnoslaskie	Poland	PL51	5.25	11410	0.03	53.3	634.83	1.08	722
Lodzkie	Poland	PL71	5.67	12261	0.05	97.4	515.49	1.32	764
Lubelskie	Poland	PL81	12.16	28592	N/A	N/A	885.97	1.40	1424
Sud-Vest Oltenia	Romania	RO41	11.21	22104	0.07	78.5	281.23	1.15	170
Vest	Romania	RO42	8.83	17397	N/A	N/A	301.36	0.98	251
Zapadne Slovensko	Slovakia	SK02	25.48	55169	N/A	N/A	N/A	0.82	365
Vzhodna Slovenija	Slovenia	SI03	1.90	3742	N/A	N/A	145.85	0.82	244

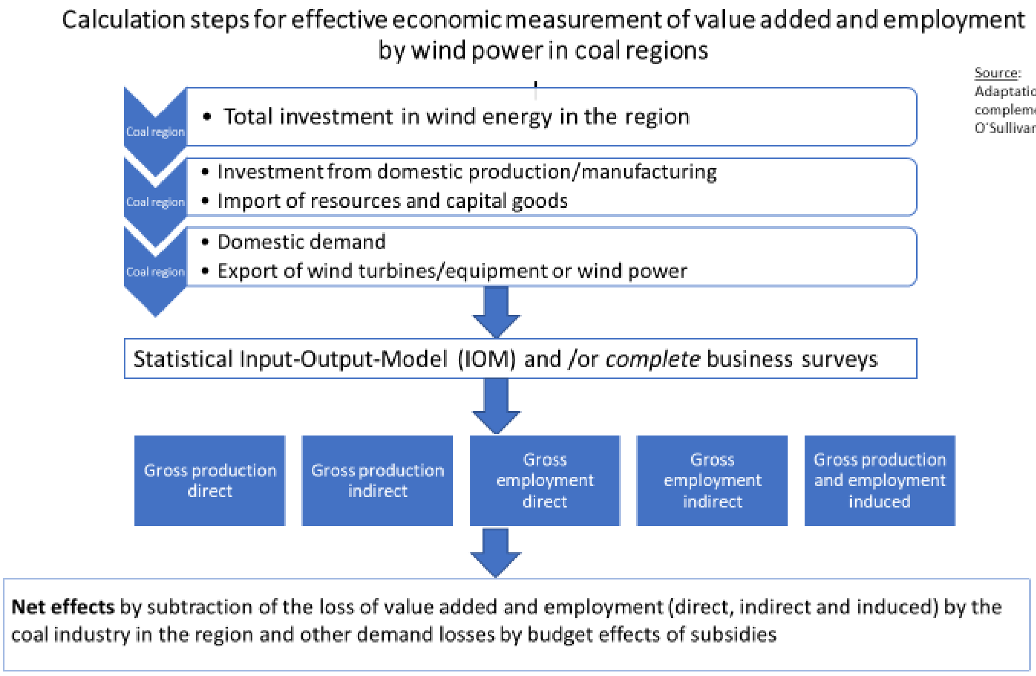
For the measurement of the (gross) employment effects of renewables in general and wind energy, in particular, it would be necessary not only to measure the direct jobs in connection with the manufacturing and installation as well as the operation and maintenance (O&M) of the plants, but also the indirect and economically induced effects on employment. The best available method for this purpose is a statistical Input-Output-Analysis, supplemented by business surveys as far and complete as possible. In Germany, O’Sullivan and Edler (2020) have done this for years by an Input-Output (IO) modeling approach, at last in 2020 for the period 2000-2018.

Their study has provided detailed insights into an approach to measure gross employment of the renewable energy industry in Germany (including the wind industry and all other relevant renewable energy technologies) in order to improve transparency and comparability. The authors have stated at the beginning,that the societal implications, especially the question of employment, have a strong impact on political decision-makers as well as on public acceptance, which result from the energy transition and the evoked change in industrial structures. They remembered that the discussion of the impact of new technologies on employment has been on the economic agenda ever since David Ricardo wrote his famous chapter “On Machinery” in (the third edition of) his *Principles of Political Economy and Taxation* in 1821. Therefore, the successful establishment of new industries in the technologies, which are drivers of the energy transition, is of particular importance for political decisions. In order to monitor and assess the development of renewable energies (RES), like wind energy, economic indicators like domestic demand and employment are essential. However, RES technologies as evolving cross-sectional technologies are not well represented in official classifications of goods and industries so that no immediate information on the RES-sector employment can be found in official statistics. RES gross employment effects must be derived by formal quantitative estimation methods.

On the one hand, while the specific numerical results of O’Sullivan and Edler (2020) are not of deeper interest in this context of wind power deployment in coal regions, their general results show the big sustained relevance of the manufacturing and installation sector (compared to O&M) in the wind and the other RES industries, as well as the variable influence of foreign trade. On the other hand, the importance of O&M is growing and plays an increasing role in providing a more stable development of employment in all RES industries. But, there are some remarkable main methodological conclusions as follows: (1) data availability was, is and remains a major challenge in assessing employment effects of specific technologies; (2) there are many different ways to apply the IO-modeling approach to specific technologies and services; (3) the transfer of results from one country to other countries is limited. (O’Sullivan/Edler 2020).

The paper of O’Sullivan and Edler (2020) has focused on the development of gross employment (direct and indirect employment), which reflects the employment attributable to the activities of the built-up and operation of renewable energy plants. Employment has been chosen as the main indicator representing economic activity connected to the built-up of the RES industry in Germany mainly for two reasons: (1) The total input requirements for labor calculated with the input-output approach encompass all stages of the value-added chain. (2) Employment is easier to comprehend and communicate than other economic indicators e.g., gross production or gross value added. Focusing on gross employment has some merits, but also some important drawbacks. Gross employment gives a broad picture of economic resources committed to facilitate the built-up of the RES industry and to put in perspective to other economic activities and the economy as a whole. With this, it allows for the monitoring of the development of the RES industry due to the expansion of renewable energy technologies in a country or regions of countries (O'Sullivan & Edler, 2020). This is of interest here with attention to wind power in the special setting of coal regions.

However, this approach neglects possible negative employment effects that are relevant from an economy-wide point of view, such as budget or substitution effect. Therefore, this approach cannot inform alone and isolated about the economy-wide effects of the built-up of RES industries. The balance of the economy-wide effects (positive and negative), generally called net effects, is essential to assess the advantageousness of economic and energy policy measures e.g., the policy measures to foster the diffusion of RES technologies. This important strand is not addressed in this study. But, it is noted and supplemented that the methods and results presented regarding gross employment form an indispensable set of information for studies on the inquiry of net employment effects. Relating to the expansion of wind energy and other renewable energy technologies in Germany and their conditions and prerequisites as a relatively reliable domestic market for wind energy without radical new developments in the time under consideration, the results hint to "small, but under most assumptions, positive net employment effects induced by the expansion of RES technologies" (O'Sullivan & Edler, 2020). A scheme to calculate the gross and net employment effects of wind energy in a coal region can be portrayed in Figure 3-2.



Source:
Adaptation of and complement to O'Sullivan/Edler 2020

Figure 3-2. Calculation steps for the effective economic measurement of the value added and employment by wind power in coal regions

6 Best Practices

The impact of renewable energy on the active mining industry is already evident and will continue to shape the operation of modern plants that meet the latest environmental standards in the future. Renewables offer a comparatively cheap alternative for miners. In addition to wind power, solar energy, geothermal energy, biodiesel and hydrogen as well as fuel cell energy are also used. The integration of renewable energies can relieve the mining industry financially and at the same time create new jobs, especially for engineers. In addition, the generation of greenhouse emissions will be greatly reduced and, with increased energy efficiency, a sustainable development of the energy industry will be promoted. Generally speaking, renewables contribute to improved power generation in mines and thus actively support innovative approaches such as hybrid power plants or hydraulic mining. The mining industry benefits from the strong expansion of renewable energy, as it is now more worthwhile to invest in further green approaches and to adapt guidelines (AngloAmerican, 2019; Igogo et al., 2021).

One example of success (in an active mine) is the Enel Green Power Company, which is now a global leader in renewables in the mining industry. They already offer their services in the USA, South America and Canada, as well as Australia and South Africa. On the one hand, they provide electricity that comes from renewable energy sources. However, because many mines are located so remote from the power grid, they also provide on-premises mini-grids. These can then be fed via wind turbines, for example. This offers mine operators the opportunity to use cleanly produced electricity and thus reduce the overall emissions of their plant. The overall goal is to support operating mines in reducing their environmental footprint and running their mines as green as possible (enel Green Power, 2023). Nevertheless, this is just one example of several successes that have been achieved.

Barrick Gold, which also specializes in renewable energy for mines, is also a leader. They financed the first wind project (in 2011) to build a wind farm for a mining company in Chile (Punta Colorada) with over 50 million dollars, whereby energy is also fed into the Chilean electricity grid. In addition, the Zaldívar copper mine (active mine) is the only mine in Chile to be operated with 100% renewable electricity. This goes back to a joint venture with the provider Barrick, which has made green electricity available since 2020. This impact on the reduction of otherwise generated greenhouse gas emissions saves a total of 350,000 tons per year.

But, the active Veladero mine (Argentina) also uses the wind turbine from Barrick and can use it to generate up to 20% of its electricity requirements with green electricity. At the same time, this wind turbine is 4,100 meters above sea level and is therefore the highest wind turbine in the world to date (Dickson, 2020).

Another active mining operation within this transition industry is Goldfields. Operations located at the Agnew mine in Australia are also switching to renewable energy for the mine. The so-called "Agnew Hybrid Renewable" project is Australia's largest hybrid micro grid for renewables and uses wind power. The project is divided into two phases. In phase 1, a new 23 MW (Mega Watt) power plant with three MW diesel generation, 16 MW gas generation and 4 MW solar generation was integrated in 2019, independently of the grid. As a result, initially 10% of the electricity requirement should come from solar generation. The 2nd phase took place a year later, in May 2020, where the share of renewables increased to 50 to 60%. For this purpose, the project received support from the Australian Renewable Energy Agency in the form of five wind turbines for installation. These generate up to 18MW and have an energy storage system with battery between 13MW/4MWh (Mega Watt per hour). It thus represents a modern control system for microgrids (Dickson, 2020; Strazzabosco et al., 2022).

In Germany, there are already a number of heaps from former mining sites, currently 8 in number (out of 58 heaps), on which wind turbines have been successfully installed. These produce around 128 gigawatt hours per year. According to the latest investigations by the Regional Association Ruhr (RVR) further heaps should come into question in order to install further systems there in the future. An example of an already equipped one is the Hoppenbruch heap in Herten in Ruhr Area (Arnold, 2022; RVR, 2023a). Within the Ruhr area, the RVR deals with regional development as well as the planning and management of infrastructure projects (RVR, 2023b). In addition, the evaluations with German experts in the form of interviews (anonymized) have shown that there are also some difficulties with the implementation of wind turbines here. The interviews confirm that waste heaps of former coal mines as locations for wind power stations have the same general problems as other locations for this purpose: The tediousness of the planning procedures and approvals (including several assessments as monitoring and soil reports), the changing of political conditions as well as the risks in construction costs and wind yields. Beside these general aspects, there are some special advantages and disadvantages. The geology and material from younger or long-term monitored dumps is usually well documented. There is therefore both well-documented knowledge of the subsoil and past mining activities in the area. In most, but not all, cases waste heaps possess a proximity to the infrastructure including the supply lines and the power connections of the former coal mine, so the connections costs and the technical expenditures for the necessary adequate connection to the power grid are relatively low. A problem is often the access to the construction and the construction site on the heap. In addition, the place on the heap is restricted. The jobs opportunities beyond the construction phase are restricted as well. If the wind turbine is in operation, there are only few additional jobs for the technical and administrative controlling and the maintenance tasks.

This shows that on the one hand, there are already many examples of success. On the other hand, this sometimes involves a lot of effort. It is not always trivial to install wind turbines at supposedly suitable locations. This is supported by the previous results, which show many advantages for the further promotion of wind power, but also come with some disadvantages. However, as mentioned above, the current boom in interest in renewable energy (trigged by global climate change and the energy crisis caused by the Russia-Ukraine War) may help to accelerate related researches. This represents the possibility of eliminating some of the still existing disadvantages through optimization in the further development.

JRC-Study on clean energy technologies in coal regions

To assess the specific opportunities for jobs and growth of wind power in coal regions, the following sections present the wind-related results of the 2020 Policy Report of the European Commission’s Joint Research Centre (JRC) on clean technologies in coal regions (Kapetaki et al., 2020). This study is based on a previous JRC study about the coal regions in the EU affected by the energy transition and their economic opportunities and challenges, which estimated in 2018 that the EU coal sector employed still nearly half a million people with around 50% of 200,000 direct jobs to be lost until 2030. Nevertheless, more than 300,000 new jobs could be created in total by deploying different clean energy production technologies, not only wind, in the same period (Alves Dias et al., 2018).

A key conclusion of the 2020 JRC Policy Report is that the European coal regions should not and do not have to stay behind in the frame of a continued economic and social evolution by the energy transition. While the transition is already happening, the clean energy potential in coal regions can enable them to be active participants in this transition. The deployment of this energy potential would contribute to energy security and provide economic value and jobs to post-mining communities. This is because the development of clean energy projects benefits from the availability of land, infrastructure, skills and industrial heritage. However, close cooperation in EU, national and regional levels between companies, regulators, investors, land-use planners and local communities is essential to identify the most sustainable options, exploit regional potential and maximize social and economic development. Two of the special main findings related to wind power are that the highest estimated technical potential for onshore wind is in the Spanish region Castilla y Leon (228 GW), almost 28% of the potential across all investigated coal regions, the highest potentially induced employment for wind energy is with estimated 16,300 jobs in the German region of Brandenburg (Kapetaki et al., 2020).

The 2020 JRC study has used a four-step analytical hierarchy process by a resource, technical, economic and market potentials schematic (Kapetaki et al., 2020). The largest potential, the resource potential, is the amount of energy physically available. Then the technical potential takes into account geographic constraints such as weather conditions and topographic conditions and system performance expressed by land-use constraint, but not economics. Economic potential is therefore the subset of the technical potential that is available when the cost required to generate the energy is below the revenues. Lastly, the market potential is the amount of energy expected to be generated through the market deployment of the special technology after considering the impact of current or future market factors including incentives and other policies, regulations, investor response, and economic competition with other generation sources. The analysis of the study is based primarily on modeling results and not on regional/local data and information and the results represent plausible technology deployment, as well as potential investments in the envisaged coal regions within a context in line with current policies as set in Europe. Country projections are translated into regional (NUTS 2) projections. Therefore, looking upon the respective coal regions, significant differences to and deviations from other studies and forecasts with other approaches, a definite regional/local data foundation or made at a later time with more up-to-date economic and political framework assumptions are possible, of course. What is to be shown are not the precisely expected numbers, but plausible magnitudes of regional growth and job opportunities estimated by special scientific methods.

Another restriction of the meaningfulness of the 2020 JRC study exists in the fact that the developed model has estimated the optimum wind power share to maximize the available technical potential in operating open-pit coal mines, of which 75 have been identified in 2017 in the coal regions in transition (including back then before the Brexit the UK coal regions, which are excluded here). For each coal mine, the model calculated the best share of wind (and other clean energy technologies) deployment based on the mine's specific resources, technical variables and land availability. The areas around the coal mines are considered on a NUTS2 level. Underground coal mines have not been considered as the surface area of these mines could not be identified sufficiently by JRC. So, also heaps and other suitable locations on the areas of underground coal mines are outside of the calculations (Kapetaki et al., 2020). Therefore, the results of the JRC study cannot be transferred to the special GreenJOBS inquiries, but give some orientation about the quantities and possibilities of wind power in coal mining regions and on coal mining sites.

7 Conclusions

The integration of wind turbines is increasing worldwide in the course of climate change and the critical energy situation. The associated expansion requires increased use of resources for the production of these systems as well as suitable locations for installation and power supply in the coming years up to the targeted climate neutrality in Europe by 2050.

Therefore, the present report has dealt in detail with the various requirements for the expansion of wind energy and analysed different aspects. For a holistic presentation of the topic, an introduction was first made to the general situation, both in Europe and globally, with regard to wind power. On the one hand, the general problems of wind power with regard to raw materials, the environment and recycling were dealt with in a more dedicated manner. On the other hand, the authors have specifically focused on the potential and limitations of wind turbines in former mining areas in order to evaluate subsequent use to conserve resources and costs in industry-intensive regions. In this context, the possible creation of new (green) jobs and the growth potential for the further integration and promotion of wind power in European coal regions were then worked out. The last major analysis point dealt with the geotechnical requirements for the (mining) site for the specific use and installation of wind turbines.

The following important implications and conclusions emerged from the assessments:

1. Russia's war against Ukraine has exposed Europe's dependence on fossil fuels and, alongside the climate crisis, poses another important reason for independence through the promotion of renewable energies such as wind power. This needs to be pushed forward as soon as possible, so all sorts of suitable sites to install wind turbines are needed. This includes the former European coalfields for the conversion and new use of closed mines and existing stockpiles.
2. Both offshore and onshore systems are required for this expansion, which enable more and more storage as these systems become larger and larger, up to and including entire wind farms. Installing these dimensions brings the potential of former mining areas into focus, in particular, to be able to supply densely populated European regions with energy.
3. Since wind turbines are still socially rejected visually and because of their volume, such a turnaround with area-wide installation can only succeed if social acceptance is created. For this purpose, transparency and communication are the keys to success as well as constant optimization and progress to eliminate current disruptive factors such as volume, effects on wild animals, etc.
4. To achieve the climate goals and the expansion of wind power, an increase in demand of between 2 and 15 times the current level can be expected. Many of the materials needed are, among others, rare earth, which are mainly found in

China. Here a 15-fold increase in demand for rare earth, which are irreplaceable for the construction of plants, can be calculated. This already exceeds the availability for the entire EU on the market and does not include other international countries.

5. The problem of recycling wind turbines is also an essential topic, which has received a lot of research in recent years. The currently most suitable and environmentally friendly method is the recycling of the residual fibers after the end of their service life by using them for the production of cement. This method for processing cement in production is also recognized in the EU. It reduces the carbon footprint by up to 16% in comparison.
6. Wind power has many advantages in the assessment: clean energy, renewable resource, operation costs for energy production itself is close to zero, cost-effectiveness when several households are supplied, technological advances benefit falling prices by 80% since 1980 and are expected to further decrease, development in design optimisation, the market potential is rising, wind farms on agricultural land or former mining sites can be lucrative for land owners and provide lots of energy at once, wind power saves water compared to traditional energy production methods, job growth
7. Wind power still has some disadvantages: competition when it comes to low costs with other renewable options such as solar power, locations are mostly remote and this makes a supply in urban areas more difficult, reliability of wind itself, wildlife is often disrupted or endangered by rotor blades, disturbance through the average noise level, the phenomenon of the shadow flicker is disturbing in urban areas, through existing regulations for the installation it is still convenient to fell trees and create fitting spots for installation even though sides would be available.
8. There are many positive examples of wind power integration in active mining regions, but also in former coal regions. This is only associated with a lot of effort, but it is worth based on the successful results.
9. With regard to the job opportunities for renewable energies or wind power, the entire value chain offers the following options: providing inputs by logging/ mining or processing of raw materials and/or procurement of intermediate goods, equipment manufacture/component assembly, logistics, project construction and installation, grid connection as applicable, operations and maintenance, energy delivery, repowering, decommission, recycling and reuse.
10. The requirements for legal planning of wind turbines avifaunistic assessment, noise assessment, shadow assessment, turbulence assessment and geotechnical report.
11. The complete geotechnical site investigation of the installation site is necessary and this includes the following aspects: Soil borings,, CPT, geophysical surveys, in-situ measurements, groundwater measurements, and laboratory testing.

12. The geotechnical investigation of European spoil heaps has determined that most of them worldwide and thus especially in Europe have a common problem: The material is too soft to withstand the superstructure and therefore requires supporting structures and soil improvements through upgrading the spoil heaps and deep foundations. This must be taken into account for the potential installation and planning of wind turbines on former mine dumps.

8 Glossary

ASD – Allowable Stress Design

CAPEX – Capital expenditure

COP – Coefficient of performance

CPT – Cone Penetration Testing

DMT-THGA – DMT-Gesellschaft für Lehre und Bildung mbH

EIA – Environmental Impact Assessment

FAEN – Fundación Asturiana de la Energía

GIG – Główny Instytut Górnictwa

GIS – Geographical Information System

HUNOSA – Hulleras del Norte, S.A.

ICP-AES – Inductively coupled plasma-atomic emission spectrometry

ICP-OES - Inductively coupled plasma-optical emission spectrometry

IO – Input-Output

IOM – Statistical Input-Output-Model

IRR – Internal rate of return

LCA – Life Cycle Assessment

MW – Mega Watt

MWh – Mega Watt hour

M&B – Magellan & Barents

NPV – Net present value

OPEX – Operational expenditure

O&M – Operation & maintenance

PP – Payback period

PV – Premogovnik Velenje d.o.o.

REA – Research Executive Agency

SWOT – Strengths, weaknesses, opportunities, and threats

TRL – Technology readiness level

ULS – Ultimate Limit State

UNIOVI – Universidad de Oviedo

WEGLO – Węglokoks S.A.

XRF – X-Ray Fluorescence

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