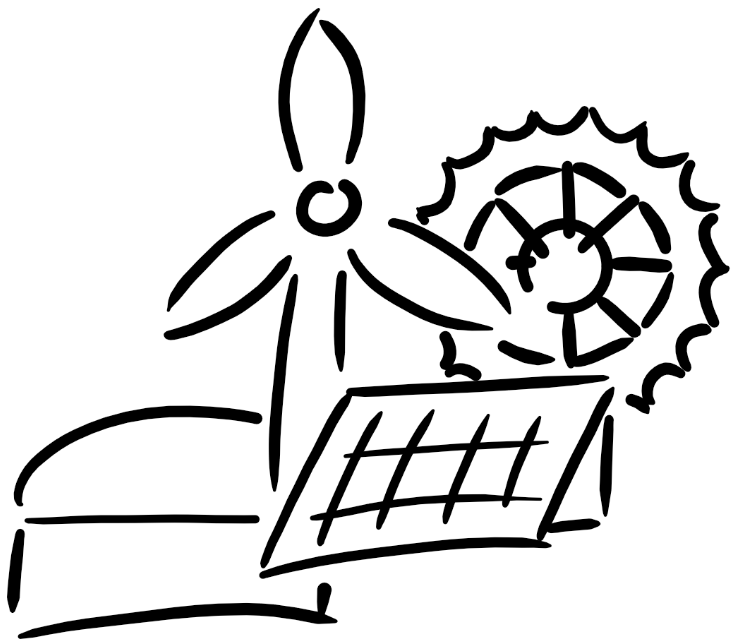
Educational Journal of Renewable Energy Short Reviews



2023

Münster University of Applied Sciences

Preface

The *Educational Journal of Renewable Energy Short Reviews* (EduJRESR, formally published as 'EGU Journal of Renewable Energy Short Reviews') is a teaching project rather than a regular scientific journal. To publish in this journal, it is a premise to take part in the master course *wind power, hydro power and biomass usage* at the department of Energy, Building Services and Environmental Engineering of the Münster University of Applied Sciences.

Students receive an equivalent of 2.5 credit points (European Credit Transfer and Accumulation System – ECTS) for their engagement in the course and for publishing a short review article of at most 3 000 words in this periodical. The publication process closely mimics the typical publication procedure of a regular journal. The peer-review process, however, is conducted within the group of course-participants.

Although being just an exercise, we think that publishing the outcome of this course in a citable manner is not only promoting the motivation of our students, but may also be a helpful source of introductory information for researchers and practitioners in the field of renewable energies. We encourage students to write their articles in English, but this is not mandatory. The reader will thus find a few articles in German language. To further encourage students practicing English writing, perfect grammar is not part of the assessment.

We especially thank our students for working with LaTeX on Overleaf, although LaTeX is new to some of them. In this way, the editorial workload was reduced to a minimum. We also thank our students for sharing their work under the creative commons attribution licence (CC-BY). We appreciate their contribution to scientific information, being available to every person of the world, almost without barriers. We also thank the corresponding authors and publishers of the cited work, for granting permission to reuse graphics free of charge. All other figures had to be replaced or removed prior to publication.

Peter Vennemann and Christian Klemm in October 2023

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Contents

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Challenges for the construction of an underground hydroelectric power plant with electricity storage (UPSHP) in terms of public acceptance and technical aspects

A Summary

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Abstract

For the increasingly important storage of renewably generated electricity, this review explains the construction of a surface and underground pumped storage power plant. The problems for the construction of an underground pumped storage power plant are further listed. These are geological, environmental and economic problems as well as a low acceptance by the population. The geological problems are concerns about leaching of minerals and heavy metals as well as the statics of the cavities. Mining companies in Germany are obligated to renaturalize the landscape areas again, which could be realised by a lake. Furthermore, care must be taken to ensure that the mine water does not come into contact with the groundwater. According to a survey by RISP on the subsequent use of the mine areas for an underground pumped storage power plant, the acceptance of the population is over 70 percent. The economic consideration concludes that the arbitrage profit for a difference between off-peak and peak of 10 €/MWh is about 2.7 M€/a and for 100 €/MWh about 27.3 M€/a. With investment costs of about 630 M€, despite the assumption of 100 €/MWh, more than 20 years are needed for an underground pumped storage power plant to be amortized.
The acceptance could be increased by creating a lake as a recreation area as well as being used as an upper storage reservoir. Thus, the cost of renaturation decrease when combined with the creation of the storage basin. The problem of ground conditions can be solved by creating new cavities by means of tunnel boring at an inclination. For static safety as well as against leaching of minerals and heavy metals, the cavity walls can be sealed with reinforced concrete. The technology of underground pumped storage power plants can be used for better utilisation of renewable energies. This is especially in flat and densely populated regions a possibility to store energy, because the main part of the power plant is underground.

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Keywords: PSH, PSHP, UPSH, UPSHP, renewable energy, lower reservoir

1 Introduction

Considering the compliance with medium- and long-term climate protection goals to reach greenhouse gas emission neutrality in 2045 [1], even more renewable energy sources must be utilised, such as wind, solar and hydroelectric power. These are subject to large fluctuations throughout the day, resulting in an increasingly volatile power grid [2]. To be able to guarantee flexible power generation adapted to the load curve with a high proportion of renewable energy, it must be possible to store this energy. For energy storage, the "Büro für Technikfolgen-Abschätzungen beim Bundestag" (Office of Technology Assessment at the Bundestag) has published a list of possible technologies [3]. For this purpose, the list was subdivided into mechanical, thermal chemical and electrical storage systems. In this review, pumped storage hydropower plants are discussed in more detail. In the beginning, the structure of a pumped storage hydropower plant is described and extended to its underground use. In the main part of this review, an overview of the problems associated with the construction of underground pumped storage hydropower plants is given. At the end of this article, the problems are compared and possibilities are listed by which the problems could be played off against each other.

2 State of the art

2.1 Pumped storage hydroelectric energy

The storage of electrical energy in Germany is realised on a large scale via pumped storage hydropower plants (PSH). For this purpose, about 37.4 GWh per charge cycle can be stored in 31 PSH plants (PSHP) [2].

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Figure 1 shows the structure of a PSHP. The plant has an upper storage basin where the water is stored and a lower storage basin where the water is discharged. When electricity is available, the pump is started and the water is pumped from the lower to the upper reservoir. On the other hand, the water from the upper reservoir flows through a turbine on its way to the lower reservoir, which generates electric power. The turbine operation is used when electricity is needed to utilise the renewable generated electric power when few renewable energy sources are available. The turbine and the pump are installed in the powerhouse.

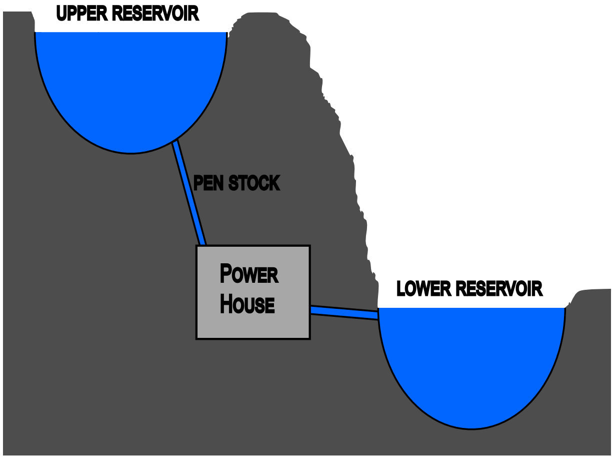

Fig. 1: Structure of a PSHP

For electricity storage, PSHP uses the potential energy of the different altitudes of the two storage basins. This depends on the earth's gravitational field, the mass of the body and the difference in altitude. [4]

$$E_{pot} = m \cdot g \cdot h \tag{1}$$

E_{pot}	potential Energy	[kWh]
m	mass	[kg]
g	gravitation	$[\frac{\text{m}}{\text{s}^2}]$
h	height	[m]

The gravitational force is almost independent of the location, so the potential energy of a PSHP depends mainly on the amount of water and the height difference between the upper and lower reservoir. The problem of reservoir development is to find new sites, which have both a certain height difference and a storage possibility for a quantity of water.

2.2 Underground PSH

The preconditions for PSH from chapter 2.1 are not given area-wide in Germany. Therefore, possibilities are being searched to develop PSH in regions that have had mining operations. This is the case, for example, in the Ruhr area in Germany. For the utilization of the potential energy, it is not relevant whether the facilities are built above or below ground, since only the difference in altitude is of importance.

The mining shafts in the Ruhr area are on average 500 - 1,000 meters deep. A larger height difference is reached above ground in Germany only in the Alps [4].

Figure 2 shows the structure of an underground PSHP (UPSHP). Here it has been assumed that the existing caverns can be used as a lower storage basin since they have a large volume of about 0.1 to 1 million m^3 [5]. Like PSHP, these UPSHP require an upper storage basin. Either an underground cavity located near the surface with a large difference in elevation from the lower storage basin or an aboveground lake can be used for this purpose. The turbine and pump are housed in the powerhouse, as in a conventional PSHP. [5]

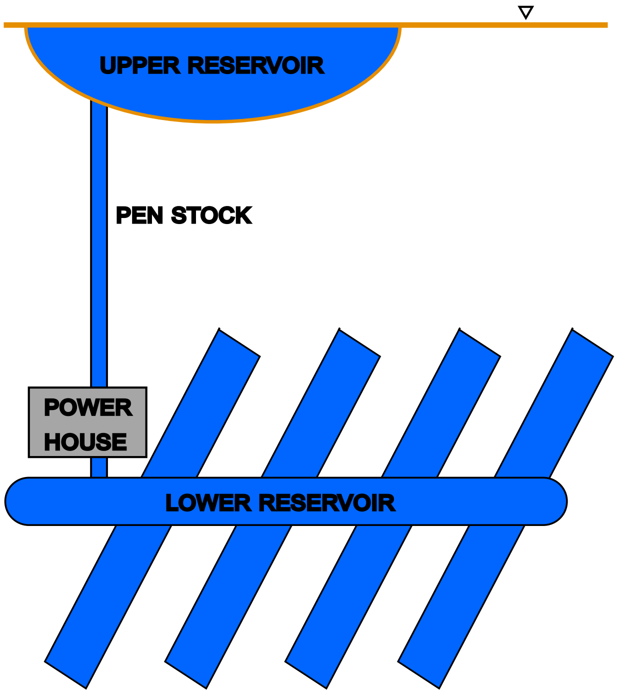

Fig. 2: Structure of an UPSHP

3 Problems of the UPSHP

3.1 Geological Problems

In an UPSHP, much depends on the nature of the lower storage basin. This should have a large volume. The implementation of this volume is a large cavity, which is created underground. For this, a check of the statics is relevant so that the cavity does not collapse. Homogeneous and stable rock layers are advantageous for good statics. These stable rock layers are only sporadically present in the area of the coal mines. [6]

In the Ruhr area, the longwall mining technique was predominantly used. Here, the surrounding rock is

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brought to collapse in a controlled manner after coal extraction. This causes the sediment in the region to sink further and further. As a result of the natural collapse of the mining network, it can be seen that the soft rock layers are not able to withstand the high mining pressure at depth. [cf. [5]]

Furthermore, it should be noted that in mining networks, water does not wash out minerals and water pollutants do not reach the surface. This is due to the fact that in mining operations the tunnel network is not fully flooded. Possible contaminants may include the following [7]:

- heavy metals
- uranium, radium, etc.
- potash and rock salt

3.2 Environment

In Germany, the operating companies of the former mining plants are obliged to restore and renaturalize the former mining areas. A lake used as an upper storage reservoir could serve this purpose. Thus, the costs of mining reclamation would be combined with the costs of creating an upper storage basin. [5]
Another environmental concern is the influx of water into the adit network. To prevent the contaminated mine water from coming into contact with the groundwater, the water level in the old mine shafts is kept at a constant level. For this purpose, a pump is operated to pump the water to the surface. The costs incurred as a result are referred to as perpetuity costs. [8]

3.3 Acceptance

A PSHP on a mountain range involves an intrusion into the natural environment. This encroachment often justifies the aesthetic and environmental concerns of local residents as well as conservationists. In the past, these concerns as well as the high technical requirements of PSHPs often led to project cancellations [5].
In a representative survey of the population in the Ruhr region in 2013, Grunow et al. [9] investigated the public opinion as well as the acceptance in the population for the after-use of the former mining area. Here it was determined that more than 80 percent of the respondents wanted a local recreation or cultural site. 63 percent of the respondents could imagine an industrial site. This subsequent use would in turn create jobs in an area where jobs are currently being lost because the decision has been made to phase out coal in Germany.
Furthermore, the population in the Ruhr region is in favor of the energy turnaround and the subsequent use of the mining site through the construction of a new UPSHP by around 72 percent. This is due to the security of energy supply in the region [9].

3.4 Economy

One of the biggest issues is the economics of a plant. For this purpose, Madlener and Specht [5] have set up an analysis in which the costs are derived in euros per kWh. Initially, the theoretical potential of a plant is determined. For this, a total efficiency for the feed-in and feed-out of 80 percent is assumed. The depths are 250 - 1,000 meters as well as a volume of the lower storage basin of 0,1 - 1 million m^3. If these values are inserted into the formula 1 and multiplied by the efficiency, a potential of 200 MWh to a maximum of 2,500 MWh capacity is achieved. This potential is in the upper middle range in the ranking for German hydropower.

For the height-dependent costs, it is assumed that the costs of the plant increase negligibly small since only the penstock become longer as well as somewhat thicker pipe wall thicknesses are used. These proportional costs are not significant when compared with the lower reservoir and the powerhouse. Thus, at 500 m depth the costs are 227 €/kWh and at 1,000 m depth 114 €/kWh. The cost difference is given by formula 1 since the same amount of energy at twice the depth requires only half the volume.

The costs for the powerhouse are the same as for a conventional PSHP. These are mainly costs for the turbines, the pumps, the excavation of the powerhouse, the tunnel boring works and the engineering works. These costs have been estimated by the design firm Black and Veatch in 2012 at 2,230 US$/kW for a conventional PSHP running 10 hours at 500 MW full load. Using an exchange rate of 0.8 € $\approx$ 1.0 $US$$, this results in 178 €/kWh. This cost is adjusted to a UPSHP because, unlike Black and Veatch, Madlener and Specht assume that a lake will be created for the renaturation of the mining areas. The brownfields used for this purpose are inexpensive and there is no need to build a dam to store water. Therefore, the cost of the upper storage reservoir in this calculation is set at 3 €/kWh instead of 33.6 €/kWh (Black and Veatch).

Combining the head-dependent costs including the lower storage basin and the costs for the powerhouse as well as the upper storage basin, an UPSHP at a depth of 1,000 m thus costs about 253 €/kWh.
Now assume that the UPSHP has 1,000 full load hours per year at a depth of 1,000 m and a lower storage

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basin volume of 1 million m^3. Madlener and Specht determined, under three different price scenarios, the profits that could be realized in an arbitrage transaction between off-peak and peak. This results in the profits per year given in the following table for an arbitrage profit of 10 €/MWh, 50 €/MWh and 100 €/MWh:

Tab. 1: Arbitrage and Revenues

Profit arbitrage	Revenue per year
10 €/MWh	2.7 M€
50 €/MWh	13.6 M€
100 €/MWh	27.3 M€

However, it should be noted that even under very good conditions, such as a large altitude difference and a large reservoir, the estimated by Madlener and Specht 630 M€ are compared, resulting in a payback of more than 20 years. [5]

4 Discussion and Summary

Electricity generation in Germany is becoming more and more renewable based on section 3 climate protection act [1]. However, due to the use of wind and solar power plants, the volatility in the power grid is increasing [10]. For this problem, it is necessary that control energy is available quickly, cheaply and in large quantities. Currently, however, only PSH is available in capacity strength so quickly [11]. PSH has an overall efficiency per charging cycle of up to more than 80 percent, which makes this technology well suited for storage and the construction of the required facilities profitable [5]. However, siting is difficult because there is often a lack of public acceptance for PSH and a lack of regulatory approvals. According to the study mentioned in chapter 3.3, the acceptance for an UPSHP is higher compared to conventional PSHP. This comes from indirectly affects local residents. Furthermore, the construction of an UPSHP in the Ruhr area creates new jobs, which are reduced by the coal phase-out in other cases. The upper storage basin could additionally increase the acceptance by a local recreation area in the region and reduce the costs of renaturation of the former mine sites by a lake [cf. [5] [8]].
On a physical level, a storage technology for energy in the flat Ruhr area would be difficult to realize and thus associated with high costs. However, due to the existing underground mining networks, an UPSHP is well suited for densely populated cities in the flat countryside to store energy at low-cost [5].

That an UPSHP is more expensive than a conventional PSHP was explained in the chapter 3.4. This is mainly due to the higher costs for the lower storage tank and maintenance and repair. Another problem with using the old underground mine shafts is that the condition of the abandoned mine shafts is no longer known. On the one hand, this means uncertainty about the statics of the walls and, on the other hand, whether or how the shafts are laid with a gradient so that the water flows back to the feed point. Madlener and Specht [5] therefore suggest that the lower reservoir be re-excavated using a tunnel boring machine. This would make technical sense insofar as a sufficient slope is ensured and the tunnels are structurally correct. If the tunnel walls are subsequently sealed with, for example, reinforced concrete, this will prevent the leaching of minerals and heavy metals and the ingress of groundwater. In addition, the problem of soft rock in the Ruhr area is then not a reason to exclude the use of UPSH.

The ability to store energy will become increasingly important in the coming years. Many technologies are currently being researched to store renewable energy in the best possible way and on a large scale. Hydropower is a widely researched and therefore favorable technology. However, PSH often encounters problems. In flat regions, however, conventional hydropower utilization is difficult to implement. In Germany, mining has been carried out in many regions. The depths reached are up to 1,000 m with a large network of tunnels. Here the UPSH could be a technology for short- or medium-term energy storage. Because PSH is highly researched, an UPSHP can be used cost-effectively and efficiently in densely populated as well as flat regions.

5 Outlook

A slightly unconventional hydropower plant is under construction in Estonia in Maardu near the port of Muuga, initially scheduled for completion in 2020. The power plant is being built by the company OÜ Energiasalv and is to be operated by ÅF-Estivo. Here, the seawater will be used as an upper storage reservoir. The outcrops in the granite at a depth of about 550 m form the lower storage basin. The capacity of the lower storage basin is about 4.75 million m^3 for a 12-hour operation. Four pump-turbines of different power levels are to be installed in the plant. This means a total output of 500 MW:

Tab. 2: power levels of the turbines in Muuga

Turbine quantity	Power per turbine
1	50 MW
1	100 MW
2	175 MW

In terms of design, care is taken to ensure protection against corrosion and penetration of organic as well as inorganic material in this plant. Cement will be placed in the lower storage basin for protection against stones made of less stable rock. For more information on this UPSH project, please refer to [12].

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Life cycle energy analysis and ecological impact of wind turbines - a comparison of life cycle assessments

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Abstract

The use of wind power is rapidly expanding worldwide. It is important to examine the impact of wind turbines on the environment to see if they provide a net benefit and to identify potential for improving. Therefore life cycle assessments (LCA) of different wind turbine types are compared in this short review. The results are then shown side by side in tables for comparison. Overall the LCAs show that wind turbines compensate the required energy and emitted pollutants after approx. 6-16 months. The energy payback period (EPP) for 2 MW onshore wind turbines remained roughly the same since 2009 with approximately 7 months. Onshore wind turbines have a higher impact due to emissions but a shorter EPP than offshore wind turbines. The estimated service life of 20 years should be maximized to ensure a high energy yield ratio. The biggest impact on the environment results from the processes to provide the building material e.g. steel and cement. That impact could be reduced by 20 % if recycled steel would be used. It is shown that wind power is one of the cleanest energy sources. But further investigations in material processing and recycling are important to improve the eco-balance of wind turbines.

Keywords: wind turbine, wind power, regenerative energy, life cycle assessment, energy analysis, ecologic, environmental impact

Abbreviations

CO_2PP	CO_2 payback period
CHP	combined heat and power plants
DDPMSG	direct drive permanent magnet synchronous generator
DDSG	direct driven synchronous generator
DFIG	doubly-fed induction generator
EPP	energy payback period
EYR	energy yield ratio
GRP	Glass fibre reinforced Plastic
I-O	input - output
LCA	life cycle assessment
Pt	eco-points

(Abbreviations of the impact categories in Tab. 4 are listed below the table.)

1 Introduction

Because of the increasing transition to renewable energy sources and demand for independency from fossil fuel suppliers, wind power is rapidly developing worldwide. 93.6 GW new wind power capacity was added worldwide in 2021. Which brings the total installed capacity to 837 GW. Compared to 2020 that is a growth of 12.4 %.[1] Considering this rapid growth, it is important to examine the impact on the environment to ensure that wind turbines are providing a net ecological benefit and to analyse if the processes of the wind turbine life cycles are improving.

This article compares different life cycle assessments of wind turbines to answer the questions,

- how clean wind energy actually is,
- which aspects of the wind turbine life cycle affects the environmental impact the most and
- how the life cycle can be improved.

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2 Methodology

The Information in this article was gathered by literature research via the internet. The search engines Google Scholar and FINDEX, a service provided by the library of the University of Applied Sciences FH Muenster, were used to find scientific articles. To ensure that important information on the subject area is considered, the most cited sources were used. In order to also cover recent developments, additional articles were picked out with the search scope set to 2018-2022. Different English keywords were used e.g. "wind turbine life cycle","wind turbine energy analysis", "wind turbine recycling". Additional information was gathered from the citations of the used articles and the search engine DuckDuckGo.

The LCAs of wind turbines mainly focus on energy analysis and emission of pollutants. The result of each article is briefly summarized. All results are put together in two tables (energy and emission) for comparison. Other impacts like visual and acoustic pollution, avian collision with birds, insects etc. and pressure waves during offshore installation are not subjects of the LCA. These are also important factors in the whole picture of wind turbines but the coverage of all impacts would be to big for the scope of this short review.

3 Life cycle assessment of different types of wind turbines

To get an idea of the structure of a wind turbine, Fig. 1 shows a wind turbine with coloured main components. Tab. 1 shows the material use per item of the components for the 850 kW and 3 MW wind turbines, used in the Life cycle assessment by Crawford [2]. Tab. 2 shows the total material consumption.

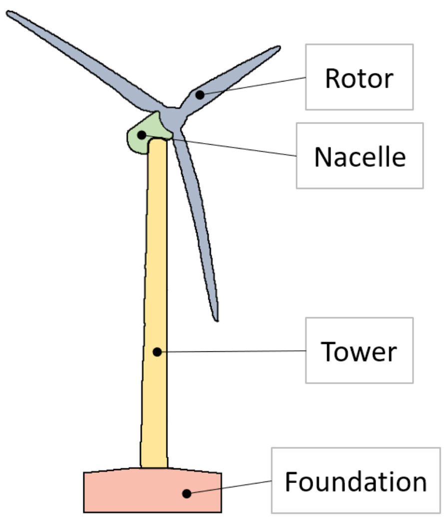

Fig. 1: Main components of a wind turbine (own image)

It is not possible to formulate a precise general statement on the benefits and ecological impact of wind turbines, because life cycle analyses depend on many different factors. First there are different tools and methods to quantify the embodied energy and emitted pollutants associated with provision of materials, transportation, manufacturing, operation, maintenance and disposal. Traditional methods are process analysis and input-output (I-O) analysis. There are also a variety of hybrid methods, combining process and I-O data, which try to minimise the errors and limitations. Errors and limitations mainly result from complex supply chains and difficulties of obtaining necessary information. Every LCA also makes different simplification and assumptions. Therefore some inputs can be incomplete or neglected. A system boundary, as seen in Fig. 2, helps to keep an overview of all in- and outputs. [2]

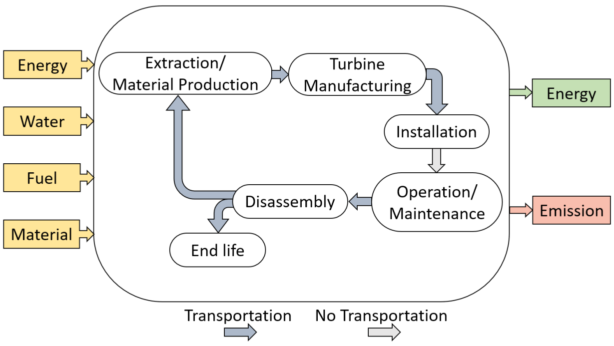

Fig. 2: Example of a System Boundary (own image, modeled after Chipindula et al.[3])

Furthermore the embodied energy and emitted pollutants during manufacturing etc. are affected by the type of wind turbine (on-/offshore), type of generator and wind turbine size [3–5]. The wind turbine size also affects the energy generation and final energy yield [2]. Energy generation and the final energy yield also depend on the conversion efficiency of the generator, wind levels at the specific location and the service life of the wind turbine, which is generally assumed to be 20 years [2–4].
Because LCAs as well as wind turbines are diverse, the results of different LCAs from 2009 to 2019 were compared. The result of each LCA is briefly described in section 4. The specifications of all assessed wind turbines are listed in Tab. 3.
Some authors analysed the energy need for manufacturing etc. and compared it to the energy yield of the wind turbine, while others focused on toxic chemicals and emission during the life cycle of the wind turbine. Therefore the gathered articles can be distinguished in two categories; life cycle energy analysis and ecological impact analysis on humans and the environment. Tab. 4 shows the results for the ecological impact analyses and the results for the life cycle energy analyses are listed in Tab. 5 for comparison.

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Tab. 1: Component breakdown and material use of wind turbines, modeled after LCA by Crawford [2]

		850 kW	3 MW
Component	**Item**	**Materials**	**Materials**
Foundation	Reinforced concrete	480 t concrete	1140 t concrete
		15 t steel	36 t steel
Tower	Painted steel	69.07 t steel	158.76 t steel
		0.93 t paint	1.24 t paint
Nacelle	Bedplate/frame	3.35 t steel	13 t steel
	Cover	2.41 t steel	9.33 t steel
	Generator	1.47 t steel	5.71 steel
		0.37 t copper	1.43 t copper
	Main shaft	4.21 t steel	
	Brake system	0.26 t steel	1.02 t steel
	Hydraulics	0.26 t steel	
	Gearbox	6.08 t steel	23.58 t steel
		0.0062 t copper	0.241 t copper
		0.062 t aluminium	0.241 t aluminium
	Cables	0.18 t aluminium	0.69 t aluminium
		0.24 t copper	0.94 t copper
	Revolving system	1 t steel	3.87 t steel
	Crane	0.26 t steel	1.02 t steel
	Transformer/sensors	0.894 t steel	3.47 t steel
		0.357 t copper	1.38 t copper
		0.357 t aluminium	1.38 t aluminium
		0.18 t plastic	0.7 t plastic
	Total	20.194 t steel	61 t steel
		0.9732 t copper	3.991 t copper
		0.599 t aluminium	2.311 t aluminium
		0.18 t plastic	0.7 t plastic
Rotor	Hub	4.8 t steel	19.2 t steel
	Blades	3.01 t fibre glass	12.04 t fibre glass
		2.01 t epoxy	8.03 t epoxy
	Bolts	0.18 t steel	0.73 t steel

Tab. 2: Total material consumption of the wind turbines in the LCA by Crawford [2]

0.85 MW	**3 MW**
480 t concrete	1140 t concrete
109.24 t steel	275.69 t steel
0,93 t paint	1,24 t paint
0.97 t copper	3.99 t copper
0.60 t aluminium	2.31 t aluminium
0.18 t plastic	0.7 t plastic
3.01 t fibre glass	12.04 t fibre glass
2.01 t epoxy	8.03 t epoxy

The life cycle energy analysis examines all energy flows over the entire life of the wind turbine. The embodied energy generally consists of energy required for the processing of building material, manufacturing, transportation, construction, installation and ongoing maintenance. [2, 6] With the embodied energy and the energy generation the energy payback period (EPP) can be calculated. Alternatively the energy yield ratio (EYR) can be calculated, by dividing the Energy generated over the wind turbines entire life by embodied energy. Contrary to the EPP the EYR takes the entire life of a product into account. Therefore Crawford [2] suggests, that the energy yield ratio offers better information. But many LCAs traditionally use the EPP method. [2]

The ecological impact analysis examines all pollutant emissions and other impacts in the environment and humans over the entire life of the wind turbine (cradle to grave). Traditionally the following stages are taken into consideration:

1. manufacture of each component part
2. transport to the wind farm
3. installation
4. start-up

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5. maintenance
6. final decommissioning and disposal

But every LCA takes different assumptions and simplifications. The impact categories do also vary, but generally follow the Eco-indicator 99 or Impact 2002+ method [7]. The impact is generally presented in Eco-points (Pt). Eco-points are used to normalize data. But some authors give the information in kg pollutant equivalent. Chipindula et al.[3] differentiate between aquatic and terrestrial ecotoxicity and acidification/eutrophication but for simplification the categories are put together in Tab. 4. The Impact categories in this review paper consist of:

- carcinogens
- non-carcinogens
- respiratory inorganics
- respiratory organics
- radiation
- global warming
- ozone layer depletion
- ecotoxicity
- acidification and eutrophication
- land use
- minerals
- fossil fuels

4 LCA results

In this section the results of each LCA is briefly summarized. All results are then compared side by side. Tab. 4 shows the results for the ecological impact analyses and the results for the life cycle energy analyses are listed in Tab. 5 for comparison. Fig. 5 illustrates the EPP of the wind turbines listed in Tab. 5. The specification of the examined wind turbines are listed in Tab. 3.

Crawford (2009) [2] examined what influence the wind turbine size has on the energy yield ratio, since "there is an increasing trend towards larger scale wind turbines"[2]. Therefore the EYR of a 850 kW and a 3 MW wind turbine are compared. For an expected service life of 20 years the EYR is 21 for the 850 kW and 23 for the 3MW wind turbine. So after 20 years the turbines have generated 21 and 23 times more energy, than needed for manufacturing etc. The EYRs increase to 32 and 35 for an expected service life of 30 years. So the benefits increase with increasing service life. The larger 3 MW wind turbine shows an 11% higher EYR, which is not considered to be significant. Because the EYR method was used, the energy payback period is estimated in Tab. 5 to allow comparison to other LCAs.

Martínez et al. (2009) [6] examined which component of the wind turbine has the biggest environmental impact. ISO 14040 and Eco-indicator 99 methods are used. The foundation affects the environment the most, especially in the respiratory inorganics category, due to the cement manufacture. So it is important to find ways to reduce air emissions of particle matter, SO_2 and NO_X. The steel of the tower can almost completely be recycled. The nacelle is the most complex component and consists of many different materials, of which copper has the biggest impact. Although it is recyclable, it would be an improvement to replace it with another material with similar characteristics without reducing the generator efficiency. The energy analysis of the same turbine was published in a different article, which results in an EPP of 0.58 years and an EYR of 34.36 [9].

Chipindula et al. (2018) [3] examined the ecological impact of three hypothetical wind farms. Onshore with capacites of 1 MW, 2 MW and 2.3 MW, offshore in shallow water with 2 MW and 2.3 MW and offshore in deep water with 2.3 MW and 5 MW. The material extraction/processing is the critical stage responsible for 72 % contribution of impact onshore, 58 % in shallow water and 82 % in deep water. The recycling of steel could lower the average impact across all impact categories by 20 %. The EPP and CO_2PP in Tab. 5 are estimated from bar charts.

Schreiber et al. (2019) [5] evaluated the environmental impact of three 3 MW wind turbines with different generator at a fictive onshore site in Germany. The three generator types are:

- geared converter with doubly-fed induction generator (DFIG)
- direct driven synchronous generator (DDSG) electrically excited
- direct drive permanent magnet synchronous generator (DDPMSG)

The DDSG nacelle weight is one third greater then that of the DFIG and more than two thirds greater than that of the DDPMSG. Due to the massive construction, the DDSG shows the highest impact in 14 out of 15 impact categories. Construction materials are the significant source of impact. The DDPMSG is lighter than the other wind turbine types and therefore requires less steel and cement. The permanent magnet production on the other hand requires rare earths and despite of its weight (1.9 t) accounts for approx. 43 % of the overall impacts compared to 108 t steel, stainless steel and copper with an accumulated share of approx. 52 %.

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Tab. 3: Specification of all considered wind turbines, information from [2–6, 8]

WT	LCA Source	Power in MW	On-/ Off-shore	Generator Specification	Location
1	Crawford(2009) [2]	0.85	on	-	Australia
2	Crawford(2009) [2]	3	on	-	Australia
3	Martínez et al.(2009) [6, 9]	2	on	DFIG	Spain
4	Guezuraga et al.(2012) [4]	1.8	-	not-geared	Austria*
5	Guezuraga et al.(2012) [4]	2	-	geared	Austria*
6	Chipindula et al.(2018) [3]	1	on	-	Texas, USA
7	Chipindula et al.(2018) [3]	2	on	-	Texas, USA
8	Chipindula et al.(2018) [3]	2.3	on	-	Texas, USA
9	Chipindula et al.(2018) [3]	2	off/ shallow	-	Texas, USA
10	Chipindula et al.(2018) [3]	2.3	off/ shallow	-	Texas, USA
11	Chipindula et al.(2018) [3]	2.3	off/ deep	-	Texas, USA
12	Chipindula et al.(2018) [3]	5	off/ deep	-	Texas, USA
13	Schreiber et al.(2019) [5]	3	on	DFIG	Germany
14	Schreiber et al.(2019) [5]	3	on	DDSG	Germany
15	Schreiber et al.(2019) [5]	3	on	DDPMSG	Germany
16	Piasecka et al.(2019) [8]	2	on	-	Poland*
17	Piasecka et al.(2019) [8]	2	off	-	Poland*

DFIG: Doubly-fed induction generator; DDSG: Direct driven synchronous generator; DDPMSG: Direct drive permanent magnet synchronous generator; * if wind turbine location is not specified, the authors location is assumed

Tab. 4: Environmental impact results for different wind turbines, information from [3, 6, 8]
black: normalized data in eco-points (pt)
blue: unnormalized data in given unit

WT	C	NC	RI	RO	R	GW	OZ	ET	A/E	LU	M	FF
	Pt	Pt	Pt	Pt	Pt	Pt	Pt	Pt	Pt	Pt	Pt	Pt
3	322	-	28041	29	16	2350	7	3156	2117	2951	46	26902
16	7000*	-	31528	-	<1000*	9138	<1000*	9860	3000*	1500*	12208	58004
17	8000*	-	24846	-	<1000*	9875	<1000*	10297	2000*	1500*	11996	41713
	kg C_2H_3Cl eq.	kg C_2H_3Cl eq.	kg $PM_{2.5}$ eq.	kg C_2H_4 eq.	bq C14 eq.	kg CO_2 eq.	kg CFC11 eq.	kg TEG	kg SO_2 eq. + PO_2H_4 P-lim	m^2 organic arable land	MJ	MJ
6-8	30	23	9×10^{-1}	2×10^{-1}	4663	440	5×10^{-5}	67827	12	7	223	6578
9,10	90	59	3	8×10^{-1}	10197	1144	10×10^{-5}	245510	32	21	590	16115
11,12	80	63	2	3×10^{-1}	8838	648	10×10^{-5}	247781	27	15	702	10930

WT = Wind Turbine; C = carcinogens; NC = non-carcinogens; RI = respiratory inorganics; RO = respiratory organics; R = Radiation; GW = global warming; OZ = ozone layer depletion; ET = ecotoxicity; A/E = acidification and eutrophication; LU = land use; M = minerals; FF = fossil fuels; *estimated from diagram

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Guezuraga et al. (2012) [4] compared the life cycle of a geared 2 MW wind turbine to a non-geared 1.8 MW wind turbine. The environmental impacts per kWh electricity delivered of the wind turbines are very similar. Because the geared 2 MW wind turbine has a higher initial energy need but also generates more energy. The energy payback period is 0.52 years for the geared 2 MW wind turbine and 0.58 years for the 1.8 MW wind turbine. Furthermore a comparison is made between wind energy and other sources of energy:

- Photovoltaic plants - amorphus, monocrystalline and polycrystalline silicon
- Hydropower plant
- Nuclear power plant (pressurized water reactor, auxiliary electricity required from diesel system, enriched uranium as fuel input)
- Gas cogeneration plant (large scale gas fired combined cycle cogeneration plant, low NOx burner fed with natural gas, credit allocated from cogeneration heat from combined heat and power plants (CHP) replaces gas heating)
- Coal power plant (hard coal as fuel)

Fig. 3 shows the CO_2 equivalent emissions per kWh produced energy. The energy payback period of the different energy sources can be seen in Fig. 4. Wind and hydro power turn out to be the cleanest energy sources.

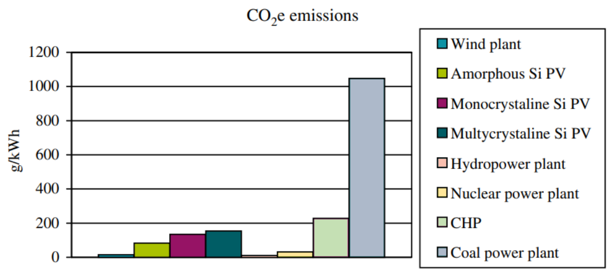

Fig. 3: CO_2e emissions/ kWh for different energy sources [4]

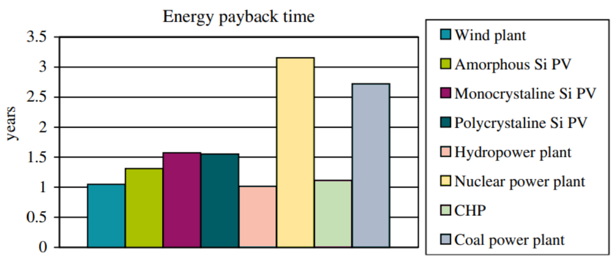

Fig. 4: Energy payback period for different energy sources [4]

Piasecka et al. (2019) [8] compared the ecological impacts of a 2 MW offshore wind turbine to a 2 MW onshore wind turbine. The onshore wind turbine has a bigger accumulated impact (125147 Pt) than the offshore wind turbine (109075 Pt). The processes connected with fossil fuel extraction (FF in Tab. 4) and emission of compounds causing respiratory diseases (RI in Tab. 4) have the largest influence.

Tab. 4 and Fig. 5 show that onshore wind turbines have a higher impact due to emission but a shorter EPP. Furthermore turbines with higher power have usually a shorter EPP. It can be seen from the course of the 2 MW turbine in Fig. 5 that the efficiency of wind turbines stayed the same since 2009 with an EPP of approx. 7 months for onshore 2 MW wind turbines. The high EPP for the 0.85 MW and the 3MW wind turbine in 2009 can be explained by the fact that the values were only estimated using the EYR.

Tab. 5: Energy payback period and CO_2 paypack period results for different wind turbines, information from [2–5, 8, 9]

Wind Turbine	EYR	EPP in months	CO_2PP
1	21.0	11.4*	-
2	23.0	10.4*	-
3	34.36	7.0	-
4	-	6.2	-
5	-	7.0	-
6	-	15.5**	7.0**
7	-	7.5**	6.3**
8	-	6.2**	5.8**
9	-	16.7**	14.0**
10	-	13.0**	10.8**
11	-	11.0	8.7**
12	-	9.6	7.2*

*estimated, **estimated from graph

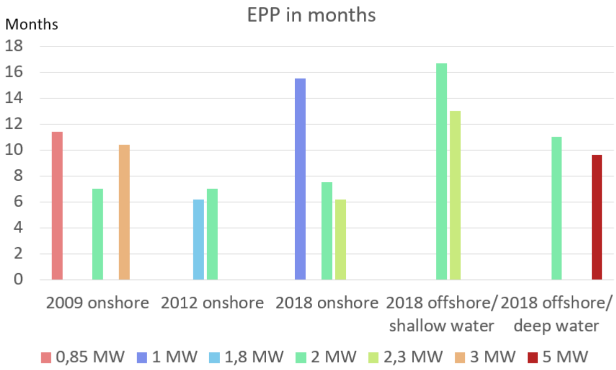

Fig. 5: Energy payback period for different wind turbines (own image, information from [2–5, 8, 9])

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5 Recycling

The recycling of wind turbine components and material has a significant impact on the LCA. As stated in section 3, the recycling of steel could lower the average impact across all impact categories by 20 % [3]. Guezuraga et al. (2012) [4] state that "80 % of a wind turbine system (including cables) can be recycled, except the blades which are made of composite materials and the foundation which is made of concrete" [4].
The turbine blades are difficult to recycle because they are made out of resin and glass fibre reinforced plastic (GRP). Possible recycling methods for the problematic turbine blades include the following [10]:

- mechanical shredding and separation into resin and fibrous products
- pyrolysis at 450°C-700°C: polymeric resin vaporizes while fibres remain inert and can be recovert
- oxidation in fluidised bed at 450°C-550°C: Combustion of the composite material in hot air flow to separate resin and fibres
- chemical: resin decomposes in chemical solution into oils, while fibres stay intact

GRP can be shredded and burned in cement kilns as the glass reinforcement and mineral fillers used in composites contain minerals that can be incorporated in cement [11]. This method is available in Germany since 2011 [12]. Zajons Zerkleinerungs GmbH provided shredded GRP to Holcim AGs cement kilns in Lägerdorf. But Zajons Zerkleinerungs GmbH has become insolvent in 2015 [13]. Another German Company recycling GRP is Neocomp in Bremen, which now provides Holcim [14]. Only a few other Companies worldwide are dealing with the recycling of GRP e.g. Eco-Wolf and Global Fiberglass Solutions [12].

Nagle et al. (2020) [15] examined the recycling possibilities of Irish wind turbine blades. It was found out that transportation and co-processing in a German cement kiln is six times better (for the environment) than depositing the blades in an Irish landfill. The theoretical co-processing in Ireland at a 10 % substitution rate would be 1007 % better than landfilling in Ireland and 78 % better than transportation and co-processing in Germany [15].
Jensen [16] examined a potential recycling of a 60 MW wind farm in Denmark. A 100 % recycling rate would lead to energy savings of approximately 81 TJ and emission reduction of 7351 t CO_2. To put the numbers in perspective, 81 TJ is the equivalent of the annual energy consumption of approximately 14400 persons in Denmark. 7351 t CO_2 savings equal around 52.5 million km of car driving, assuming an average emission of 0.17 kg CO_2/km. [16]

So it is worthwhile to further investigate recycling options, as it is beneficial for the environment and also profitable to save material and energy during production.

6 Conclusion

The various life cycle assessments are not always easy to compare due to different assumptions and used methods. Visual and acoustic pollution as well as avian collision with birds, insects etc. and pressure waves during offshore installation are not taken into account in LCAs. With the rising development of wind energy these aspects are also important to investigate. But overall the LCAs show that the energy payback period for wind turbines is approx. 6-16 months. The EPP for 2 MW onshore wind turbines remained roughly the same since 2009 with approx. 7 months. The CO_2 payback period is approx. 6-14 month. So after 6-16 months wind turbines compensate the embodied energy and their negative impacts on the environment and produce clean energy. The service life is important for the total energy yield. With an estimated service life of 20 years and an energy payback period of 12 months a wind turbine produces 20 times more energy than required for manufacturing etc. Chipindula et al. [3] show that wind and hydro power are the cleanest energy sources. The LCA of wind turbines would even be better, if energy required in material processing and manufacturing would be regenerative energy or if the process of material provision e.g. steel production would be more efficient. Recycling is also an important factor. Most of the materials can already be recycled but the blades and the foundation are still a problem. Another solution for the problematic blades would be to examine if other materials than resin and GRP are suitable for wind turbine blade manufacturing. So further investigations in recycling methods and material processing are important to improve the already good eco-balance.

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Current systems and potential areas for tidal power plants - A review

Using the example of the United Kingdom

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Abstract

This review is about where and which tidal power systems are currently deployed. It starts with an insight into the variety of different tidal power systems. With the help of a list from the European Marine Energy Center about currently used systems for tidal power plants, it quickly becomes apparent that two systems stand out. These are the vertical and horizontal turbines. The latter are particularly common, as they are used for both tidal stream and tidal range power plants. Determining the regions with high potential for tidal power is not always easy due to the many influencing factors. Influencing factors are, for example form and conditions of the seabed, topographical features of the coast or currents in the sea [1]. Therefore, each region must be considered separately. n this paper the focus is on the UK, the literature shows that the coastal regions around the UK provide about 50 TWh/year of the European tidal power potential. This is due to the location between the oceans and the geological conditions, which act as a channel for the tides. The two areas with high potential where planning and construction of tidal power plants is currently underway are in the north of Scotland and in the southwest of England in the Bristol Channel.

Keywords: renewable energy, tidal range, tidal current, ocean energy, potential areas

1 Introduction

The importance of renewable energies is increasing, especially in recent years and months. So far, wind power and photovoltaic plants are very often erected, which generate electricity from renewable sources. With these two methods, electricity generation is difficult to predict and is highly volatile [2]. Until now, fossil fuels in the power industry have compensated for the planning difficulties and volatility of renewable energy. However, the use of fossil fuels is to be reduced to an absolute minimum in the future. There are various ways to compensate the planning uncertainty and volatility of wind and photovoltaic plants. Examples are electricity storage or the production of hydrogen. These two methods can be used in case of overproduction of electricity, which mainly absorbs the volatility and increases the planning reliability to a certain extent. Another method is the production of electricity from tidal power. Tidal power has very high predictability and low volatility in electricity generation [3]. Therefore, a large portion of the base load in the power grid can be covered by tidal power. This paper first gives a general insight into the different tidal power systems, from which the two application types tidal current and tidal range emerge as the currently most effective and widespread methods. This is followed by an insight into the potential of tidal power in the world. The UK has about 48 % of the potential for tidal power in Europe, with an estimated 50 TWh/y [4]. The focus of this paper is therefore on the region around the UK. At the end, the insights gained are brought together while practical examples of tidal stream and tidal power plants are briefly presented.

2 System variants categorize and emergence of tides

2.1 Appearance of the tides

In any large sea, the water level regularly rises and falls. This phenomenon is called tides. This course is divided into two processes low tide and high tide. The latter describes the process of rising water level. No seashore is free of ebb and flow, but the manifestations of the two processes are sometimes very weak and not noticeable.[5]
The cause of high and low tide lies in the interaction of the gravitational pull of the Earth and the Moon. The water on the Earth is attracted by the Moon, and some of the water flows towards the Moon. Due to the rotation of the two masses in relation to each

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other, additional centrifugal forces occur, which ensure that water also flows towards the opposite sphere of the Earth. This increases the water level at two opposite points on the globe. The sun also has an effect on the tides with its gravitational pull, but the sun's influence is much less than that of the moon.[5]
The influence becomes particularly clear after full and new moon, since the tidal range can assume highest values. The centrifugal forces are in equilibrium, but they are not equally strong at all points on the earth's surface, two elevated water heights opposite each other on the earth's sphere are formed due to the centrifugal force. Due to the rotation of the earth and the standing water elevations, low tide and high tide arise. [5]

2.2 Overview of tidal power plants

At the beginning, the difference between tidal stream and tidal range power plants is pointed out. In addition, there are turbine systems and non-turbine systems. A list of common examples of the two types of systems is presented in Tab. 1. With this table, the variety of different applications of tidal energy can be seen. In case of tidal current, the energy is usually drawn from the moving fluid via rotor blades. As with wind turbines, the turbines in tidal stream power plants have rotor blades with an airfoil cross-section which operate according to the principle of aerodynamic lift [6]. Tidal range power plants use the height difference between high and low tide to generate energy. The water is dammed up in a basin before it is released over turbines [7].
The following list by M.J. Khan [3] shows interconnected concepts for the use of tidal power. These concepts are divided into two classes (turbines/non-turbines). This list gives an impression of the different possibilities to use tidal power. For a more detailed explanation see M.J. Khan [3].

Tab. 1: Possible systems for the use of tidal power [3]

Turbine Systems	Non-Turbine-Systems
Axial (Horizontal)	Flutter Vane
Vertical	Piezoelectric
Cross-flow	Vortex induced vibration
Venturi	Oscillating hydrofoil
Gravitational vortex	Sails (Tidal Kite)

We cannot consider all types of tidal power plants in this paper. For this reason, the focus is placed on the systems that are most frequently encountered in practice. To identify these systems, a list of the European Marine Energy Center (EMEC) [8] is used. EMEC is a facility where different tidal projects are

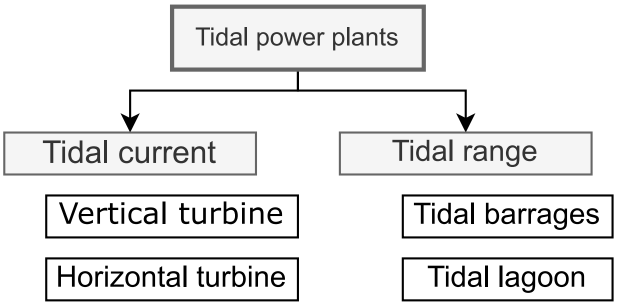

Fig. 1: Overview of the considered tidal power systems in this review, own image

listed with project specific data, giving an overview of the systems currently in use. An overview of the tidal power plants considered in more detail in this paper is developed in Section 3.1.

3 Superior tidal power systems and potential areas

3.1 Considered tidal power plant systems

As mentioned, the list of tidal power plants under consideration is now being developed. For further consideration it is important that the systems have left the status „proof-of-concept“and are used in first full scale projects. The list from EMEC includes 97 systems from real projects, and there are two systems that are particularly common. These are the systems with a horizontal turbine (43 out of 97) and the systems with a vertical turbine (16 out of 97) [8]. These two turbine systems are used especially for tidal currents. In the case of tidal range power plants, horizontal turbines are often installed in the dams [7]. Figure 1 illustrates the systems considered in more detail in this paper. It is pointed out that this figure is not complete. Likewise, if the criteria remain the same, the content may change in the future.
A short explanation of each system is given, for more detailed explanations, the following sources are recommended [3, 7].
Tidal current:

- Vertical turbine: The axis of rotation of the rotor is perpendicular to the water surface and also orthogonal to the incoming water stream. Lift or drag rotor blades are used [9].
- Horizontal turbine: Rotating axis is parallel to the incoming water stream. Also employing lift or drag type blades [3].

Tidal range:

- Tidal barrages: These are structures built around bays or estuaries. With the surrounding

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land a basin is formed, in which water can be dammed up [7].

- Tidal lagoon: A tidal lagoon consists of completely man-made basins in whose walls the turbines are built [7].

In the Fig. 2, the two turbine systems, vertical and horizontal, are illustrated schematically. The basic difference lies in the flow of water through the turbine respectively the orientation of the rotational axis of the rotors.
The generator of the vertical turbine is usually above the water surface and the turbine is connected to a floating body or to the shore [7]. In the horizontal turbine, all components are often below the water surface. There are also designs where the generator is above the water surface and the rotors are placed horizontally below the water surface [3].
Similar to wind power, only a certain amount of kinetic energy can be extracted from a moving fluid [6]. In order to exploit the potential of tidal power, large series of tidal turbines have to be erected in many cases. For a large tidal power plant, it is important to know and evaluate the existing tidal current in advance [10]. Areas with high potential for tidal power plants are discussed in more detail in the following section.
Each tidal power plant has its own tidal currents, which means that the design and construction of the turbines must be adapted. As a result, the manufacturing costs for tidal power plants increase, which is why a high yield is important for the economic operation of a plant [10]. For this reason, areas with a naturally high potential for tidal power are currently being selected for the construction of power plants. The next section presents areas with high potential for tidal power.

3.2 Areas with potential for tidal power

It is difficult to determine the tidal current velocities at different locations in the world using a general approach. The reason for this is the strong dependence of the current velocity on the local topography. Constrictions of a tidal channel or of a headland are usually strong influencing factors for high current velocities.[11]
However, there are basic principles on which the highest current velocities are based. As explained earlier, tidal waves are a reaction of the gravitational balance between the earth and the moon. At the University of Hull, Jack Hardisty and his team have conducted an analysis of the tidal current force. Eight regions with potentially high tidal currents were identified [11]. These eight regions are listed in Tab. 2.

Tab. 2: Regions with potentially high tidal currents [11]

Potential Regions for Tidal power in the World
North America and Canada
Barents Sea
South America
East Africa
West India
Australia
China Sea and Japan
North-West-Europe

In the region in northwest Europe, the areas in northwest France and around the United Kingdom (UK) in particular provide a great potential [11]. In this paper we will focus on the area around the UK.
The ABP Marine Environment Research Ltd. has identified 12 areas around the UK with high potential for tidal stream power [1]. These areas are listed in Tab 3.

Tab. 3: High potential areas for Tidal stream around UK [1]

Potential areas for tidal power around the UK	
A	Orkney Islands
B	Pentland Firth
C	Humber
D	Norfolk
E	Dover
F	Isle of Wight
G	Portland
H	Channel Islands
I	Severn Estuary
J	Anglesey
K	Isle of Man
L	North Channel

The Fig. 3 illustrates the areas with high potential for tidal power around UK mentioned in Table 3. Studies were carried out by Hardisty et all [11] for tidal power plants on the British coast. For shallow water tidal range power, two sites were identified:

- Pembrokeshire (1.4 km^2 and 110 MW)
- Bristol Channel (10 km^2 and 800 MW)

Similarly, three deepwater sites were identified:

- Angelesey (176 km^2 and 14 080 MW)
- Pembrokeshire (0.6 km^2 and 40 MW)
- Bristol Channel (8 km^2 and 640 MW)

4 Conclusion

Now we combine the findings from the previous sections. From the Table 3 and Figure 3, respectively,

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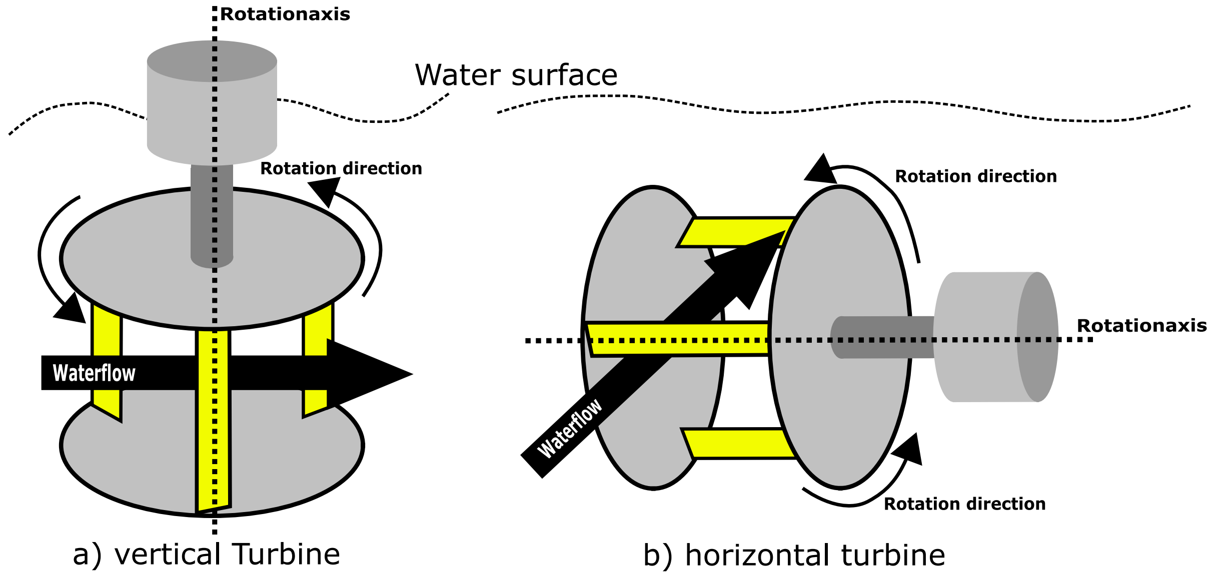

Fig. 2: Schematic drawing of vertical and horizontal turbine, inspired by [3, 7]

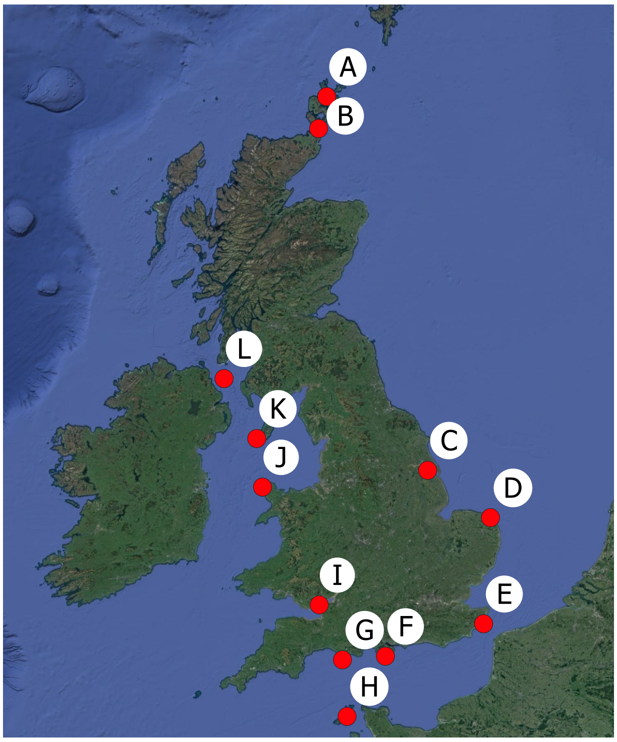

Fig. 3: Map of areas with high potential for tidal power plants around UK

it can be seen that the areas with high potential for tidal currents are distributed quite evenly, especially in the south (English Channel), and west of UK. Two potential areas are located in the north of Scotland. The coasts to the south and west act as a channel that increases the tidal current velocity [11]. The same applies to the Orkney Islands area in the north of Scotland. These naturally occurring channels make these areas particularly suitable. In the English Channel, however, the installation of a tidal power plant would be more difficult because there is a lot of shipping traffic.

With this knowledge and the findings of the EMEC [8] list, it can be said that it is appropriate to install the first tidal power plants in the west of the UK and in a smaller area in the north of Scotland. The high potential of the tidal stream makes it easier to establish economic viability. At the same time, experience can be gained for the technology of tidal power plants and thus a cost reduction of the technology can be expected.

The same applies to tidal range power plants. Here, especially bays that can be used as a natural dam to keep the construction cost low. The Bristol Channel is often mentioned as a bay with high potential for a tidal range power plant. [7, 11, 12]. There are also opportunities along the Scottish east coast for tidal range power generation with significant 24-hour power output [4].

5 Practice examples and Outlook

Tidal power has gained more attention in recent years. Accordingly, the technical systems have been further developed and are increasingly being operated economically on an industrial scale. Large tidal power plants are needed to make the most efficient use of the high potential worldwide. However, smaller plants also contribute to gaining experience for the technology of tidal power plants and thus to reducing the construction costs. For the most profitable operation, regions with high potential are preferred. Around the UK, these are particularly the areas in the north of Scotland and in the east and west of England, where the largest bays are located. There is also high po-

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tential in the English Channel, but here it would be more difficult to build a tidal power plant because there is a lot of shipping traffic. In general, it can be said that high potentials for tidal power can be found where coasts serve as channels and thus increase the potential for tidal power. In order to extract the kinetic energy from the moving fluid, mainly vertical and horizontal turbines are currently used, similar to wind turbines.
Two practical examples of tidal power plants in the UK are presented. One is a tidal stream power plant in the north of Scotland and the other is a tidal range power plant in the Bristol Channel.
Example No. 1 (tidal stream) - MeyGen project: This is a tidal stream project on the Inner Sound in the Pentland Firth, Scotland, which is expected to have a final output of around 398 MW [13]. It is the largest fully permitted tidal stream project in Europe and is considered a flagship project for the industry. In this project, horizontal turbines were installed on the seabed [13].
Example No. 2 (tidal range) - Bristol Channel: The actual project is called Swansea Bay Lagoon. There are other good positions for several tidal power plants in the Bristol Channel bay. Swansea Bay Lagoon is the first project of its kind in the world, and will eventually have a capacity of about 240 MW [14]. The area covered by the lagoon is about 11.5 km^2, for which a wall about 9.5 km long will be built an average of 3.5 m above the water level [7].
In this work, there are points that have not yet been sufficiently covered, such as optimization through smoother surfaces of the wings to reduce marine fouling or possibilities to increase the kinetic potential by increasing the height difference. As can be seen, there are many more possibilities for further investigations.

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Open-Power System Modelling

A Review of Existing Methods and Models

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Abstract

This review paper presents a short overview of current power system modelling tools especially used for analysing energy and electricity systems for the supply and demand sector. The main focus of this review lies on open source tools and models which are written and used in the programming language "Python". The modelling tools are represented in a comprehensive table with key information. Five modelling tools with an open source license can be filtered out. The modelling tool PyPSA can be considered as a high performing tool especially as the gap between power system analysis tool (PSAT) and energy system modelling tool.

Keywords: energy system modelling, grid modelling, power system modelling, open source, renewable energy

Abbreviations

ESM	energy system modelling
GHG	greenhouse gas
LP	linear programming
MILP	mixed integer programming
OPSM	open power system modelling
PSAT	power system analysis tool
RES	renewable energy sources
VRES	variable renewable energy sources

1 Introduction

The European Climate Law as part of the European Green Deal leads the path to climate neutrality by 2050. A central target is the reduction of greenhouse gas (GHG) emissions of at least 55 % until 2030 compared to 1990 levels [1]. The electricity generation from renewable energy sources (RES) is increasing in Europe, driven by ambitious targets for emission reductions set by the European Commission (EC). The EU also states that all sectors have to contribute to this reduction, but the sector with the highest potential for cutting emissions is the power sector [2]. Through increasing the share of zero-emitting RES in the electricity mix, the power sector can almost totally eliminate its emissions by 2050 [2, 3]. Energy system models can give a deep inside how our energy system can evolve. But how should we deal with that rising amount of electricity. Due to the fact that energy models were mostly proprietary and closed to the community, the interest in energy system modelling as an open source approach has renewed. There has been an increase in developing several open source tools to give new insights for these challenges and answer present questions [4]. Therefore, the aim of this research is to give an overview of current existing power modelling tools with an open source license including a specific scope for power system analysis. Furthermore, the filtered tools are shortly presented and additional information for further research is given.

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2 Review Method and Methodology

The contents of this short review were acquired through a literature research using search engines like *Google* and *Google Scholar*. The search for further literature has been expanded onto the library of the University of Applied Sciences Muenster using the search engine *FINDEX*. The main focus was to get a broad overview on review papers. After finding relevant reviews with suitable models, the research is extended by looking for additional information to define the concept of energy system modelling (ESM) in more detail. To describe the examined software in more detail e.g., websites, documentation of models is included in this research. For the research different English keywords where used e.g., *energy system modelling, open source, power system analysis tools, grid modelling.*

The energy modelling area is vast and complex. The most interesting models for this kind of research are those that consider the electricity aspect of the grid, especially for the distribution area and the interaction between the energy and power system. For this reason, models that do not meet these criteria are

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excluded. The models should have at least a purpose to analyze the power system by interacting with large shares of RES. Hereby it must be mentioned that this review does not explicitly distinguish between models or modelling tools. Some models can also be declared as frameworks[1] or tools, due to the fact that there is no data already available. However, with input data, equations and constraints a specific model can be built [3].

Given the large amount of information and publications in this area, it was not possible to cover all the information in this article. The focus lies on selected review articles. Table 1 below lists the primary articles that have already made a contribution to this topic. Other information or further models, which are not based on the main source have nevertheless a justification and are not considered only due to the scope of this work. Furthermore, other sources were consulted to cover the periphery of the paper and to provide additional information on the topic.

Tab. 1: Relevant recent reviews of energy system modelling.

Publication	Coverage
Klemm and Vennemann [5]	Modeling and optimization of MES (145 models reviewed)
Ringkjøb et al. [3]	Overview of modelling tools for energy and electricity systems (75 models)
Foley et al. [6]	Overview of electric systems models
Hall et al. [7]	Classification of 22 models (22 models)
Groissböck [4]	Open source models (31 models compared)

3 Classification of Energy System Models

According to Hiremath et al. “Energy models are, like other models, simplified representations of real systems.” [8]. Therefore ESM are handy and useful to describe, optimize or even predict the assumptions by the user for the current problem. Ringkjøb et al. [3] and Klemm and Vennemann [5] give a broad overview of existing tools and categorize every model by their characteristics. They describe general characteristics, which every model has in common according to their general logic, spatiotemporal resolution and technological/economic parameters. According to the structure of Després et al. [9] and the model selection of Ringkjøb et al. [3] the reader can choose the right model by the certain criteria. In the following, these criteria are described and the process is shown in figure 1. Furthermore, this flow chart is used to expose the criteria highlighted in the table 2 and identify the appropriate tool.

3.1 General Logic

After defining the problem statement, the reader can specify the right model by choosing the needed logic. This logic is divided into *purpose*, *approach* and *methodology* [3].

3.1.1 Purpose

Models can be categorized into four areas of application:

- **Power System Analysis Tool**: This is for the purpose to study power with high degree of detail at short scale.
- **Operation Decision Support**: For optimization of operation/dispatch in the energy/electricity at large scale.
- **Investment Decision Support**: Optimization of investment in the energy/electricity system on long-term.
- **Scenario**: Investigation of future long term scenarios and for the evaluation of several policies.

3.1.2 Approach

There are three possible approaches:

- **top-down**: It is suited for economic approach, considering macroeconomic connections and long-term changes.
- **bottom-up**: It is based on detailed technological descriptions of the energy system.
- **hybrid**: Combined approach of top-down and bottom-up method when estimating the integration variable renewable energy sources (VRES).

3.1.3 Methodology

The methodologies of all energy models can be classified into three main categories:

Simulation models: Simulation or moreover forecasting of an energy system is based on specified equations and characteristics. In most cases they follow the bottom-up approach and are best suited for testing of different topologies and investigating the impacts of these scenarios. The **Agent-based simulation** is more of a specific simulation case with

[1] Frameworks include a runtime environment, libraries and a number of other components to provide the optimal basic structure

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actors (agents) included.
Optimization models: Optimization of an existing quantity of energy. Most of these models use **linear programming** (LP) as the mathematical approach where an objective function either minimized or maximized e.g., minimizing the total system cost by a set of constraints balancing the supply and demand in the grid. **Mixed-integer linear programming** (MILP) allows giving an integer value as the result of how many power plants the user should invest. **Stochastic programming** and **Artificial intelligence** are also relevant mathematical approaches in this area, but not further discussed.
Equilibrium models: These models can represent the energy sector as a part of the whole economy and their relation to it. Therefore, they serve as an evaluation of the impact of various policies on the whole economy.

3.1.4 Spatiotemporal Resolution

The spatiotemporal resolution is particularly crucial for choosing the right model and it's application. Especially, in a system with a large share of VRES it is quite important to capture the variability of solar and wind resources. The temporal resolution can vary from milliseconds to several years or decades. Also, the geographical resolution can vary from a single building or project to modeling the energy system of the whole world.

3.1.5 Technological and Economic Parameters

According to Ringkjøb et al. [3] "Measures such as grid development, energy storage and demand side management have been identified as some of the key contributors for successfully building an energy system containing large shares of VRES." Therefore, he categorized model components and properties:

Conventional Generation: Modelling each power plant individually or by combining all plants of the same technology in the region.
Renewable Generation: Renewable generation (except geothermal and tidal) is related to meteorological conditions. Due to this fact, these conditions can be modelled by meteorological data e.g., wind speed for this region by stochastic methods.
Energy Storage: Due to the variable and volatile renewable generation and the inconsistency with the demand side, energy storages are necessary. As the locations for pumped hydropower storage are limited, solutions like hydrogen, batteries or compressed-air energy become much more important. [3]
Grid: PSAT can model a detailed overview of power systems, including power flows (e.g., linear or non-linear), short-circuit calculation, detailed modelling of distribution grids.
Commodities: Many models come with a specific focus on one commodity e.g., electricity (power sector), some of them can cover multiple commodities at the same time (sector coupling) e.g., heat, electricity and hydrogen.
Demand Sector: This is where the end-user is addressed. It can be split up into the building (commercial/residential), industry (agriculture included), transport sector.
Demand Elasticity: The demand elasticity can forecast how consumption may decrease when the price of e.g., electricity increases.
Demand Side Management: Demand side management addresses the consumer (end-user) side of the energy system. Aspects like energy efficiency, energy conversion and demand response can be measured. DR is a measure for shifting certain loads when the demand is higher than the supply [10].
Costs: Costs are important for the modelling results, but very difficult to model accurately.
Market: Most models balance the supply and demand under perfect market conditions. Some models can treat the spot market (merit-order), the reserve or even the balancing market.
Emissions: Some models can represent GHG as a side product of generation e.g., CO_2, NO_x etc.. Other models treat GHG emissions as CO_2 equivalents.

3.2 Power System Modelling

Energy and power system tools are applied to model the impacts of increasing shares of variable generation at various levels of detail. Therefore long-term energy system models can analyze the evolution of the energy system on a temporal resolution over several years and include non-electricity demand sectors e.g., heat or transportation. The investment decisions e.g., monetary or reduction of emissions and policy recommendations derived from such models may serve as input for a more detailed analysis of electricity markets based on power system models. Commonly, power system models focus exclusively on electricity and the power sector, but can also include sector coupling. They model on shorter time horizons up until several years and are more detailed. On the basis of their calculations, power system models may analyze the implications of increasing shares of renewables on the grid (e.g., by assessing the resulting load flows or potential faults) [11].

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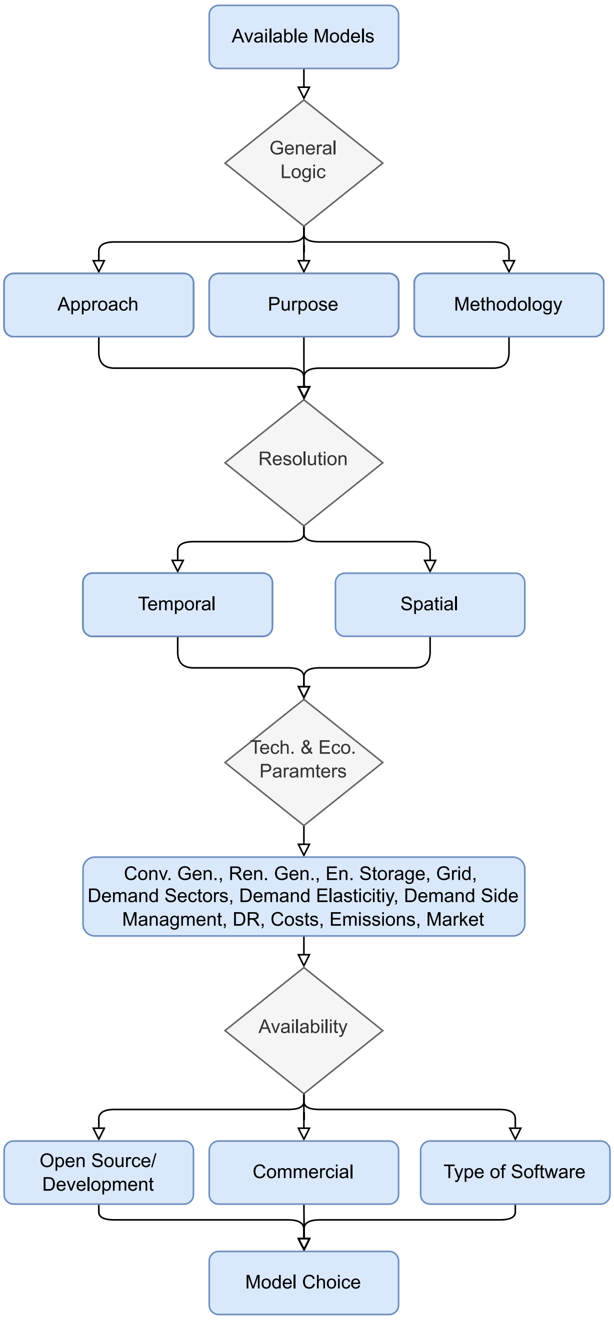

Fig. 1: Classification for model choice, adapted from Ringkjøb et al. [3]

4 Results and Filtered Models

During this research a total of five PSAT have revealed. All of them have a purpose for the analysis of the current power system. Spatialtemporal resolution and technological/economic parameters are spreaded. Also the criteria of availability e.g., programming language, open source/commercial and current development can differ. Due to this fact, a filter is applied over the mentioned criteria to highlight a few modelling tools for this area of application, following the logic of figure 1. Foremost, the model should have at least a purpose for analyzing the power system. The resolution should be at least one hour or less and for the geographical area user-defined. For the technological/economic parameters it should contain the component for considering the grid. Lastly, the availability should contain the criteria for an open source licence and should be written in the programming language "Python". After applying these filters, 16 models can be classified as PSAT. Five out of 16 models are coming with an open source licence. In table 2 are the filtered models shown. If the programming language aspect with "Python" is taken into account, **PyPSA** and **RAPSim** are the final models for this review.

5 Discussion and Conclusion

To answer the question of which is declared in the introduction, five of the reviewed existing modelling tools can be classified as power system modelling tools which has at least a purpose to analyze the electricity grid and are coming with an open source licence. The scope of this review is not a comparison or a benchmark of these tools, it rather is a selection.

Another important point in using open source is the performance of these tools. There are existing reviews for the comparison of several open source tools which are also based on Python where PyPSA is also included. Groissböck [4] compared several open source tools for energy system modelling with commercial closed source energy modelling under targeted functionality. PyPSA can be considered as a high performing tool for short-time planning and small-time steps. It can be used as a gap between load flow analysis software and energy system modelling software and has good grid modeling properties which is quite important for the integration of renewables and possible electrification of the transport and heat sector [4, 17].

In comparison to pandapower, PyPSA has more features for the economic analysis e.g., sector coupling. Pandapower provides non-linear operational power flow, short circuit calculations, state estimation, modelling of switches and three-winding transformers which is currently missing in PyPSA. [17, 18].

6 Outlook and Future Work

Several critics address that public policy energy models are insufficiently transparent. If not explicitly published, the source code and data sets should be available for peer review. This should be done to improve transparency and public acceptance. The quality of data is crucial for the electricity and energy system modelling. To overcome these challenges many models are undertaken as open-source software projects e.g., open-eGo project [19] and the Open Power System Data platform provide centralised and

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Tab. 2: Modelling tools that are suitable for power system analysis as open source. Abbreviations used in the table: **Purpose**: PSAT - Power System Analysis Tool, S - Simulation; I - Investment Decision Support, ODS - Operation Decision Support, **Approach**: BU - Bottom-Up, BBM - Bus-Branch Model; **Methodology**: ABS - Agent-based Simulation, LP - Linear Programming; **Temporal Resolution/Modelling Horizon/Geographical Coverage:**: UD - User-Defined

Tool	GridLAB-D	OpenDSS	PyPSA	RAPSim	pandapower
Purpose:	PSAT	PSAT	PSAT, I/ODS	PSAT	PSAT/S
Approach:	BU	BU	BU	BU	BBM (BU)
Methodology:	ABS	S	LP	S	S
Temporal resolution:	Seconds–Years	UD (1s to 1h)	Hourly	Minutes	Milliseconds
Modelling horizon:	3-5 Years	UD	1 year	days	UD
Geographical coverage:	Local-National	Community-Continental	Local-Continental	Local	UD
Reference	[12]	[13]	[14]	[15]	[16]

open data sets [20]. There is no tool that can tackle all the energy problems of the future. One solution could be a linking approach of two models. For instance, feeding the results from one model into the input of the other model. This process should ideally lead to convergence through an iterative approach [3]. There are also hard-linked models where two models are fully integrated into a single iteration product [21]. Otherwise it is a trade-off which properties and features the model should have for which application. Recently, there has been a huge development in the field of open source models and are shared via GitHub and on the openmod list [22]. The efficiency and performance of these tools heavily rely on contributions to this kind of platforms.

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