Life Cycle Assessment of Electricity Production from Airborne Wind Energy

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August 2015

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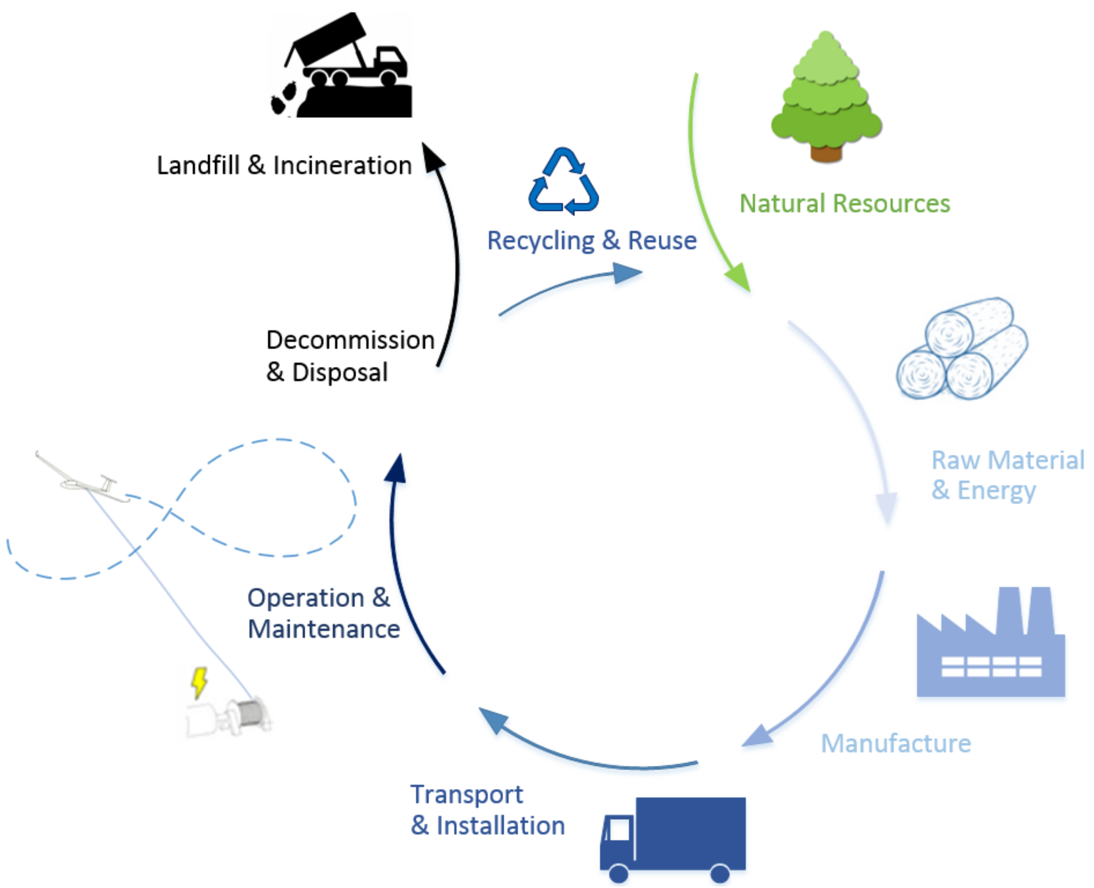

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Life Cycle Assessment of Electricity Production from Airborne Wind Energy

by

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STATUTORY DECLARATION

I declare that I have authored this thesis independently, that I have not used other than the declared sources and means. The thesis has not been submitted to any other examining body and has not been published.

Hamburg, 03 August 2015

Abstract

Global energy supply is closely linked with some of the greatest challenges of our society. A rising demand has to be met whereas conventional energy sources are depleting and emit considerable amounts of greenhouse gases. Renewable energy technologies are increasingly promoted to face these issues, especially in the electricity industry. Research has shown, that renewables are superior to conventional energy technologies in many environmental aspects but are not free of burdens. However, the main causes of impacts are shifted to other life cycle phases than operation. The emerging of airborne wind energy (AWE), as a new stakeholder within the renewables, presents an ecologically promising option since it accesses wind resources of outstanding quality with little material consumption. As of now, there is no environmental assessment of this new technology available.

The goals of this study are (1) the determination of environmental burden of electricity generation with AWE on the categories global warming and consumption of energy resources, (2) the identification of main contributors to these categories, (3) the determination of the energy payback time and (4) an assessment whether use of this technology would lower impact of electricity supply in the mentioned categories. An AWE design is chosen for the investigations, which appears possible to become a dominating design. Even though uncertainties arise from the analysis of a specific design, the outcomes of the study could serve as a first reference for system developers and for decision-makers to evaluate support or engagement in this technology.

To this end, a life cycle assessment (LCA) was executed, which allows tracking of category indicators from cradle to grave. Specific AWE facilities of 1.8 MW were defined and analyzed in a 300 MW plant under low wind conditions. The modeling follows an estimated dominating design or conservative choices. The results are expected to be on the upper range. The results of the model are presented and discussed and checked for robustness in a sensitivity study. A comparison to a similar conventional wind power plant and the electricity grid mix allows a better classification of the results.

The category indicator result in global warming potential (GWP) is 5.611 $g_{CO2\text{-}eq.}$/kWh. 65 % of that occur in the phase *raw material and manufacturing*, 3 % during *installation*, 28 % during *operation* and 4 % in *disposal*. The cumulated energy demand (CED) is 75.2 kJ-eq./kWh. The invested energy during the entire life cycle is 2.1 % of the total generated electricity and is recovered after 5 months or 153 days of operation. This corresponds with an energy yield ratio of 48%. The tether accounts for 5.5 and 8.1 % in GWP and CED, including its replacements. Lower lifetimes have significant influence, higher are with marginal effect. The environmental effects from the wing manufacture arise by 75% from the carbon fiber reinforced polymer but are only 2.6 and 5.6 % in GWP and CED. The biggest contribution is from generator and gearbox, which account for 35 and 30 % in GWP and CED respectively, including replacement of all gearboxes. In total, 30 % of the impacts come from balance of station components and 70 % from the AWE facility. The latter is the percentage that the system developer can influence directly.

Compared to a conventional wind plant that was modeled in a similar way, the AWE plant consumed 23 % of the mass, causes 49 % of the GWP and consumes 55 % of the CED. Energy payback time was 2 times lower. Compared to German electricity mix the plant causes 0.87 % of the GWP and has 0.74 % of the CED. Even with a conservative approach the study confirms the expectation of low impact in the considered categories and presents first numerical results.

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Abbreviations

AWE	Airborne wind energy
BOS	Balance-of-station
CED	Cumulated energy demand
CFRP	Carbon fiber reinforced polymer
EPD	Environmental product declaration
EPT	Energy payback time
FlyGen	Airborne generator
GroundGen	Ground based generator
GWP	Global warming potential
HAWT	Horizontal axis wind turbine
IEC (III)	International electrotechnical commission standard III
LC	Life cycle
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LLS	Launch and landing system
O&M	Operation and maintenance
PED	Primary energy demand
PE-UHMW	Ultra-high molecular weight polyethylene

Units

kg	Kilogram
$kg_{CO2\text{-}eq.}$/kWh	Kilogram CO_2-equivalent per kilowatthour
kWh	Kilowatthour
MJ	Magajoule
MJ-eq./kWh	Megajoule-equivalent per kilowatthour

1 Introduction

The emerging airborne wind energy (AWE) technology might be a promising contribution to meet problems of global energy supply. A rising energy demand worldwide is expected, whereas availability of today´s main source, fossil fuels, is depleting and is rising concern about its potential to change earth´s climate.

Governments set goals and the scope to encounter these issues. German Bundestag stipulates an energy concept in 2010 that comprises (1) the reduction of **greenhouse gas emission** of at least -40 % from 1990 to 2020, (2) a decrease in **primary energy use** by 20 % in the same time span, (3) an increase in **energy productivity** of 2.1 % per year related to final energy use, and (4) share of **renewables in electricity** of 35 % in 2020 with an 15 %-points increase every 10 years, reaching 80 % by 2050. In 2014, the actual share in electricity generation was 25.8 % [1], requiring intensive efforts in the coming years. [2]

Renewable energy sources are focal point of efforts because they tackle all of those goals. Greenhouse gas emissions and share of renewables are closely connected, since around half the emissions are caused from electricity industry [3]. Energy productivity of renewables is considered with 100 % in those goals. The use of fossil primary energy is reduced tremendously but not entirely with renewable energies.

Wind power for example uses an abundant resource while harnessing it causes practically no carbon dioxide during operation. However, during its life cycle from manufacturing to disposal there are effects on the environment. Related issues are material and energy use for manufacturing, rare metal and aluminum consumption, toxicity of lacquers, bird and bat death and blade waste handling. Limited availability of sites on land currently leads to installations off-shore, where civil engineering efforts are higher and environment conditions are harsher. Considerable amounts of aluminum, zinc and other metals are released from the protective sacrificial anodes [4].

Airborne wind energy is expected to pose an additional renewable technology that could overcome some of wind energy problems within a few years [5]. Driven by the 1970´s energy crisis, AWE was scientifically investigated by the end of the same decade [6] and had a recent boost with the availability of high performance and lightweight tether material, computational power and control technologies [7]. SkySails GmbH was founded in 2001, developing kite based ship propulsion systems and in 2006, makani power was founded developing fast flying airfoils to generate electricity. More than 50 organizations in industry and academics are involved in research and development today. Accessing better and unused wind resources with considerably less material requirements, AWE appears beneficial from an economic and ecological perspective.

The remarks above highlight that even though renewables present an environmentally superior alternative in many aspects, they do have effects on the environment that should be assessed. The goals of this study are

1) to quantify environmental impacts of electricity generation in terms of their contribution to global warming and depletion of energy resources,

2) to identify the main contributors in such a system for possible savings and consideration in system design,

3) to estimate the energy payback time that the system needs to be operated to generate the energy it consumes over its life cycle from manufacture to disposal and

4) to rank the technology against competitive technologies in the mentioned categories.

Life cycle assessment (LCA) was chosen as a tool to achieve these goals since it allows holistic accounting of a certain environmental indicator through the entire life cycle of a product from raw material production through manufacturing, installation operation and maintenance to decommission and disposal. The methodological foundation is described in DIN EN ISO 14040 [8] and 14044 [9].

The structure of this report is as follows. After this introduction an overview of Related background (chapter 2) to the assessment of AWE is given. Starting from the atmospheric research that describes the wind resource, a brief introduction in AWE is given and its components and manufacturing are presented. The LCA tool is introduced and related previous LCA studies are presented. Chapter 3 is the first stage of the implementation of the LCA defining goal and scope of the study. The studied product system “AWE plant” is defined, as well as its function, system boundaries, assessed impact categories and the functional unit to which category indicator results are related. Chapter 4, Life Cycle Inventory analysis, represents the second stage of the LCA. Data and its collection for all phases and components are explained for the AWE plant and a comparable conventional wind energy plant. The results of calculations with this data are presented and discussed in chapter 5, which corresponds with the 3rd (life cycle impact assessment) and partially 4th stage (interpretation) of the LCA. First, results for material, cumulated energy demand and global warming potential for the baseline model are investigated. In a sensitivity study, single parameters are varied to further investigate their contribution to the results . The values are then compared to a conventional wind power plant and the electricity mix. The uncertainties and limitations of the approach are discussed in a separate section. Conclusions and further research (chapter 6) complete the 4th stage of the LCA. Findings of the study are summarized and recommendations for future work are given.

2 Related background

This chapter introduces into topics related to this works to better evaluate the modeling and results. First, a brief introduction into the underlying atmospheric research in relevant heights is given. Then, motivation for airborne wind energy, implemented concepts and the status of this young technology is given. Its components and manufacturing are presented in a separate section. The life cycle assessment (LCA) tool that is used in this study is explained, as well as several LCA studies for electricity generation technologies.

2.1 Atmospheric research

Before investigating the technology to harvest wind energy, an understanding of the resource wind is necessary. This section gives a brief overview of atmospheric models and research, as well as an estimation of the energy that is potentially available from winds at certain heights.

Air mass in the upper atmosphere is dominated by geostrophic winds, which result from pressure differences due to global differences of solar irradiation and the Coriolis force. Closer to the earth´s surface winds are dominated by boundary layer effects. Friction and turbulence effects lower the wind speed. Within the boundary layer wind speed is commonly calculated by the empirical power law or the theoretically supported log law, where the latter is defined as

$$v_w(h) = v_w(h_{ref}) \frac{log\left(\frac{h}{z_0}\right)}{log\left(\frac{h_{ref}}{z_0}\right)} \tag{2.1}$$

h	*Height above ground*	[m]
h_{ref}	*Reference height*	[m]
z_0	*Roughness length*	[m]

The log law is only valid for altitudes up to 500 m. Above this height other than boundary layer effects become more prevailing. Even though it´s common practice it is questionable whether the application of the power law is the best approach to estimate wind speeds. The study does not go into more detail in this respect.

The power P_w of wind flowing through a certain cross section A can be expressed as

$$P_w = \frac{1}{2}\rho A {v_w}^3 \tag{2.2}$$

Since AWE devices are not limited to a persistent cross section in space but sweep a large volume another quantity is often considered instead, wind power density p_w, which is related to a unit area:

$$p_w = \frac{P_w}{A} = \frac{1}{2}\rho {v_w}^3 \tag{2.3}$$

In Figure 2.1 typical curves for wind speed, wind power density and air density are depicted. As displayed, changes in air density are rather low over the first 500 m of altitude whereas wind speed changes comparatively much and, in addition, enters cubically in wind power density. The cubic relationship means that the available wind power is very sensitive to wind speed. Small changes in wind speed or imprecise forecasts will therefore affect the power extraction significantly. A 10 % reduction in wind speed leads to 27 % less available power.

It is important to mention that even though the mentioned wind speed models are often applied, real measurements can deliver surprisingly different results. When comparing Figure 2.1 and Figure 2.2 it becomes evident, that the theoretical wind speed models can deviate significantly and have to be handled and interpreted carefully. The wind speed maximum in Figure 2.2 was measured at 130 m at the depicted site. Local particularities can dominate the vertical airflow scheme. Measurements should be taken to obtain reliable data for a specific site.

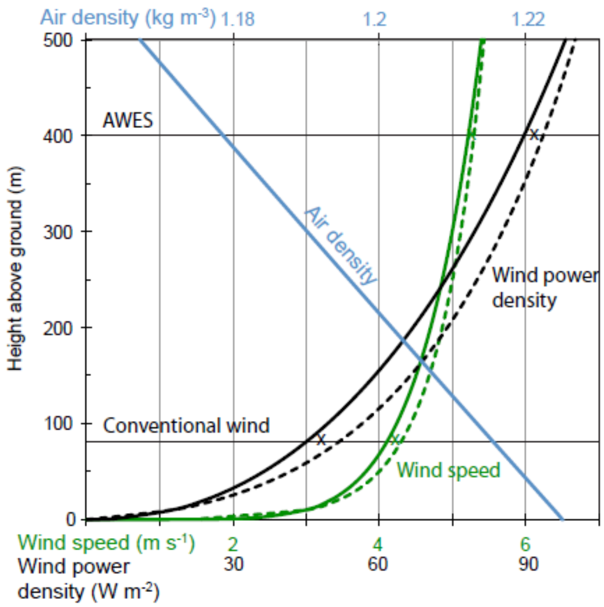


Figure 2.1: Typical vertical profiles in the boundary layer [10].

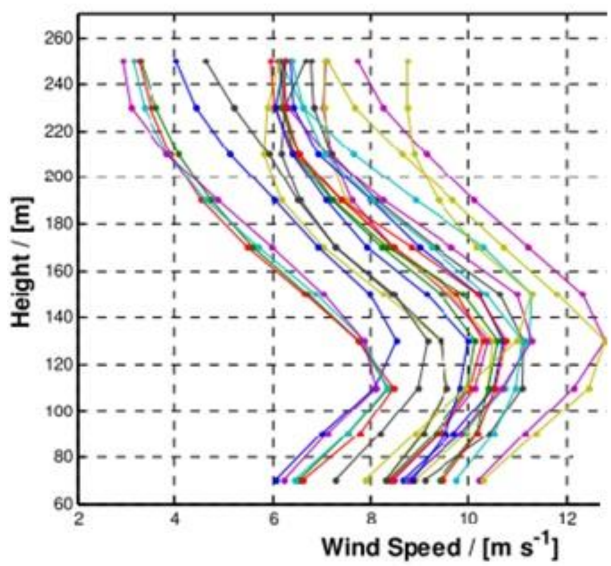


Figure 2.2: Vertical wind speed profile measurements in the North Sea [11].

Weibull distribution

To account for the variations in wind speed in strength and probability of occurrence, a Weibull distribution is commonly used, c.f. [12]. The statistical distribution of wind speeds can be modeled with it. The Weibull probability density function $pdf\ (x, k, \lambda)$ treats the variable $x > 0$ and requires the predefinition of two parameters, the shape parameter k and the scale parameter λ. Those can be obtained from literature, c.f. [13] or more adequately from measurements at a particular site. For the estimation of available wind power, x is replaced by v_w and the respective distribution is

$$pdf\ (v_w, k, \lambda) = \frac{k}{\lambda}\left(\frac{v_w}{\lambda}\right)^{k-1} e^{-(v_w/\lambda)^k} \tag{2.4}$$

The cumulative distribution function cdf, often referred to also as density function, describes the probability for a random variable to have a value smaller or equal to v_w.

$$cdf\ (v_w, k, \lambda) = 1 - e^{-(v_w/\lambda)^k}\ . \tag{2.5}$$

Unlike winds at altitudes that are reached with conventional wind turbines there, is little data available from measurements at higher altitudes. Canale, Fagiano and Milanese (2007) estimate that the jet streams alone contain around 100 times the global demand for energy. The global wind power resource from 0.5 to 12 km was assessed by Archer and Caldeira in 2009 for the first time, using wind data from different institutes recorded over 28 years. Besides the stronger winds, the study showed further benefits of wind at higher altitude. The high availability of the resource wind is of great interest for electricity generation purposes and is particularly high in high altitudes. Several global maps of optimum wind power densities for certain availabilities are published in [16]. Figure 2.3 shows the case for the annual optimum wind power density at 50, 68 and 95 % of the year at 80 m and 500 m. It can be deducted, that at 500 m, which is a relevant height for today's AWE applications, the optimum wind power is significantly higher and remarkably more available throughout the year at nearly every spot. Over 95 % of time, a high wind power density of up to 0.5 kW/m² was found for several spots at 500 m, which can practically not be found near ground level. The report also states optimum wind power densities for different seasons. Generally it is imaginable to use different wing sizes and tether lengths for different seasons to increase power output.

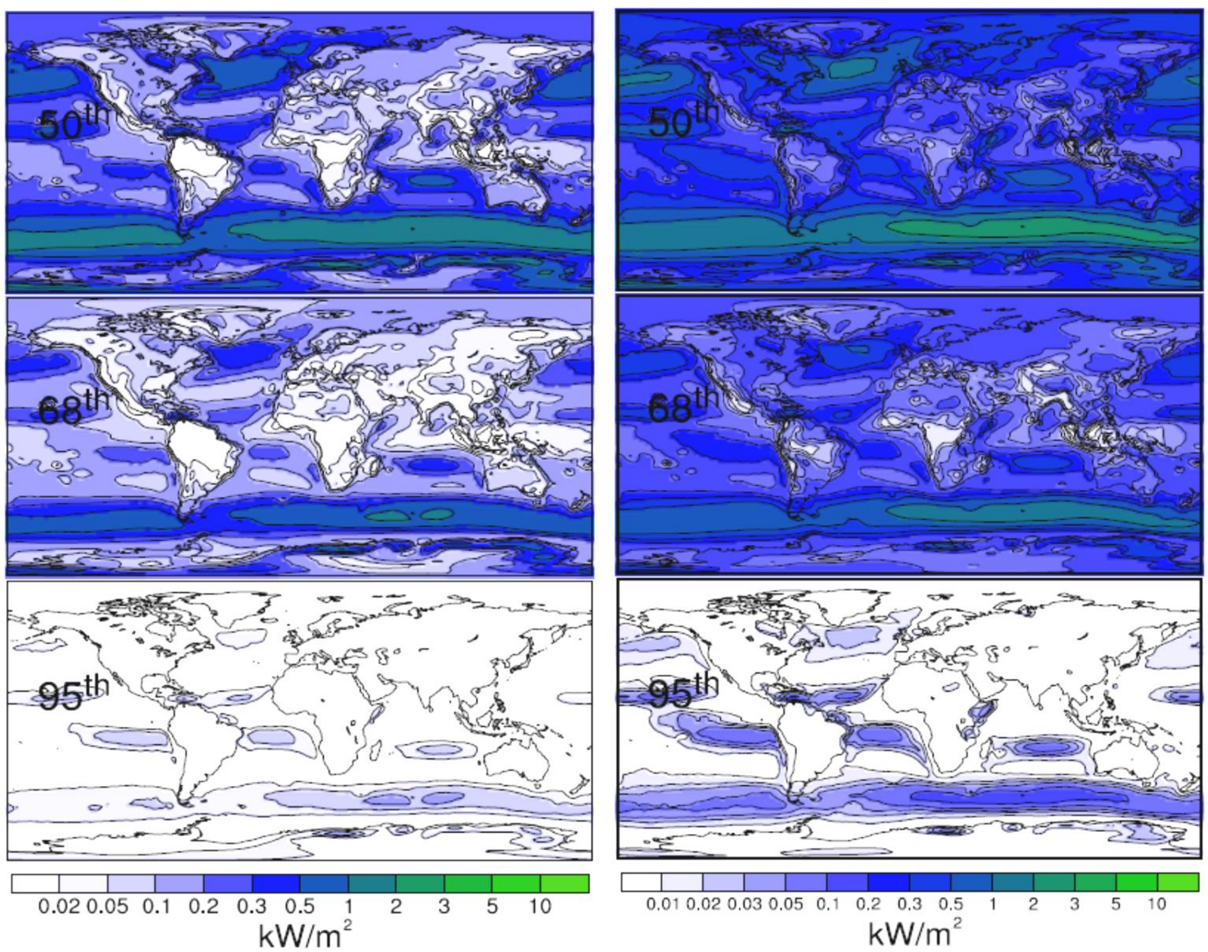


Figure 2.3: Annual optimum wind power density at 50, 68 and 95 % of the year at 80 m (left) and 500 m (right) [16].

Investigations of winds at higher altitudes have been intensified in the last years. Whereas *Archer and Cladeira* [15], [16], [10] assessed wind resources for AWE systems up to many kilometers of altitude, other investigations of the recent years such as in *onkites* report of *Fraunhofer IWES* [17] or by *European Weather Consult* [18] focus on altitudes of several hundred meters. The estimated potential or measurements thoroughly suggest promising benefits for the use of winds at altitudes envisaged with AWE technologies. In a study on full load hours for the Enerkite EK100 AWE system in Germany with meteorological data from 2012 was calculated. Downtimes due to de-icing, low visibility and a minimum wind speed of 2 m/s at 50 m height for operation have been considered. Figure 2.4 shows the results for Germany, where up to 8000 full load hours can be achieved and almost everywhere at least 5000. Considering that a 5000 full load hours site is regarded excellent for conventional wind turbines in Germany, the outcome of this study makes AWE very promising.

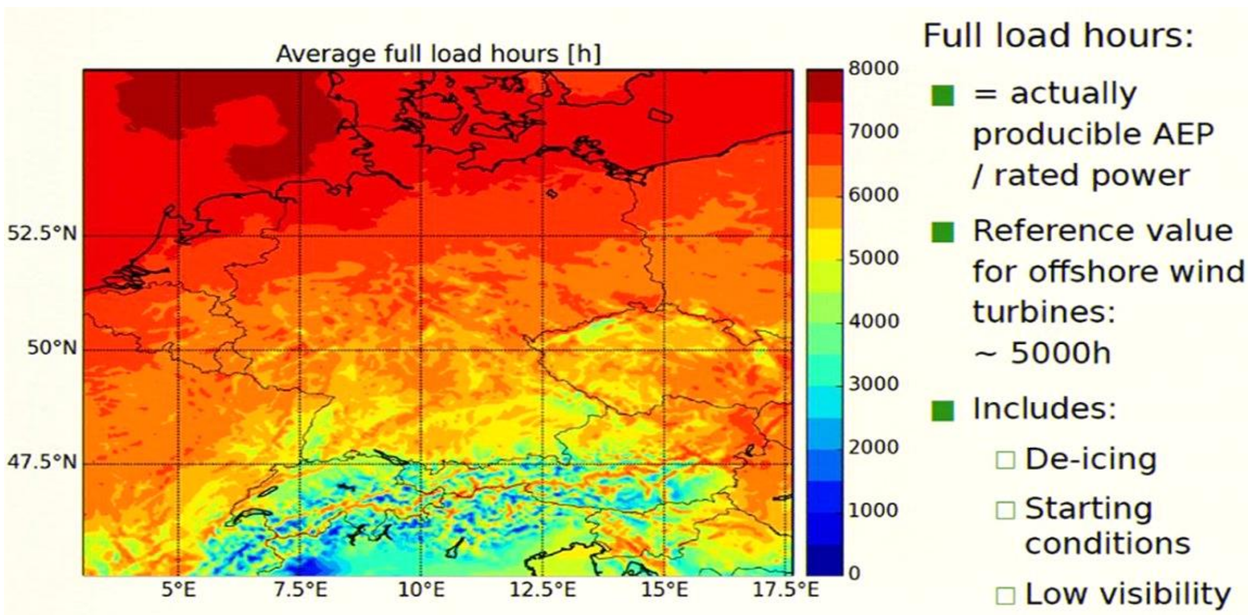


Figure 2.4: Capacity factor due to de-icing, low visibility and minimum wind speed for a specific AWE system in Germany [18].

2.2 Airborne Wind Energy

In this study, Airborne Wind Energy is understood as the conversion of kinetic energy from moving air masses to mechanical and finally electrical energy using an airfoil / kite, which is tethered to a ground station. Only systems flying crosswind are considered. Compared to a conventional wind power turbine, less structural and supportive components are needed to operate the functional system. For an easier understanding one can consider that the three blades are replaced by a fast flying airfoil, the nacelle is put on the ground and instead of a massive tower an adjustable tether is used, as illustrated in Figure 2.5. Other designs are explained later.

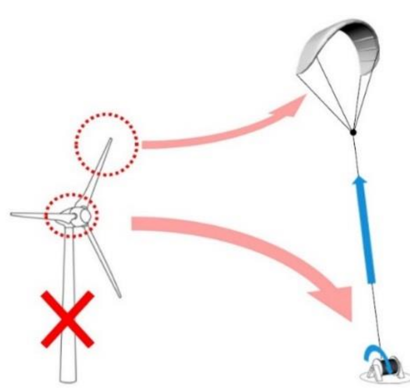


Figure 2.5: Illustration of conceptual differences between conventional and AWE systems [19].

2.2.1 Motivation for AWE

The motivation for airborne wind energy is manifold. As highlighted in the previous chapter one main advantage is the wind characteristics in high altitudes that entail several advantages for electricity production such magnitude and as persistency of wind speeds at higher altitudes, use of sites and spaces that aren´t adequate or accessible for conventional wind power and the vast amount of energy available from that resource. By adjustment of the tether length, an optimum operation altitude can always be chosen. A further interesting consideration is that the outer 25 % of the rotor blade make up for over 50 % of the energy produced in conventional wind power plants due to the high apparent wind speed [20]. In AWE systems, only a fast flying airfoil is used.

Additional advantages are that AWE system are more mobile and can be installed at sites with limited accessibility and potentially integrate better into landscapes. The material consumption is considerably less. When not operation, all components are on the ground and are easily accessible, which reduces maintenance efforts.

Predictions for Levelized Cost of Energy are promising. A study conducted by Fraunhofer IWES found, that AWE has the potential to supply electricity at the cost of coal power or even lower [17].

2.2.2 Implemented concepts

There are many different AWE concepts being developed and several possibilities to classify them. Early scientific considerations about kites for power generation have been published by M. Lloyd in 1980 [6]. Two types of design were distinguished there, *drag power* if air-turbines are mounted on the airfoil and *lift power* where power is generated by pulling a load via the tether. These types are illustrated in Figure 2.6.

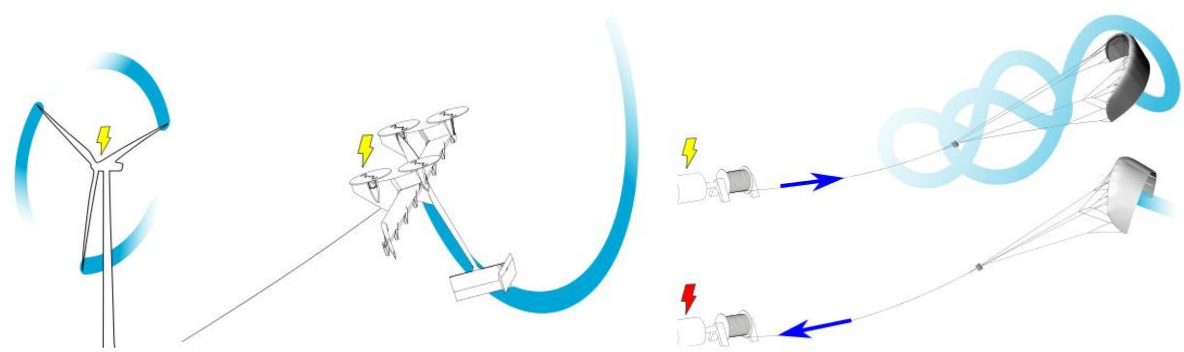


Figure 2.6: Schemes of HAWT (left), AWE type drag power (middle) and AWE type pumping lift power in both, traction and retraction phase (right), [21].

The drag power concept is sometimes also referred to as FlyGen because generators are part of the airborne system. The blades experience the high apparent wind speed of the wing and rotate the generator with high speeds to generate electricity. This needs to be transmitted to the ground. The tether has thus a double requirement, transmitting electricity and tensile force. Main disadvantages of drag power concept is the high airborne weight and additional drag from longitudinal tether cross section and propellers resulting in lower cut-in wind speeds and lower apparent wind speed. Advantageous is the high level of active control over the wing, allowing even launch and landing by using the generators as motors. In addition, the operation in a comparatively regular shape and a mainly fixed tether length are beneficial for lifetime of the components, in particular of the tether.

Currently most researchers investigate lift power systems of so called pumping kite or yo-yo design. An airfoil is operated in crosswind flight during traction phase to generate power. The lift force on the wing pulls a tether which is thus reeled out from a winch on the ground. This winch is coupled to a generator that generates electricity from the rotation. Accordingly, those systems are also called GroundGen systems. When reaching maximum tether length, angle of attack is reduced and the airfoil is pulled back, investing a certain portion of the generated power and winding the tether back on the winch. The reeling in and out is executed periodically. Figure 2.7 shows measurements of mechanical power and energy generation of the kite power system of TU Delft, which represent typical courses of power and energy over several cycles. The periodic operation is reflected here in repeating patterns of positive and intermittent power generation during dynamic figure-8 flight in traction phase and negative power of smaller magnitude during retraction. Generally, this concepts has advantages in a lower airborne weight, scalability, potentially less drag and higher wing speeds. The weakness of this system is quick tether wear due to combination of tensile and bending stress and intermittency of power generation.

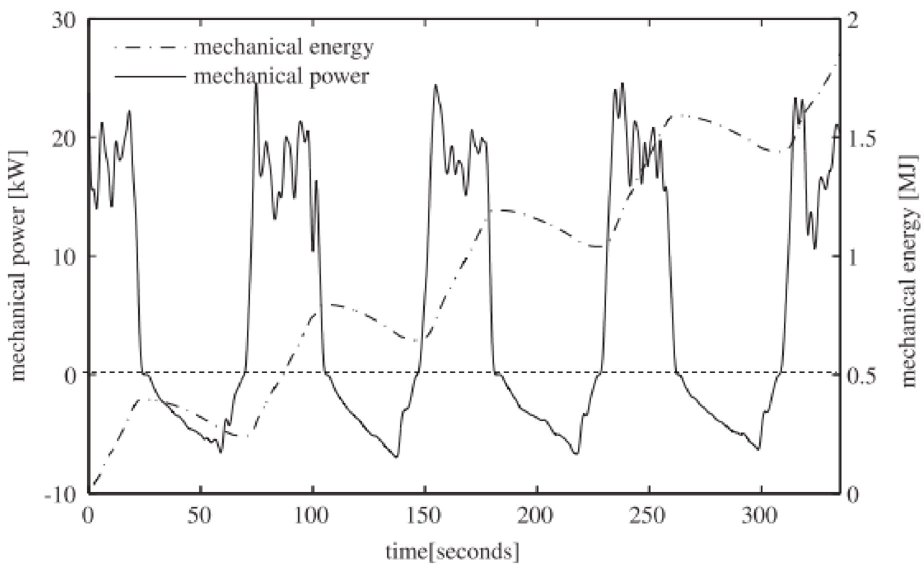


Figure 2.7: Course of mech. power and energy during several pumping cycles [22].

Currently, a Leading Edge Inflatable Membrane (LEI) kite is used. It is lighter than rigid structures and is relatively save from collapsing in many flight conditions. The aerodynamic shape is amongst the worst and lifetime with today's textile materials is very low under the high forces in operation. This system is designed rather for learning and teaching and will soon be replaced by a rigid wing. Lift power AWE systems allow for many different types of wings since the structure does not need to be rigid for mounting heavy components. The choice of wing results in different system properties and behavior in performance, lifetime and handling as described in [23].

2.2.3 Technology status

A fast growing number of teams is working on AWE worldwide. Some are marked in the world map in Figure 2.8. The status of AWE in 2015 was assessed with a survey amongst many stakeholders in the field

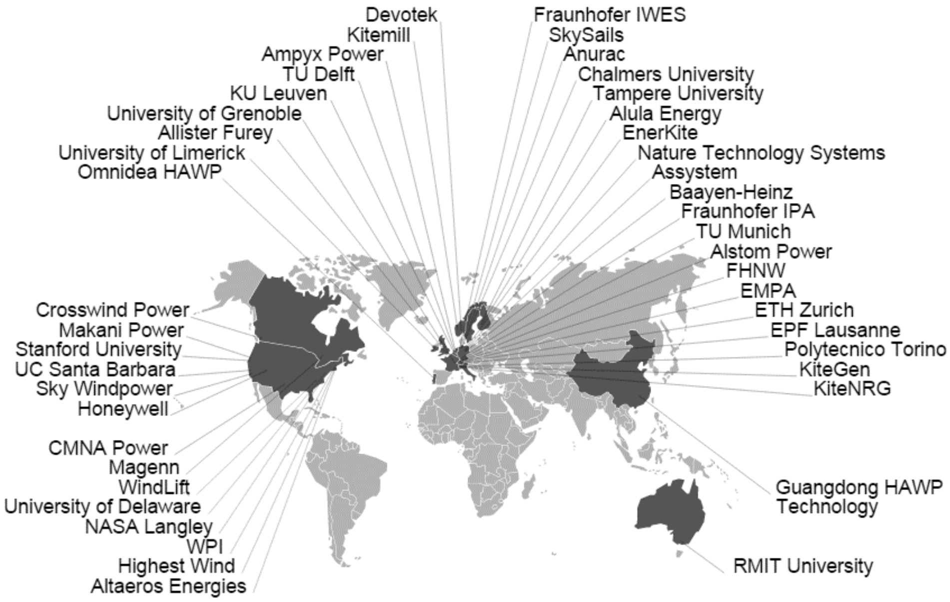


Figure 2.8: AWE stakeholders worldwide [22].

[5]. It showed, that technology is not yet mature and still in stage of research and development. The number of teams from both, universities and industry, that investigate and develop AWE systems and components increased considerably over the past 10 years worldwide. Latest boost might be enabled due to availability of computation power for complex flight path algorithms, lightweight high strength tether material and general support for renewable energies. Current problems are seen still in technological complexity like the control algorithms but also in the access to financial resources and uncertainties about legal framework according to the mentioned survey amongst the developers. None of the systems is in operation yet.

The Hamburg (Germany) based company SkySails Installed several kites on modern container ships not for electricity generation but as auxiliary propulsion engine, as shown in Figure 2.9. The company claims to generate traction power of up to 2 MW, saving 10 tons of diesel a day [24]. The kite system is attached to a single line and steered by an airborne control pod that deforms the kite. Launch and retrieval is executed

Figure 2.9: SkySails technology: SkySails Marine in traction operation (left) and SkySails Power vision of the off-shore lift power yo-yo system (right) [24].

on a telescope mast. The technology is transferred to an electricity generating application of yo-yo type, called SkySails Power. Only a 55 kW (installed generator power) system was deployed as of now.

The Berlin (Germany) based company EnerKite reported the longest continuous flight up to now with 74 hours. The company develops mobile small scale systems of yo-yo-type as depicted in Figure 2.10. The latest design includes a semi-rigid wing structure that is attached with a tether and two small diameter lines for steering. Launch and landing is executed with a rotating arm.

The same figure also shows the previous wing system of The Hague (Netherlands) based company Ampyx Power, which is also of yo-yo-type lift power but with a rigid wing. It is steered with onboard electronics and requires only a single line for tensile load. The company is amongst the leading ones in the field.

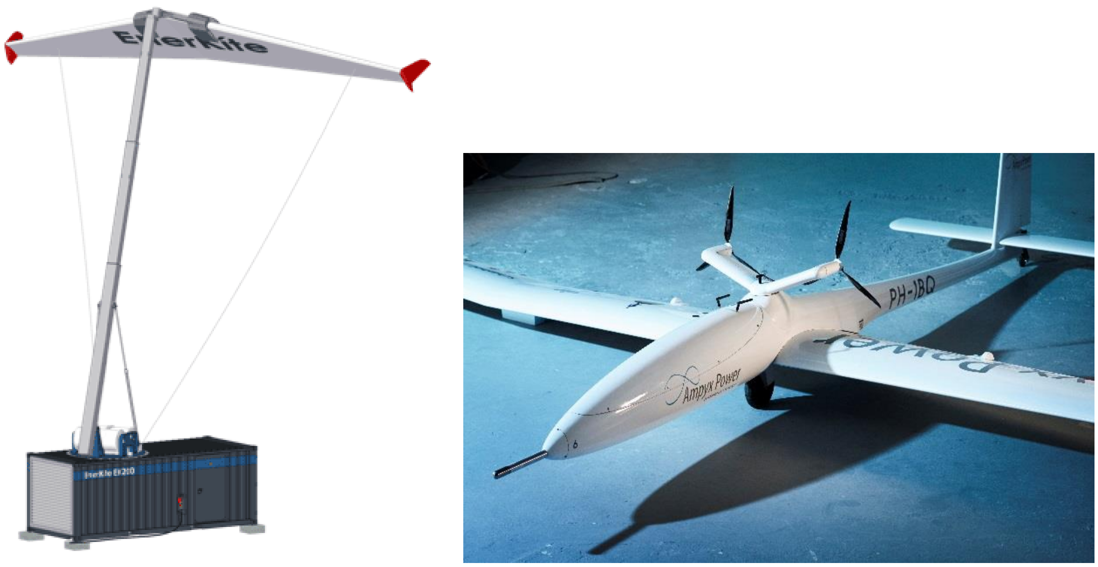


Figure 2.10: Two lift power yo-yo-concepts, the mobile small scale system of EnerKite (left) and of Ampyx Power, aiming utility scale (right) [25].

The biggest existing AWE-system is currently a 600 kW drag power prototype by makani power, USA, which completed successful hovering flight in June 2015 as depicted in Figure 2.11. The octocopter is operated by applying power to the reversely operated generators. A carbon fiber tether is used for tensile forces, wrapped in an aluminum conductor to transmit electrical power to the ground. It is expected to be operational by the end of 2015.

About half of the developing teams expect to have a commercial product by 2018. The same percentage develops systems in the range of 100 to 1000 kW, mostly for off-grid applications but also grid-tied are frequent. In the recent years a shift towards rigid wing systems in yo-yo-operation can be seen [5].

Figure 2.11: Drag power system of makani power in hovering flight position, at launch and landing station in June 2015.

2.3 Components and Manufacturing

This section gives an overview of the components of an airborne wind energy system and design options.

The exact composition of a pumping kite system differs to some extent from system to system. TU Delft´s design, as depicted in Figure 2.12, can serve as an example to get familiar with general system components [22]. The launch and landing system is not included here. The AWE-system consists of

- wind capturing components including wing / kite and bridle line system
- system control components including Kite Control Unit and sensors
- structural components including tether and launch-/landing system (not depicted)
- mechanical power conversion components including drum and generator
- electrical power conversion components including battery, inverter, transformer and other power electronics and

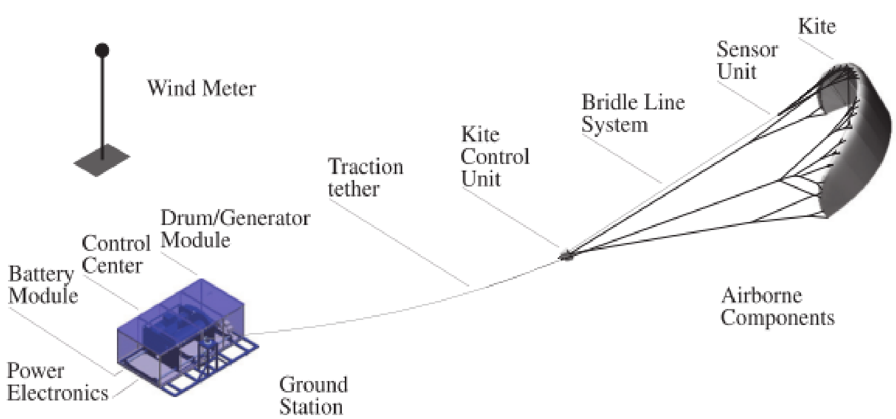


Figure 2.12: Pumping kite system and its components [22].

- various additional devices such as foundation, monitoring devices, wind meter, etc. to enable a connection to the electricity grid.

2.3.1 Wind Capturing components

The selection of the wing is certainly one of the main design choices for AWE systems. The airfoil is shaped with a certain profile to generate dynamic lift from the airflow around it. A major design criterion is a low lift to drag ratio for which a precise shape of the wing is required. Other criterions like mass, safety, controllability, maximum loading and durability might lead to AWE specific trade-offs. Differences in wings were studied in detail in [23].

Mainly investigated wing types are the flexible ones, ram-air-kite and leading edge inflatable (LEI) membrane kite, rigid wings similar to gliders or drones. Schematic drawings of those wing types and the cross section are presented in Figure 2.13. Pictures of the different wing types are shown in Figure 2.14, including a hybrid wing with a rigid structure of carbon fiber reinforced polymer with a lightweight covering to form the aerodynamic shape of the wing.

Figure 2.13: Model and cross sections of a ram-air kite (left), a leading edge inflatable tube kite (middle) and a glider / sailplane (right).

Generally, rigid wing structures are significantly more robust and durable, which leads to higher component lifetimes and finally higher availability or lower replacement expenses. The good aerodynamic properties cause also higher wing speeds which entail a greater generation of noise. Together with safety concerns this could lead to a more reluctant attitude of public.

Flexible wings, in turn, can be designed with a very low mass per wing area and the manufacturing can be done at comparatively low cost; due to the flexible material and low density it is expected to be safer in a case of damage; The small packaging size promises some advantages in ground handling and storage; mayor drawbacks, however, are constraints from manufacturing, resulting in lower glide ratios; the possibly strong and detrimental bidirectional correlation between structural dynamics and fluid dynamics, lowering the aerodynamic performance; There are also limitations from material strength which allow less wing loading and require a denser and drag causing bridle system. In addition, they are also more affected by environmental conditions such as extreme temperatures, humidity, rain, hail, snow, icing, UV, lightning and salinity reducing lifetime and temporally may increase weight significantly. As a consequence, frequent replacements might lead to a bigger mass of material consumed over the lifetime than for a rigid wing.

Ram air kites are mainly made from nylon of at least two layers and ribs. The wings have basically the same cross section as a rigid wing, usually with an approx. 15 % increased section thickness, cf. Figure 2.13. At the bottom front an inlet is cut out to allow inflow of air. This provides the inner pressure of the kite to maintain its shape. The inlet must be at the stagnation point to assure stability, which also gives restrictions for the range of allowed angles of attack. A system of bridle lines takes up forces from many reinforced points. Bridle lines are usually made from poly-aramid or ultra-high molecular weight polyethylene. For better performance and protection, a specific coating is applied.

Ram-air wings have comparably good aerodynamic properties for flexible wings with glide ratios just above 10. There are some reasons why values as those of rigid wings aren´t reached from which some are the following: One, the inlet cut that increases drag and decreases lift. Two, the higher the aspect ratio the better the performance since the fraction of induced drag is less. There are, however, design limits which make aspect ratios of (only) up to 7 possible by now. Three, imperfections from manufacturability like from sewing or the shape that is up to 1.5 times thicker between the ribs than at the ribs themselves. Those prevent a perfect air flow around the wing. Four, a certain anhedral arch is required for maneuverability, stability in turbulence and other. But it also changes the direction of local lift vectors whereas the vertical lift is reduced as a result.

Besides the aerodynamic properties, advantages of ram-air wings are their relative light weight, their robustness and bearing capabilities of extreme loads, the potential for scaling, the technical experience from parachutes in sports and military applications, the small packing size and steerability. Since they are without rigid elements, they can twist, deflect, fold and also collapse. This leads to the disadvantages of this wing type. It needs a stable planform, trim and a minimum anhedral arc and is only stable under load. Once collapsed, it cannot recover. The safety for workers can be a risk due to the many bridle lines. The kites used by SkySails Marine have a weight per square meter wing of around 0.85 kg/m², including the kite control unit.

A more detailed elaboration on ram-air kites and design for AWE can be found in [26].

LEI (Leading edge inflatable) kites have a stable skeletal structure made of tubes filled with compressed air and spanned with a membrane. It is therefore not necessarily a pure flexible wing. The wing is interesting for AWE applications mainly because of its structural stability at still low weight, the possible maneuvers and depower capabilities. The most significant disadvantages, however, are the bad aerodynamic shape, the ground handling (de-/inflation) and general complexity and liability of the inflated parts.

Gliders have been constructed for many decades now, mainly for sports applications nowadays. They are designed for high lift-to-drag-ratios to sink as slow as possible to extend the duration staying airborne. The Main structural material is glass or carbon fiber reinforced polymer. The rigid construction entails various differences to soft wings. Due to the higher material strength higher aspect ratios. Induced drag from wing tips has less contribution and LoD rises. The aerodynamic shape can be manufactured precisely and gliders with glide ratios of over 70 were already reached with the glider *eta*; its aspect ratio is 51.33 [27]. But also increased weight comes with the rigid material. A modern glider has around 25 kg/m², including the cabin and instruments.

Rigid wings used in AWE applications could be similar to conventional gliders but they are tethered and adapted in design. To take higher wing loads, the structure has to be enforced by additional material which adds weight or by lowering aspect ratio which reduces bending moment on the wing and its root. Also too high aspect ratios would require too many bridle lines which add drag significantly.

Also ultralight aircrafts have interesting properties. Since they are motorized the design goal is shifted from gliding as far as possible towards generating a high lift. This is necessary because of their bigger

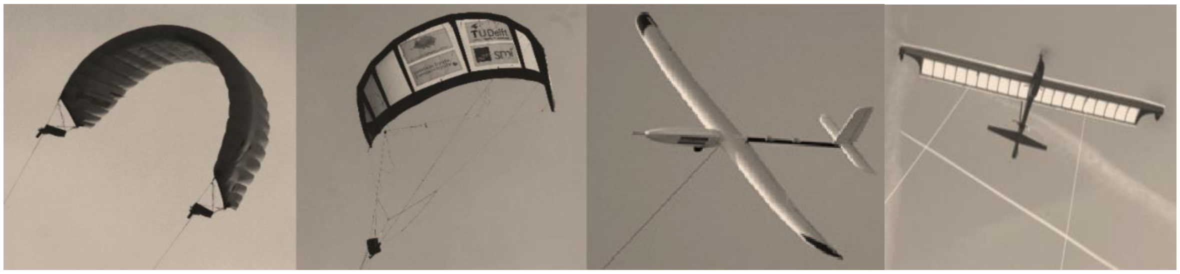


Figure 2.14: Ram-air kite (left), leading edge inflatable tube kite (LEI) (middle left) [22], glider or sailplane (middle right) [28] and hybrid wing with rigid structure and light canopy [29].

weight and the wings are designed accordingly. Wing features that are mountable on the rigid structure allow for further improvements and regulation of life coefficient in different situations.

Semi-rigid wings are also applied by some AWE groups. Depending on the definition a LEI kite could also be included in this group. In general the term describes wings that have stiff structure that is spanned with a soft canopy. With this concept it is tried to achieve aerodynamic performances close to those of gliders and a structure that resists high wing loadings at a low weight. The EMPA group developed a wing with 16 % more weight but 3 times higher maximum wing loading than with conventional airbeams.

2.3.2 System Control Components

An airfoil can be controlled by passive control design features and actively by changing the airflow around the wing and thus the aerodynamic forces acting on it. The steering mechanisms can be called kite control unit (KCU). Its implementation can differ greatly between the systems. It usually contains sensors that trigger steering inputs and computer chips for the control algorithms and processing of data. In addition an additional battery and onboard charger system can be necessary.

A glider can usually rotate around 3 perpendicular axes, fulfilling roll, pitch and yaw movement, by the deflection of ailerons, elevators and rudder, respectively. For the operation of the control surfaces actuators with metal beams or even ropes can be used. In AWE applications, one or more of these functions are often executed from the ground using steering lines on additional winches.

A soft kite is steered by deformation of the whole kite in two ways, torsion of the kite and change in angle of attack on one side of the wing [31]. In Figure 2.15 different wing types with exemplary turning mechanisms are presented. The illustration to the left shows rolling of a rigid wing. The picture in the middle helps to understand turning after pulling the left (in flight direction) steering line of a LEI kite. The schematic drawing to the right shows a possibility to operate steering lines of a ram-air-kite with an actuator which is instead airborne.

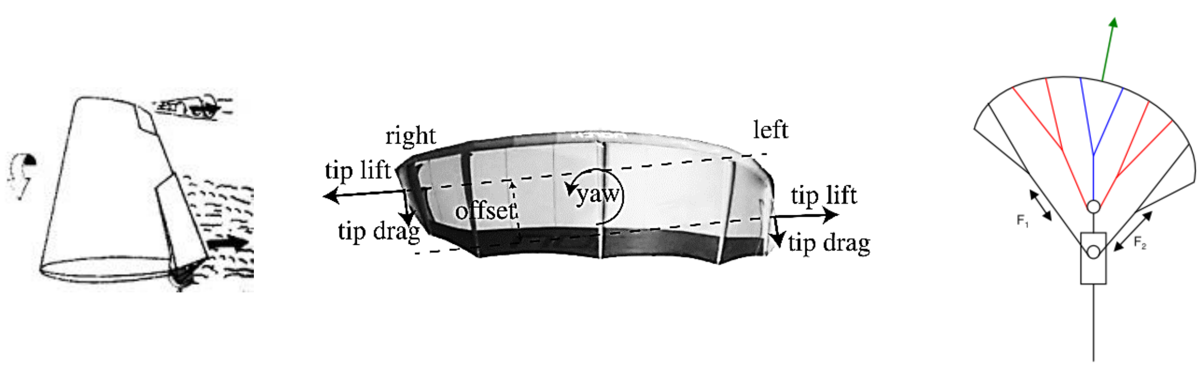


Figure 2.15: Examples for turning of a rigid wing (left) [30], a LEI kite (middle) [31] and a ram-air kite (right) [32].

2.3.3 Structural Components

Tether

The tether connects the wing system to the ground station. It´s main function is the transmission of tensile forces resulting from aerodynamic forces of the wing. There are several side conditions that should be fulfilled such as low weight since it is airborne, low drag especially in the fast moving part, high resistance for bending and pulling as well as environmental degradation such as UV radiation, a certain temperature range and dust and potentially be conducting.

The selection of the material determines the tether characteristics to a large extend. Mostly plastics are used for that purpose. Some of the available material is high modulus or ultra-high molecular weight polyethylene (PE-UHMW) (trade name: Dyneema or Spectra), high modulus polyamide (trade name: Technora, Kevlar or Twaron) or Poly(p-phenylen-2,6-benzobisoxazol) (trade name: Zylon) and aramids. According to the manufacturer Dyneema ropes bear around 10 times higher tensile forces than steel based on the same weight [34]. Alternatively, carbon fiber based tethers are investigated, too.

In addition, tether properties can be influenced by its construction, the coating or finishing and auxiliary equipment. The pattern of twisting and braiding the extruded fibers, as well as the number and cross section of strands can be optimized for the above mentioned parameters. Figure 2.16 shows an industrial braiding of a cover around the core consisting of multiple prefabricated strands. The coating which is applied afterwards to the tether is usually polyurethane based but manufacturer specific and can improves properties significantly. Sheaves and other tether handling material is designed for little bending, which often results in big diameters. Further basic information on tethers and manufacturing is available on [35].

In general, scaling up a wing results in higher tether force which requires a thicker tether. Effective drag increases with the square root of tether cross section. The relative influence of tether drag gets smaller with increasing wing size. A semi rigid wing might have additional benefits when scaling up considering weight.

Launch and landing system

The launch and landing system is an AWE specific component. Many different concepts are followed by the different research and developer groups. Implemented or aimed concepts are a tiltable mast [36], rotating arm [37], catapult [38] multicopter [39], fan [29], pulley [40], lighter-than-air and manual. Especially for rigid wing structures, there is similar technology available to what is required from UAV, sports glider and military flight vehicles. A dominant design, however, cannot yet be observed.

For launching soft kites there are principles based on static lift of the deflated kite, usually supported by a mechanism to access higher wind speeds for the launch like lifting on a (tiltable or telescopic) mast, with a second (magnus) kite or balloon, a quadrocopter or even a canon. Those usually depend on high wind

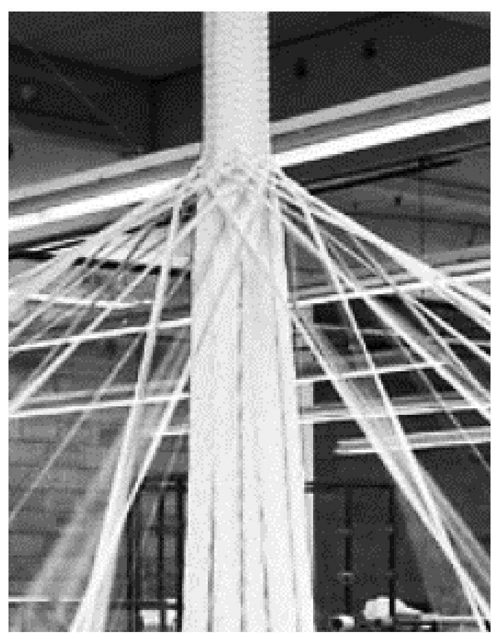


Figure 2.16: Industrial braiding of a cover around a multiple strand core of a polymer rope [33].

speeds at ground level to launch, even if winds at high altitudes are strong. To increase cut-in wind speed, other principles increase apparent wind speed by using a pulley system, a fan, a rotating arm, a catapult or a slingshot. Especially rigid systems require external forces for launch. Figure 2.17 depicts a typical

launch of a manned glider. A winch is pulling and accelerating the glider for around 40 m or 4 seconds until the glider takes off with around 20 m/s [42]. The necessary distance is limited by the acceleration of

Figure 2.17: Winch start of a sports glider [41].

the pilot and can thus be reduced for unmanned vehicles. 700,000 launches are executed that way every year in Germany alone. Figure 2.18 shows a catapult solution to launch UAV in military applications. Since todays AWE gliders usually do not have a chassis and thus, might be captured by a system. On the right side of the figure a proposal designed for aircrafts without chassis is shown. It is able to retrieve a flying device by following it on a rail track and bringing the docking cart into the right position by yawing and transversal and lateral movements.

Figure 2.18: UAV catapult launch (left) [43] and ground based landing system for air vehicles without chassis (right) [44].

A mast system for launch and retrieval of large ram-air kites is operated by SkySails for several years on ships. Figure 2.19 shows steps of landing, docking in and reefing the landed kite on a mast top. The example shows, that principally relatively simple components can be used to deploy and retrieve a kite and to handle the various flexible parts of the kite and bridle lines. For pumping kite systems the system can possibly be easier considering the design constraints given by the installation on a ship. The ground station doesn´t move onshore, the mast needs to be less complex, e.g. without telescope function and there is more space in wind direction to enable pulley supported starts. Especially shortly after releasing the kite or before docking in the kite is difficult to control and a longer tether length increases stability of the system since significantly.

The packed 225 m² SkysSails kite if reduced in volume from 200 to 3 m³. To unpack and deflate it, the present wind is used. When using a LEI kite, additional facilities are required to inflate the wing before launching and eventually to deflate after retrieval. [45] designed an automated launch and retrieval station for LEI kites.

Figure 2.19: Landing and reefing a 225 m² ram-air kite on a mast [36].

2.3.4 Mechanical power conversion components

The ground station performs the conversion of mechanical power from the tether to electrical power. This is usually done by using the traction power to reel out tether from a winch which is coupled to a generator. The winch has a big diameter to not bend the tether too strong and to have enough storage available for the tether length on usually not more than three layers. For a precise adjustment of tether length inertia of the winch should be small. Lighter material than typical steel drums might be expected. To account for the variable speeds, especially between reeling out and reeling in at the end of a cycle, a gearbox is necessary between these two devices when using typical induction generators. When using a permanent magnet generator, direct coupling is possible. Off-the-shelf generator technology is applicable. The rated power is adapted to the traction phase. In retraction phase it is operated as a motor to reel in the tether with comparatively high rotation.

2.3.5 Electrical power conversion components

The characteristics of the generated electrical power possibly needs to be adjusted for transmission within a farm, for grid connection or other purposes. Conventional electronics as used in wind power turbines and plants are needed including inverter, transformer and other power electronics. Eventually, additional equipment is needed for the particularity of AWE systems. The intermittency of electricity production during traction phase, as well as between traction and retraction phase, as shown in Figure 2.1, needs to be smoothened for many consumers. Developer companies do not yet disclose information on that. Generally, there is the possibility to synchronize the flight trajectories and reeling scheme of the single AWE systems in a farms such that the farm output is more balanced. Additionally, power storages might necessary that can not only buffer large amounts of energy but also handle big power densities. For the specific AWE design and its application flywheels, batteries, supercapacitors, the generation of intermediate material such as hydrogen or others might be the appropriate choice.

2.3.6 Various additional

For maintenance and protection from extreme weather situations the airfoil or even the complete facility might be protected in a hangar or other shelter.

In a wind power farm, additional components are necessary. The internal cabling within the plant and external power cable can be massive. Between these two cable systems, a power transformer of the rated power of the plant is installed to transform electricity to higher voltages for transmission and / or grid connection.

2.4 Life cycle assessment

This section explains the LCA tool which is used in this study to assess environmental effects from electricity generation with an AWE system. First, some general aspects and the principle of the tool are explained. Then the four stages of implementing the tool are presented.

2.4.1 General aspects and principles

Life cycle assessment (LCA) is defined as "compilation and evaluation of inputs, outputs and the potential environmental impacts of a product system throughout its life" [8]. That means that natural resources that are taken from the environment, as well as emissions to air, soil and water are recorded for the whole life cycle and analyzed with respect to their effect on the environment. It is a technique that can help determining and/or improve the environmental performance of a product. It can also be used to inform the public and decision makers in companies, NGOs and politics for strategic reasons, planning or design purposes.

While use or operation phase is most familiar to most users, significant or even entire environmental impacts of a product can be located in a preceding or subsequential life cycle phase. A cradle-to-grave approach for a power plant starts with the analysis of the extraction of natural resources for raw material and energy supply. The manufacturing phase requires further inputs and causes emissions. Also transports of all materials, (sub-) products and waste streams are considered. Further exchanges occur during the long years of operation, including maintenance and replacements. Finally, end-of-life routes of the materials are studied. These can after decommissioning be disposed of in landfilling or energetically recovered in incineration plants or take a route, where they are at least partially fed back to the raw material stream of its lifecycle or of a different product by recycling or even reuse. The lifecycle stages are illustrated in Figure 2.20.

Important organizations that shaped the LCA as a tool are the *Society of Environmental Toxicology and Chemistry* (SETAC), the *International Organization for Standardization* (ISO) and the *United Nations Environmental Program* (UNEP). SETAC evoked research and the development by bringing together different stakeholders and by organizing workshops on LCA at an early stage. ISO´s standardization activities in the field of environmental management started in the 1990s and are captured in the 14000 series. In 2006 ISO 14044 was released compiling the four phases of a LCA. UNEPs activities in the LCA context are more of practical nature and directed towards its application, particularly in developing countries [46]. The first environmental impact analyses were executed in the 1960s, mainly with the purpose to compare the effect of two different product variations on the environment. Over the years, assessments broadened and more and more aspects are taken into account. Starting from merely energy analyses, models were extended by environmental burden, costing models and social aspects. [47]

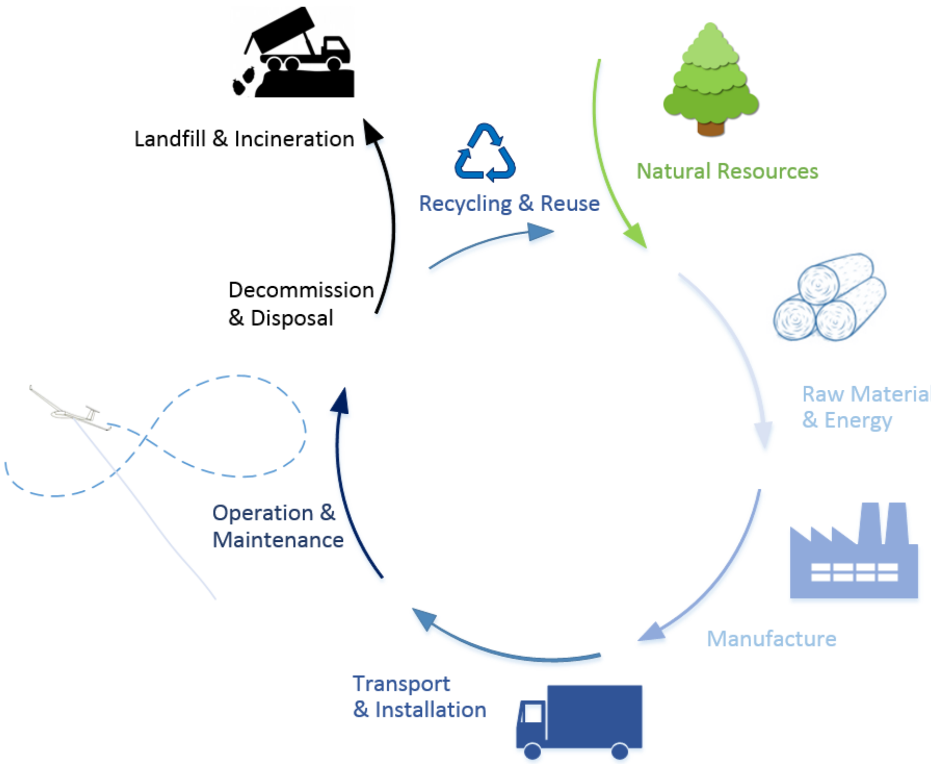


Figure 2.20: Phases in cradle-to-grave life cycle assessment for an AWE power plant.

2.4.2 Stages of a LCA

In this section, the requirements for the conduction of a LCA are briefly introduced as suggested by the International Organization for Standardization (ISO) in its standards 14040 and 14044. It consists of four general phases: (I) goal and scope definition, (II) inventory analysis, (III) impact assessment and (IV) Interpretation. These blocks are usually executed in the given order but are interdependent and can comprise several iterations. Especially the interpretation phase can lead to findings that require adjustment of the other phases. After finding a major share of one component or process in the results, it might be desired for example to refine the scope and data requirements for this component. The stages and interrelationship of the LCA framework are visualized in Figure 2.21 and presented in the following.Figure 2.21 The conclusions and recommendations from interpretation phase can directly be applied in many cases for product development and improvement, strategic planning, public policy making, marketing and other.

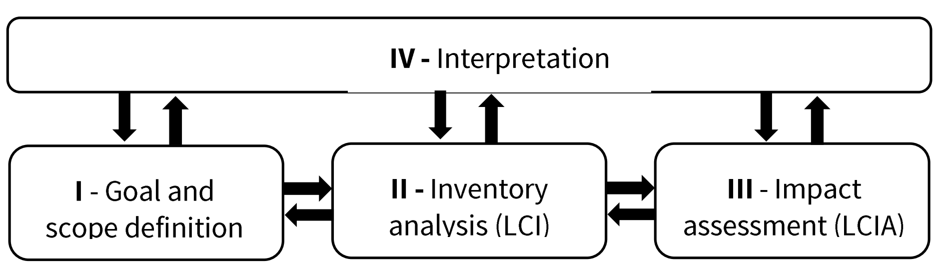


Figure 2.21: Stages of the life cycle assessment framework.

2.4.2.1 Goal and scope definition

Goal and scope definition give the initial plan that is executed in the LCI.

The goal definition should comprise a sound description of the intended application, the reasons for carrying out the study, the intended audience of the report and whether results are used for “comparative assertions intended to be disclosed to the public”.

The scope definition informs about a number of aspects in order to ensure that breadth, depth and detail of the study are met with respect to the goal. It defines the product system that is studied and its function. From that, the functional unit can be derived. The functional unit is measurable reference to which input and output streams are related. Possibly, multiple product streams are generated and procedures for allocation must be defined. The description of the system boundaries must be stated clearly for the audience to know which processes are part of the study and which are excluded. Also, the selection of impact categories and assessment method must be stated here and argued why they are selected and other categories neglected. With those aspects, data requirements can be derived and should be stated. It is important at this point, to inform the audience about the assumptions that were made for the modeling and the limitations of the approach. Finally, the type of critical review should be mentioned if conducted, as well as type and format of the report. Those aspects might be iterated during the study.

System boundary

The system boundary should define in breadth and depth the unit processes and flows that are considered for the study, or eventually neglected or excluded. According to [8] it should be reflected on

- Acquisition of raw materials
- Inputs and outputs in manufacturing
- Distribution and transportation
- Production and use of fuel, electricity and heat
- operation and maintenance of the product
- disposal of process wastes and products
- recovery of products at end-of-life (either energetic recovery, recycling or reuse)
- manufacture of ancillary materials
- manufacture, maintenance and decommissioning of capital equipment and
- additional operations.

A process flow diagram might support the understanding of the processes and interrelationship. The definition of **cut-of criteria** might become necessary. It define the level of completeness of data collection that is to be achieved and allows neglecting streams that are below the criterion. Common criteria are the cumulative contribution of a stream to overall mass, energy or environmental significance. Further restrictions might be made like the limitation of the sum of these small streams to a certain percentage. It should be clearly stated and the consequences on the results described. It must be ensured, that overall conclusion is not significantly changed.

A sensitivity analysis can serve to check, whether each life cycle stage and unit process is significant with respect to the results or not. This might lead to the inclusion of additional unit processes, inputs or outputs but also to their exclusion if they turn out insignificant

Data quality requirements

Specifying the characteristics of the required data serves to evaluate the reliability of the study results. The type and source of data should be indicated, whether it is measured, calculated or estimated and who provided it. Time-related, geographical and technology coverage must be described as well as precision of data, completeness, representativeness, consistency, reproducibility, sources and uncertainties. The pedigree-matrix, Table 2.1, is an exemplary tool to assess data quality with respect to the mentioned parameters.

Comparison between systems

Equivalence of systems should be described before interpretation of results and it has to be assured, that equivalent methodology is applied. Differences between the systems and its parameters should be described, as well as how missing data is treated.

Table 2.1: Pedigree-matrix for assessment of data quality in LCA.

Indicator	1	2	3	4	5
Reliability	verified data based on measure-ments	verified data based partly on assumptions or non-verified data based on measurements	unverified data based partly on assumptions	qualified estimate	unqualified estimate
Completeness	representative data from an adequate sample of sites over an adequate period	representative data from a smaller number of sites over an adequate period	representative data from an adequate number of sites but over a shorter period	representative data from a small number of sites over a shorter period or inadequate data from adequate number of sites	unknown or incomplete data from a small number of sites
Temporal	< 3 years difference	<6 years difference	<10 years difference	<15 years difference	unknown or > 15 years
Geographical	data from an adequate area	average data from a larger area	data from an area with a similar production structure	data from an area with a slightly similar production structure	unknown or different area
Technological	data from processes under study and company specific	data from processes under study for different companies	data from processes under study with different technologies	data from related processes and materials, same technology	data from related processes and materials, different technology

2.4.2.2 Life cycle inventory analysis (LCI)

The LCI is the second phase of a LCA and executes the plan that was set in goal and scope definition. Its mayor output is a list with the compiled and quantified inputs and outputs of the product system throughout its lifecycle, associated with the functional unit. This part can become a dominant of the work. The LCI data can be used on its own to understand the resource consumption, wastes and total emissions associated with the studied product system or to improve performance of production or product.

Collecting data

The collection of data is a key task of the LCI phase. Each unit process should be defined to avoid misunderstandings and the data collection should be described. An important information is whether the data was estimated, calculated or measured. It should be noted that the use of secondary material can lead to limitations in choosing allocation rules, cut-off-criteria, sensitivity and uncertainty analysis. Energy, raw material, ancillary and other physical inputs as well as products, co-products, waste but also releases to air, water and soil are the mayor categories for the collected data. The data is investigated in a sensitivity analysis and the system boundaries and streams can be refined, either broadened or narrowed, if data shows high or low significance.

During **data calculation**, collected data is validated and related to unit processes and the reference flow of the functional unit. As a rule of thumb, single streams that contribute to more than 5 % of the indicator result should assigned specific process data [48]. It is recommended to base calculations on actual production mixes [9].

Data validity can be checked for each unit process with mass or energy balance or other analyses of release factors. An additional way is the comparison with other data sources. Data gaps can be filled with justified estimations on sectoral level or calculations based on similar applications. If still lacking data, quantification can be qualitatively described. As a last choice, the value can be set zero which has to be clearly reported. In general, cut-off should be avoided as much as possible. In practice, not all data can be collected may it be due to non-accessibility or inadequate efforts. In any case, significance of the approach for missing data should be estimated.

For confidentiality reasons, data might be aggregated. In this case it must be avoided that the character of information is changed and the procedure needs to be described.

Allocation

In many cases, inputs and outputs need to be allocated to the different products. If possible, this should be avoided, for example by expansion of the product system. If it is necessary, physical relationships should be used. Sometimes other procedures like economic value of the product need to be used. This has to be described precisely.

Complexity increases if recycling or reuse is present. It might happen, that inputs and outputs during life cycle stages are shared by different product systems. In addition, reused and recovered material might not be an equivalent quality.

Special care is required for the definition of the system boundaries when recycling is executed. It is distinguished between closed loop systems (CLS) and open loop systems (OLS), depending on whether material is recycled within the product system or for other product systems. The allocation procedures are defined slightly differently. Closed loop allocation procedure is applied, when recycled material does not experience inherent changes of properties. Open loop allocation procedure is applied when it undergoes inherent changes. A CLS avoids allocation since secondary material displaces use of primary (virgin) material. In OLS recycling takes place into other product systems. Exemplary allocation rules are presented in Figure 2.22.

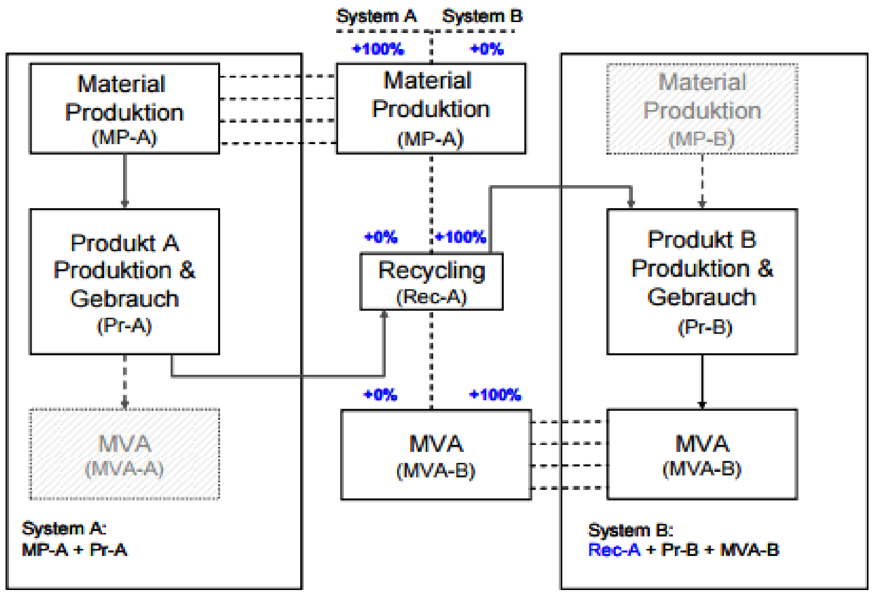


Figure 2.22: Scheme for 0% allocation of coupled systems with “disposal” of A in system B [49].

2.4.2.3 **Life cycle impact assessment (LCIA)**

The LCIA phase has the purpose to foster the understanding and to evaluate magnitude and significance of potential environmental impacts of the product system throughout its life cycle. The LCI results are linked to the impact categories. An adequate category indicator is defined and indicator results collected.

According to ISO 14044 [9] the LCIA consists of the three mandatory elements

- selection of impact categories, category indicators and characterization models
- classification: assignment of the LCI results to the selected impact categories
- characterization: calculation of category indicator results.

Each element can be defined and considered separately in the goal and scope definition, which also helps the quality assessment, critical review and transparency. Optional elements of the LCIA are normalization, grouping and weighting. This way, the executer of the study can bring in his own preferences and perspective.

The s**election of impact categories** should cover the relevant environmental issues related to the product system. The effects of activities in the technosphere on the environment are manifold. For a better awareness, a few categories should be mentioned:

- Global warming potential (GWP)
- Photochemical ozone creation potential (POCP)
- Acidification potential (AP)
- Eutrophication potential (EP)
- Human toxicity potential (HTP)
- Land use (LU)
- Primary energy from renewable materials
- Primary energy from resources
- Recyclability

The categories act in different scales ranging from global (GWP), to regional (AP) and local (POCP, EP and HTP).

The **characterization model** represents the environmental mechanism by describing the relationship between LCI results, category indicators and eventually category endpoint(s) and allows the determination of characterization factors. Figure 2.23 should help to understand this relationship and the terminology and gives examples for the impact category *global warming potential*.

At the starting point of the LCIA, LCI results are available in the form of elementary exchanges related to the functional unit. The values relevant for the selected impact category are assigned to it in the first step, the classification. In this case, gases are selected which contribute to the global warming, so called *greenhouse gases*. Carbon dioxide, carbon monoxide, methane, sulfur hexafluoride and many others contribute in different intensity to the impact category and are additionally caused in different amounts per functional unit. Therefore, they can be assigned a distinct category factor with which they score on the category indicator *infrared radiative forcing*. This step is called characterization. Optionally, the LCIA can include analysis of category endpoints. This could be coral reefs, forests and other biotic systems, temperature disturbances, weather phenomena and abnormalities and others. The environmental relevance of the model should be stated at least qualitatively in terms of how well it represents real situation for the impact category.

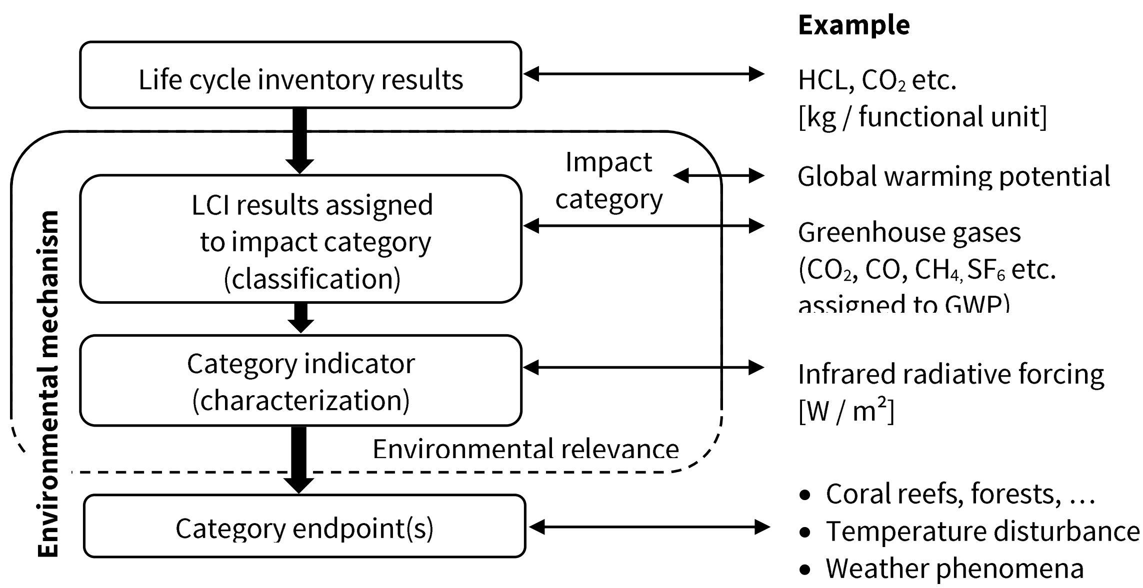


Figure 2.23: Characterization model in LCIA phase with example.

For a better understanding of the significance, uncertainty and sensitivity of LCIA results additional tools can be used: gravity analysis to find the data that has the most significant contribution, uncertainty analysis to determine the reliability of the results and sensitivity analysis to determine how changes in data and methodology impact on LCIA results.

2.4.2.4 **Life cycle interpretation**

The life cycle interpretation phase has the purpose to evaluate LCI and LCIA results with respect to the goal and scope definition in order to draw conclusions and elaborate recommendations by identifying, , qualifying, checking, evaluating and finally presenting them. It includes the following steps

- Identification of significant issues based on LCI and LCIA results
- Evaluation, including completeness, sensitivity and consistency check
- Conclusions, limitations and recommendations.

The interpretation also includes an evaluation of the choices made in the previous LCA phases.

Identification of significant issues is to include implications of the assumptions made, the methods used, and so forth for the preceding phases. The for necessary types of data are the results of preceding phases, methodological choices, value choices and role and responsibility of interested parties

During the **evaluation**, the results of the study should be presented in a way that the outcome of the study becomes clear and understandable to the audience. Completeness check assesses, whether all relevant data and information is available and complete. Sensitivity check assesses the reliability of the final results and how robust they are against the uncertainties. The consistency check assesses, whether assumptions, data and methods are consistent with the goal and scope definition.

2.4.3 Auxiliary tools

The software tool *Umberto NXT LCA* is chosen to support analysis, assessment and visualization of the LCA. The following steps are executed with the tool:

- Drawing of life cycle model or process map, consisting of processes, input and output places
- Specification of processes and activities with user-defined datasets or from ecoinvent database
- Calculation of the material and energy flows
- Execution of the LCIA
- Processing and visualization of results

Activities and processes can already be assigned to the different life cycle stages when creating the process map by placing them in the respective area along the cradle-to-grave path. Input and output streams will be automatically assigned to the respective stage, too. For the understanding of the graphs of the Umberto model that are shown in this study, the symbols are presented in Figure 2.24.

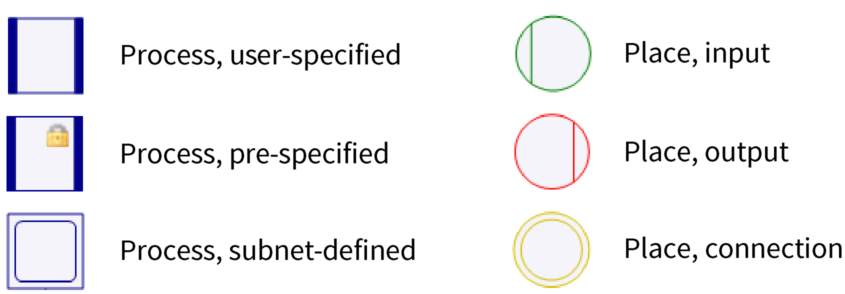


Figure 2.24: Symbols for processes and places in Umberto NXT LCA.

For the definition of processes, only the quantified relation between input and output streams is relevant, not the actual value. There is the possibility to specify the process manually with measured, literature or other data or to use processes from the database. The software provides over 4500 pre-specified datasets for upstream processes like the extraction of many raw materials and supply of energy, as well as downstream processes like end-of-life treatment [50]. It resorts to the ecoinvent database version 2.2 and 3, which is the most comprehensive database for LCI [51]. The methodology and other background information about the datasets are documented in the ecoinvent reports that are available online [52]. The GaBi database was not used for this study.

For calculation of the life cycle model all flows of the inventory are considered with their quantities and characterization factors for LCIA. The program uses the specified relationships between the flows to compute the actual flows with respect to the specified reference flow. This calculation delivers the LCI results.

Only streams that cross the system boundary, so called elementary exchanges, are assigned with a characterization factor. The intermediate flows within the system boundaries do usually not contribute. If all elementary flows are attributed with values for the selected impact categories, the program can run the calculation for the selected LCIA methods. For this study, the methods *cumulated energy demand* and *global warming potential* in a 100 years perspective (GWP100a) were chosen.

Results can be obtained in tables, which allow processing with other softwares. Microsoft Excel was used for further specific calculations and visualization. Umberto NXT LCA offers visualization with Sankey diagrams for material and energy flows and also for each of the “weighted impact flows” of predefined impact categories. This is helpful to understand how the several process streams contribute to the overall result. Additionally it is used for consistency check since streams that are not plausible become easily apparent.

2.5 LCA in wind power

This section should present findings from previous LCA studies as a starting point for estimations of the qualitative behavior and for later comparison and evaluation of the AWE results.

Typical life cycle stages and activities for a conventional wind plant are

- Raw material and manufacturing: prod. of components for turbine, foundation, substation etc.
- Installation: Transportation to site, installation of turbine, foundation, cabling, roads etc.
- Operation: electricity generation, maintenance, replacements, service
- End-of-life: Transportation from site, dismantling, scrapping, recycling, incineration, etc.

In conventional fossil fuel based power plants, production and combustion of fuel has 10 times higher impact on GWP than construction of its infrastructure [53]. For renewable energies this factor is missing and construction of plant becomes dominant factor. As shown in Figure 2.25 for a certain wind power plant it is typical that the significant environmental impacts occur after and particularly before operation, during production of raw material and manufacturing. The only cause for emissions during use phase is from maintenance and repair. If recovery of material or energy is applied after decommissioning, this energy or savings for subsequent processes can be credited to the wind plant. As a result, the last life cycle stage can have an contrary impact on the environment, lowering the overall indicator result (CO_2-equivalents).

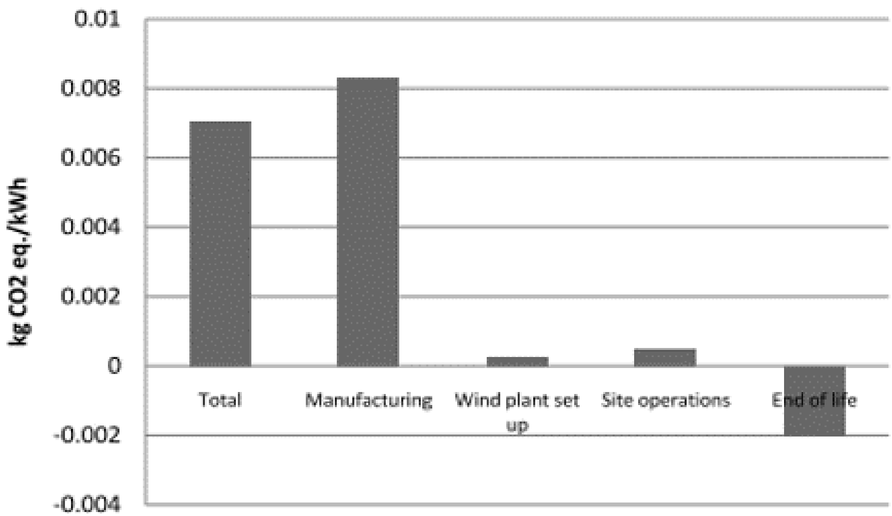


Figure 2.25: Category indicator results for a conventional wind power plant [54].

Figure 2.26 shows the relative contribution of the component groups of a 5 MW off-shore wind power plant to mass, cumulated energy demand and global warming potential. According to this result, the rotor causes 20 % of the categories` result, tower and nacelle 40 % each. Compared to their masses, the environmental effects of the rotor is highest.

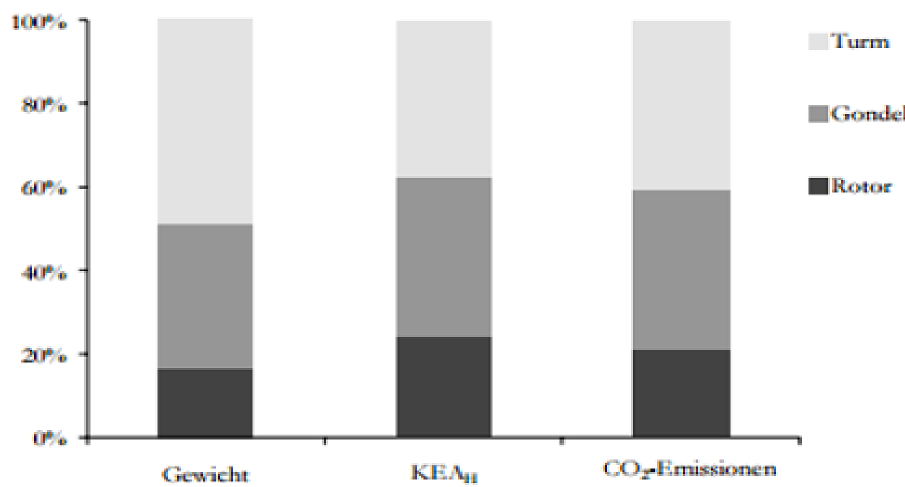


Figure 2.26: Contribution of component groups of a 5 MW off-shore turbine to mass, CED and GWP [55].

Figure 2.27 shows the relative contribution of plant components and also life cycle phases of a 100 MW plant consisting of 3 MW onshore turbines. It becomes visible that the towers account for the largest single contribution in most investigated categories (12 of 15). Gear and mainshaft could be considered in combination with nacelle as one component which dominated many categories. In the categories primary energy demand and global warming potential they have a contribution of around 20 % in the whole plant. Blade manufacture is particularly high in those two categories with around 20 % contribution, too. The tower accounts for around 35 %.

There is SF_6 in switchgears of wind power plants which is often not included in LCA of wind power [54], [56]. Care has to be taken in every specific case, whether this assumption is justified since the effect of SF_6 on climate change is 23,000 times stronger than that of CO_2.

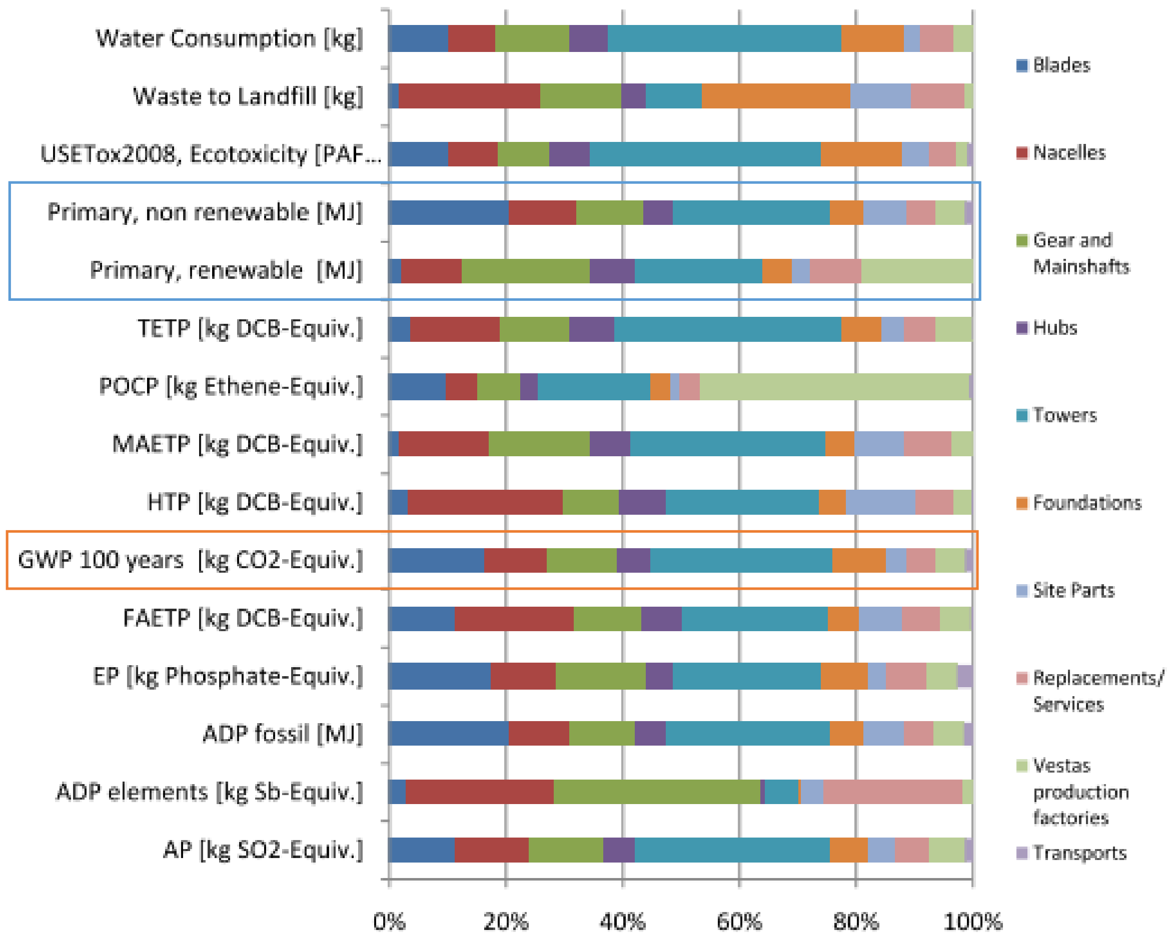


Figure 2.27: Category indicator results for a conventional wind power plant [54].

The different results in the range of environmental impact categories show that the same component can have very different impact in different categories. It should also highlight that choosing cumulated energy demand and global warming potential as impact categories in the study reflects only a small excerpt of the environmental burden.

In addition, results can vary significantly for the same technology and the same impact category. They are influenced by system boundary and level of detail of the model, rated power and actual energy production, recycling scenario or installation off-shore or onshore. Table 2.2 compiles data for global warming potential and cumulated energy demand adopted or calculated from different literature sources. The rated power of the turbines is between 1.5 - 3 MW. GWP ranges from 5 - 45 $g_{CO2\text{-}eq.}$/kWh. CED ranges from 54 – 648 kJ-eq./kWh. The wind speed that is underlying the calculations is indicated, too. The results for the 3 MW turbine [54] at 7 and 8 m/s show, how relevant the wind speed is. Maintaining all other parameters constant, the reduction by 1 m/s yields 23 % higher results. The differences in wind speed have to be considered when comparing the values. It is remarkable, that values that stated by companies

(Enercon, Vestas, Siemens) rank below average for GWP, capacity factors are positively estimated and plant sizes are rather high.

Table 2.2: Selected literature values for global warming potential and cumulated energy demand of wind turbines.

Source	**Turbine power in MW**	**Wind speed in m/s**	**GWP in $g_{CO2\text{-}eq.}$/kWh**	**CED in kJ-eq./kWh**	**Remarks**
Guezuraga [57]	2	7.4 (at hub, ca. 104m)	9.7	118	Includes two gear replacements
	1.8	6 (at hub, ca. 104m)	8.8	116	Gearless nacelle
Kaltschmitt [58]	2.5	4.5 (at 50m)	30	(128)	12.5 MW plant,
	2.5	5.5 (at 50m)	18	(77)	CED only from fossils
	2.5	6.5 (at 50m)	13	(56)	
	1.5	4.5 (at 50m)	31	(121)	7.5 MW plant
	1.5	5.5 (at 50m)	18	(74)	CED only from fossils
	1.5	6.5 (at 50m)	13	(54)	
Martínez [59]	2	n.d.	6.6	105	cf = 22.8%
Marheineke [60]	1	5.5 (at 10 m)	21	288	cf = 27%; backup and primary energy from wind excluded by recalculation
	1	4.5 (at 10 m)	45	648	
	1	6.5 (at 10 m)	15	216	
	1.5	5.5 (at 10 m)	19	288	
Siemens [61]	2.3	8.5 (at hub, ca 100 m)	5	76.6	46 MW plant
Enercon [62]	2.3	(medium)	8.7	100	
Vestas [54]	3	8 at hub (ca. 84 m)	7	120	cf = 43%; 100 MW plant
	3	7 (at hub, ca. 84 m)	8.61	148	
Vestas [56]	1.65	7.38 (at hub)	7.05	108	cf =40.8%; 300 MW plant

cf = capacity factor

3 Goal and scope definition

Following the LCA scheme presented in 2.4 this chapter defines the first stage, goal and scope of the study. It provides the plan for the subsequent LCA stages in the next chapters. A detailed description of the studied product system and its energy yield, the functional unit and system boundaries, as well as a description of the selected impact categories, data collection procedure and the assumptions is given in this chapter.

3.1 Goal of the study

This section describes the goals for carrying out the study and also the intended application and audience.

This study pursues multiple goals. First of all, the environmental burden by means of contribution to global warming and consumption of primary energy associated with generation of electricity with AWE systems should be estimated. In this regards, no scientific study in this could be found in literature as of now. The statements on environmental impacts of this technology are often based on intuition or common sense. Renewable energies are commonly considered as sustainable. However, considering the whole life cycle of a technology, resources are required from the environment and emissions are released to it. This study should give a first numerical estimation based on one specific system design.

Two, it is tried to evaluate whether developing this new technology would lower global warming potential of electricity supply. The numbers should be compared to other electricity generation technologies and the production mix. This information could help to assess how important R&D efforts for this technology are for climate goals for example.

Three, it should be estimated how long a AWE system needs to be operated until invested energy is recovered.

Four, the main contributors to environmental burdens should be determined, as well as the greatest potential for savings. The technology is still only in demonstrator stage. The early stage of technological maturity causes uncertainties to the assessment but at the same time holds the potential to consider the findings for an environmentally improved system design at an early stage. In particular, the effects of use and replacement of the tether should be investigated.

Decision-makers in politics (national and international) and finance might use this information for strategic and planning purposes, industry might use the information to assess their own system for improvement of its carbon footprint, in certification process and marketing and also the public might be interested in these particular aspects of the technology.

The LCA approach is chosen because it considers the selected impact categories holistically from cradle to grave. In that way it is avoided that environmental burdens are shifted from one phase to another outside of consideration or to other processes in the same phase. For example would the emissions in manufacturing of an electric vehicle and supply of electricity for its operation become transparent and could hardly lead to a designation like “zero emission car”. The LCA approach is also chosen because it allows consideration of single environmental aspects which lead to a simplification that makes the assessment feasible within the scope of this study. It is important to keep in mind that there is more parameters concerning the environment that what the study assesses and therefore the study does not aim to yield a final or general environmental evaluation. Another beneficial aspect of the LCA tool is the relative approach that makes it easier to compare the studied system to other product systems. Especially in the energy sector, environmental impacts from generation technologies can be related to the generated electricity as a common functional unit.

3.2 Scope of the study

3.2.1 Function and functional unit

The function of the investigated system is the generation of electricity. All energy and material flows are assigned to the generated electricity output. The functional unit denotes the quantified primary function that a product system fulfills. In this s study the functional unit is 1 kWh electricity that is delivered to the grid by an airborne wind energy plant under low wind conditions (IEC III).

Wind classification is specified in DS/EN 61400-1:2005 for wind turbines, which differentiates low, medium and high wind class designations. Supplement E details wind classes further. IEC III conditions were chosen since it is a very conservative estimate and a realistic scenario for early application of AWE since most sites with good wind conditions are not available anymore and because most likely AWE plants will not be installed at best sites until technology maturity is not proven. Compared to better wind sites, more facilities or more material is required to yield the same power.

Alternatively, 328 MW installed electrical power could have been chosen as functional unit, since power plants are usually indicated by their rated power. This approach is not followed in this study since actually generated electricity of different types of plants of the same rated power can differ significantly. In this way, specific characteristics of the technology like capacity factor, technical availability and other energy yield parameters are included in the consideration.

3.2.2 System boundaries

The study follows a cradle-to-grave approach. The product system and system boundaries for this analysis are illustrated in Figure 3.1. Elementary input and output flows of the product system, resulting from energy and material flows of the processes in the life cycle phases raw material acquisition, manufacture, installation, operation and maintenance, decommissioning and disposal, are calculated.

Raw material and Manufacturing are merged to one phase for practical reasons. For some components, better data can be found for those two phases combined. It is expected that the major contributions to the selected impact categories are caused here. It is shown in LCAs that this is the case for conventional wind energy and is assumed to be similar for AWE [54], [63], [64], [58]. The raw material acquisition includes the extraction and processing of resources from the environment for energy or material demand. Manufacturing includes the production of intermediate material, subcomponents and components of the AWE plant as defined in section 3.2.3. The production of the AWE plant is assumed to be only an insignificant fraction of the lifetime production of capital equipment. Production facilities are therefore neglected in this study.

Installation includes transportation from manufacturer to installation site by specific type of transport and distance, as well as excavations for cabling on site. Possible road construction and other erecting efforts appear insignificant and are neglected.

Operation, maintenance and replacement includes energy for launches and steering of the wing systems, daily transportation of staff to the site, oil exchanges over the plant lifetime. Exchanges of plant components with a lifetime lower than the plant are included and assigned to this phase. Also transportation for replaced material is included. Electrical losses are considered within the plant. Losses in the grid on the way to the consumer are not included.

Decommissioning and disposal are modeled with the cut-off-rule. All material is assumed to go to landfilling for which only transportation of waste is considered. In long term, degrading of waste has impact on waste and soil, but as of now this is not easily possible to model with current LCA tools [56]. In addition, the effects are considered to be insignificant in this case, since most material is inert. Recycling and reuse is thus not included in the analysis. This is expected to be a conservative approach since recycled or reused material or energy might be credited to the product system. Energetic recovery from incineration of plastics or replacement of virgin steel by recycled steel for example could lower the calculated overall environmental burden.

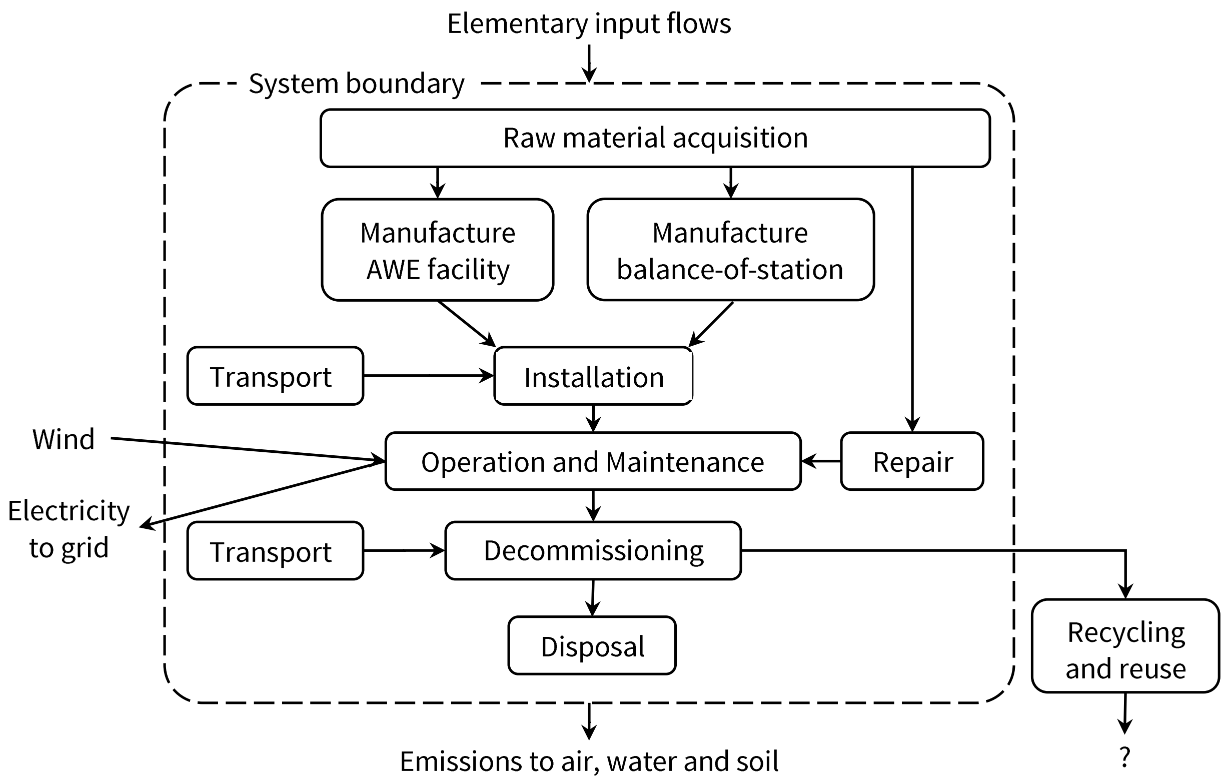


Figure 3.1: Schematic representation of the product system “AWE plant” and system boundaries.

3.2.3 Product system: AWE plant

The investigated product system in this study is a fictitious AWE plant that generates electricity in utility scale, which is of a size comparable to other generation technologies. The AWE farm delivers 300 MW to the grid and comprises 182 facilities of 1.8 MW rated (cycle) power each. This energy is expected at a wind speed of 7.4 m/s at “hub height”, which is the average operation altitude in this case. The plant has a lifetime of 20 years. The facilities are not build nor being developed in that exact design by any institution.

The design choices are considered as possible to become dominating design or to be a conservative choice for future systems with respect to the study results.

The facilities are ground based lift power generation systems of yo-yo type. As illustrated in Figure 3.2, each of the 182 AWE facilities consists of the 5 component systems

- Wing System
- Tethering
- Ground Station
- Launch System
- Landing System

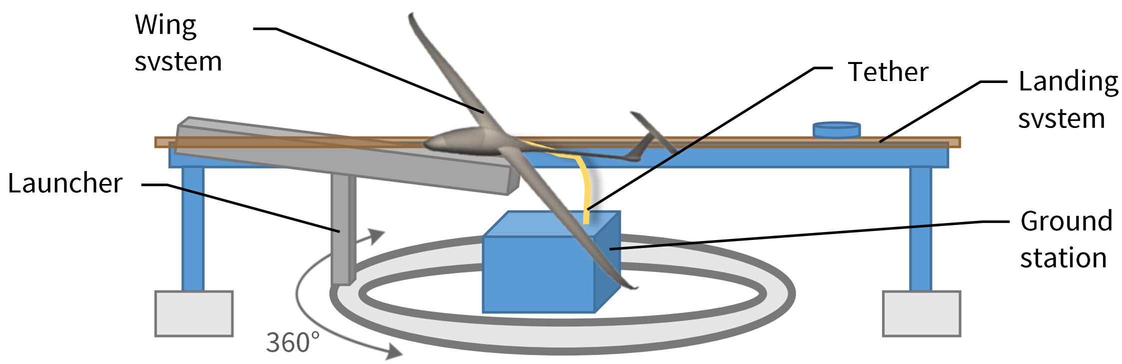


Figure 3.2: Schematic drawing of the studied AWE facility.

It was decided to separate the term ground station from launch system and landing system, since one is mainly state of the art technology and the others can vary considerably depending on design choices of the AWE developer. The foundation is part of the ground station and the landing system.

Additionally, the facility has a share of the balance-of-station components

- Internal cabling
- Energy storage (buffer)
- Hangar
- Control tower
- Transformer station
- External cabling (connection of the wind farm to grid).

The **wing system** is automatically steerable and has the purpose to generate aerodynamic lift. It comprises a unmanned glider-like carbon fiber reinforced polymer structure, equipped with actuators for steering, ram-air-turbine and battery for onboard electricity supply and auxiliary propulsion as well as several sensors and other components.

The **tethering** is lightweight and transmits the aerodynamic forces as tensile forces to the ground. It basically consists of a coated ultra-high molecular weight polyethylene rope.

The **ground station** handles the tether and converts the mechanical power to electrical. It consists mainly of a winch, a gearbox, generator, converter, a steel structure, foundation and others.

The **landing system** allows safe retrieval of the wing system from any direction. It consists of a steel structure with wooden deck and a foundation. Additional equipment for deceleration the wing system is mounted on the deck.

The **launcher** should launch the system independently of the wind speed and direction. It consists of a pneumatic catapult that can rotate 360 ° on a rail track.

The facilities are spaced 400 m from each other and are interconnected with an internal cabling. The intermittency of electricity generation is smoothened mainly by synchronization of the facilities. Additionally, 1 % of the plant power is buffered by a flywheel. For maintenance, a two transportable tent structures are considered. Operation is monitored from a small cottage on the farm. The internal cabling leads to a power transformer, that transforms electricity from medium to high voltages for transmission. The plant is assumed to be far from the grid, requiring 50 km of external cabling. Roads and their construction are not considered since simple dirt roads are probably sufficient and their contribution is expected to be insignificant. Figure 3.3 shows a schematic drawing of the AWE plant to visualize main data.

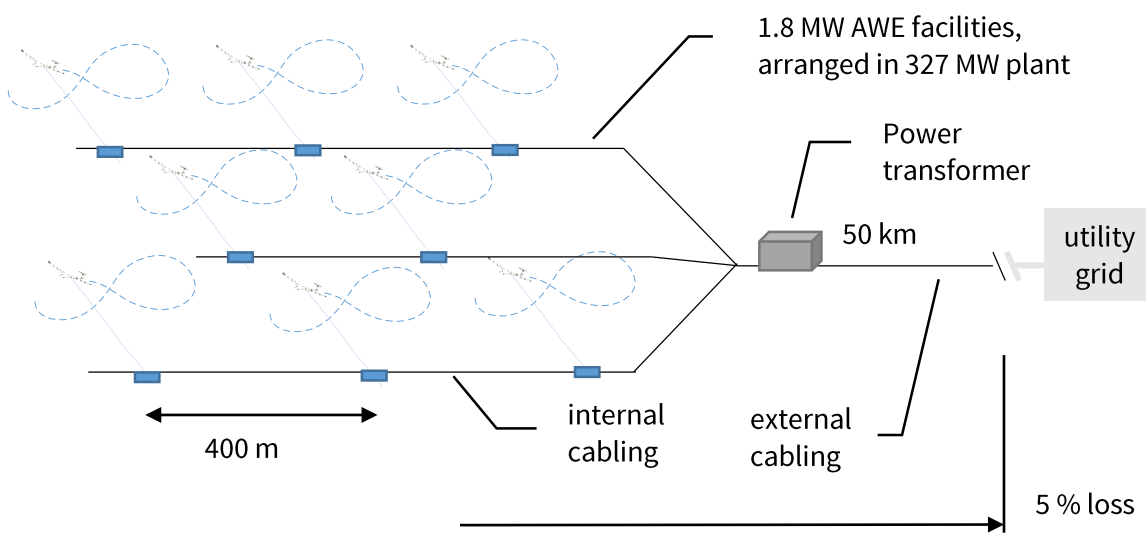


Figure 3.3: Schematic drawing of the studied AWE plant.

3.2.4 Energy yield estimation

The installed generator has an installed power of 2.5 MW. Due to the pumping cycle operation of the AWE facility, the average electricity production is lower. It is assumed, that 1.8 MW can be delivered continuously by one facility. The rated power of the AWE facility is thus $P_{fac} = 1.8\ MW$. Losses of 5 % between the facilities and after the power transformer are considered. The farm efficiency is thus $\eta_{plant} = 0.95$. With its technical specifications the wing operates at the site defined conditions of IEC III equivalently to full load in 3592 hours a year. The capacity factor is $cf = 0.41$. The annual energy production is computed as

$$AEP_{fac} = P_{fac} \cdot 8760 \frac{h}{y} \cdot cf \cdot \eta_{plant} = 6{,}142\ MWh/\mathrm{y} \tag{3.1}$$

The 182 facilities have an installed power of $P_{plant} = 327\ MW$. In its lifetime lt_{plant} the AWE plant produces a cumulated energy of

$$EP_{plant,20y} = P_{plant} \cdot 8760 \frac{h}{y} \cdot lt_{plant} \cdot cf \cdot \eta_{plant} = 22{,}355{,}555\ MWh. \quad (3.2)$$

3.2.5 Impact categories

For this study, two categories are selected that are assumed to reflect the most significant environmental issues related to electricity production from AWE, global warming potential and cumulated energy demand. This should not imply that other categories are insignificant but is chosen to limit necessary efforts and to address most discussed issues associated with electricity generation, where there is a good database to compare results of this new technology to.

This study does not go as far as to assess the endpoints, such as loss of biodiversity, damage to human health, etc. caused by these impacts but considers midpoints of the cause-effect-chain. The results are not ranked nor normalized. There is no scientific consensus on how to weigh the different impact categories against each other. There is a subjective component on how to weigh for example severity of effects on global warming against effects on human toxicity.

3.2.5.1 Climate change

Climate change or global warming is a consequence of increased radiative forcing on earth, enhanced by the ability of several gases in the atmosphere to reflect a part of the heat radiation to the earth. The intensity of contributing to this effect varies from gas to gas, cf. Table 3.1. The concentration of those gases in the atmosphere is decisive for the magnitude of the effect.

According to the explanatory illustration in Figure 2.23, the indicator for the category climate change is infrared radiative forcing [W/m²]. The LCI results contain masses of greenhouse gas emissions to the atmosphere. The characterization factor is mass of carbon dioxide equivalents ($kg_{CO2\text{-}eq.}$) to consider global warming potential in a timeframe of 100 years. It includes an consideration for the magnitude with which emissions contribute to GWP equivalently to carbon dioxide which is different for each greenhouse gas. The factors to convert GWP of a greenhouse gas to CO_2 equivalents is called characterization factor. In this study the values found be the intergovernmental Panel on Climate Change (IPCC) are considered. In Umberto, elementary flows are associated with characterization factors according to the CML2001 method as described in [65]. The method CML2001 itself is defined in [46]. Thus, the calculation of the model returns the indicator result in mass of carbon dioxide equivalent with respect to the functional unit, $kg_{CO2\text{-}eq.}$/kWh.

Table 3.1: Global warming potential for selected substances in a 20, 100 and 500 years horizon [66].

Substance	Formula	Lifetime [y]	GWP20	GWP100	GWP500
Carbon dioxide	CO_2	variable	1	1	1
Methane	CH_4	12±3	56	21	6.5
Sulphur hexafluoride	SF_6	3,200	16,300	23,900	34,900

3.2.5.2 Cumulated energy demand

The cumulated energy demand represents the “energy intensity” of a product. It can serve to assess and compare the demand for primary energy throughout the life cycle of a good or service to achieve a certain function.

As of now, there is no standardized way for the implementation of this method. For this study, the approach as described in [65] is used as a basis but the split up in 8 categories of source (3 for non-renewables, 5 for renewables) are summarized in this study

An interesting measure is the energy payback time EPT. It can be computed as the ratio of cumulated energy demand CED for manufacturing, operation and disposal of the power plant and the total energy $E_{gen,plant,life}$ that is produced over the plant lifetime, cf. equation (3.3). In the study the this magnitude comprises a reduction by electricity demand for operation of the plant and losses. Alternatively, the energy for operating the plant could have been taken from the grid, whereas whole production is fed in. It should be highlighted that in this study, CED includes both, fossil and renewable energies. Other definitions of EPT might consider only non-renewable energy demand.

$$EPT = \frac{CED}{AEP_{plant}} EP_{plant,lt} \tag{3.3}$$

3.2.6 Data requirements, collection, quality, constraints and allocation

For the standard components that are used, supplier data of specific sites is preferred. This is the case for example for power transformer, generator and cabling. Since it is unclear how the future system(s) on the market will be designed, the gathered AWE-specific data is of more general type than of a specific manufacture site. Average production values, standard processes for intermediate works and common characteristics are assumed. Thus, data for standard components should be from measurements and calculations. Data for AWE-specific components can be from literature values of similar applications or expert consultations or other type of sound estimations.

The procedure for data collection starts with the creation of a component tree for the AWE plant as represented simplified in Figure 3.4. Data for material type and mass is researched or defined for all items on the list, as well as information on their production process and associated emissions with respect to the selected impact categories. If not indicated, the respective data for material type and manufacturing is taken from *ecoinvent* database. The following d**ata sources** are used:

- Consultation of potential industrial suppliers
- Ecoinvent database v2.2 and v3 and respective reports
- Industry associations (world steel association)
- University experts for different materials
- Scientific literature
- Environmental Declarations according to ISO 14025, commonly called Environmental Product Declarations (EPDs)
- Data sheets
- (Material) safety data sheets ((M)SDS) / product safety data sheet (PSDS)
- Technical sales documents (TSD)
- Environmental statements

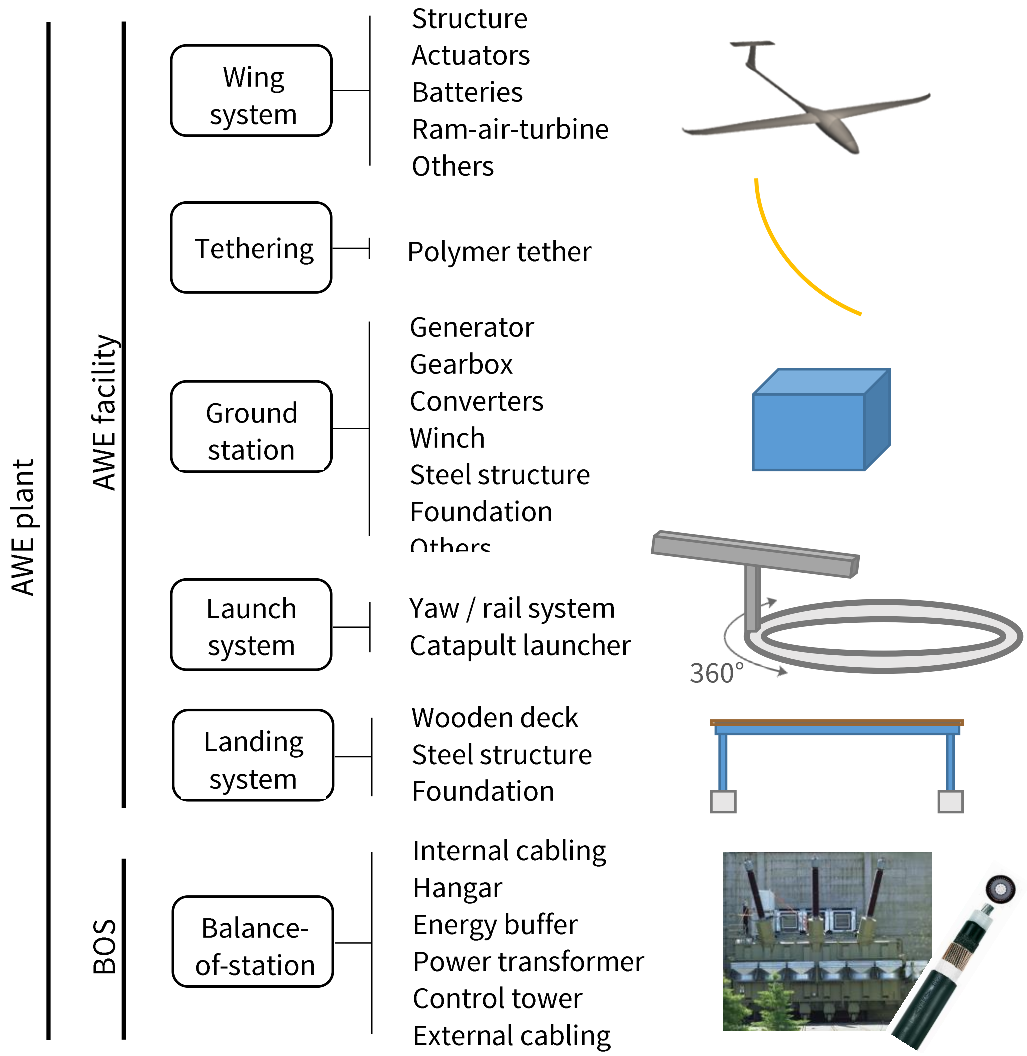


Figure 3.4: Component tree of the studied AWE plant.

The study is conducted for the operation fictitious AWE plant of 300 MW with 182 AWE facilities as described in section 3.2.1. **Technological coverage** is limited to the described product system. Other AWE systems designs and site conditions can yield significant different results. The data might be a helpful starting point for estimations and transfer for other systems. **Temporal coverage** is limited since strong improvements in production processes of modern material like carbon fiber reinforced polymers, and particularly improvements in design and efficiency of AWE systems can be expected within a few years.

The g**eographical coverage** is given for Europe with some limitations. For the study, a fictitious site was chosen. The purpose is to give a likely realistic case for central Europe rather than a particular location. Distance between manufacturer and installation site are 400 km on land. Some datasets are valid worldwide, others are particular for certain countries like the electricity supply. Also the plant design can vary in other locations, e.g. grid connection.

A **cut-off criteria** was applied to include 99 % of mass and energy collect 99 % of mass with type and to assume same material composition for rest.

Since the system is not yet constructed and there is only very little experience with demonstrator versions, broader assumptions need to be done and the assessment needs to be updated with probably rapid technological developments.

The only product of the product system is electricity. **No allocation** between different streams is necessary and all environmental exchanges are assigned to the generated electrical energy.

Following the choice of application of the cut-off-rule, the recycling is handled with the open loop allocation procedure. All occurring exchanges in the context with recycling, recovery or reuse are assigned to a different product system, which uses the decommissioned material.

3.2.7 Assumptions

As of now, system properties like design, energy yield, lifetime and so forth are based on assumptions and have to be iterated in future. Data for operation, maintenance and repair entails high uncertainties, since there is almost no experience available worldwide with operation of AWE facilities. Information from similar applications is applied, where possible or estimated.

It is assumed, that viable future commercial AWE systems could have environmental burden (wrt the selected impact categories) at least as good as computed. The LCA is designed to yield a rough estimation for environmental burden of AWE systems and is executed for a fictitious AWE system. Thus, all data are calculated not for a real system but representatively for a system design that seems promising. Consequentially data for material, processes, energies, distances and so forth are based on conservative or likely assumptions for assembly and installation in central Europe.

The generated electricity is assumed to be comparable to electricity from any other generation technology. In a specific case it should, however, be assessed if the quality is really the same. It can for example differ in stability of its properties (frequency or voltage) and geographical or time-related coherence of supply and demand.

Data on cabling and electrical system of the plant is assumed to be identical to conventional wind power plant of the same size.

4 Life Cycle Inventory analysis

In this section the data for the calculations are presented and explained. The structure follows the life cycle phases. After a brief comment on *raw materials and manufacturing* in general, separate sections for all component systems are presented, followed by the LC phases *installation*, *operation, maintenance and replacements* and *decommissioning*. Particular focus is on raw material acquisition and manufacturing. Figure 4.1 shows the main net of the Umberto-model where the LC phases and their top-level processes can be seen. It can serve as an overview of the sections in this chapter.

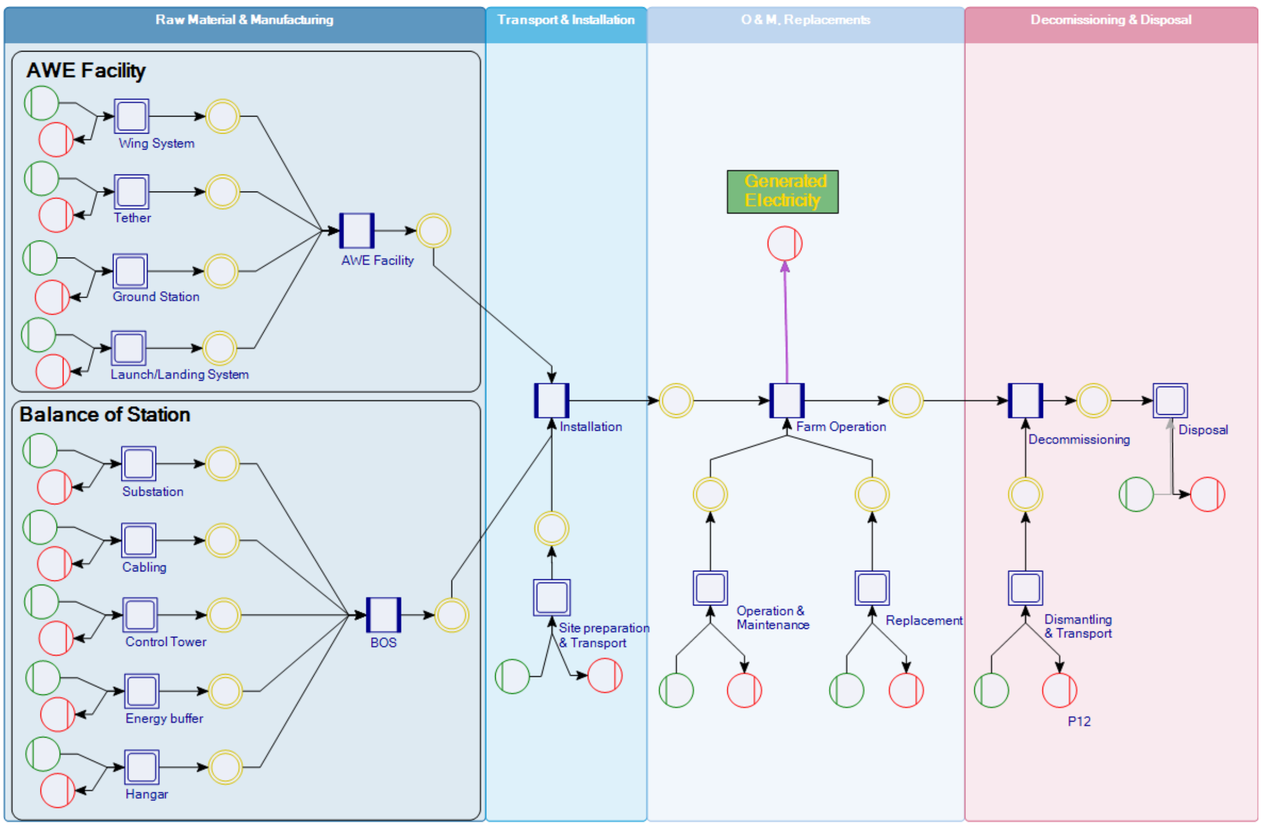


Figure 4.1: Main net of the AWE plant model in Umberto.

4.1 Raw material and manufacturing

Raw material acquisition includes transportation of resources to the raw material supplying plant but not to the manufacturing site. If not indicated differently, a virtual manufacturer location was chosen 400 km from the AWE operation site, from where the parts are transported to the AWE plant. Further information on the raw material and production processes is presented in the respective sections on the component systems below and if no other source is indicated, from the ecoinvent reports on

- Metal processing [67]
- Metals [68]
- Plastics [69]
- Transport [70]

and other reports available on the same source.

4.2 Wing system

The wing is remotely controlled and is able to launch, fly in a defined trajectory and land automatically. The aerodynamic shape is designed for high lift to drag ratios since its main function is to generate high tensile forces in the tether. Thus, a wing with a rigid structure was chosen that can bear high wing loadings in operation and during landing. The wing also comprises core material, some electronics, sensors and mechanical equipment. The weight is 2,500 kg and the lifetime is assumed to be 10 years. The transport of the assembled wing system from manufacturer to the site is modeled with large size lorry (>32 t).

The **structure** is made of the composite carbon fiber reinforced polymer (CFRP). The binding material or matrix is an epoxy resin and carbon fibers are chosen as reinforcement material for its comparatively high strength at low weight, as is trending in aerospace. Research shows that composites are up to 35% lighter than aluminum and 60% lighter than steel but also consumes between 14 [71] and 4.6 times [72] more energy in production than conventional steel. Figure 4.2 compares fatigue and mechanical strength of different composites and metals. To replace expensive resin, fillers are often added. Another purpose that is also pursued with additives is the improvement of physical and chemical resistance, manufacturability and performance of the resin [10]. For the sake of simplicity, it is assumed that all material is resin or carbon fiber, which should be a conservative approach for the energy intensive production of carbon fiber.

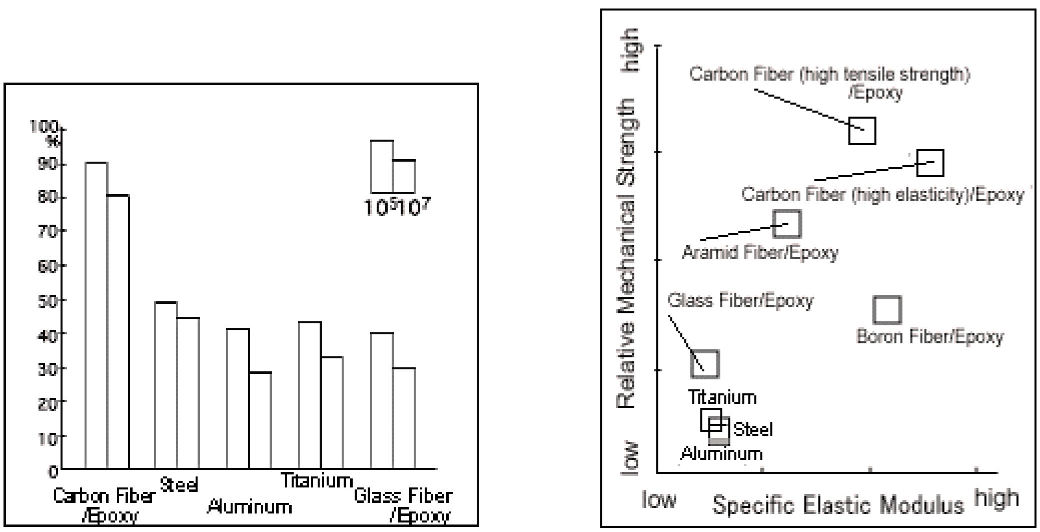


Figure 4.2: Fatigue resistance (left) and mechanical strength (right) of different composites and metals [73].

For structural applications, thermoset resins are used. It hardens permanently when cross-linked irreversibly when curing at elevated temperatures. The used raw material is liquid epoxy resin.

Strength and stiffness of the composite are determined by the reinforcement. Amongst carbon, aramid, glass and natural fibers, carbon fiber have highest strength and is resistant to high temperatures and corrosive environment and is little moisture sensitive. Downsides are its brittleness and high cost. Carbon fiber production via PAN was chosen over rayon or petroleum pitch since it is the most common industrial process [74]. The source material for PAN type carbon fibers is the acrylonitril. It is polymerized to polyacrylonitriol (PAN) resin. Acrylic fiber is spun and oxidized and finally carbonized to carbon fiber of high tensile strength [73]. Polymerization and carbonization require main amount of heat and electricity.

As composite manufacturing process, injection molding is chosen, which follows the conservative approach. Other processes like autoclave, pultrusion, resin transfer molding and sheet molding compound are probably associated with lower environmental burden [75]. A supplier suggests to use medium temperature molding for light aircrafts and UAVs [76]. Before mass production, manual processes are also very likely.

CFRP: A study on CED and GWP of different carbon fiber source material and CFRP production methods found gives insight in the effect of production choices [77]. The study found for the CFRP production scenarios

- 234 MJ/kg for virgin CF/EP (286 MJ/kg for the virgin CF with a fraction of 69.2 %–wt., 76 MJ/kg for thermosetting epoxy (EP) and 13 MJ/kg for resin transfer molding
- 155 MJ/kg for virgin CF/PP (286 MJ/kg for the virgin CF with a volume fraction of 46.2 %–wt., 24 MJ/kg for thermoplastic propylene (PP) and 10 MJ/kg for preform matched dying
- 23 MJ/kg for recycle CF/PP (286 MJ/kg for the virgin CF with a volume fraction of 46.2 %–wt., 24 MJ/kg for thermoplastic propylene (PP) and 10 MJ/kg for preform matched dying) with worse mechanical properties and
- 36 MJ/kg for a hybrid of recycled and 40 %-vol. CF/PP.

Recycling energy intensity of CFRP was 15 MJ/kg, the matrix is not recycled. If applied in AWE, the different weights and impact on energy yield have to be considered, too.

A more recent study literature study from 2012, found a cumulated energy demand and greenhouse gas emissions of 76-137 MJ/kg and 4.7-8.1 $kg_{CO2\text{-}eq.}$/kg for liquid epoxy, 286-704 MJ/kg and 22,4-31 $kg_{CO2\text{-}eq.}$/kg for PAN based carbon fiber and for injection molding 21.1-29.9 MJ/kg and 0.5-1.2 $kg_{CO2\text{-}eq.}$/kg [75]. The respective average value is chosen and a ratio of 43.4 kg carbon fiber per 31.4 kg epoxy resin.

For the calculations an average of the literature study of 495 MJ/kg and 26.7 $kg_{CO2\text{-}eq.}$/kg is used for the carbon fiber and data from ecoinvent for liquid epoxy resin and injection molding. Considering the range of available data that can be more than factor 10 lower, this is considered a conservative choice.

As **core** material Nomex could be used, which is the trading name of a meta-aramid. It is a heat and flame resistant fiber that is also widely used in aircraft construction, such as Airbus A380, in honeycomb structures for its low weight and non-corrosiveness as a textile but stiff characteristics. Its chemical structure is similar to nylon. The trivial name is poly(m-phenylen-isophthalamid).

In the model, manufacturing of nylon 6-6 was chosen as an equivalent process from ecoinvent 3.01 database since chemical structure of poly(m-phenylen-isophthalamid) and nylon 6-6 is similar and both are manufactured in similar processes, polycondensation. Production of 450 kg nylon 6-6 is considered per wing [78], [79].

The **coating** provides the airfoil with good surface properties against environmental influences and for the aerodynamic properties and also protects the structure from lightning due to its high conductivity. An epoxy-based polymer based solution is used for that, modeled with 85 kg liquid epoxy resin per wing. The solvent can be water, methyl-ethyl-ketone or methanol. It is, as other possible constituents as a heat-triggered curative, proprietary additives, and a conductive filler [80],estimated to be insignificant. Also the curing is neglected, which could be done at low/medium heat, for 30 min at 50 °C and 2 hours at 100 °C.

The **glue** is modeled with 100 kg of polyurethane per wing.

Hardener was neglected within this study for its small flow of mainly methyl ethyl ketone peroxide (30 %) and 2,2,4-Trimethylpentanediol- (70%).

Electronics and sensors are represented in the model with the ecoinvent dataset "electronics production for control units" with 25 kg in triple execution.

Batteries inside the wing structure are required for steering and auxiliary propulsion during launch and low wind conditions. Looking at the rangone plot for different storage options, cf. Figure 4.3, it becomes evident, that lithium-based batteries allow greatest amount of energy stored per mass of storage medium. Predefined data for rechargeable Li-ion batteries is used for a 15 and a 75 kg batteries.

Onboard mechanisms are considered with a permanent magnet generator of 25 kg for propulsion from literature data [82], a ram air turbine which was modeled with 20 kg of ecoinvent dataset for electric scooter motor and an actuator system of 5 kg of the same dataset and 145 kg of hot rolled steel.

5 kg of additional steel for miscellaneous like screws and 25 kg of high density polyethylene for bridle system is included.

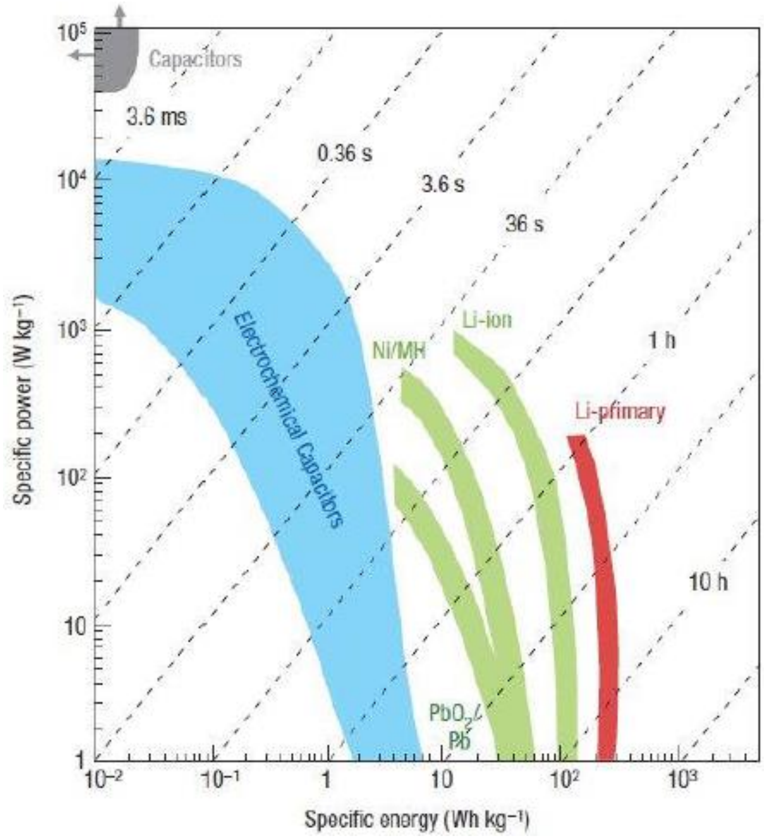


Figure 4.3: Rangone plot plotting specific power versus specific energy for different storages [81].

4.3 Tethering

The tether must be lightweight and low drag and not only suspend the kite but transmit extreme tensile forces. It must bear the combined load of pulling from the kite and bending over the winch when reeling out. As almost all developers do, a ultra-high molecular weight polyethylene (PE-UHMW) fiber is chosen for the tether production. The lifetime of the tether is assumed to be 10 years in the part that is bend on the winch only when launching or landing and 2 years for the part that is permanently winched in and out during operation. This is above today´s tether lifetime but according to several experts these numbers seem realistic, since due to the novelty of stress situation on the tether, new R&D activities might lead to significant improvements in the coming years. Additionally, 1 tether for each facility is added for unforeseen events destroying the tether once in a plant lifetime. Since there are rope manufacturers close to Northern Europe shore, a transport distance of 100 km by lorry of up to 7.5 tons is modeled.

The tether is constructed from several straits that form the core, which is enclosed by a mantling and finally finished with a coating.

The coagulated polyethylene that is used for production is first processed to filaments in the wet spinning process which is an extrusion from a dissolved state in a solution of 100 % anhydrous sulfuric acid through a spinneret into a nonsolvent coagulating bath [83]. Afterwards the fibers are drawn to achieve better properties like higher modulus and less extension at break. Most production is then crimpled, cut and balled for textile industry [78]. For tether production usually different companies twists the yarns, braid the twines and strands and finally the tether from those filaments by twisting and braiding [35]. The construction of the tether has a significant impact on several properties such as tensile strength, bending resistance, drag and noise. For further desired properties, such as limited abrasion, UV resistance, lower water absorption, and longevity in general, the tether is treated with a special coating. This makes up around 10 % of the final weight [84].

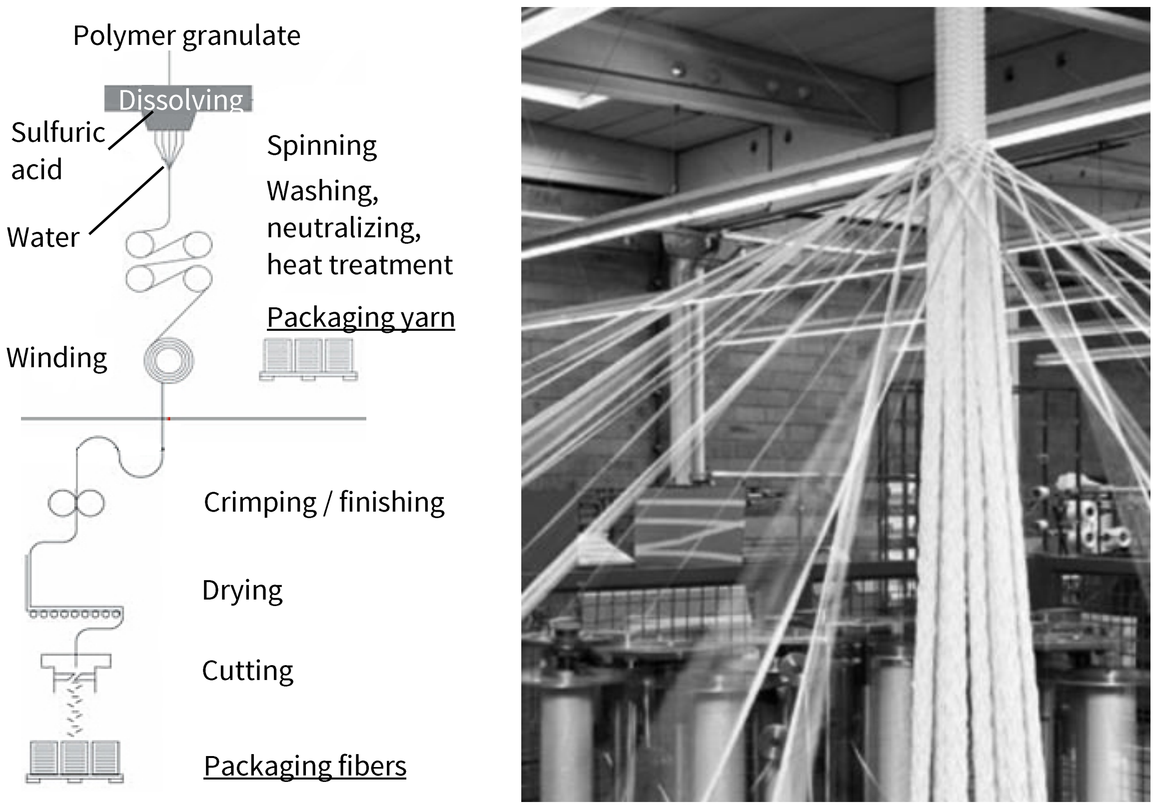


Figure 4.4: Process flow diagram for PE-UHMW fiber production from monomers (left) [85] and construction of the tether [33].

Little data is available on the environmental impacts of tether or rope production. In a similar application, fiber production accounts with over 80 % for the biggest share of GHG emissions of the product [86]. Therefore the choice of fiber material determines the results to a large extend. CO_2 emissions associated with the production of 1 kg PE-UHMW fiber notably lower than for comparable fibers [87].

The production of 1 kg vest made of Dyneema fiber is associated with approx. 16 $kg_{CO2\text{-}eq.}$ [86]. According to ecoinvent database the production of the PE-granulate contributes with approx. 1.95 $kg_{CO2\text{-}eq.}$to this number. A supplier statement confirmed this number [88]. Assuming that 10 % of the energy is thermal needed for heating and 90 % for electricity in the Netherlands, it can be calculated that around 85 MJ are provided to process 1 kg of granulate with this GHG emission. Plaiting of the tether is assumed to be insignificant and is neglected. The uncoated tether is modeled with a weight of 450 kg per facility.

The **coating** itself accounts for 10 % of the final tether mass or 45 kg and is made from a thermoplastic polyurethane. The ecoinvent dataset for polyurethane was used. Further energy for drying (microwave, infrared and hot air heating) and drive mechanism is needed. The required energy is estimated with equation (4.1), which is scaled for the required tether diameter from measured data up to 20 mm diameter from TU Chemnitz [89]. The density of the tether is assumed with 826 kg/m³ [84] resulting in a tether length of about 500 m for a tether diameter of 37.5 mm. 271 kWh of electricity are modeled with Dutch electricity mix from ecoinvent database.

$$E = 8{,}583\ \text{kWh} + 67{,}4\ \text{kW}*(0{,}5666\ \text{h} + 0{,}006666\ \text{h/m}*L) \tag{4.1}$$

E	Required electrical energy	[kWh]
L	Length of the tether	[m]

A cleaning step is usually executed in a solution of water, acetone and ethanol (1:1:2) which can be regenerated. This step is neglected in the study.

4.4 Ground station

The ground station has the function to convert the tensile forces from the tether into electrical energy. This is done mainly with state-of-the-art technology. Only the winch is of particular big diameter.

The **winch** stores the tether and converts the linear motion of the tether into a rotation. The big diameter is necessary to lower bending stress on the tether. It consists of a drum and structure, consuming 5,300 kg of low alloyed steel and around 7 kg alkyd paint. For the processing, section bar rolling of 1,000 kg, sheet rolling of 1,300 kg, average of metal working and 20 m welding are considered as defined in ecoinvent. Steel was chosen, since it is the most common material for winches and easy to process. The big mass of the rotating drum might cause difficulties in precise and fast operation. It is possible that CFRP or other high strength material with lower weight will be applied. This could lead to a higher environmental impact, so in this case state of the art was chosen over the conservative approach.

Alkyd paint / enamel is estimated to yield 6m²/l [90]. Only the alkyd production is considered in this study, the solvent is neglected.

The **generator** converts the mechanical power of the winch to electrical power and can be operated as an electrical motor to operate the winch to reel in the tether. Both functions could possibly be executed by different machines with higher efficiency because of the different rotation speeds but lead to more material and investment cost. The rated power of the generator must be greater than the rated power of the facility to compensate for the time without generation plus the required energy during retraction phase. It is assumed that a 2.5 MW generator is required to deliver 1.8 MW continuously.

A permanent magnet generator or asynchronous induction machine represent viable concepts for this application. It was decided for the latter since space requirements are not an issue for the AWE ground station, it´s common technology and it´s likely to be in line with the conservative modeling approach since a gearbox is needed additionally. To assess environmental issues associated with permanent magnet generators like acquisition of rare metals and energy consumption for manufacturing of permanent magnets are beyond the scope of this study.

Data is taken from the environmental product declaration of generators of AMG series from the ABB Automation factory in France [91]. CO_2-equivalents is linearly interpolated with the rated powers of AMG450 (900 kW) and AMG 630 (4300 kW) for the installed generator power of 2.5 MW. CED is reconstructed with indication for electrical and heat energy consumption. Separate models for both generator types are modeled in umberto with the material composition and supply for heat and electricity from the respective country where manufacturing takes place according to the EPD. The resulting CED from the simulation was interpolated as the GWP. Thus, and 50,978 $kg_{CO2\text{-}eq.}$ are modeled as elementary flow of carbon dioxide on the output and 439,117 MJ-eq. inserted in the main model introducing an input stream of hydropower of the respective energy on the input side.

It should be highlighted that electricity mix at this plant includes 74.4 % hydropower and 14.3 % nuclear which leads to considerably less GHG emissions than in European average. It was chosen not to model the generator with the listed input materials but to take the stated indicator results. This is considered to be more precise since own modeling brings further uncertainties, especially for CED since resource requirements for uranium for example are rounded to 0.00 kg per MW rated power but still nuclear power covers almost 75 % of the electricity demand.

Materials are considered for computations of overall material consumption. The generator has a weight of 12,700 kg and consists of electrical steel (55 %), other steels (36.5 %), copper (6.1 %), insulation material (1.3 %), impregnation, paint and solvent. The transportation is considered with 700 km by train and 200 km by lorry from the manufacturer site indicated in the data source.

Dismantling of the generator is not considered in the study but is commented here for completion. By removing the bolts, frame, bearing, housing, covers and fan are made from structural steel and can be recycled separately. Stator and rotor contain a considerable amount of copper which can be separated in a proper heat treatment process, where the organic binder materials of the electrical insulation are gasified. Mainly O_2-, CO-, CO_2-, NO_x-, C_xH_y-gases and microscopic particles are released. The oil from the lubrication system is a hazardous waste. All insulation material can be handled as a land fill waste [92].

In the chosen design, a **gearbox** is necessary to convert the low rotation speed of the winch to high rotation speed of the generator during traction phase and vice versa during retraction. AS a reference model, one of the smallest version of the Bosch Rexroth REDULUS GPV-D series [94] was analyzed, which is illustrated in Figure 4.5. The model 530 D works with conventional wind turbines generators of 2.5 MW rated power and has a weight of 21,600 kg [95]. The material is estimated downscaled from to a supplier statement for a 5 MW turbine [64]. It is 42.6 % 18CrNiMo7 for gears and shafts, modeled with the chromium steel dataset, 45.9 % cast iron for the casing and 11.5 % low alloyed steel for bearings and others. The steel processing is considered with average metal working for steel products.

Figure 4.5: AMG induction machine [91] (left), gearbox Redulus GPV-D for multi-megawatt turbines [93] (middle) and exemplary winch (right).

The **Converter** adapts the output frequency of the generator to the desired frequency. The converter ACS800-07-0750-7 by ABB was considered for the studied system. The ACS800 series handles a power range from 1.1 to 5,600 kW. Following a similar process as for the induction engine, the data from its environmental product declaration [96] is scaled from 630 to 2,500 kW for GWP and a separate model in umberto for the converter was implemented to obtain the CED. This is considered as a conservative estimation since environmental effects per rated power tend to decrease with product size. For GWP 14,700 $kg_{CO2\text{-}eq.}$ are included and 133,772 MJ-eq. CED. The lifetime is 15 years at 5,000 hrs of operation a year and therefore needs to be replaced once.

The converter weighs 3,310 kg and consists of steel (51.9 %), cast iron (16.1 %), copper (18.3 %), Aluminum (9.2 %), polyethylene (1.9 %), fiberboard (1.2 %), alkyd paint and epoxy resin.

The **foundation** distributes the weight of the ground station to the ground according to its bearing capacity. It consists of concrete and reinforcing steel. The amount of concrete is roughly estimated with the simplified equation (4.2) to 6,310 kg(4.2). The values for typical soil in Europe are chosen as 0.7 m depth to prevent lifting from freezing of groundwater, a bearing capacity of 150 kN/m² and the density of concrete is 2385 kg/m³ as defined in ecoinvent database. Per m³ concrete 100 kg reinforcing steel are considered, resulting in 265 kg. For foundation and sole plates high cement content are used. For this study, the respective dataset from ecoinvent was used with a density of 2,385 kg/m³ was used, consisting of cement (325 kg), water (180 kg), gravel (1,880 kg) and considering wastewater treatment.

$$V = \frac{m\,SF}{\frac{\sigma_{zul}}{h\,g} - \rho_c} \tag{4.2}$$

V	Required volume of concrete	[m³]
m	Mass	[kg]
SF	Safety factor	[-]
σ_{zul}	Bearing capacity of soil	[N/m²]
h	Depth of foundation	[m]
g	Gravitational acceleration	[kg m/s²]
ρ_c	Density of concrete	[kg/m³]

For **iron and steel** ecoinvent dataset is used, where primary steel is called converter steel and is produced in basic oxygen furnaces (BOF) and secondary steel from scrap is called electrical steel and is produced in electric arc furnace (EAF). The iron ore content of mined banded iron formations as underlying the dataset used in this study is 45 %, which is lower than global average and thus, a conservative approach. It is reduced in blast furnaces consuming per kg 0.5 kg of coke and some other fossil fuels as well as electricity.

Cast Iron is one of the little processed intermediates and has a carbon content of 2.8 – 4 %. Steel has a carbon content lower than 2.1 % and is forgeable. The thousands of kinds of steel can be categorized in

a) unalloyed steel with very little fraction of alloy elements, used for construction and reinforcements,
b) low-alloyed steels with less than 5 % of alloy elements, which consist in the used dataset of 2.15 % Cr, 1 % Ni, 1.1 % Mn, 0.034 % Mo, 0.066 % Nb, 0.084 % W, 0.059 % V and 0 % Cu and
c) stainless steel, having higher alloy content. In this dataset, stainless steel has 18 % Cr and 8 % Ni

Further information on the dataset can be found in [68].

4.5 Launch and landing system

Launch and landing apparatus is considered separately from the ground station in this study. With the tendency for rigid wing systems, UAV or drone technology find´s it´s way to AWE design, too, as became apparent in many presentations of the Airborne Wind Energy Conference 2015 (cf. Schnez, Kruijf and Zillmann) [97].

The **launcher** consists of a steel frame and cart with linear actuator arm on a rail round track. The wing system can be launched independently from wind direction by positioning the launcher 360° along the track. A commercial product for the size of the studied wing size has a weight of 5,000 kg. No detailed information on the material was available from the supplier. It is assumed that it consists purely of steel, of which one half is rolled to section bars and the other half processed as average metal working. 40 kg of the steel are drawn to pipes and 50 m of welding arc is included. The launcher requires 100 l of lubricating oil and 9.1 kg alkyd paint. The transportation of this component is modeled with 1200 and 400 km by ship and lorry from manufacturer to AWE plant site.

Additionally a propulsion charging system is modeled. A 150 kg pipe system including drawing is considered with ecoinvent data, as well as 50 kg charger system (*charger, electric passenger car*). The pump is modeled with EPD data from a 250 kW HXR machine by ABB [98].

The **yaw system** is based on a circular railway track with a diameter of 12 m. Standard tracks S 54 with 54 kg/m are modeled with steel 4,070 kg section bar rolled steel [99]. Sleepers of are spaced every 63 cm with each consisting of 300 kg concrete and 8 bars of reinforcement steel with 2.6 kg/m are included [100]. For connections, 500 kg of average worked steel are added to the model. This layout is covered with a 3 m wide and 40 cm deep gravel layer of 78,200 kg.

For a 2.5 MW wind turbine 6 yaw motors of 4 kW are used [101]. These are represented in this study with data from EPD for a 22 kW low voltage cast iron motor [102].

The **landing system** consists of a steel structure with foundation, a 32 m diameter wooden deck and UAV technology arresting system. Plywood landing deck has a lifetime of 10 years, the rest lasts for the whole plant life. To resist the bending stress of the landing wing system, the thickness is estimated with 1.71 cm [103], leading to a 13.75 m³. The supportive structure is made of 15,000 kg low-alloyed, section bar rolled steel, including 5 m welding. 19.66 kg alkyd paint are used for protection. According to equation (4.2) 2.16 m³ concrete and 216 kg reinforcing steel are used for the foundation to bear 35 tons. For the arresting system 2,000 kg low-alloyed and 250 kg chromium steel are used which are considered with average metal working for their types.

4.6 Balance-of-station

The power **transformer** changes the electricity from the internal grid (32 kV) to high voltage (150 kV) for low-loss transmission to the grid. It has a weight of 141,000 kg. In own calculations, GWP was calculated 44 % lower than in the EPD of a manufacturer [104]. In line with a conservative approach, data was rather taken from this EPD. Scaled down to a 300 MW transformer, the values for GWP is 657,012 kg $CO_{2\text{-eq.}}$. The value for CED was calculated by modeling the provision of the used materials in Umberto and adding electricity and heat energy consumption during production as indicated in the EPD for 300 MW. This leads to a total energy demand of 12,308,593 MJ-eq.. Transportation is modeled for a distance of 1000 and 200 km by train and lorry (>32 tons) from manufacturer site indicated in the EPD to the AWE plant site.

ABB disclosed EPDs for a 250 MW and a 500 MW transformer within a short period of time from production sites in Italy and Sweden respectively. Notably, the electricity used in production are 37100 and 1500 kWh/MW rated power, respectively. This means that the total electricity consumption for manufacturing the smaller transformer consumed more than 12 times the electricity than the version of double the rated power. For heat consumption the factor is 2. Additionally the electricity generation in Sweden is less carbon-dioxide-intensive. In addition, less material was used per MW, the GWP100 from manufacturing the 250 MW system is 2600 $kg_{CO2\text{-}eq.}$/MW vs. 2190 $kg_{CO2\text{-}eq.}$/MW for the 500 MW trafo. The 500 MW dataset was used since it seemed more plausible and is much closer to own calculations. In some aspects, such as the contribution of materials used, the other report [105] was more detailed and used to detail the delivery processes.

The **hangar** is a shelter for aircrafts during repair or maintenance work a transportable tent structure is considered. It consists of 8 steel pipe arcs of 40 m diameter stringed with canvas. 50 kg steel, 360 m² tin plating and 1,533 kg polyvinylfluoride (PVF) are needed for one tent. Assuming that 1 % of the facilities are in maintenance, two such constructions are needed permanently for the whole plant.

The pipes are calculated with inner and outer diameter are 48 and 52 mm, a length of 63 m each and a density of steel of 7800 kg/m³ and the canvas with a surface of $S = \frac{4 \cdot \pi \cdot R^2}{2} = 2513\ m^2$ and an aerial density of PVF of 0.61 kg/m².

An **Energy buffer** is needed to ensure a constant power supply to the grid. The greatest part of the fluctuations of production can be levelled out by adapting the wings trajectories accordingly. An energy storage of 1 % of the plant power is considered. This is implemented using a flywheel, with a specific power of up to 4 kW/kg [106] resulting in a total mass of 750 kg that is modeled with low-alloyed steel and average metal working processing, as well as 12 HXR motors as used and explained for the launch and landing yaw system.

As **control tower** three laptops and a 60 m² wooden hall construction from ecoinvent database are used.

Internal and external cabling is realized with the same material but of different cross sections since the transmitted power is different. Figure 4.6 shows the construction of a cable in the this application. It has 4 main components. One, the conductor consisting of multiple copper or aluminum wires. Due to lower conductivity, an aluminum conductor has a 60 % bigger cross section to transmit the same power but is 35 % lighter for its lower density. Decisive to consider Aluminum conductor in this study is that costs are about 80 % lower. Higher cost for more specialized clamps are overcompensated for big conductor cross sections [107]. Two, an insulation consisting of an inner and outer semi-conductive screen for a smooth boundary layer of the e-field and an elastic cross-linked, thus low density polymer insulation, usually polyethylene. Three, a metallic screen, in this case copper. Four, an outer covering against mechanical stress and is therefore made of high density polyethylene. The shown thin aluminum layer is optional to prevent lateral water diffusion. Other material like swelling tape or powder to ensure longitudinal water proof are not considered for the study.

In a LCA study of similar plant size of conventional wind power, 95 km of 32 kV cable with aluminum conductor were used to connect the facilities to the transformer [56]. The cases are considered as comparable and the same cabling is used for this study. It is assumed that the conventional wind turbines were spaced 4 times the rotor diameter and that a medium voltage cable is guided to the nacelle at 80 m height. Since the power generation apparatus of the AWE system is on ground with 400 m spacing, the cable length is scaled by factor 400/(4x82+80)= 0.98. 62,157 kg Aluminum, 30,294 kg copper and 54,118 kg polyethylene is required.

The external cabling consists of two high voltage (150 kV) cables of 50 km, identically to the reference mentioned above. 953,000 kg Aluminum, 238,600 kg copper and 1,519,000 kg polyethylene is required. Both, internal and external cable are considered with 200 km transportation distance.

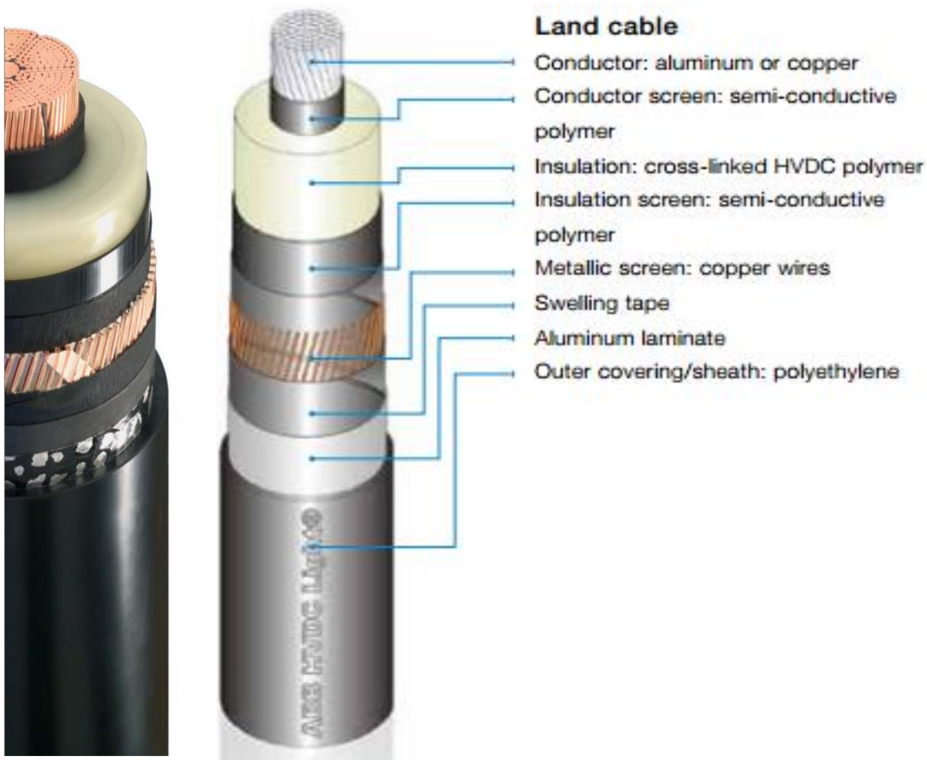


Figure 4.6: Picture (left) [108] and scheme (right) [109] of the construction of a land cable.

4.7 Installation

The installation phase comprises transport from manufacturer to the site and efforts for installation on the site. In a relevant study on CED of the installation / erecting of a HAWT it was concluded that of the onsite works only lifting of the system components tower sections, nacelle and blades are significant [110]. Since the whole installation of the AWE facility takes place on ground level, no efforts are considered for this study. Only the laying of internal and external cabling is estimated. Hydraulic excavating requires approximately 0.036 $L_{Diesel}/tn_{excavation}$ [111]. The lower calorific value of diesel is around 42.8 MJ/kg [112] and the density 850 kg/m³. Assuming a soil density of 1.3 tn / m³ and cable bed of 0.6 x 0.8 m with 182 x 400 m for internal and 50,000 m for external cabling the energy demand from diesel is 100,357 MJ.

$$E_{Diesel} = C \cdot \rho_s \cdot V \cdot LCV \cdot \rho_D \tag{4.3}$$

E_{Diesel}	Required energy from diesel	[MJ]
C	Specific consumption	[m^3/tn]
ρ_s	Density of soil	[tn/m^3]
V	Excavation volume	[m^3]
LCV	Lower calorific value of diesel	[MJ/kg]
ρ_D	Density of diesel	[kg/m^3]

For transportation efforts to the site, the masses, distance and type of transportation are listed in Table. The transport effort in tons times km [tn·km] is modeled with respective ecoinvent activities with

- 2,181,687 tn·km: market for transport, freight, lorry 3.5-7.5 metric ton, EURO5 [GLO]
- 11,674,111 tn·km: market for transport, freight, lorry 7.5-16 metric ton, EURO5 [GLO]
- 181,864 tn·km: transport, freight, lorry >32 metric ton, EURO5 [RER]
- 1,772,134 tn·km: market for transport, freight train [Europe without Switzerland]
- 1,636,106 tn·km: market for transport, freight, sea, transoceanic ship [GLO]

4.8 Operation and maintenance

Launch energy is required every two days according to expectations of a AWE developer company. A potential catapult launcher supplier states indicated the required energy to launch the studied wing system with 0.625 kWh per launch, resulting from loading the gas tanks of the pneumatic system at 7.5 kW for 5 min resulting. It accumulated to 415,188 kWh in 20 years for 182 facilities.

For O&M a **staff** team is assumed to drive 2x50 km (there and back) 5 days every week, using a car of 2 tons. The total distance over 20 years is 521,429 km. The ecoinvent activity “transport, passenger car, large size, diesel, EURO 5 [RER]” was used.

Exchange of **lubrication** oil mainly for maintenance of gearbox and generator but also motors, winch, and launcher are required. The resin molded transformer doesn´t require oil exchange. It is assumed that 500 kg oil have to be replaced after 45,000 h which corresponds to 3 exchanges per facility over the lifetime, resulting in a total of 273,000 kg. [113]

For **replacement** the manufacturing of components according to their specific lifetime as explained above in relation to the plant lifetime, as well as transportation to the site is included. Frequency of component replacements, their masses, transport distance and type of transportation are listed in Table 4.1.

Table 4.1: Data for replacement of parts and components of the AWE plant.

Transport for Replacement	Replacements per facility	Mass total in kg	Type of Transport	Dist. in km
Wing System	1	377,650	lorry, >32 t	400
Gearbox	1	3,931,200	lorry, <16 t	400
Oil, lubricant	3	273,000	lorry, <16 t	400
Wood, Plywood	1	1,564,362	lorry, <16 t	400
Batteries main (24V)	(20/2-2)	21,840	lorry, <7.5 t	400
Batteries Propulsion (120V)	(20/4-2)	40,950	lorry, <7.5 t	400
Tether, bottom part	(20/2-1)	327,600	lorry, <7.5 t	100
Tether, upper part	(20/10-1)	45,500	lorry, <7.5 t	100
Converter	1	602,333	lorry, <7.5 t	200
Converter		602,333	train	700
Total		**7,184,436**		

Transportation efforts are modeled with respective ecoinvent datasets in tons times km [tn·km] with the following total masses:

- 151,060 tn·km: transport, freight, lorry >32 metric ton, EURO5 [RER]
- 2,307,425 tn·km: market for transport, freight, lorry 7.5-16 metric ton, EURO5 [GLO]
- 182,893 tn·km: market for transport, freight, lorry 3.5-7.5 metric ton, EURO5 [GLO]
- 421,633 tn·km: market for transport, freight train [Europe without Switzerland]

4.9 Decommissioning and disposal

As described in the system boundaries (section 3.2.2) all material is landfilled for which no relevant emissions occur since the material is mostly inert material like gravel and metals. Only dismantling and transport to landfilling are considered.

Dismantling of reinforcing steel can be executed with a speed of approx. 0.173 h/m³ with a consumption of 19 kg diesel per hour, which has a lower calorific value of 42.8 MJ/kg [112]. This leads to the energy consumption of 140.85 MJ/m³ in form of diesel. For 5,330,679 kg of concrete it adds up to 264,841 MJ. Diesel consumption for excavation of cabling bed is assumed to be the same as for cable laying, 100,357 MJ. All other components are assumed to be loaded on trucks without significant efforts.

Transportation from site to landfilling can be executed the same way as they were delivered to the site for many components. Others need special waste vehicles. In this study only trucks of different sizes are considered since the difference is assumed to be small. The loaded trucks are modeled for a transport distance of 400 km, which is assumed to also accounts for the unloaded way to the site. The transport effort is

- 363,727 tn·km: transport, freight, lorry >32 metric ton, EURO5 [RER]
- 14,552,970 tn·km: market for transport, freight, lorry 7.5-16 metric ton, EURO5 [GLO]
- 3,080,744 tn·km: market for transport, freight, lorry 3.5-7.5 metric ton, EURO5 [GLO]

Detailed information about the transported components, their weight, and type of transportation can be found in Table A.2.

Waste Treatment

Even though waste treatment is not considered for the calculations, the treatment of different materials is briefly described here for awareness about the omitted data. Not only environmental burden are caused by the end-of-life route. Recovery can replace use of primary material or energetic resources which could possibly be credited to the product system. The potentially high recycling rate of the used metals lead to a great potential to reduce the carbon footprint.

GFRP: The borderline between energetic recovery and thermal disposal is a calorific value of 11 MJ/kg. Pyrolysis or heat for cement production [114]**.** The energetic recovery of CFRP yields a negative CED of 31.7 to 34 MJ/kg and causes around 3.3 $kg_{CO2\text{-}eq.}$/kg [75]. This number should be compared to the specific electricity mix to assess whether energetic recovery is beneficial in terms of GWP at the specific place. Recycling consumes with 10-15 MJ/kg less energy than production from primary material

Plastic waste: Thermal recovery or recycling is possible and common but mechanical or chemical recycling and reuse present environmentally preferred options. Theoretical composition of elements for each plastic type can be computed and possibly corrected by observations and measurements of real plastic waste and implemented with the ecoinvent database [115]. Rope manufacturers offer to take back the used tether material to produce new products like nonwoven fabrics, yarn or insulation material [116]. However, energetic recovery by means of incineration might be the most likely end-of-life route. The calorific value of UHMW-PE is approximately 40-45 kJ/kg [86].

Metals: In small amounts or in small pieces like screws or scrap from certain processes they can be sent to MSWI. Bulk metal and larger components are usually recycled [115]. Most of the metal can be reused or recycled. Recycling rates for steel, iron, copper and aluminum can be 90 % or higher, up to 10 % need to be sent to landfill in any case [56].

Wood materials: Fiber board contains a glue besides the wood. It is estimated that other than untreated wood, this material contains 7.5 % urea-formaldehyde resin [115]. As for other woods, energetic recovery is a viable option.

Steel-reinforced Foundation: After decommissioning of wind power plants, those are usually left on site. Therefore no direct emissions are considered for on-site landfilling [115]**,** [117]. It is more likely that future systems will be removed completely. After demolition, the material is easily separated and treated as other concrete or reinforcement steel.

Structural inorganic building materials: Inert materials like concrete and gravel do not cause emissions in landfills but in the upstream processes like sorting cement from concrete, which can be disposed of in fine fraction of sanitary landfill. Concrete can be recycled by 50 % and 50 % need to be landfilled [64].Gravel and concrete can partially be reused in road constructions for example. 20 % of gravel and sand need to be landfilled with residual material, 80 % is transported to special washing facilities and reused [118]. Around 2 %-wt. of the material are fines that removed from the gravel in that process. Thus, most of the used rail track material can be recycled.

Bitumen: It is assumed, that cabling is removed from soil at decommissioning and with it also the bitumen seal. Typical disposal is sanitary landfill [115].

Paint: An ecoinvent process for emulsion paint disposal is available.

Used **lubrication** oil can be recovered 60 % as material and the rest energetically [64].

MSWI: Residuals from incineration like ashes and sludges are solidified by adding water and cement and then landfilled with other residual material [115]. Especially heating value and content of climate active material of the waste are relevant for this study.

4.10 Conventional wind turbine

For the purpose to validate the AWE model, a comparable conventional wind turbine is modeled for which data can be found in literature. The modeling process is generally the same for the airborne and conventional wind energy plant. Many processes can be transferred. If not specified differently, masses of the material types for each assembly group as stated in [56] are modeled with ecoinvent database for material acquisition and average processing works.

Rotor and Foundation manufacture is entirely modeled after this procedure.

The **nacelle** is similar to the ground station of the AWE plant. The components generator, gearbox and converter are modeled as for the AWE system but all flows scaled down linearly to 1,650 kW. The generator accounts for 37,901 $kg_{CO2\text{-}eq.}$/kWh and 315,374 MJ-eq./kWh and the converter for 9,702 $kg_{CO2\text{-}eq.}$/kWh and 88,290 MJ-eq./kWh. The difference between the mass indications by type in [56] and the used materials in the downscaled models was added to the manufacture process of the nacelle together with average processing activities for the respective material.

Installation is done as for the AWE plant but masses to be transported are higher and additional energy for erecting of the towers is considered. The blades modeled with transportation of lorry of >32 tons size, the remaining party with lorry of up to 16 tons.

$$CED_{erecting} = G_D \frac{1}{\eta_M} \cdot m \cdot g_P \cdot H \cdot \frac{1}{10^6} \tag{4.4}$$

$CED_{erecting}$	CED for erecting	MJ
G_D	Supply factor for Diesel	MJ/MJ_{end}
η_M	Efficiency of Diesel engine	-
m	Moved mass	kg
g_P	Gravity constant	m/s^2
H	Height	m

According to [110], the cumulated energy demand for erecting $CED_{erecting}$ the wind turbine can be estimated using equation (4.4) with a supply factor for Diesel $G_D = 1.09$ MJ/MJ_{end}, an efficiency for the Diesel motor of $\eta_M = 0.2$, the hub height of 80 for nacelle and blades and 40 m as an average for the tower sections, and the respective masses as

$$CED_{erecting} = 1.09 \frac{1}{0.2} \cdot \left(42.2 + 51 + \frac{136}{2}\right) \cdot 80 \cdot 9.81 \cdot \frac{1}{10^6} = 6.895e2 \text{ MJ}.$$

Energy for cable laying is same as for the AWE plant and a total $CED_{installation}$ of 225,842 MJ for the plant is calculated.

The **tower** comprises instead of average processes sheet rolling of steel, 2x78 m arc welding, tin plating of the surfaces and painting. For each tower, 80 m of cabling are included in the same way as internal cabling.

Balance of station is almost identical for airborne and conventional wind energy plant but no hangar and energy buffer are needed. The internal cabling is 2 % longer due to distance between turbines but the material composition is the same.

O&M is same as for AWE plant, but no wing launches are required.

Replacement comprises also generator and converter, but of the downscaled size. Transportation efforts are lower accordingly

Decommissioning is modeled as for the AWE plant but with consideration for the different mass to be transported to disposal and higher energy demand to tear reinforced concrete. Following the same calculation, the tearing consumes 8,946,510 MJ.

5 Results and discussion

This chapter covers both, life cycle impact assessment (LCIA) and interpretation (except conclusions and recommendations). First, the material composition of the AWE plant is analyzed. The category indicator results for cumulated energy demand and global warming potential are presented and discussed. It is analyzed, what the contribution of certain components and material is and how those aspects behave in comparison and further characteristic numbers are derived. A sensitivity study analyzes the robustness of the category indicator results to changes of certain crucial parameters. This also supports the understanding of particularities o AWE systems like tether and wing launches. In a separate section uncertainties of the results are discussed. Finally the AWE model is validated against a model of a known conventional wind energy plant. The results of the AWE plant are compared to the numbers of this system and to other selected electricity production methods as a reference.

5.1 Baseline results for the AWE plant

This section presents an discusses the potential environmental impacts in global warming and the use of primary energy resources of the airborne wind energy plant as defined in the goal and scope definition and with the data and procedure for collection explained in the LCI. Calculations for classification and characterization are executed with the software Umberto.

For the purpose of a better overview and understanding, the composition of mass and numerical results are summarized in Table 5.1. The values are presented in three layers, for the life cycle phase, for the component system or activity and for components or subcomponents. The mass is indicated not for the plant but for one facility including its share on the common balance-of station like cabling and substation. The percentage indicates the share in the respective life cycle phase. For the categories GWP100a and CED, the absolute values are listed for the product system (AWE plant). The additional 3 columns indicate the share of the respective value in the whole product life cycle (LC), the respective LC phase and in their component / component system. The figure can should help to maintain the overview of the results, whereas the single values will be analyzed and further detailed in the following sections.

Table 5.1: Overview over composition of mass and numerical results for category indicator results.

LC phase	Mass per facility		GWP 100a (CML 2001)				CED			
Component System	**[kg]**		**[$kg_{CO2\text{-}eq.}$ /kWh]**	**LC share**	**phase share**	**comp. share**	**[MJ-eq. /kWh]**	**LC share**	**phase share**	**comp. share**
Raw material & Manufacturing	**207,769**	**100%**	**3.636E-03**	**64.8%**			**4.578E-02**	**60.9%**		
Wing System	**2,075**	1.0%	**2.322E-04**	**4.1%**	**6.4%**		**4.187E-03**	**5.6%**	**9.1%**	
CFRP structure	450	0.2%	1.652E-04	2.9%	4.5%	71.1%	3.118E-03	4.1%	6.8%	74.5%
Core	1,100	0.5%	2.980E-05	0.5%	0.8%	12.8%	5.038E-04	0.7%	1.1%	12.0%
Coating & glue	215	0.1%	8.896E-06	0.2%	0.2%	3.8%	1.765E-04	0.2%	0.4%	4.2%
Electronics	115	0.1%	2.131E-05	0.4%	0.6%	9.2%	2.946E-04	0.4%	0.6%	7.0%
Mechanisms	195	0.1%	6.501E-06	0.1%	0.2%	2.8%	7.728E-05	0.1%	0.2%	1.8%
Misc	30	0.0%	5.183E-07	0.0%	0.0%	0.2%	1.698E-05	0.0%	0.0%	0.4%
Tether	**495**	**0.2%**	**5.582E-05**	**1.0%**	**1.5%**	**100.0%**	**1.097E-03**	**1.5%**	**2.4%**	
Ground Station	**50,172**	**24.1%**	**1.443E-03**	**25.7%**	**39.7%**		**1.550E-02**	**20.6%**	**33.9%**	
Winch	5,307	2.6%	1.471E-04	2.6%	4.0%	10.2%	1.610E-03	2.1%	3.5%	10.4%
Gearbox	22,100	10.6%	7.375E-04	13.1%	20.3%	51.1%	9.103E-03	12.1%	19.9%	58.7%
Generator	12,701	6.1%	4.232E-04	7.5%	11.6%	29.3%	3.575E-03	4.8%	7.8%	23.1%
Converter	3,310	1.6%	1.197E-04	2.1%	3.3%	8.3%	1.089E-03	1.4%	2.4%	7.0%
Foundation	6,654	3.2%	1.413E-05	0.3%	0.4%	1.0%	1.045E-04	0.1%	0.2%	0.7%
Misc.	100	0.0%	1.948E-06	0.0%	0.1%	0.1%	2.118E-05	0.0%	0.0%	0.1%
Launch/Landing System	**138,283**	**66.6%**	**8.011E-04**	**14.3%**	**22.0%**		**8.610E-03**	**11.4%**	**18.8%**	
Launcher	5,441	2.6%	1.682E-04	3.0%	4.6%	21.0%	1.725E-03	2.3%	3.8%	20.0%
Landing deck	28,851	13.9%	4.041E-04	7.2%	11.1%	50.4%	4.453E-03	5.9%	9.7%	51.7%
Yaw system	101,559	48.9%	1.469E-04	2.6%	4.0%	18.3%	1.507E-03	2.0%	3.3%	17.5%
Landing mechanisms	2,250	1.1%	8.194E-05	1.5%	2.3%	10.2%	9.262E-04	1.2%	2.0%	10.8%
Cabling	**15,699**	**7.6%**	**1.059E-03**	**18.9%**	**29.1%**		**1.569E-02**	**20.9%**	**34.3%**	
Internal cabling	805	0.4%	6.410E-05	1.1%	1.8%	6.1%	8.521E-04	1.1%	1.9%	5.4%
External cabling	14,893	7.2%	9.954E-04	17.7%	27.4%	93.9%	1.484E-02	19.7%	32.4%	94.6%
Substation	**846**	**0.4%**	**3.209E-05**	**0.6%**	**0.9%**		**6.012E-04**	**0.8%**	**1.3%**	
Energy buffer	**182**	**0.1%**	**7.744E-06**	**0.1%**	**0.2%**		**4.944E-05**	**0.1%**	**0.1%**	
Control Tower	**0**	**0.0%**	**1.116E-06**	**0.0%**	**0.0%**		**1.284E-05**	**0.0%**	**0.0%**	
Hangar	**17**	**0.0%**	**2.852E-06**	**0.1%**	**0.1%**		**3.597E-05**	**0.0%**	**0.1%**	
Installation			**1.755E-04**	**3.1%**			**2.764E-03**	**3.7%**		
Site preparation & Transport			**1.755E-04**	**3.1%**	**100.0%**		**2.764E-03**	**3.7%**	**100.0%**	
O & M & Replacem.	**40,975**	**100.0%**	**1.577E-03**	**28.1%**			**2.317E-02**	**30.8%**		
Operation & Maintenance	**1,500**	**3.7%**	**4.041E-05**	**0.7%**	**2.6%**		**1.659E-03**	**2.2%**	**7.2%**	
Replacement	**39,475**	**96.3%**	**1.537E-03**	**27.4%**	**97.4%**		**2.151E-02**	**28.6%**	**92.8%**	
Transportation		0.0%	2.973E-05	0.5%	1.9%	1.9%	4.701E-04	0.6%	2.0%	2.2%
Wing System	2,075	5.1%	2.324E-04	4.1%	14.7%	15.1%	4.191E-03	5.6%	18.1%	19.5%
Tether	2,050	5.0%	2.543E-04	4.5%	16.1%	16.5%	4.999E-03	6.6%	21.6%	23.2%
Plywood, deck	8,595	21.0%	1.504E-04	2.7%	9.5%	9.8%	1.747E-03	2.3%	7.5%	8.1%
Batteries	345	0.8%	1.788E-05	0.3%	1.1%	1.2%	2.452E-04	0.3%	1.1%	1.1%
Converter	3,310	8.1%	1.197E-04	2.1%	7.6%	7.8%	1.089E-03	1.4%	4.7%	5.1%
Gearbox	23,100	56.4%	7.327E-04	13.1%	46.4%	47.7%	8.772E-03	11.7%	37.9%	40.8%
Disposal	**248,744**	**100.0%**	**2.223E-04**	**4.0%**			**3.497E-03**	**4.6%**		
Dismantling & Transport			**2.223E-04**	**4.0%**	**100.0%**		**3.497E-03**	**4.6%**	**100.0%**	
Total	**248,744**		**5.611E-03**	**100.0%**			**7.522E-02**	**100.0%**		

5.1.1 Material consumption

This section presents the composition of facility and plant by material type and mass. Over its lifetime, the AWE plant consumed 45,308 tons of material, which is 249 tons per facility. The greatest single contribution is from gravel with around a third, followed by steel with 30 %. The material consumption is composed by 44 % gravel and concrete, 42 % metals, 7 % plywood, 5 % plastics and 1 % carbon fiber reinforced polymer. This is illustrated in Figure 5.1.

The mass of a facility alone, without its share on balance-of-station components is 191 tons at installation. This number increases by 21 % to 230 tons over the lifetime due to replacements and material for maintenance. The mass distribution by material type for the facility as installed and over the life cycle is illustrated in the two graphs on the bottom of the figure. At installation, gravel and concrete dominate the material requirements with 56 %. The plastics have a low contribution but a strong increase over lifetime, driven by replacement of the tether, which requires 495 kg at installation and 3,245 kg in total.

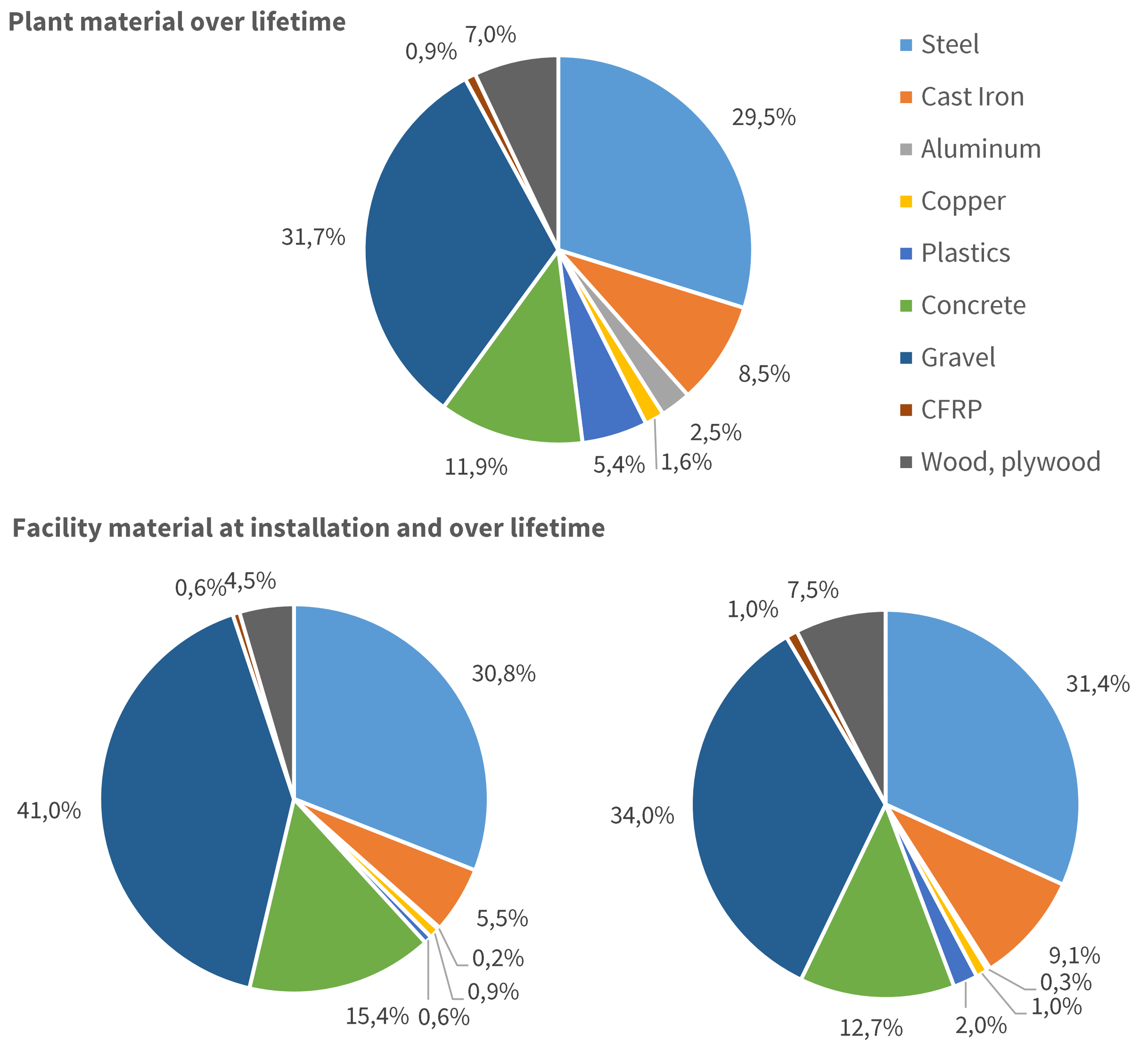


Figure 5.1: Contribution of material consumed for installation of a facility (left) and over the lifetime of a facility (right) and the plant (middle)

Contribution of metals in general is quite stable between 37 and 42 % but with increase of cast iron share in specific.

The detailed numbers of material types and masses can be found in Table.

5.1.2 CED and energy payback time

The overall indicator result for electricity production with the AWE plant in the impact category **cumulated energy demand** is **7.522E-2 MJ-eq./kWh**. When merging the energy units, one can find that in theory 2.1 % of the lifetime energy production are needed for its own manufacture, operation and disposal.

With the simulation results of the CED and the assumptions for the electricity production of the plant the energy payback time can be calculated. According to equation (3.2), as explained in section 3.2.4, the product system (AWE plant) generated electrical energy $EP_{plant,lt} = 22{,}355{,}555\ MWh$ fed to the grid within the lifetime lt of 20 years. Equation (3.3) can be simplified and the **energy payback time** EPT can be computed as

$$EPT = \frac{CED\ \frac{1kWh}{3.6MJ}}{AEP_{plant}} EP_{plant,lt} = \ CED\ \frac{1kWh}{3.6MJ}\ lt_{plant} \qquad (5.5)$$

$$= 7.522\mathrm{E}-02\ \cdot \frac{1kWh}{3.6MJ}\ 20 \cdot 12\ months$$

$$= 5.01\ months$$

$$= 152.5\ days.$$

This result means, that the cumulated energy that is spend over the whole life cycle of the AWE plant is recovered within 5 months of operation. Further analysis of CED is included in the following section.

Another interesting number is the **energy yield ratio**. It indicated the ratio between energy that is produced by the plant over its lifetime and energy that is invested. For the investigated AWE plant this number results $EYR = 47.86$, meaning that around 50 times more energy is produced by the AWE plant than it required for manufacturing, operation and disposal. When comparing to values from other sources it should be considered, that this number contains energy from both, renewable and non-renewable sources but often values are found that contain only investment of non-renewable energy.

5.1.3 GWP and analysis of category indicator results

GWP

The overall **indicator result** for electricity production with the AWE plant in the impact category *global warming potential* in a 100 year´s perspective after the CML2001 method is **5.611E-3 kg$_{CO2\text{-}eq.}$/kWh**. The Sankey diagram of the top-level processes for GWP in Figure 5.2 should give a clearer overview over their relative contributions. Besides the top-level processes themselves, their categorization in the four life cycle stages can be seen. It already becomes apparent that there are great differences between the single streams, consolidating in the virtual output stream of 1 kWh electricity (functional unit).

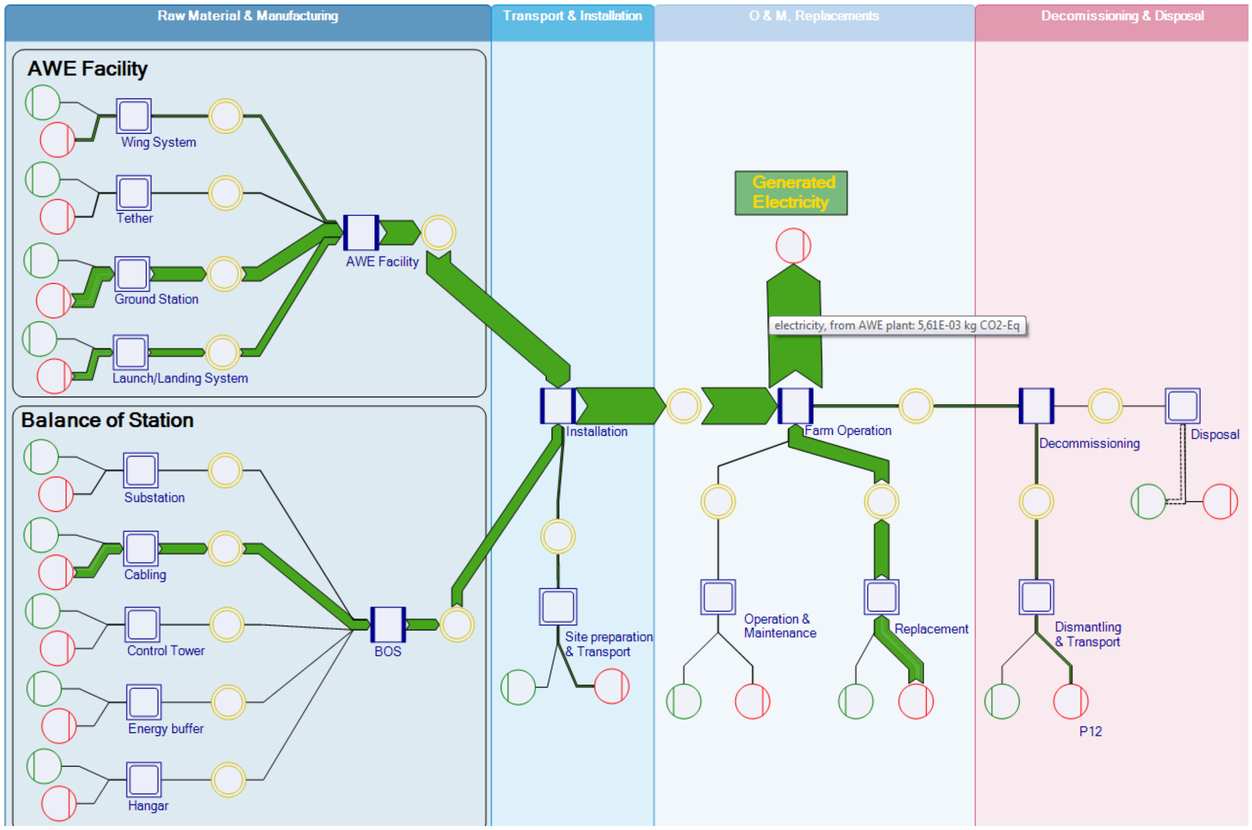


Figure 5.2: Sankey diagram for global warming potential (GWP100a) of the top-level processes of the AWE plant.

As displayed in Figure 5.3, the distribution over the life cycle stages I) raw material and manufacture II) installation III) operation, maintenance and replacement and IV) disposal is 65, 3, 28 and 4 %, respectively.

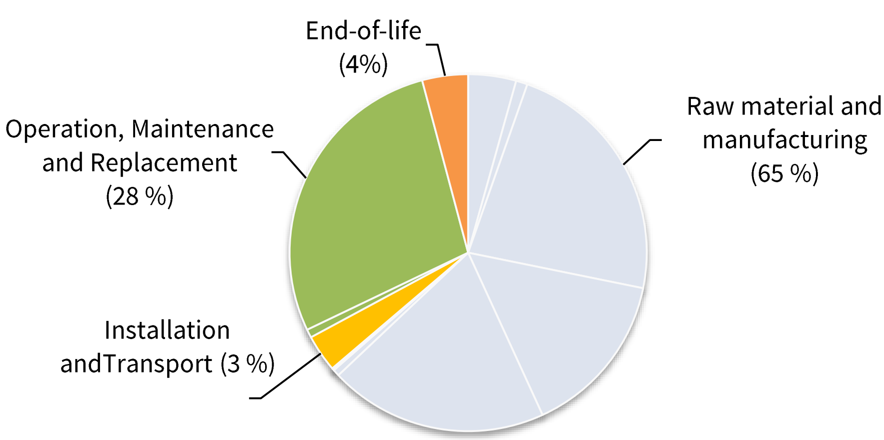


Figure 5.3: Global warming potential for the life cycle stages of an AWE plant.

Figure 5.4 allows further insights by presenting GWP and CED indicator results of all contributors along the life cycle with their percentage-wise contribution to the respective category. Besides the container term "replacement" (27 and 29 %) main contributions come from ground station (26 and 21 %), cabling (19 and 21 %) and launch and landing system (14 and 11 %). The contribution of the tether is minor, as well as contributions of substation, installation, operation and maintenance and disposal. Hangar and control tower cannot merely be displayed for their low contribution. Phase II) and IV), consisting mainly of transportation, are of very limited influence for the developers of an AWE system and additionally of marginal contribution. The impact caused by balance-of-station in phase I) is 20 % of the overall result and can merely be influenced, too. It is dominated with over 90 % by efforts for external cabling, followed by internal cabling (6 %) and the power transformer (3%). Only the impact from internal cabling might be influenced with the farm arrangement but its life-cycle-contribution to GWP is just 1.1%.

Consequentially, the greatest potential for savings lays in phases I) and III). Obviously, the 43 % of greenhouse gas emissions that are caused for the construction of the AWE facility are a key issue, followed by 27 % from replacements. Together, they represent manufacturing of the facilities and its replacement parts and make up over 2/3 (70 %) of the GHG emissions. This is the number that can directly be influenced by the AWE developer.

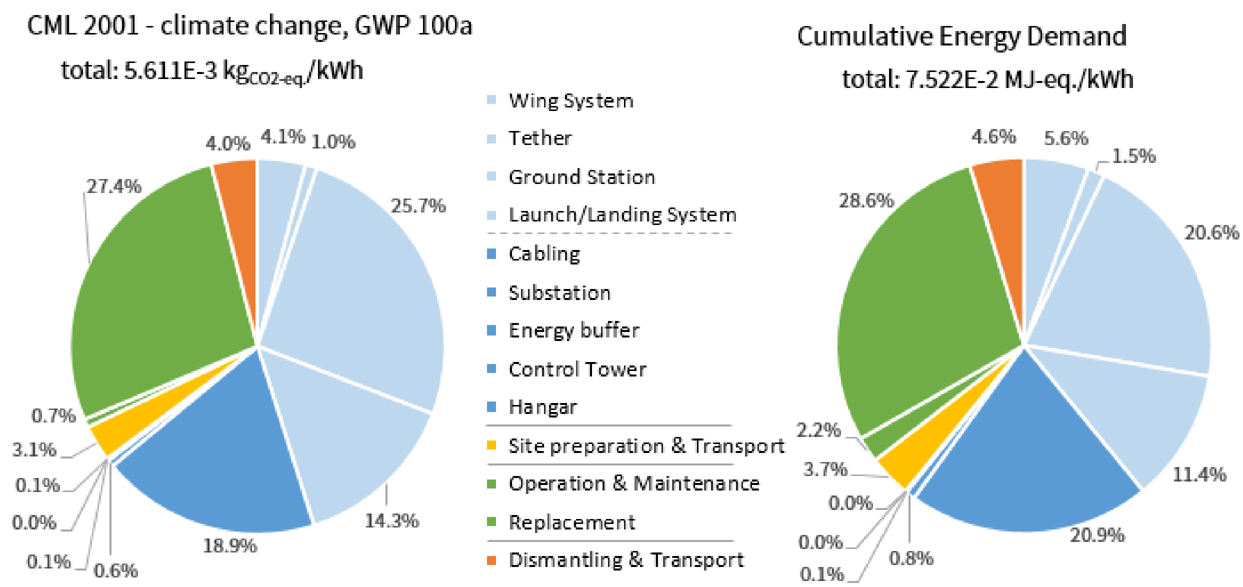


Figure 5.4: Global warming potential and cumulated energy demand over the life cycle of an AWE plant.

It can also be concluded from the figure that GWP and CED are well correlated for most component systems. This could be explained by the consideration, that if ratio between heat and electricity, as well as their supply source are comparably for most manufacture processes, a change in energy consumption is directly correlated with a change in emission of greenhouse gases. In turn, the relationship between the two categories might change, when energy is provided from a different electricity mix or when a process requires a higher share in heat or electricity than average. Material like cast iron require mainly heat, whereas copper for cabling is produced electricity-intensively. The same components are illustrated in Figure 5.5 with respective numerical values for GWP

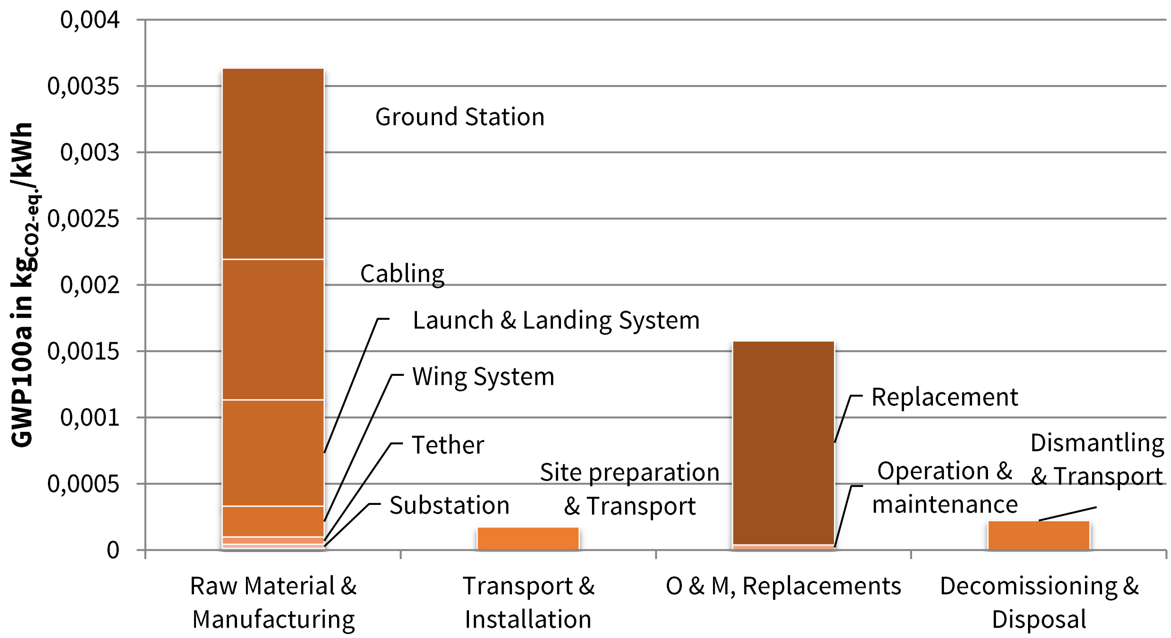


Figure 5.5: GWP for the life cycle stages and components of an AWE plant.

Component systems

From the previous considerations, the four areas *wing system*, *ground station*, *launch and landing system* and *replacements* turned out be promising for savings potential and should be analyzed in more detail in the following.

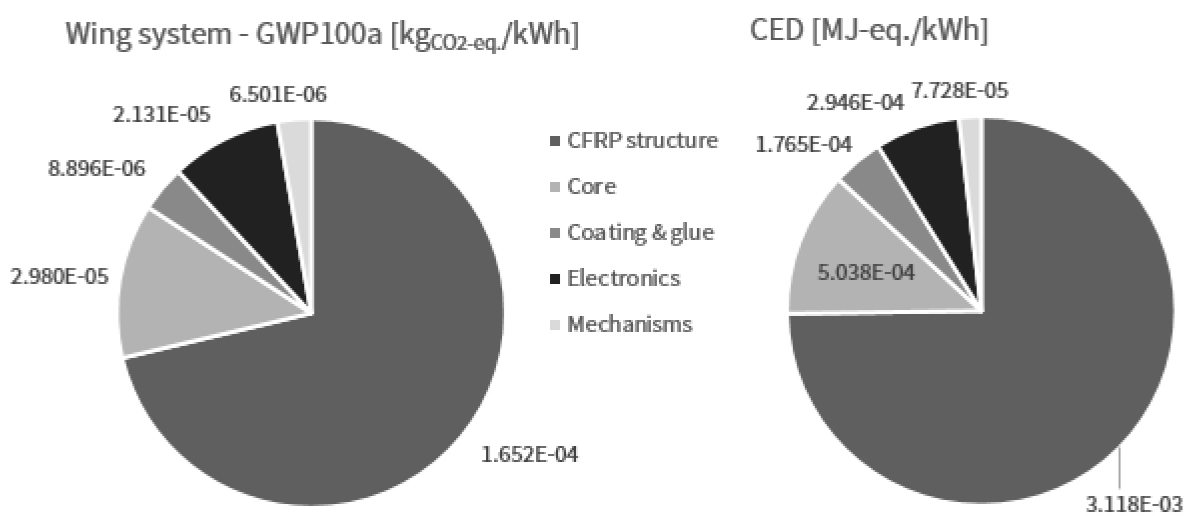


Figure 5.6: GWP and CED contribution of the components of the wing system.

GWP and CED of the wing system are displayed in Figure 5.6. The impact categories are dominated with around ¾ by the wing structure made of carbon fiber reinforced polymer (71 and 75 %). The aramid core contributes with around 12 and 13 %. The electronics account only for 9 and 7 %. Whether the environmental burden per kWh would be lower with other material than CFRP cannot be concluded without further investigations. These are beyond the scope of this study but it should be mentioned here, that material that is less energy intensively produced might have lower stress resistance. Thus, more material would be required and the energy yield could be lowered. Furthermore, the big share of CFRP in the wing system should be put into perspective with the contribution of this component to the overall result. Since this is low for the wing system, CFRP-structure has an overall contribution to GWP and CED of 2.9 and 5.6 % .

The gearbox dominates the environmental burden of the ground station with over 50 % of the contribution of GWP and CED, as can be derived from Figure 5.7. The winch adds another 10 %. The generator accounts for 29 and 23 %.

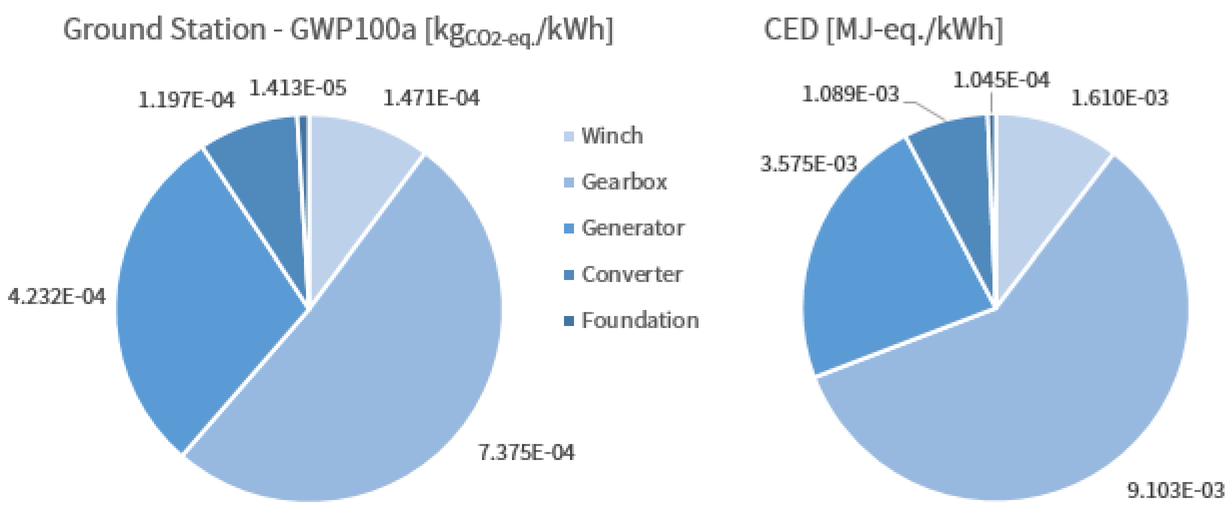


Figure 5.7: GWP and CED contribution of the components of the ground station.

Gearbox and generator combined make up over 80 % in both impact categories for the ground station and 21 and 17 % in the overall result and thus, bear a great potential for savings. As an option in the design, these could potentially be replaced by a permanent magnet generator. The production of the permanent magnet is very energy intensive but could be overcompensated by the considerable weight reduction. However, it is questionable whether the use of permanent magnets is beneficial from an environmental perspective. Other than the considered impact categories, there is for example a big consumption of rare metals (in particular Neodym, Praseodym, Dysprosium and some Terbium). Per MW of a conventional wind power plant with permanent-magnets, 500-600 kg NdFeB are used and additionally Dysprosium for support of temperature stability [119].

GWP and CED of the launch and landing system are displayed in Figure 5.8. Slightly above half of the impacts come from the landing deck. Plywood alone makes up 39 % of that. Launcher system and yaw system account for another 20 % each, approximately. All components have almost the same share for GWP and CED.

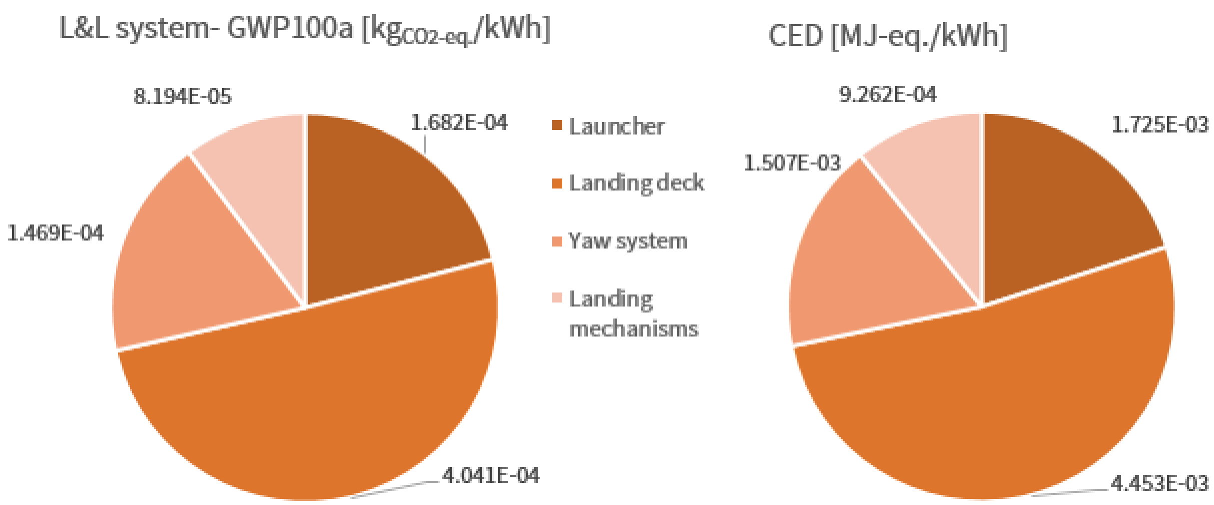


Figure 5.8: GWP and CED contribution of the components of the launch and landing system.

GWP and CED of the phase *operation, maintenance and replacements* are displayed in Figure 5.9. The gearbox is dominating with 48 and 41 % in those categories. Considering that 48 % of the O&M efforts are due to lubrication oil for the gearbox, 48 and 41 % of this phase are caused by this component. This aspect should be considered in the discussion above about environmental effects of using a permanent magnet generator. Summarizing generator and gearbox manufacture, its replacement and maintenance an overall contribution to GWP and CED of 28 and 26 % can be noted, not included the transportation to and from the site.

The tether accounts for 17 and 23 % of GWP and CED in this life cycle phase. The overall contribution of replaced tether to the life cycle of the power plant is 4.5 and 6.6 % and thus (as expected) much higher than the effect from tether at installation.

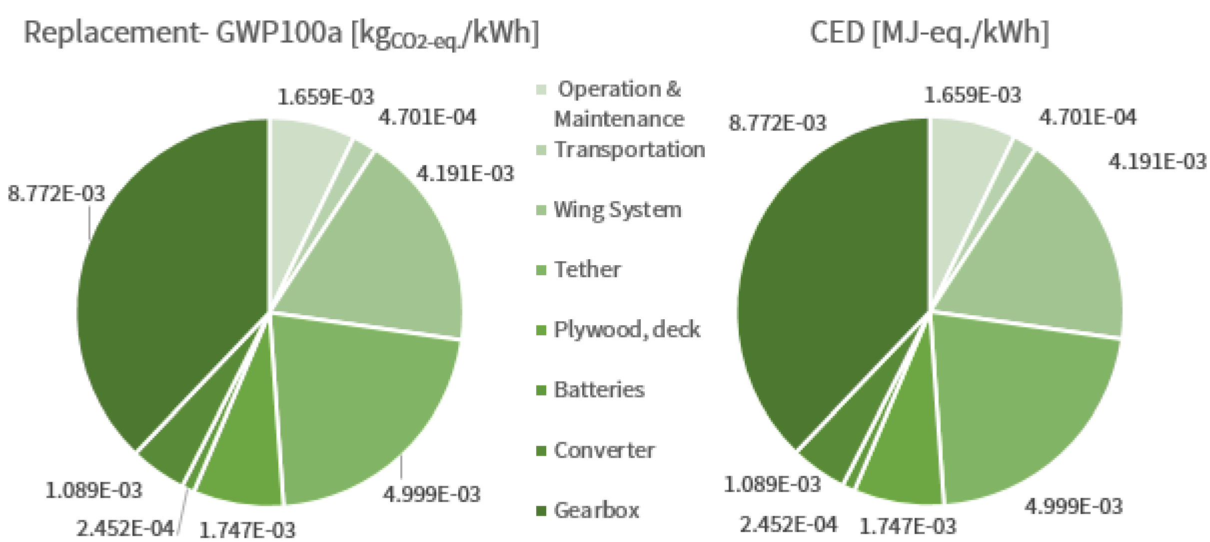


Figure 5.9: GWP and CED contribution of the components for replacement.

5.1.4 Correlations between categories and mass

Several selected components are presented in Figure 5.10 to point out, that in some cases there might be a relationship between mass, GWP and CED of a component, but it is generally not the case. Examples can be found in the product system, where a component contributes negligibly little to the mass but significantly to some environmental effects or reversely.

In particular for the generator, but also for the ground station in general or the landing deck, the three parameters mass, CED and GWP are balanced. This means that considered the components have an (mass weighted) average cause of the considered environmental burden within the product system.

The yaw system consists mainly of gravel which is used as a little processed resource, and thus has a high mass but no strong impacts on environment. It contributes to 40.8 % of the mass but only 2.6 % to GWP and 2 % to CED. The other big material components of the yaw system combined, concrete and steel, seem to be in average with respect to the relationship between those parameters, as found before. Therefore, they probably reduce the discrepancy compared to gravel alone. The foundation, which consists mainly of concrete, shows a similar behavior as the yaw system.

Cabling, on the other hand, behaves contrarily. The used mass is not negligible but the required energy and greenhouse gases that are caused during production have a much higher contribution in comparison. The cabling consists of metals and plastic. Metals are produced under high energy intensity and are required in high purity in this application for good conductivity.

A similar relation shows the wing system. Contributions are lower here but the discrepancy between mass and environmental effects is even higher. This is caused by the energy intensity of the carbon fiber production. The greatest imbalance in this way is observed for the tether. It contributes with 0.2 % to the mass of a facility at installation but contributes with 1.6 and 8.7 % to GWP and CED respectively. This is

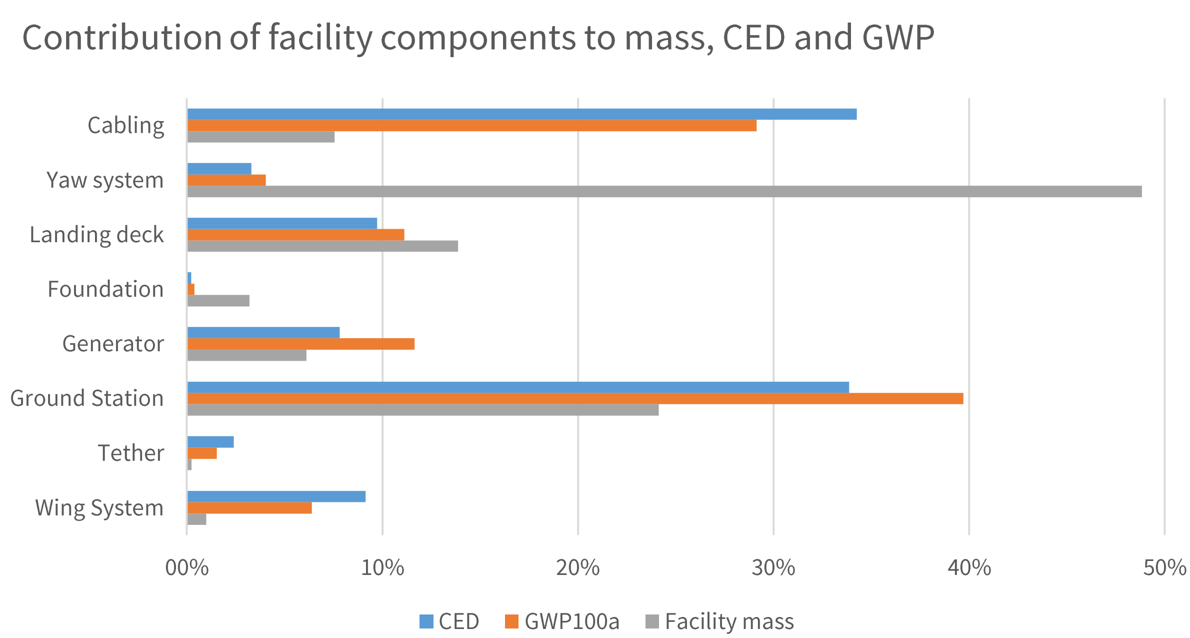


Figure 5.10: Contribution of selected components to mass, CED and GWP of the facility as installed.

mainly due to the energy intensive process from granulate to fiber on the one hand and the low density of polymers on the other hand.

For selected materials Table 5.2 lists the share in mass, GWP and CED over the life cycle of the plant. This highlights the point, that material with a high mass can have little impacts (cf. gravel, plywood or reinforced concrete) and reversely (cf. tether).

Table 5.2: Share in mass, GWP and CED over the plant life cycle for selected materials.

Material	Mass	GWP	CED
Gravel	31.7 %	0.2%	0.2%
Plywood	7.0 %	2.0 %	2.0 %
Tether	1.0 %	5.5 %	8.1 %
Reinforced concrete	13.1 %	3.7 %	0.3 %

5.2 Sensitivity study

The sensitivity analysis is to check the robustness of the results to changes in the parameters and the influence that some assumptions on system design have. Only variation of single parameters are since no complex interrelationships are expected that require sensitivity check for parameter sets. Sensitivity was studied for parameters that industry experts showed interest in in personal conversations and for parameters that showed to have big contribution to the results. Those are

- Power output of the plant
- Size (rated power) of the plant
- Frequency of wing launches
- Distance to the grid
- Replacement of tether
- Replacement of gearbox

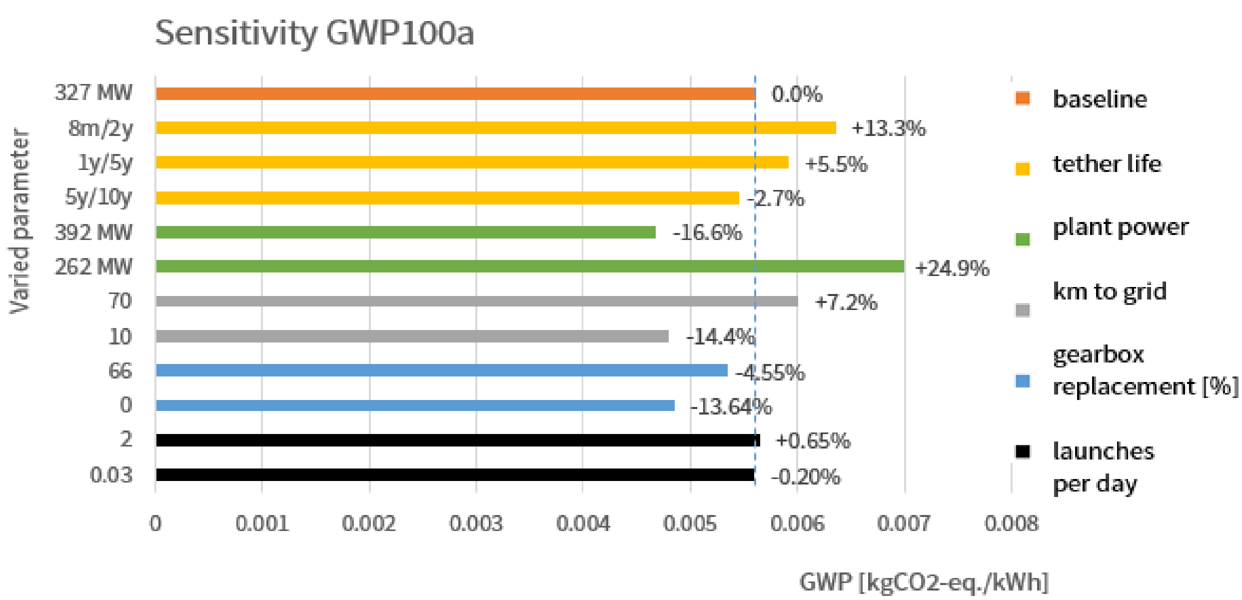


Figure 5.11: Summary of baseline scenario and selected values from the sensitivity study.

Figure 5.11 presents a summary of selected results from the sensitivity study that will be detailed in the following. Detailed numerical results of the sensitivity study can be found in Table A.5. The single sensitivities are discussed in the following.

Plant power output

This analysis considers the effect of change in power output with the same plant. This is the case when higher or lower actual wind speed are present at the site than predicted, for downtimes due to legal requirements, technical availability and others. This assessment is equivalent to changes in capacity factor. Only the power output is changed, not the design of the plant. If power output changes +/- 10 %, specific environmental effects change about the same percentage. At higher power outputs, reductions flatten out, whereas at 50 % lower power output they almost double. If better wind conditions are known in a real project, not only the specific environmental effects would be lowered but also less material is required.

A sensitivity study for a 100 MW wind plant operating under medium wind (IEC II) conditions was assessed for operation in low wind (IEC III) for a sensitivity study. As a result, an increase by 23 % in all categories was found [54]. AWE facilities might be less affected by this, since they can adjust in operation altitude more easily. Future plant operations will show and a prediction goes beyond the scope of this study.

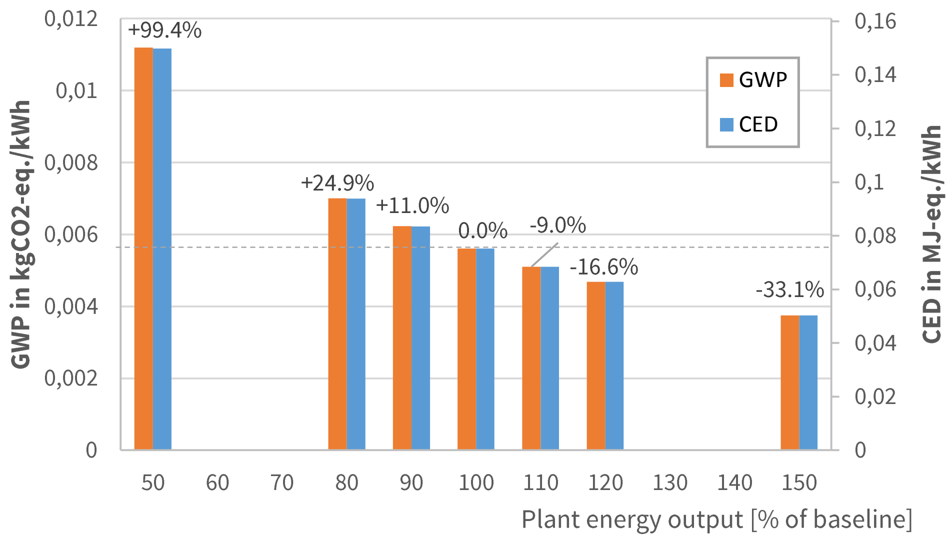


Figure 5.12: Sensitivity for changes in energy output of the plant.

Plant size

The investigated plant with 182 facilities is rather on the upper range of conventional wind power plants. Except the energy buffer, control tower and external cabling, all parameters are linearly correlated to the number of facilities, whereas only the latter is relevant anyhow. Since there is no difference to the conventional wind energy plant, a respective sensitivity study is considered sufficient to conclude that a plant size of 30 facilities has no significant influence, when instead of 2 external cables only 1 is needed [56].

Frequency of wing launches

For this analysis, the energy that is required to launch the wing system is varied. The energy yield, component lifetime and other parameters are unchanged. In the baseline model, the wing was launched every other day. Over the plant lifetime it sums up to 87,600 launches.

The sensitivity of the selected impact categories for changes in frequency of launches is shown in Figure 5.13. If the wing is launched 4 times more often, impact categories change less than 1 %. For 10 launches a day, they would increase by 4.1 (GWP) and 5.1 % (CED). This is considered as unrealistically high frequency and the assumption that energy yield is constant becomes questionable. If launching the wing system only about once a month, no significant savings can be achieved. Thus, frequency of wing launches is not a relevant issue.

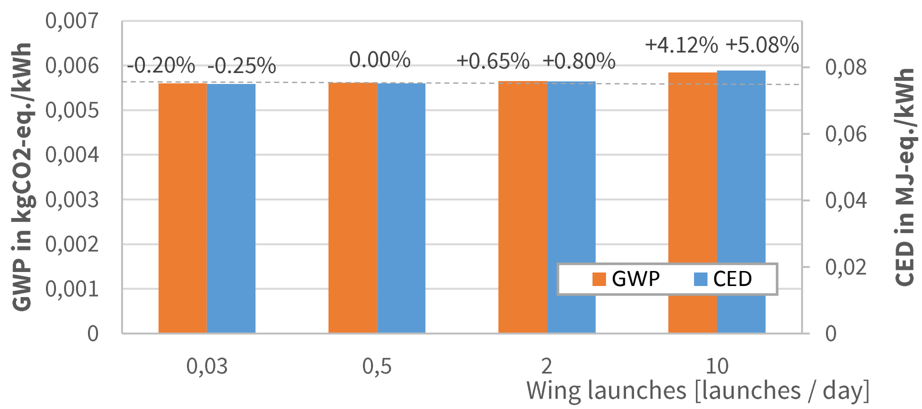


Figure 5.13: Sensitivity for changes in frequency of wing launches.

Distance to grid

For this analysis, cable material according to length and transportation to and from the site are varied, losses within the plant and cable cross section are unchanged.

The sensitivity of the selected impact categories for changes in distance from substation to the grid is shown in Figure 5.14. GWP and CED are 14.4 and 16 % lower when the plant is 80 % closer to the grid. Impacts of other distances can be linearly interpolated.

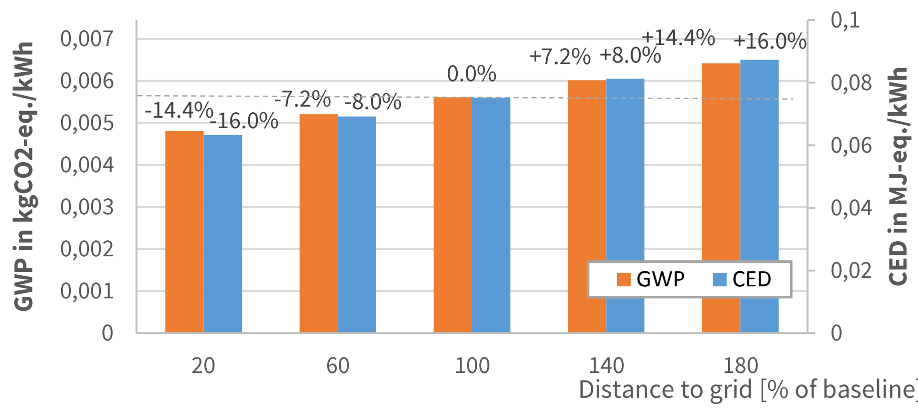


Figure 5.14: Sensitivity for changes in distance to connect the plant to the grid.

Tether replacement

For this analysis, the frequency of tether replacement is varied in different combinations of the upper and lower part. Production of new tether in the phase of the replacement is considered, extra transportation is considered insignificant and neglected.

The sensitivity of the selected impact categories for changes in lifetime of the two tether sections is shown in Figure 5.15. With own calculations from [84], current material is estimated with around 4 months for the tether part that is reeled in and out frequently, and 1 year for the upper part. GWP and CED are almost 1/3 and 1/2 higher than for baseline, for which 2 and 10 years are assumed for the two tether sections. Not only from an environmental point of view but also from an economic perspective, research and development in tether performance are attractive and improvements are expected. The material is not yet much optimized for AWE applications since comparable applications are not common. The baseline scenario is considered achievable but further developments only have little effect on the impact categories. Extending bottom tether part lifetime by factor 2.5 lowers GWP only by 2.7 %. The improvements to achieve the baseline scenario, however, are important.

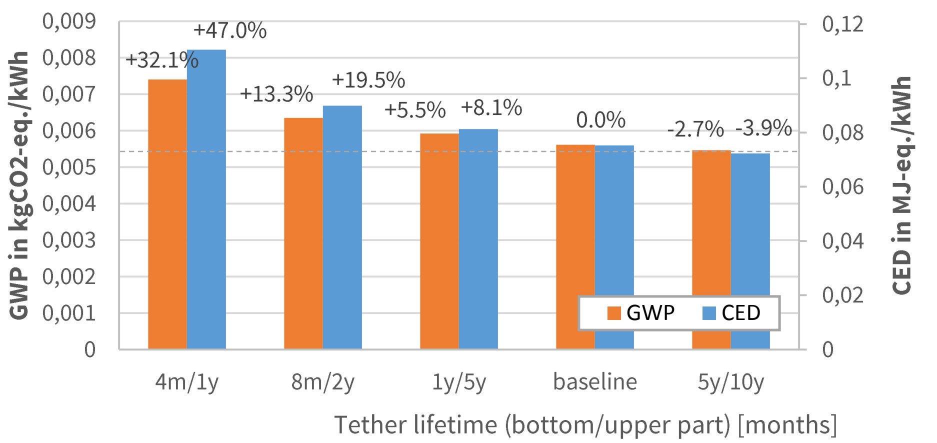


Figure 5.15: Sensitivity for changes in lifetime of bottom and upper part of the tether.

Gearbox replacement

For this analysis, the production of gearboxes in the O&M life cycle phase, as well as transportation to the site and to disposal are considered.

The sensitivity of the selected impact categories for changes in share of the gearboxes that have to be replaced within the plant`s lifetime is shown in Figure 5.16. Compared to the baseline scenario, where 100 % of the gearboxes are exchanged, GWP and CED are 13.6 and 12.4 % lower, when no replacement is necessary. Between these extremes, values can be linearly interpolated.

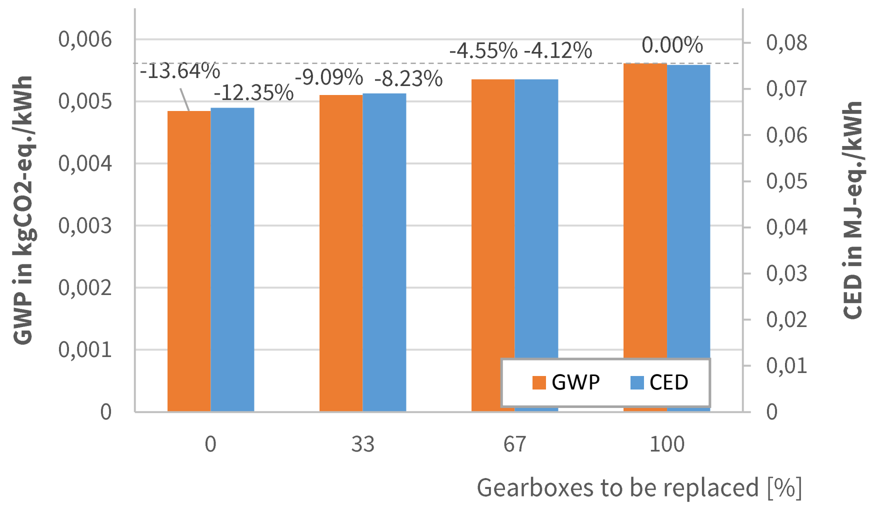


Figure 5.16: Sensitivity for changes in share of gearboxes that have to be exchanged during plant life.

5.3 Comparison to conventional wind power and validation

The numbers of the AWE system alone have a limited power for conclusions. The numbers are relative and should therefore be compared to a system that was modeled with a comparable approach. The conventional wind power system for this comparison is modeled with comparable system boundaries, properties of the product system such as facility size, rated power and site conditions and data acquisition. A list of characteristic parameters of both systems can be found in Table 5.3.

Table 5.3: Characteristic facility and plant parameters of airborne and towered wind energy system.

Parameter	HAWT	AWES	unit
Rated facility power	1,650	1,800	kW
Installed generator power	1,650	2,500	kW
Capacity factor	40.8	41.0	%
Number of facilities	182	182	units
Rated plant power	300	328	MW
Farm efficiency	95	95	%
AEP (plant)	1,020	1,118	MWh
Plant lifetime production	20,393	22,356	MWh
Plant lifetime	20	20	yrs
Distance to grid	50	50	km
Distance between facilities	408	400	m
Av. wind speed at respective hub height	7.38	7.4	m/s

A HAWT in the modeled plant consumes a total of 1,097 tons material over its lifetime, including the share for balance-of-station. Figure 5.17 displays the composition of this mass by material type. Over ¾ of the mass is concrete for the foundation. Slightly over 20 % is metals. The weight of different components and replaced material can be found in Figure 5.18.

The category indicator results of the simulation are 1.150e-2 $kg_{CO2\text{-}eq.}$/kWh in GWP and a CED of 1.426e-1 MJ-eq. /kWh. The CED corresponds to an energy payback time of 9.5 months.

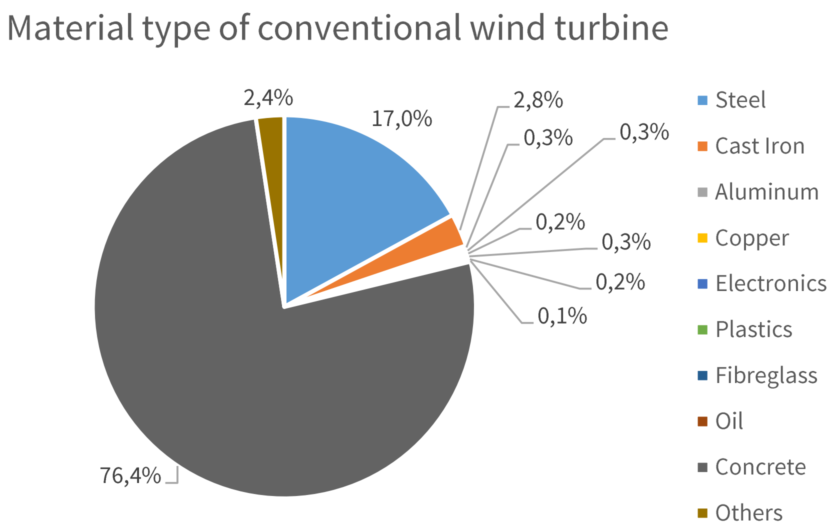
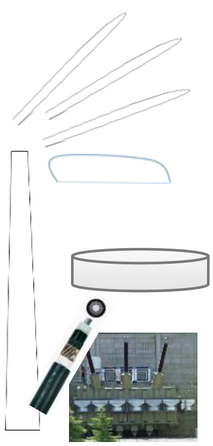


Figure 5.17: Composition of material types in tons for a conventional HAWT comparable to the studied product system.



HAWT	Mass [t] at installation / in lifetime		AWES
Rotor	42.2	2.1 / 4.5	Wing system
Nacelle	51 / 68	50.2 / 76.6	Ground station
Tower	136	0.5 / 2.5	Tethering
	(0)	138 / 147	Launch/Landing
Foundation	832	(0)	
Cabling	15.7	15.7	Cabling
Substation	0.8	0.8	Substation
Total	**1,078 / 1,095**	**208 / 249**	**Total**

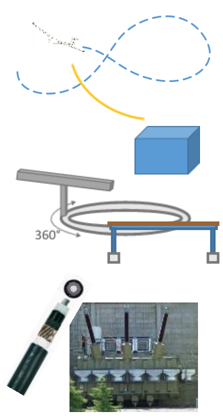


Figure 5.18: Masses of component systems of comparable conventional and airborne wind energy plants at installation and in a plant lifetime (data for horizontal axis wind turbine from [56]).

Literature data and comparison

A study on a conventional horizontal axis wind turbine plant with parameters as listed in Table 5.3 was conducted and published [56]. It assesses the Vestas V82 1.65 MW turbines in a 300 MW plant. One important difference is, that the system boundary in this study include recycling of metals and other material as disposal scenario of the plant. The metals are recovered by 90 % and replace virgin material. The credits are fully assigned to the wind power plant. Further recycling and thermal recovery for example for plastics are also credited. The calculations result for GWP100a 7.05e-3 $kg_{CO2\text{-}eq.}$/kWh. The energy payback time was calculated as 7.7 months.

The sensitivity study shows that an increased recycling rate from 90 to 96 % would reduce GWP by 3 %. Linearly correlating this number to a recycling rate of 0 % as modeled in the present study leads to 10.22e-3 $kg_{CO2\text{-}eq.}$/kWh. This is 12.5 % lower than the value that was achieved by own modeling for the conventional wind energy plant with the similar approach to the AWE plant model. The lower assumptions for replacement and Vestas-specific production processes compared to average industry data easily lead to a deviation of this magnitude. Thus the modeling approach in this study is considered sufficient to meet the goal and scope definition when data from own simulations is used in both cases.

Literature might suggest that the use of AWE systems can be expected to have environmentally beneficial aspects sins the manufacture of the towers has the greatest contribution (most significant for twelve of the fifteen categories assessed) [54] in conventional wind plants but is not required in AWE systems.

Indeed, the studied AWE plant consumes only 22.7 % of the mass, causes 48.8 % of its GWP and consumes only 54.9 % of the CED compared to a conventional wind turbine. If a different kind of yaw system was chosen, weight could be even much lower. These numbers suggest, that the studied conservatively designed AWE plant bears half the global warming potential than a comparable conventional wind plant and pays back consumed energy over its life cycle in 55 % of the time. The listing of component system masses of both technologies in Figure 5.18 show that the airfoil in the AWE system requires only 10 % of the mass. The tower, which has a big share in mass but represents only structural functions to position the airfoil in operation altitude is over 55 times heavier than the equivalent in the AWE plant, the tether. The power generating system in both cases is of comparable size but higher for AWE. The launch and landing system is the biggest fraction for the AWE plant and is not required for a conventional wind turbine. This is overcompensated, however, by the massive foundation that contributes to over 75 % of the mass in conventional wind but is already included in the numbers of AWE for ground station and launch and landing system.

Figure 5.19 allows better comparison how GWP and CED for both technologies are composed. Also here, the different impacts of rotor / wing, tower / tethering and foundation or launch and landing system become apparent. What´s more, the massive difference in replacement becomes obvious. Whereas replacements account for 27 % of the assessed impact categories for AWE, its only 6 % for conventional wind energy. As a consequence raw material and manufacturing phase accounts for 78 and 73 % of the GWP and CED for conventional wind, whereas it´s 65 and 62 % for AWE.

The values for each system varies strongly with rated power and number of the facilities, the installation onshore or offshore, site conditions and many others. Other LCA studies on a 3 MW offshore turbine by Vestas generates 5.23e-2 $kg_{CO2\text{-}eq.}$/kWh and assessed in an onshore application the result was 4.64e-2 $kg_{CO2\text{-}eq.}$/kWh [120]. The study assumed installation at IEC II (medium wind) conditions. The sensitivity analysis for this V112-3.0 MW turbine showed that all environmental impacts of the turbine increase by 23 % when assessed for operating the plant under IEC III (low wind) conditions [54]. It might be possible that AWE facilities are less affected by changing wind conditions due to their adjustability in operation altitude.

It should be mentioned that the 1.65 MW wind power plant is used as a reference is not a modern turbine. Nevertheless, it was chosen to use this for comparison since the comparison to a modern 8 MW turbine is considered to have more limitations for the immaturity and different properties of the technology.

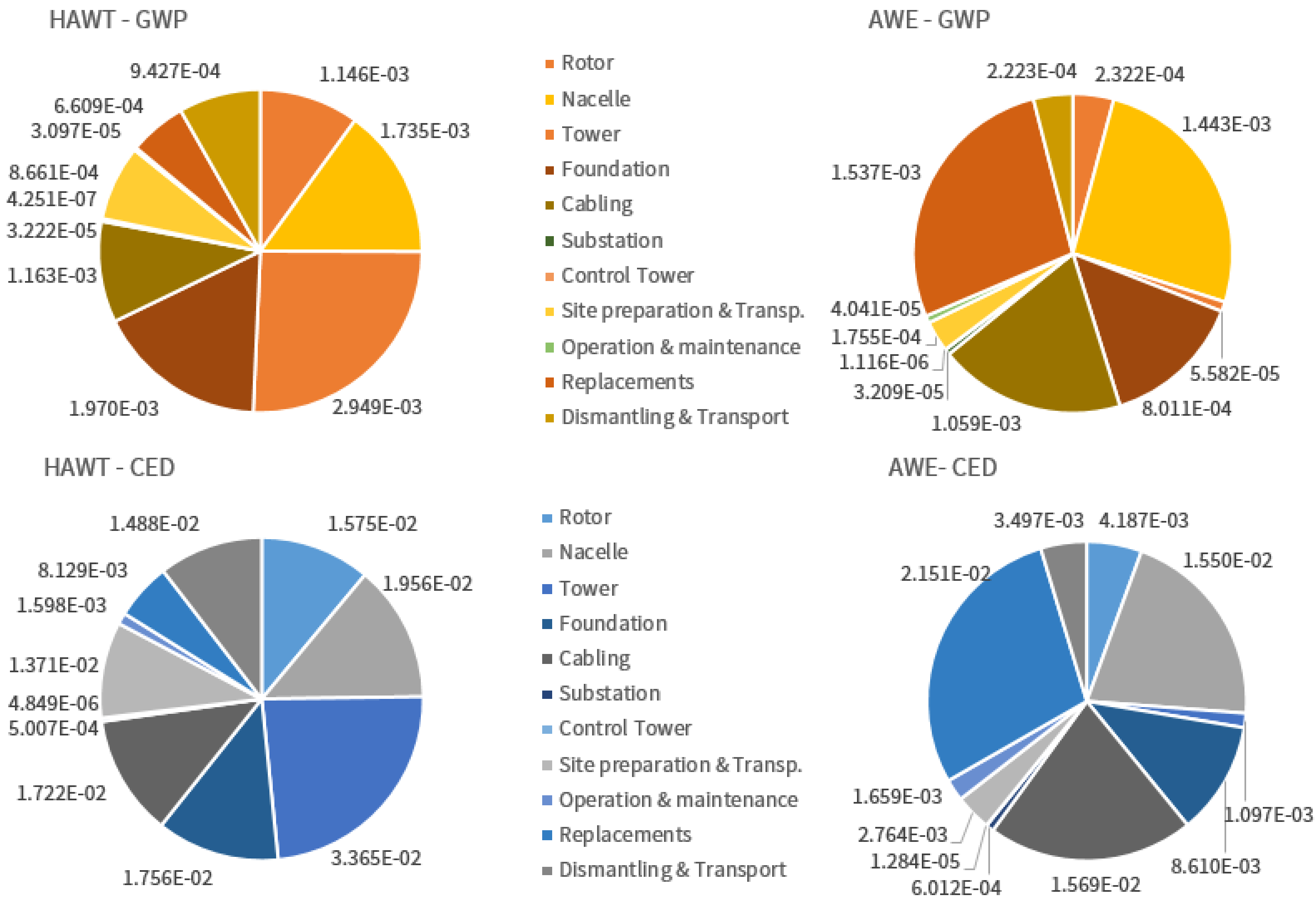


Figure 5.19: GWP and CED for the different units of a conventional and an airborne wind energy system.

5.4 Comparison to other energies

The comparison to other electricity generation technologies is of more limited reliability than the comparison to the conventional wind energy system in section 5.3. The product systems and system boundaries are likely to be significantly different. However, it allows a rough evaluation and better understanding of the results of AWE in relation to current technology.

The values for "AWE" and "Conventional Wind" are the results of the own modeling. The values for wind in the 1-3 MW range, lignite, and the electricity mix are calculated with the respective ecoinvent datasets. The electricity mix in Europe has a wide range in environmental impacts. The dataset for electricity mix in Norway is associated with 31 g_{CO2}/kWh and 1040 in Poland [121]. For this study the German electricity mix is used as a reference.

The GWP of the AWE plant compared to the conventional wind energy plant and average turbines of 1-3 MW size is approx.-factor 2 and 3,7 times less. However, all of them are marginal compared to the electricity mix and even more compared to lignite which had a 25.6 % share in electricity production in Germany in 2014. GWP and CED of the AWE plant are 0.87 and 0.74 % of that of the German electricity mix, which causes in average 644.2 g CO2-eq./kWh and requires 10.6 MJ/kWh. AWE seems to be the preferred option In terms of global warming and primary energy requirements for electricity production.

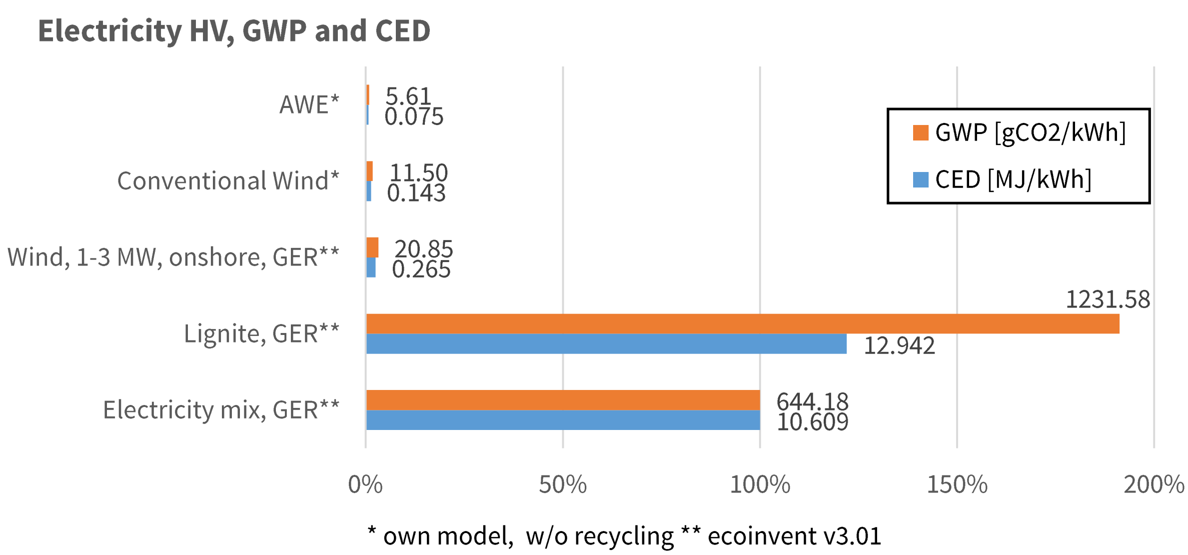


Figure 5.20: GWP and CED for several sources of high voltage electricity generation.

5.5 Uncertainties and limitations

The assessment of a premature technology obviously comprises great uncertainties. This section qualitatively discusses sources for uncertainty of the data to confer a better estimation of the reliability of the results They might be separated in uncertainties arising from the modeling procedure and external uncertainties and limitations due to the nature of the used tool.

The modeling heavily depends on the quality of the used datasets. Since several new or not yet developed materials are used, data is likely to deviate from the actual case for the future real systems. For example tether material and coating might be subject to changes, as well as the process of manufacturing carbon fiber reinforced polymers in general. Data on these components are not or only in a very wide range available. Analysis and discussion of results showed, that the fraction of those “non-standard” materials is low. The values that are used are rather a upper estimation since production processes (cf. CFRP) tend to become less energy intensive.

Another source of uncertainty from the model is the end-of-life scenario. It was assumed that all material goes to landfill as a disposal scenario. It is rather likely, that most of the metal components, which contribute about ¼ to the mass, are recycled. Typical recycling rates are around 90 % for metals in comparative applications but can be as high as 96 % today. Plastics can partly be thermally recovered. The yields and savings in subsequent processes by replacement of virgin material can be credited partially or fully to the studied system, which could significantly lower the category indicator results since the great majority is caused from metals.

External u**ncertainties** are manifold. To start with, it is not clear yet, what will be the dominating design of potential future commercial systems. As presented in chapter 2, there are lift and drag power systems, rigid and flexible wing concepts, massive and simplistic launch and landing system designs and so on. A frequently replaced soft wing from plastic fibers might lead to different environmental impacts than a long lasting but energy intensive rigid wing with carbon fibers and epoxy resin. In addition, the actual implementation for a certain dominating system design can vary substantially in production processes, used materials, location of suppliers and customers, handling of waste etc. What´s more, the lifetime of the used materials is unclear. The tether life expectancy has a great span. But also how generator and gearbox cope with the intermittency of power generation will need to be proofed.

Another issue that tests and operation have to show, is the actual performance of the systems. The capacity factor estimation still contains many uncertainties. The technical availability could be low for the first systems. The pumping cycle efficiency leaves room for improvements. The performance in low wind situations can change capacity factor significantly.

The undefined legal state leaves open, how close facilities can be spaced within the farm and to surroundings, which could lead to changes in cabling requirements.

Project specific properties like distance to grid (cabling), size of farm, site conditions and so forth influence the results strongly. This is partly shown in the sensitivity study.

There are many factors that could be listed here. What can be concluded is, that uncertainties for absolute numbers are high and external factors are decisive. The numbers should therefore not be used as absolute values but rather for relative comparisons and qualitative conclusions. This way, uncertainties can be reduced since they might apply for all compared systems in a comparative way. As examples, the approach might be useful to determine the effect of design choices, to analyze potentials for savings or to just give a rough estimation on environmental effects compared to other technologies. A certain system design needs to be assessed with its specific data for more accurate numbers.

Limitations of the LCA-tool

Even though the LCA considers environmental impacts associated with the use of materials and energies during the considered product life phases it does not deliver final decision or evaluation of the “eco-friendliness” of a product. Further impacts are possible that are not known yet or not included. Furthermore, some environmental aspects cannot be covered with the LCA approach, such as effects from noise and shadowing, as well as impacts on landscape, flora and fauna. Other environmental management tools are valuable, like risk assessment, environmental performance evaluation, and further environmental impact assessment but also tools to assess social and economic aspects, which are not covered with the LCA approach. Further limitations to the LCA approach lay in its narrow view on a certain product and possibly its alternatives which might ignore side effects such as rebound effects, indirect land use, market mechanisms which might result in undesired effects on food market, scarcity, social structure, land use and others.

6 Conclusions and further research

6.1 Conclusions

Airborne wind energy (AWE) is considered as an emerging technology, that has the potential to provide significant contribution to the global energy demand. The study investigates an airborne wind energy system for its demand in energetic resources and its contribution to climate change as an electricity generating technology. By choosing the LCA (life cycle assessment) approach, the selected environmental impact categories are analyzed over the entire product life cycle, from cradle to grave.

The study allows to foster understanding of the environmental implications of design choices of developers during the design. In addition, the study might provide data to support decision process for parties that evaluate support of this technology. Due to the novelty and not yet achieved maturity of AWE technology, frequent and significant changes in system designs can be expected. Nevertheless an assessment at this early stage is executed, since the uncertainties are overcompensated by the benefit from having a first numerical reference.

The main research questions for this study were to analyze the following aspects:

1. Determination of environmental burden of electricity generation with AWE systems by means of contribution to global warming and consumption of primary energy resources.
2. Identification of the main contributors to the caused environmental burdens and potential for savings.
3. Determination of the time that the plant needs to be operated to recover the energy invested over the life cycle.
4. Assessment whether developing this new technology would lower global warming potential of electricity supply.

A selection of literature was presented explaining the potential and motivation for AWE. The wind resource in the concerned altitude and technological concepts to harvest it were presented. An overview of the required functions of the components and the range of technological implementations that are possible or actually being developed. In addition, some of the literature on environmental impacts of electricity generating technologies is presented. The life cycle assessment tool, that was used for this study, is introduced.

The product system “AWE plant” was defined with specific properties that are considered like to be dominating design or that represent a conservative choice within the range of reasonable possibilities. This was done after reviewing the available information on potential airborne wind energy system designs, and corresponding with industry experts. The investigated plant consists of 182 interconnected facilities, each having a rated power of 1.8 MW installed under low wind conditions. As functional unit, to which the category indicator results are assigned, 1 kWh generated electrical energy delivered to the grid was chosen. The selected impact categories are one, the global warming potential in a 100 years perspective (GWP100a), indicated in $kg_{CO2\text{-}eq.}$/kWh and two, the cumulated energy demand (CED), indicated in MJ-eq./kWh. The data collection is explained in the life cycle inventory analysis. The calculations were implemented with the software Umberto NXT LCA. The used material, GWP and CED were analyzed for a baseline dataset and then checked for its robustness and effect of certain parameter choices to the results in a sensitivity study. The results are summarized in the following.

The investigated plant consumes a total 249 tons of material per facility over the lifecycle, whereas 230 tons are for the facility manufacture, replacements and maintenance and the rest for its share in balance-of-station. The material of the defined product system is mainly gravel (32 %), metals (42 %), plywood (7 %) and plastics (5 %). Carbon fiber of the wings accounts for less than 1 %. The total weight of the AWE plant is 23 % of a comparable conventional wind turbine over the life cycle. Main difference is in the weight of the wind capturing device (rotor vs. wing system) with 38 tons saving, the structural element tower (136 tons) vs. tether (2.5 tons) and the foundation with 832 tons, which is not required in this form for AWE facilities. The particular extra weight for the AWE plant is launch and landing system with 147 tons in the chosen design.

The category indicator results for electricity from the AWE plant are 5.611 $kg_{CO2\text{-}eq.}$/kWh in global warming potential in a 100 year´s perspective (GWP) according to CML2001 method and a cumulated energy demand (CED) of 7.522E-2 MJ-eq./kWh. For most component systems GWP and CED are well correlated. Only for a few components like the tether cause of greenhouse gases and consumption of primary energy are not in a relationship as in the data average. From the resulting CED it can be derived that the energy payback time is just 5 months or 153 days. By then, the energy that was invested in the entire life cycle over manufacturing, operation and disposal is recovered as electrical energy. This is equivalent to 2.1 % of the lifetime energy generation or an energy yield of 48 times more generated than total invested energy.

The cause in GWP is distributed over the life cycle phases with 65 % in raw material and manufacturing, 3 % from installation, 28 % from operation, maintenance and replacements and 4 % from end-of-life / disposal. The share of the AWE facility from raw material, manufacturing and disposal combined is 70 %, which is also the share in GWP that developers can directly influence. Its components were further analyzed. Around 75% of the wing system's cause in GWP and CED come from the carbon fiber reinforced polymer structure. The overall contribution of this component is low (2.6 and 5.6 %). More potential for improvements lay in the design of the launch and landing system. Half of the impacts come from the landing deck. It might be possible to find designs that are less massive with different material to yield a lower impact. The biggest savings potential might lay in the system design off mechanical to electrical power conversion. Without replacements, the ground station accounts already for 21 and 26 % in total in GWP and CED respectively with over 50 % from the gearbox alone in each category. On top of that, the gearboxes account for almost half the impacts of replacements. Sensitivity study shows, that overall impacts decrease linearly when reducing the share of replaced gearboxes from all to none by around 13 %. Of the whole life cycle impacts, generator and gearbox combined account for 35 and 30 % in both categories, not including their transport. Even though, great potential for savings lays here, the alternatives should be evaluated carefully.

The impact of the tether as a single component was of special interest in this study. Due to replacements, its initial share in mass increased from 0.2 % to 1.5 %. The contribution to the impact categories is with 5.5 and 8.1 % significantly higher than to the weight. The sensitivity study showed that further optimizations than the assumed lifetime do not have significant impacts but lifetimes that seem likely at this time would lead to an increases of ⅓ and ½ in GWP and CED respectively.

Further results of the sensitivity study are that changes in plant power output have considerable effects on the result. If power output is 20 % higher than expected, actual impacts would be lowered by 17 %, and increased by 25 % when output is 20 % lower. Impacts are around 15 % lower, when distance to grid is lowered from 50 to 10 km. Energy for wing launches is irrelevant for the whole range of reasonable launch frequencies.

Compared to a conventional wind energy plant that was modeled in comparable size and procedure, the AWE plant needed a 50 % bigger generator and gearbox. Nevertheless, it had a 2 times lower energy payback time, 5 compared to 9.5 months. The studied AWE plant consumed only 23 % of the mass, caused 49 % of its GWP and consumes only 55 % of the CED compared to a conventional wind turbine.

The comparison to other energy technologies is of limited validity due to different system boundaries and data base. The numerical results for the modeled systems are expected be significantly higher than a comparable approach would deliver. Having that in mind, it is expected global warming potential of electricity from AWE is at least 117 times lower than German electricity mix or, respectively 0.87 % of it. For cumulated energy demand, the fraction of requirements for AWE compared to grid mix is 0.74 %.

Limitations

The numbers should be only used, having in mind the relative nature of the LCA approach and the specific uncertainties as described in section 5.6. The numbers apply only for the system as specified and can deviate considerably for other AWE systems. Uncertainties of the model arise from the novelty of technology and assumptions that have to be made for data on design choice, system performance (mainly generated power, efficiency and lifetime), actual kind of application, material and energy consumption, manufacture processes to mention only some. The developments of the industry have to be observed and assessments conducted for specific systems.

6.2 Further research

Further research is recommended in three categories

- Sophistication and expansion of the model
- Environmental aspects beyond the scope of LCA
- multidimensional (sustainability) assessment: economy, environment, society and others

Sophistication and expansion of the model

Data needs to be revised in quite short time since technology and its processes develop fast.

An interesting model expansion could be the inclusion of further and more sophisticated end-of life scenarios. Most of the used material can be recycled or energetically recovery to a high percentage or even be reused. Depending on the applied credit system, the impact category results could be affected (lowered) significantly.

Also the investigation of different design and material choices could lead to interesting insights. One example is the assessment whether it is beneficial to use a long lasting massive wing structure of carbon fiber reinforced polymer as in this study or to use polymer-based soft kites that probably have a shorter lifetime and different performance. Other examples are the use of permanent magnet generators instead of conventional generator with gearbox or the implementation of different launch and landing systems since this is a very specific choice in this study or the investigation of a utility scale system as in this study compared to a mobile small scale system.

Environmental beyond LCA

This study considered only two environmental impact categories. There many further topics that should be checked for their relevance and assessed like the effect on fauna, noise or toxicity. In fact, a recent study found that (conventional) off-shore wind was associated with a higher indicator result in the category human toxicity compared to the electricity mix [122].

For this study, LCA was chosen over other tools. For further investigations, several tools could be interesting, such as environmental impact assessment (EIA), environmental management accounting (EMA), hazard and risk assessment of chemicals, substance and material flow analysis (SFA and MFA) , risk analysis and risk management of facilities and plants.

Multidimensional assessment

As a first step that might be interesting for companies to implement is the development of a tool execute “eco-economic” system optimizations.

In recent scientific assessments the classical one-dimensional approach of ecology is extended to three or more dimensions to a life cycle sustainability assessment (LCSA). The three pillars of sustainability are completed by assessing also economic aspects with a life cycle costing (LCC) and social aspects with social life cycle assessment (SLCA). The categories of LCA, LCC and SLCA can be weighed against each other. The implications can be assessed not only on product level but also on meso and economy level. The latter could mean the analysis implications of substituting other sources by introduction of large-scale AWE-farms for power generation, which might evoke additional effects on the meso-level compared to product level.

Other studies go even further. In a 4-D approach (+ technology) 10 sustainability indicators are defined, focusing on electricity generation [123]. Those indicators are LCOE, ability to respond to demand, efficiency, capacity factor, external cost (environmental and human), land use, job creation, social acceptability and external supply risk.

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Appendix

Material consumption

Table A.1: Required total masses by type of material for facility and plant over lifetime or at installation.

material type	1 facility, Install. in kg	Total replacem. in kg	1 facility, lifetime in kg	Share, facility, lifetime	Plant, lifetime in kg	Share, plant, lifetime
Steel				31.6%		29.67%
low alloyed	47,984	792,572	52,338		9,610,321	0.00%
chroimium	9,607	1,675,593	18,813		3,423,987	0.00%
reinforcing	1,247		1,247		226,965	0.00%
Cast Iron	10,552	1,901,263	20,998	9.2%	3,821,719	8.55%
Aluminum	317	56,953	630	0.3%	1,132,076	2.53%
Copper	1,657	111,105	2,267	1.0%	711,525	1.59%
Plastics				2.0%		5.42%
PE-HD	25	50	26		4,650	0.00%
PE-LD	160	11,556	223		1,618,063	0.00%
PE-UHMW	450	455,000	2,950		536,900	0.00%
polyurethane	145	71,890	540		98,280	0.00%
polyvinylfluoride					1,533	0.00%
meta-Polyaramide	450	81,900	900		163,800	0.00%
Concrete	29,289	0	29,289	12.8%	5,330,679	11.93%
Gravel	78,263	0	78,263	34.2%	14,243,931	31.87%
Alkyd Paint	91	4,333	115	0.1%	22,558	0.05%
Epoxy Resin	176	19,081	280	0.1%	51,311	0.11%
CFRP	1,100	200,200	2,200	1.0%	400,400	0.90%
Glass Fiber	0	0	0	0.0%	1,455	0.00%
Glass	0	0	0	0.0%	1,736	0.00%
Oil	100	0	100	0.0%	18,200	0.04%
Wood, plywood	8,595	1,564,362	17,191	7.5%	3,128,725	7.00%
Wood, Fiberboard	49	7,222	88	0.0%	24,561	0.05%
Wood, Kraft Paper	0	0	0	0.0%	1,966	0.00%
permanent magnet	1	214	2	0.0%	428	0.00%
el. motor, for electric scooter	25	4,550	50	0.0%	9,100	0.02%
Electronics, charger passenger car	50		50	0.0%	9,100	0.02%
batteries, LiPo	90	79,170	525	0.2%	95,550	0.21%
electronics, for control unit	25	4,550	50	0.0%	9,100	0.02%

Transport data

Table A.2: Transport data for disposal of the AWE plant components.

Transport for disposal	Mass total in kg	Type of Transport	Source	Dist. in km
Gearbox	4,022,200	lorry, <16 t	Installation	400
LLA Structure	23,734,494	lorry, <16 t	Installation	400
Cabling, internal	146,569	lorry, <16 t	Installation	400
Cabling, external	2,710,600	lorry, <16 t	Installation	400
Gearbox	3,931,200	lorry, <16 t	Replacement	400
Oil, lubricant	273,000	lorry, <16 t	Replacement	400
Wood, Plywood	1,564,362	lorry, <16 t	Replacement	400
GS structure	2,176,920	lorry, <7.5 t	Installation	400
GS back-end electronics	602,333	lorry, <7.5 t	Installation	400
Asynchronous Induction Motor	2,311,594	lorry, <7.5 t	Installation	400
Tether	90,090	lorry, <7.5 t	Installation	400
LLA Electronics	96,865	lorry, <7.5 t	Installation	400
LLA Mechanisms	1,363,422	lorry, <7.5 t	Installation	400
Hangar	3,165	lorry, <7.5 t	Installation	400
Energy buffer	33,192	lorry, <7.5 t	Installation	400
Batteries main (24V)	21,840	lorry, <7.5 t	Replacement	400
Batteries Propulsion (120V)	40,950	lorry, <7.5 t	Replacement	400
Tether, bottom part	327,600	lorry, <7.5 t	Replacement	400
Tether, upper part	45,500	lorry, <7.5 t	Replacement	400
Converter	602,333	lorry, <7.5 t	Replacement	400
Wing System	377,650	lorry, >32 t	Installation	400
Substation	154,018	lorry, >32 t	Installation	400
Wing System	377,650	lorry, >32 t	Replacement	400

Table A.3: Summary of transport data for installation of the AWE plant.

Transport for Installation	Mass total in kg	Mass inkg	Type of Transport	Dist. in km
Gearbox	4,022,200	22,100	lorry, <16 t	400
LLA Structure	23,734,494	130,409	lorry, <16 t	400
Cabling, internal	146,569	146,569	lorry, <16 t	200
Cabling, external	2,710,600	2,710,600	lorry, <16 t	200
GS structure	2,176,920	11,961	lorry, <7.5 t	400
GS back-end electronics	602,333	3,310	lorry, <7.5 t	400
Asynchronous Induction Motor	2,311,594	12,701	lorry, <7.5 t	200
Tether	90,090	495	lorry, <7.5 t	100
LLA Electronics	96,865	532	lorry, <7.5 t	400
LLA Mechanisms	1,363,422	7,491	lorry, <7.5 t	400
Hangar	3,165	3,165	lorry, <7.5 t	400
Energy buffer	33,192	33,192	lorry, <7.5 t	400
Wing System	377,650	2,075	lorry, >32 t	400
Substation	154,018	154,018	lorry, >32 t	200
LLA Mechanisms	1,363,422	7,491	ship	1200
Asynchronous Induction Motor	2,311,594	12,701	train	700
Substation	154,018	154,018	train	1000
Total	**37,823,112**	**3,238,618**		

Baseline results

Table A.4: Mass, GWP and CED for the life cycle stages for comparable conventional and AWE plants

HAWT	facility mass [kg]	GWP [$kg_{CO2-eq.}$/kWh]	CED [MJ-eq./kWh]	AWE	facility mass [kg]	GWP [$kg_{CO2-eq.}$/kWh]	CED [MJ-eq./kWh]
Raw material & manufacture	**1,077,766**	**8.996E-03**	**1.042E-01**		**207,770**	**3.636E-03**	**4.871E-02**
Rotor	42,200	1.146E-03	1.575E-02	Wing system	2,075	2.322E-04	4.187E-03
Nacelle	51,000	1.735E-03	1.956E-02	Ground station	50,172	1.443E-03	1.550E-02
Tower	136,000	2.949E-03	3.365E-02	Tethering	495	5.582E-05	4.187E-03
				Launch/Landing	138,483	8.011E-04	8.610E-03
Foundation	832,000	1.970E-03	1.756E-02				
Cabling	15,720	1.163E-03	1.722E-02	Cabling	15,699	1.059E-03	1.553E-02
Substation	846	3.222E-05	5.007E-04	Substation	846	3.209E-05	6.012E-04
Control Tower		4.251E-07	4.849E-06	Control tower		1.116E-06	1.284E-05
Installation		**8.661E-04**	**1.371E-02**			**1.755E-04**	**2.939E-03**
Site preparation & Transp.		8.661E-04	1.371E-02	Site preparation & Transp.		1.755E-04	2.939E-03
O&M&R	**18,940**	**6.919E-04**	**9.727E-03**		**40,975**	**1.577E-03**	**2.317E-02**
Operation & maintenance	1,500	3.097E-05	1.598E-03	Operation & mai	1,500	4.041E-05	1.659E-03
Replacements	17,440	6.609E-04	8.129E-03	Replacements	39,475	1.537E-03	2.151E-02
Disposal		**9.427E-04**	**1.488E-02**			**2.223E-04**	**3.497E-03**
Dismantling & Transport		9.427E-04	1.488E-02	Dismantling & Transport		2.223E-04	3.497E-03
Total	**1,096,706**	**1.150E-02**	**1.426E-01**		**248,744**	**5.611E-03**	**7.832E-02**

Sensitivity study

Table A.5: Results of sensitivity study for GWP and CED.

		GWP in $kg_{CO2-eq.}$/kWh	Sensitivity	CED in MJ-eq./kWh	Sensitivity
Tetherlife (upper/bottom part)					
4m/1y		7.410E-03	32.1%	1.106E-01	47.0%
8m/2y		6.355E-03	13.3%	8.985E-02	19.5%
1y/5y		5.921E-03	5.5%	8.131E-02	8.1%
2y/10y		**5.611E-03**	**0.0%**	**7.522E-02**	**0.0%**
5y/10y		5.462E-03	-2.7%	7.229E-02	-3.9%
Distance to grid					
10 km	20	4.806E-03	-14.4%	6.321E-02	-16.0%
30 km	60	5.208E-03	-7.2%	6.921E-02	-8.0%
50 km	**100**	**5.611E-03**	**0.0%**	**7.522E-02**	**0.0%**
70 km	140	6.014E-03	7.2%	8.122E-02	8.0%
90 km	180	6.416E-03	14.4%	8.723E-02	16.0%
Farm Size					
164 MW	50	1.119E-02	99.4%	1.498E-01	99.2%
262 MW	80	7.006E-03	24.9%	9.387E-02	24.8%
294 MW	90	6.231E-03	11.0%	8.351E-02	11.0%
327 MW	**100**	**5.611E-03**	**0.0%**	**7.522E-02**	**0.0%**
360 MW	110	5.104E-03	-9.0%	6.843E-02	-9.0%
392 MW	120	4.681E-03	-16.6%	6.278E-02	-16.5%
451 MW	150	3.751E-03	-33.1%	5.035E-02	-33.1%
Frequency of L&L					
0.03/d	6	5.600E-03	-0.20%	7.503E-02	-0.25%
0.5/d	**100**	**5.611E-03**	**0.00%**	**7.522E-02**	**0.00%**
2/d	400	5.648E-03	0.65%	7.582E-02	0.80%
10/d	2,000	5.842E-03	4.12%	7.904E-02	5.08%
Replacement					
0%	0	4.846E-03	-13.64%	6.593E-02	-12.35%
33%	33	5.101E-03	-9.09%	6.903E-02	-8.23%
66%	67	5.356E-03	-4.55%	7.212E-02	-4.12%
100%	**100**	5.611E-03	**0.00%**	**7.522E-02**	**0.00%**

Umberto model

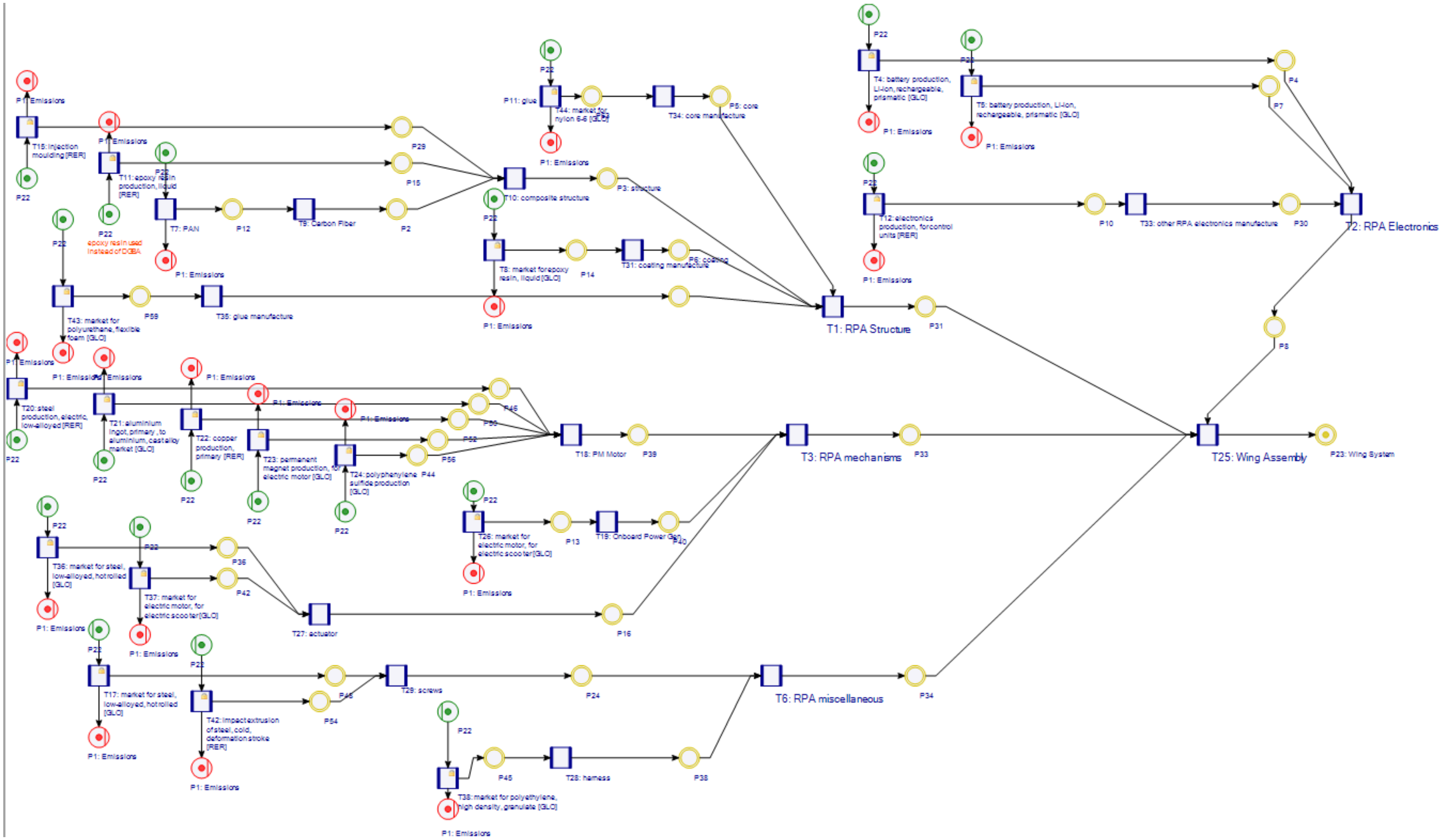

Figure A.1: Umberto model – subnet wing.

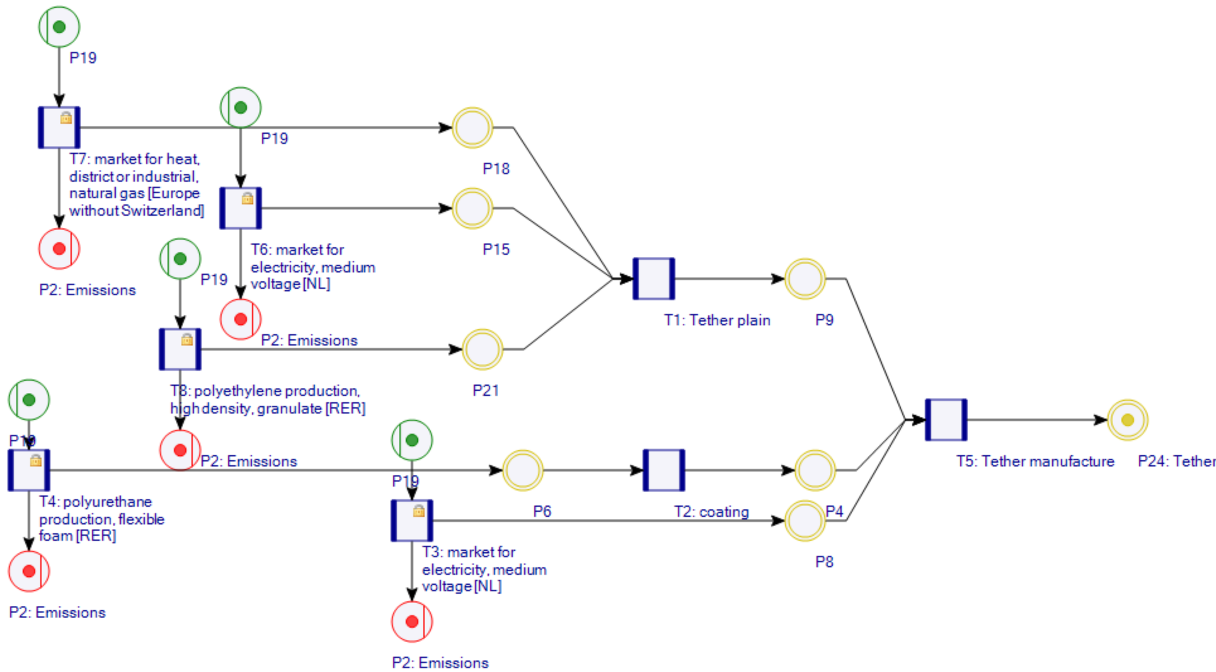

Figure A.2: Umberto model – subnet tether.

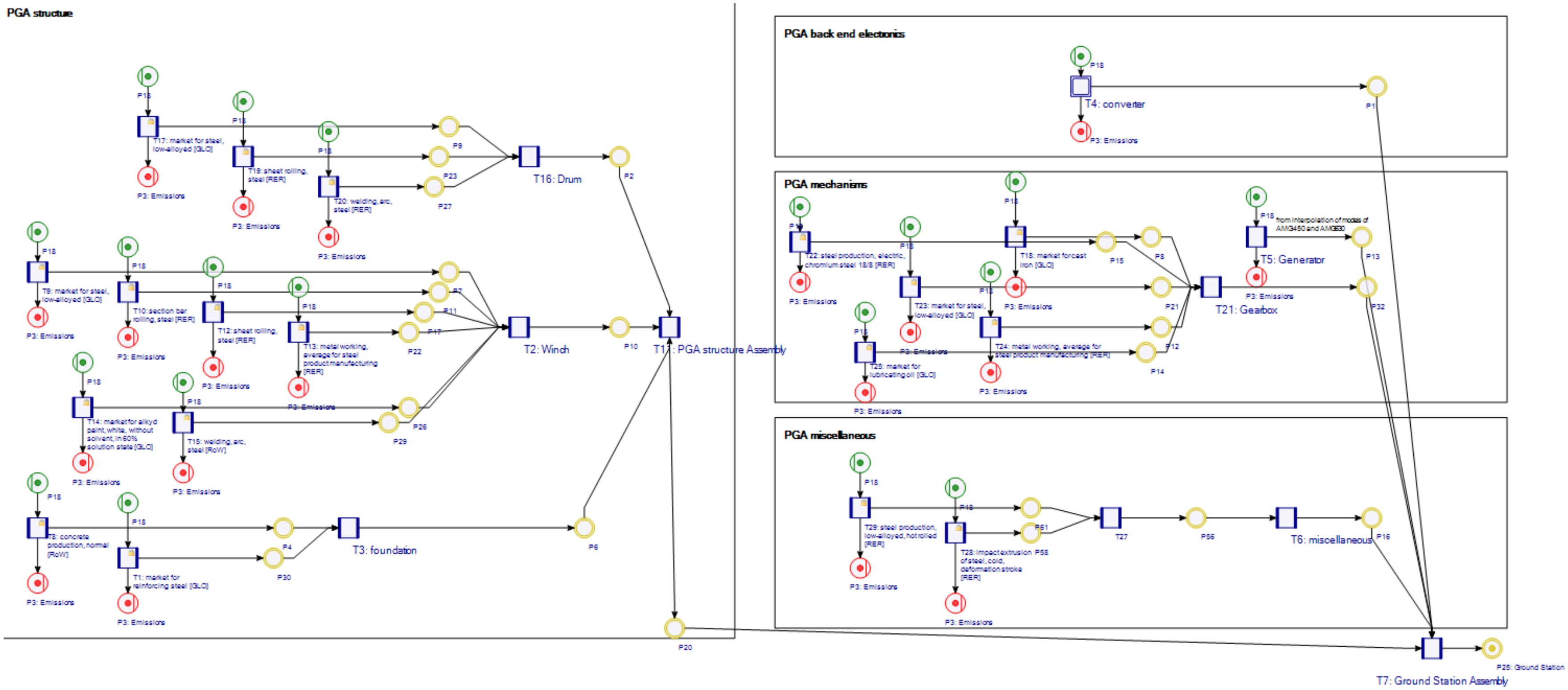

Figure A.3: Umberto model – subnet ground station.

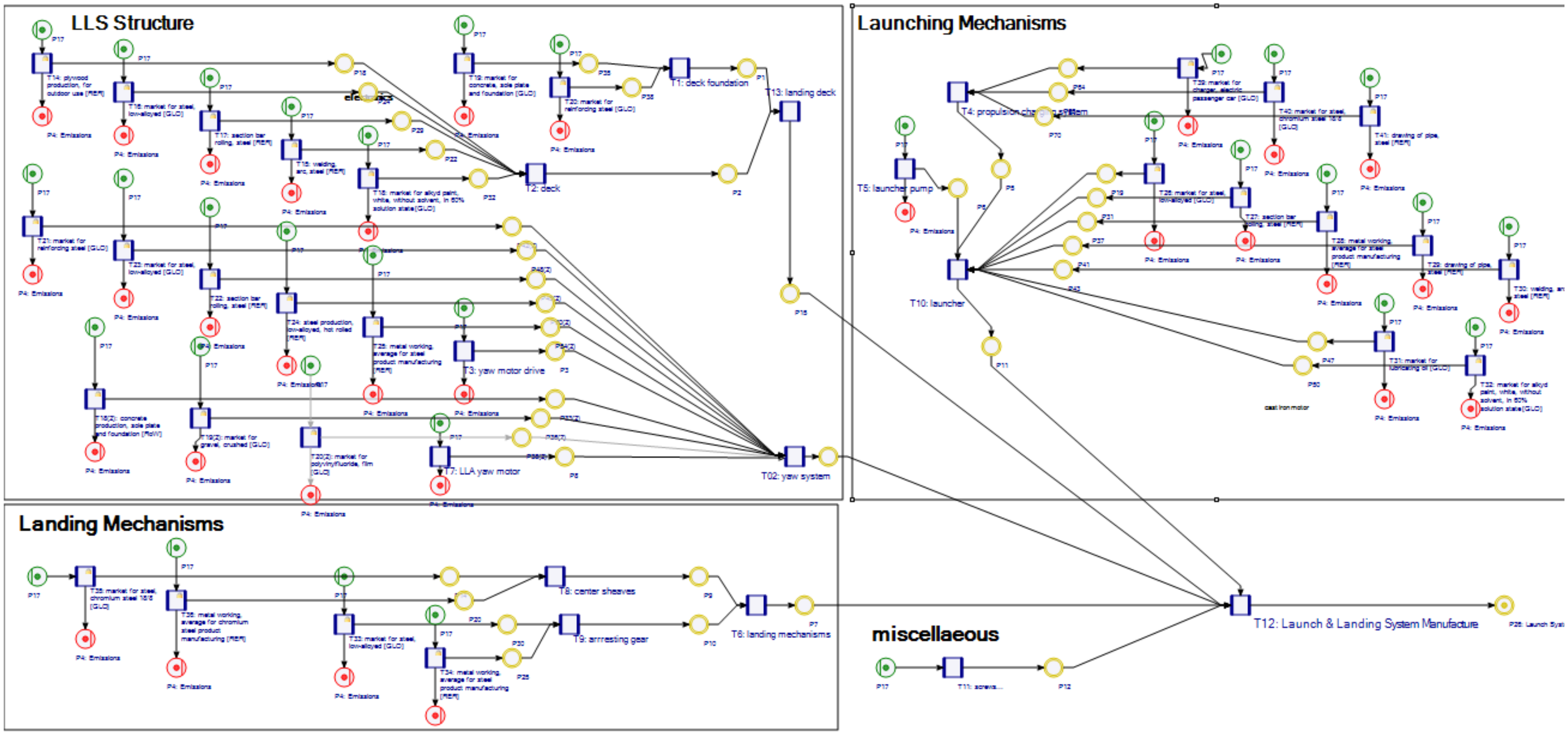

Figure A.4: Umberto model – subnet launch and landing system.

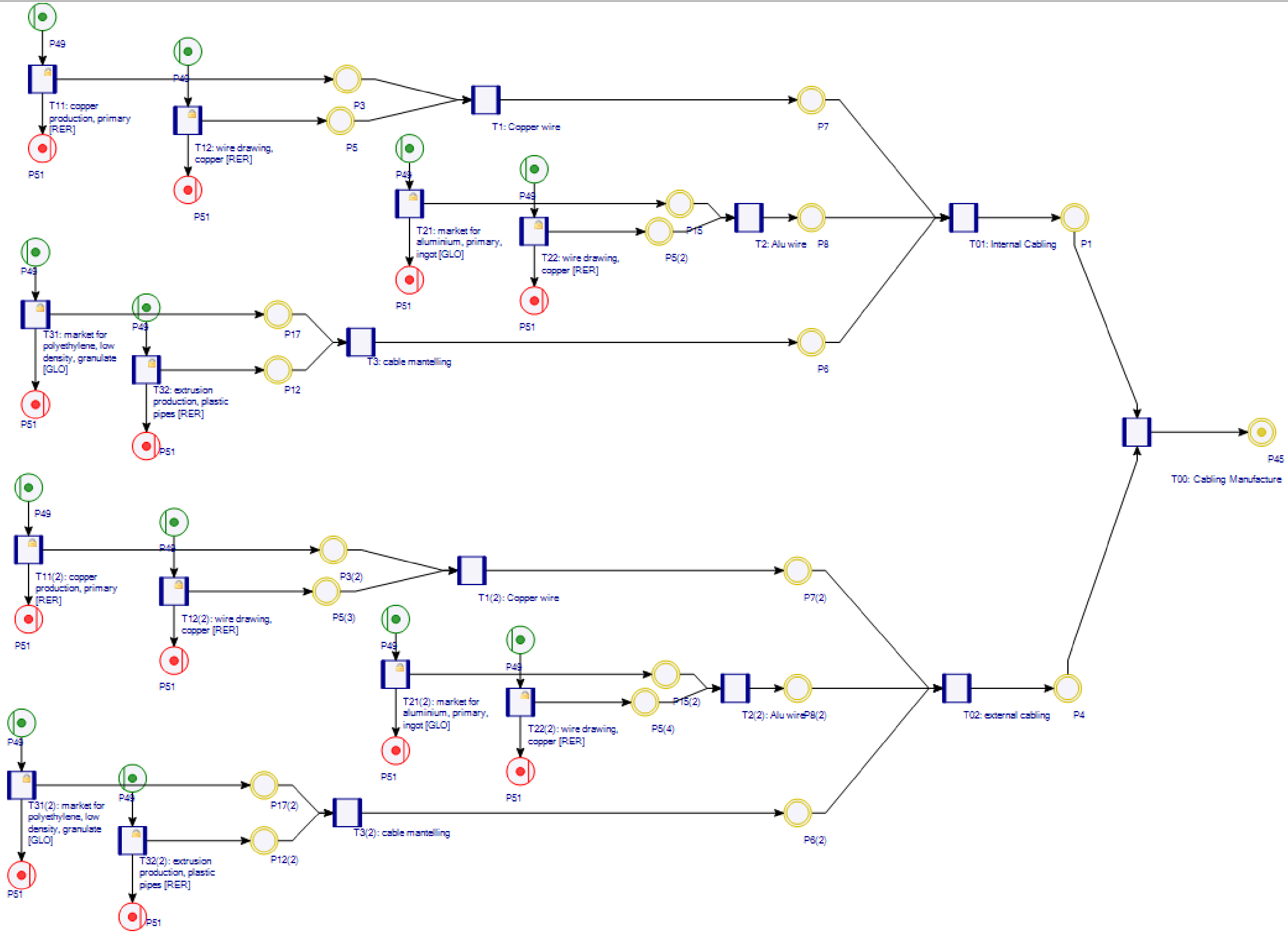

Figure A.5: Umberto model – subnet Cabling.

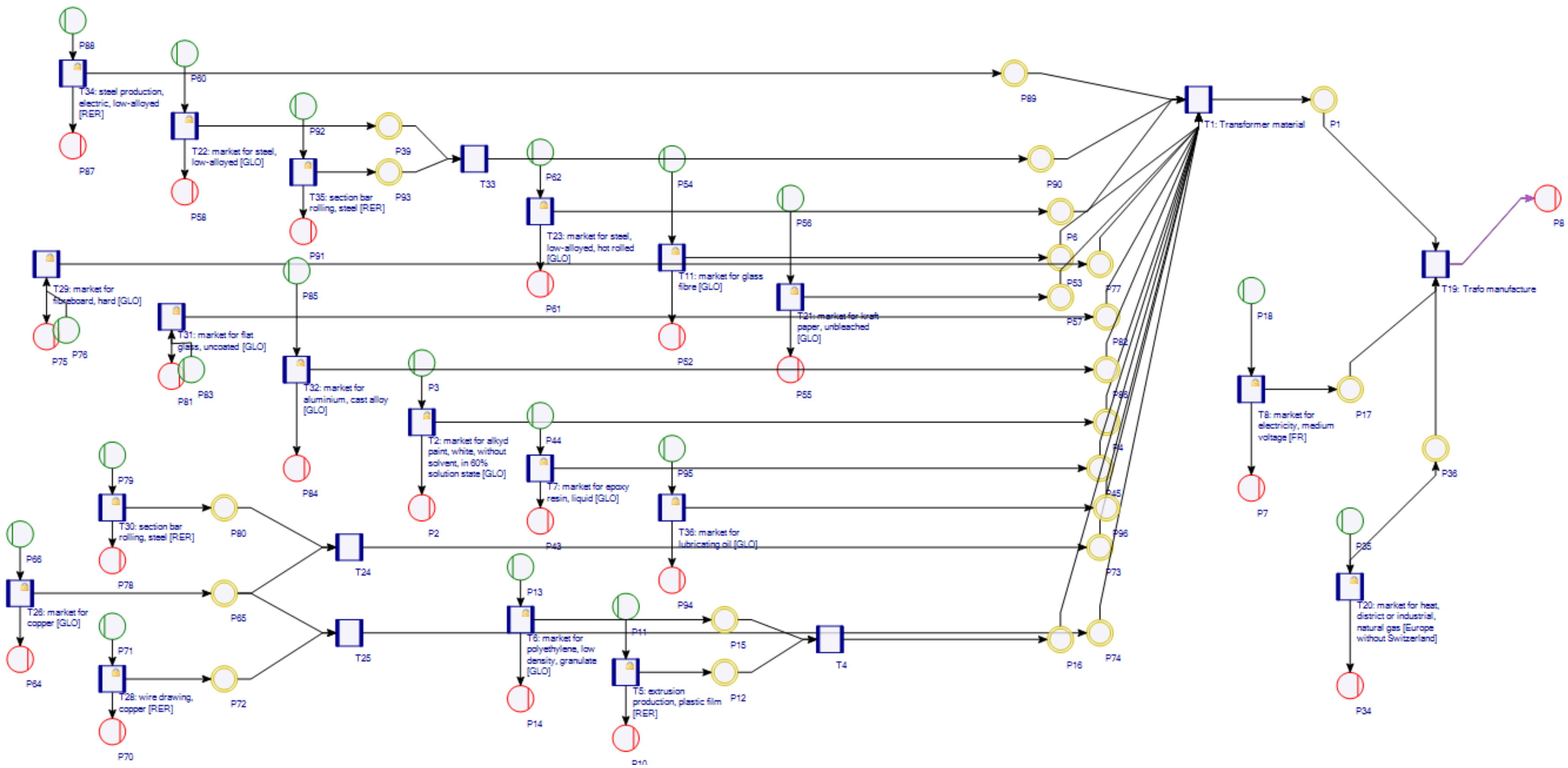

Figure A.6: Umberto model – subnet Power Transformer.

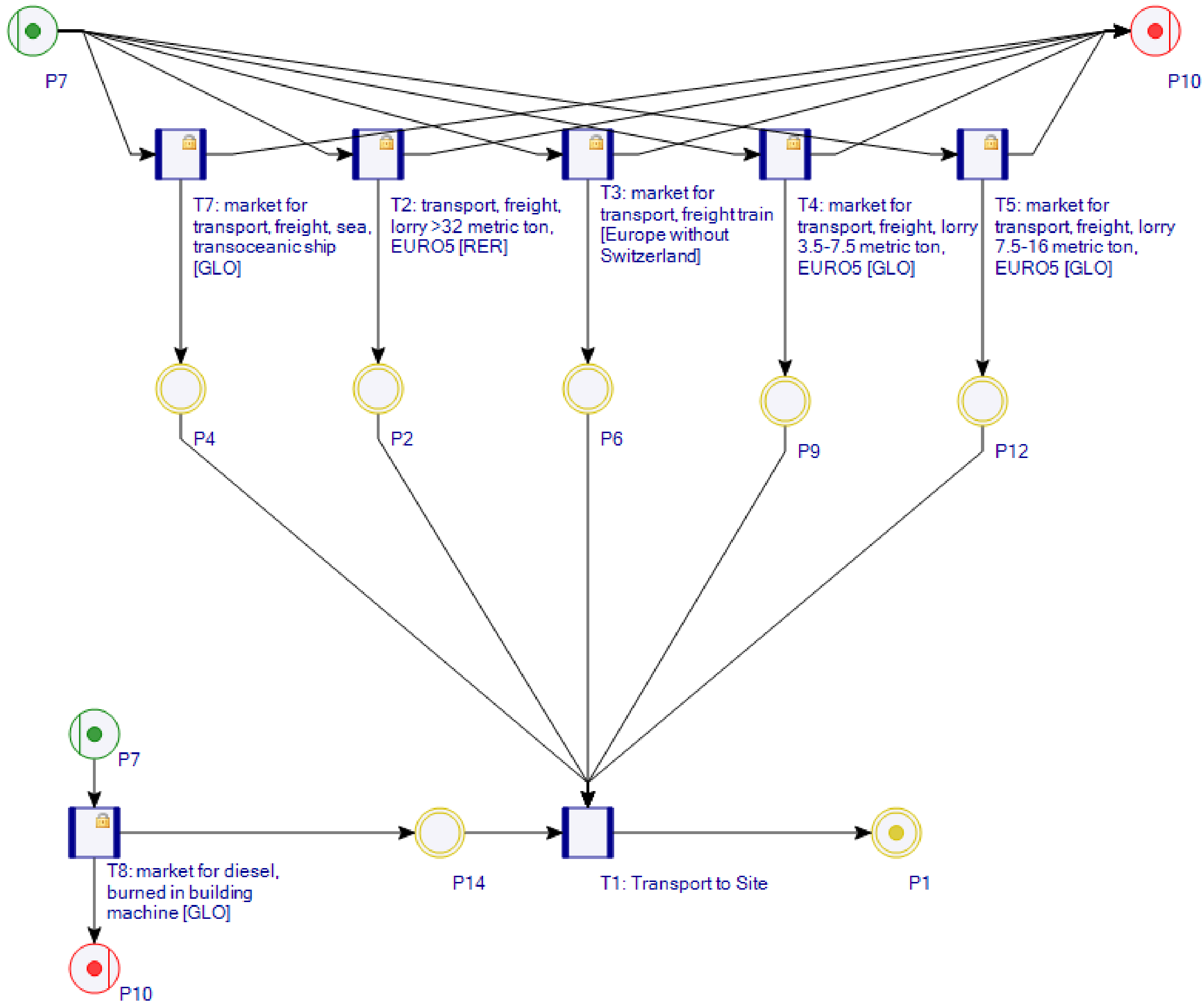

Figure A.7: Umberto model – subnet Installation.

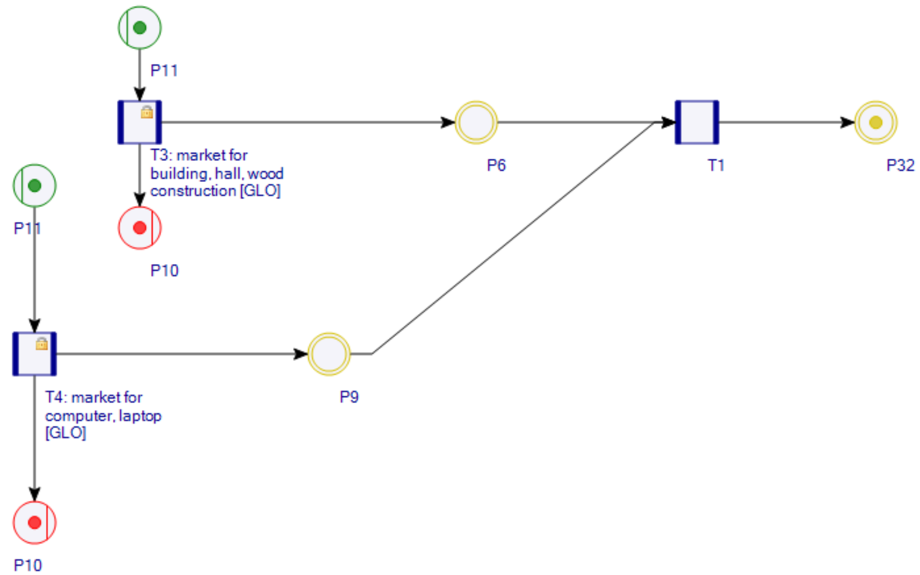

Figure A.8: Umberto model – subnet control tower.

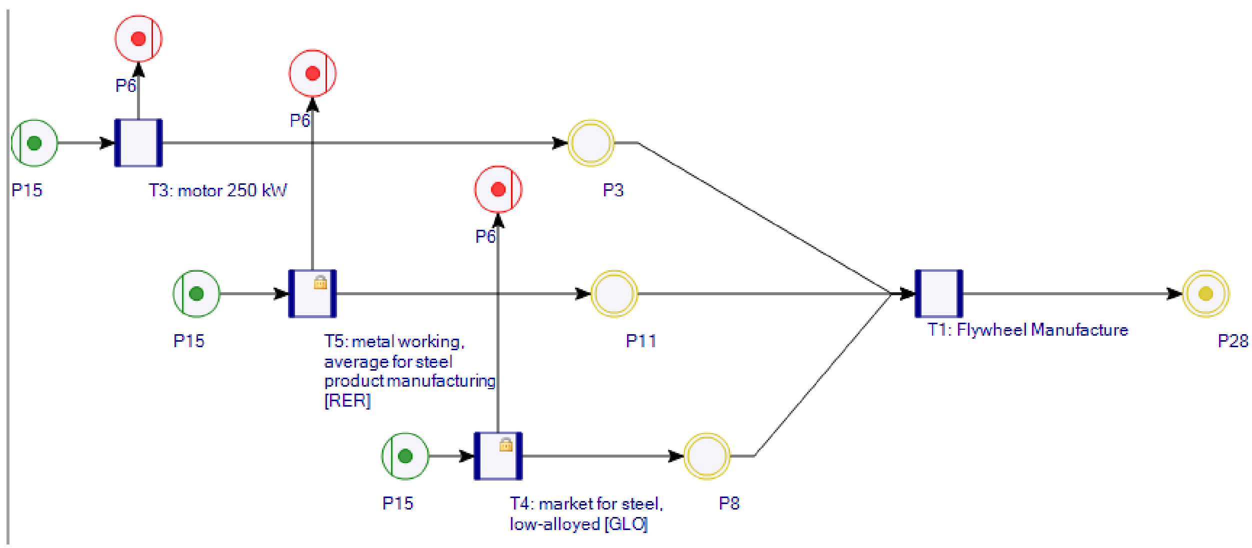

Figure A.9: Umberto model – subnet energy buffer.

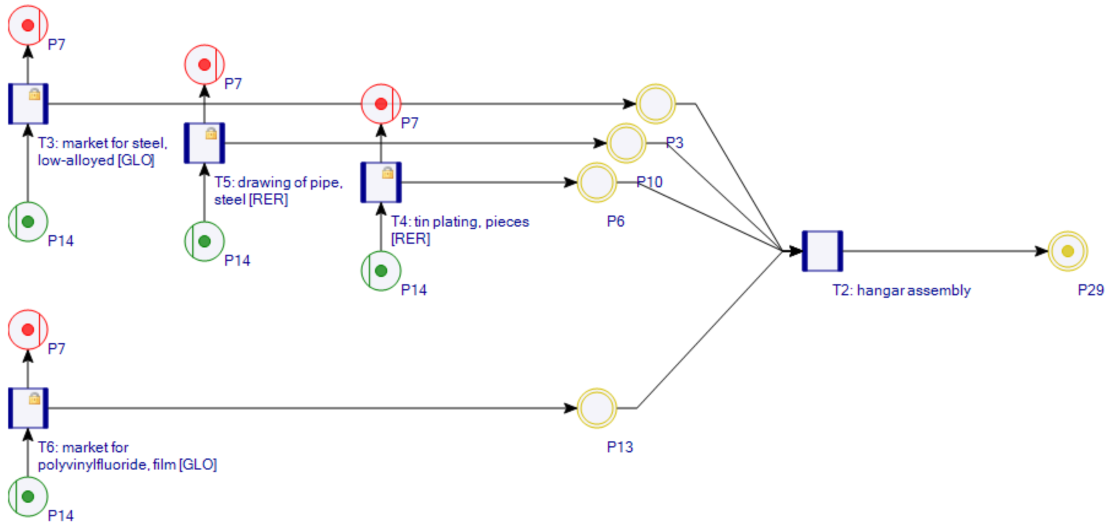

Figure A.10: Umberto model – subnet hangar.

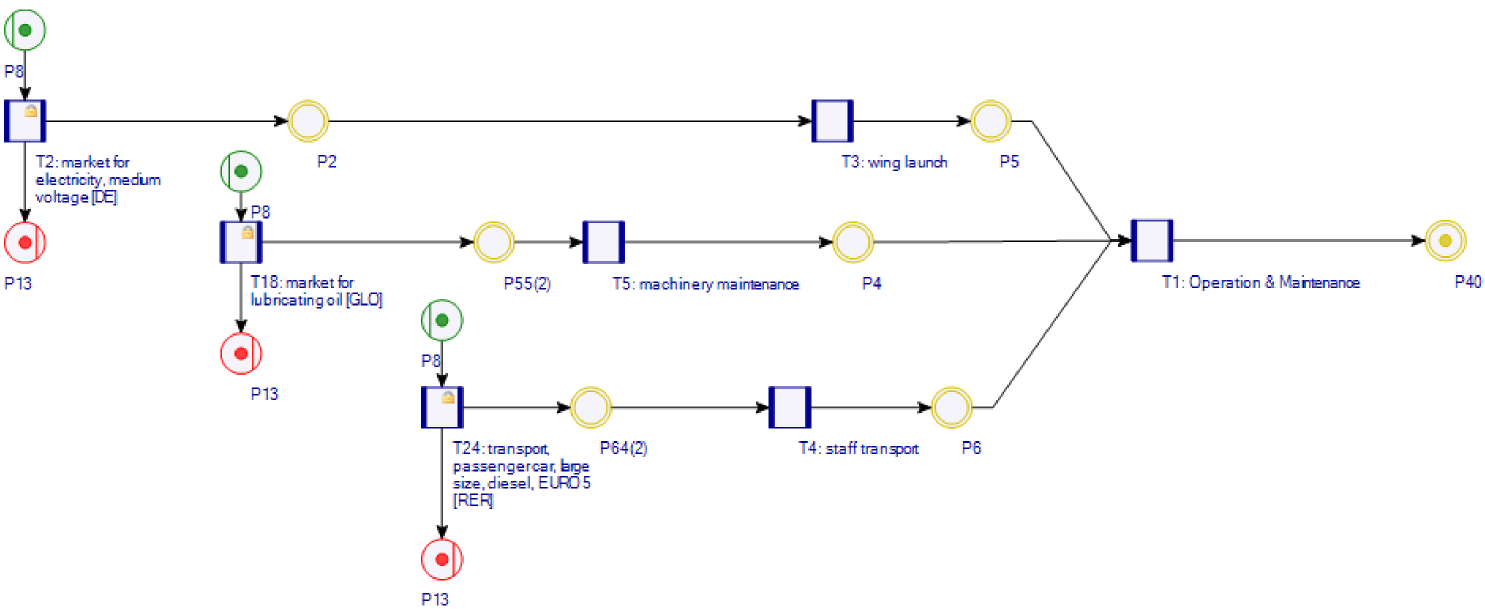

Figure A.11: Umberto model – subnet operation and maintenance.

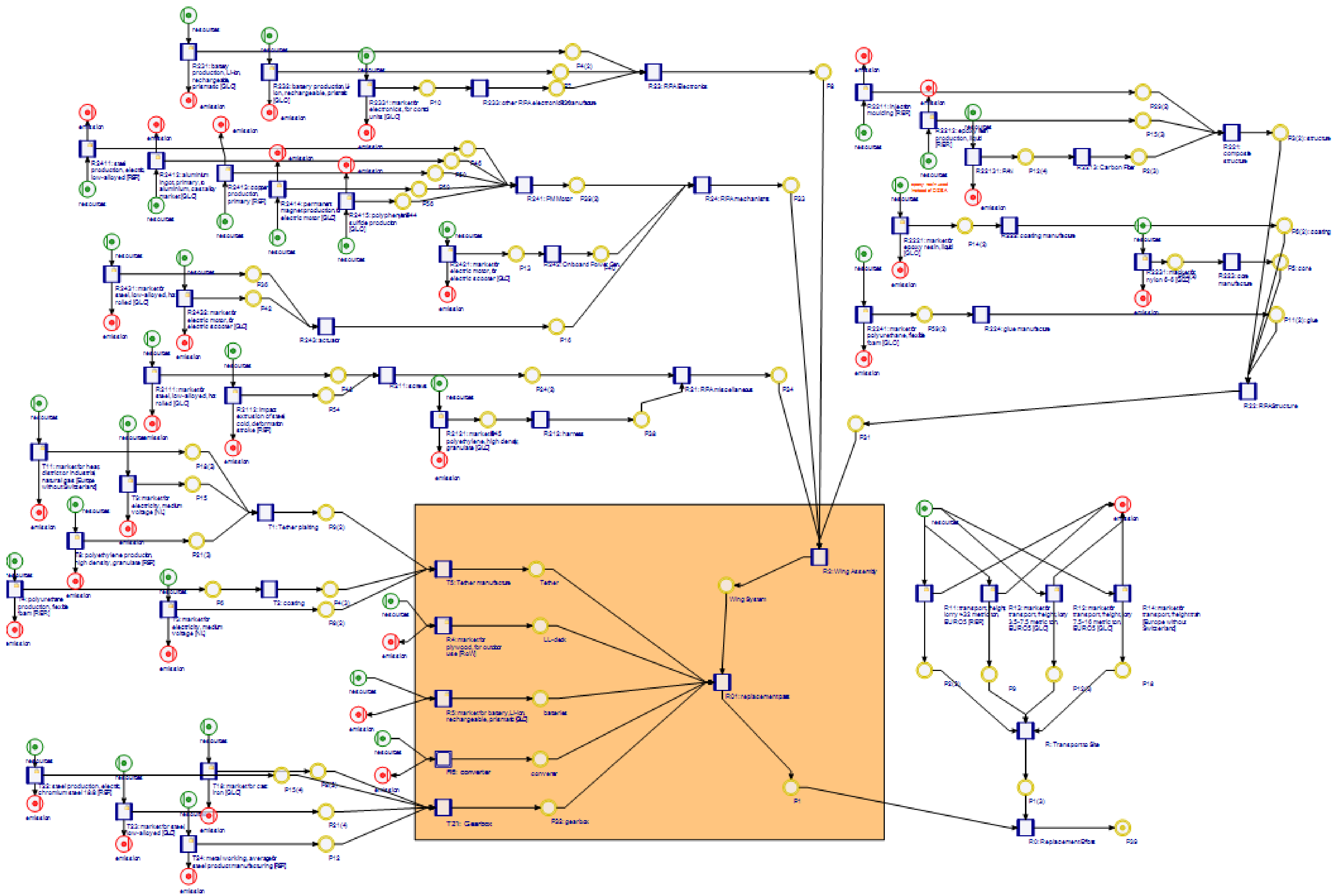

Figure A.12: Umberto model – subnet replacements total.

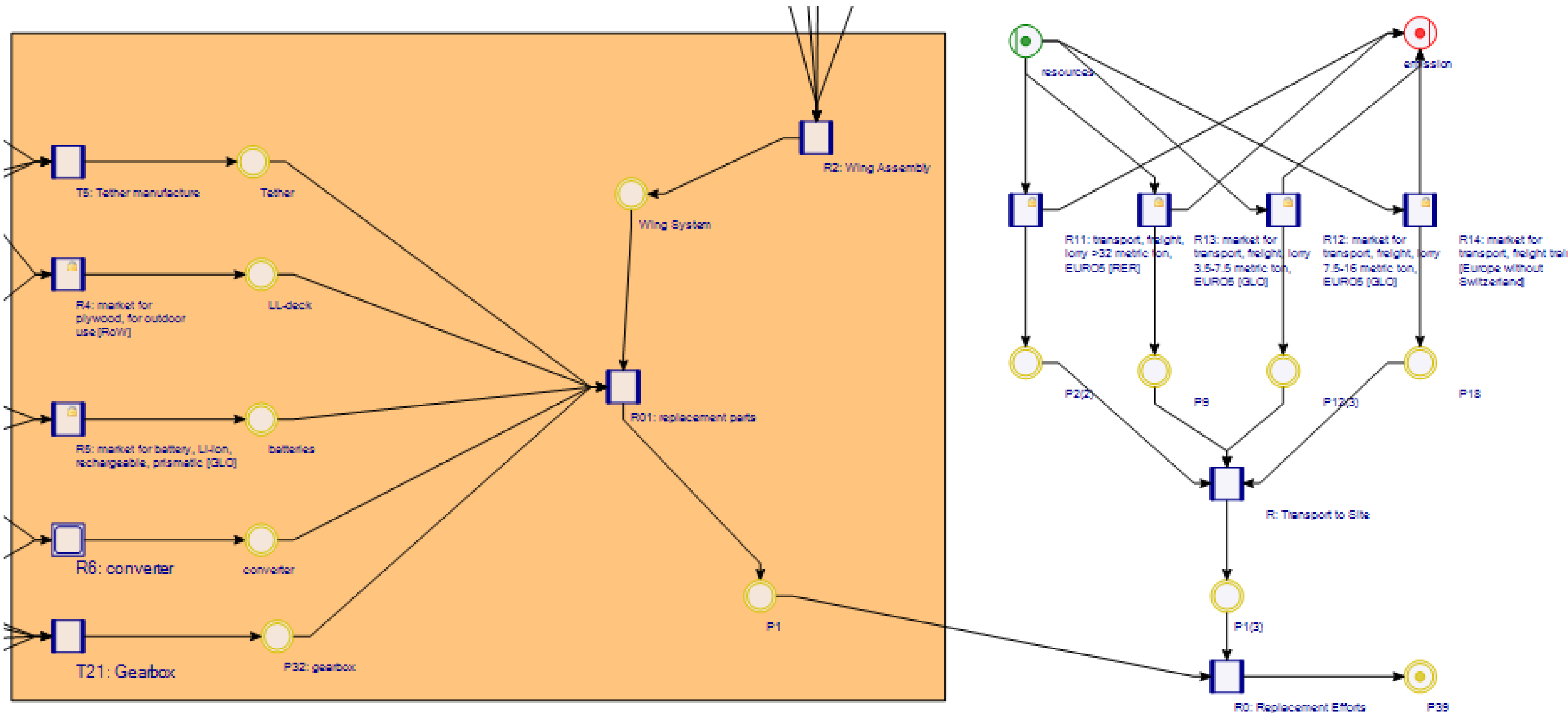

Figure A.13: Umberto model – subnet replacements zoom-in.

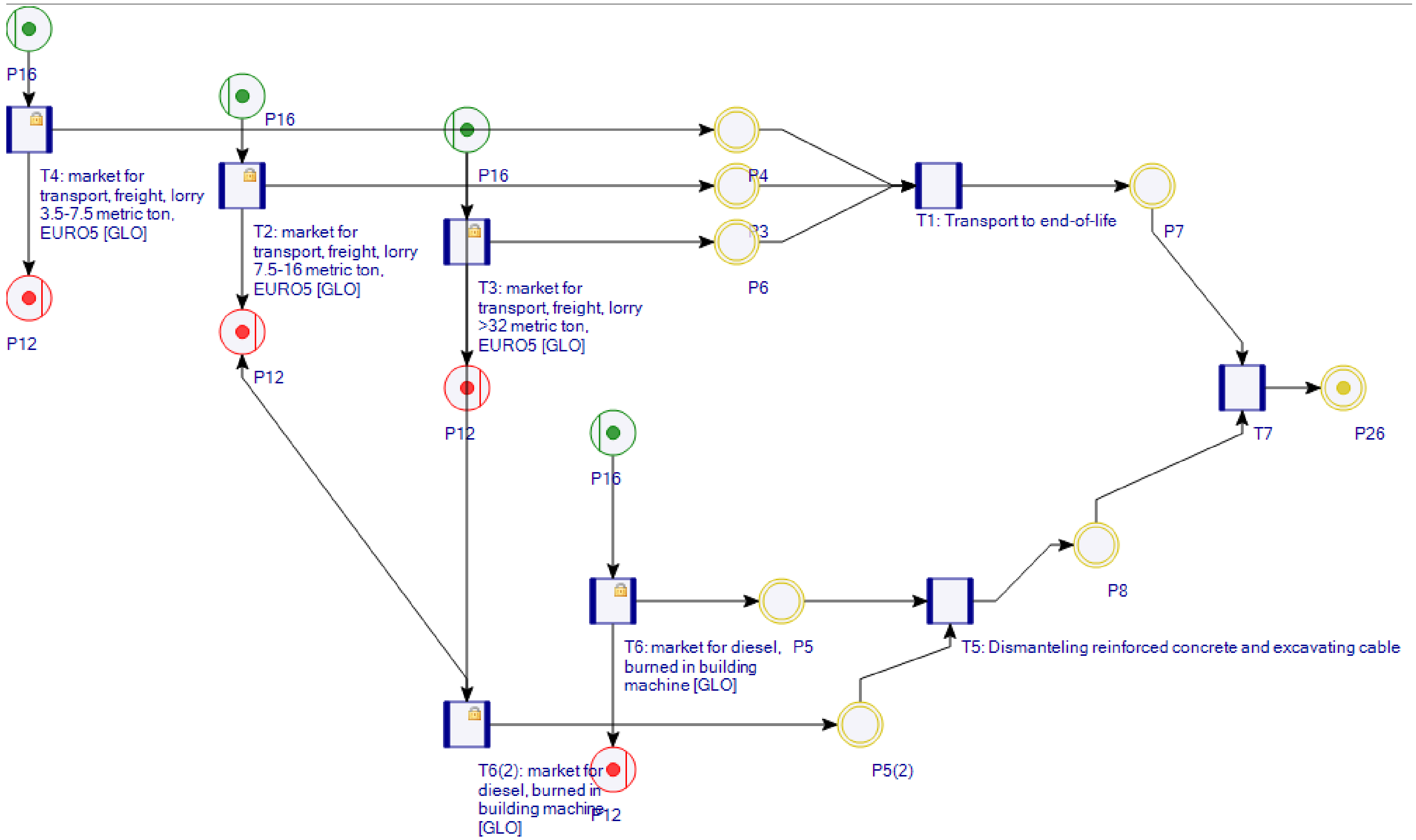

Figure A.14: Umberto model – subnet disposal.

Appendix