Life Cycle Assessment of Electricity Generation from Airborne Wind Energy

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Intoduction

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 economic and ecologically promising option. It has the potential to provide significant contribution to the global energy demand since it accesses wind resources of outstanding quality [1] with little material consumption. As of now, there is no environmental assessment of this new technology available.

Most AWE systems today follow the lift mode as described in [2] in a pumping cycle operation [3]. The airfoil is connected via a tether to a ground based winch which is coupled to a generator. The lift that is generated from crosswind flight pulls tether from the winch and its rotation is converted to electrical power. When reaching maximum tether length, the airfoil is depowered and a small portion of the generated electricity is invested for reel-in and to complete one cycle of this periodic operation. Compared to a conventional wind power plant, one could imagine that the function of the blades is fulfilled by a smaller fast flying airfoil, the tower is replaced by a polymer tether and drivetrain and other components are ground based [4].

Approach

The goals of this study are:

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.

To this end, a life cycle assessment (LCA) was executed, which allows tracking of category indicators over the whole life cycle from cradle to grave. A specific AWE design is chosen, which appears possible to become a dominating design. 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) according to CML2001 method, indicated in $kg_{CO2\text{-}eq.}$/kWh and two, the cumulated energy demand (CED), indicated in MJ-eq./kWh. 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.

Life Cycle Assessment

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 the AWE facility. 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 5.6 $kg_{CO2\text{-}eq.}$/kWh in GWP and a CED of 75 kJ-eq./kWh. 65 % of that occur in the phase *raw material and manufacturing*, 3 % during *installation*, 28 % during *operation* and 4 % in *disposal*. For most component systems GWP and CED are well correlated. 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 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.

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 achieved 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 conventional wind power plant model is within the range found in literature [5], [6], [7]. Compared to German electricity mix AWE causes less than 1 % of emissions [8].

The relative nature of the LCA approach and the specific uncertainties should be considered when interpreting these numbers. The results might strongly depend on design choices, estimated system performance (mainly generated power, efficiency and lifetime), procedure of data collection and the system boundaries, including farm size and recycling scenario. More reliable are comparative numbers obtained with a comparative approach as done for conventional and airborne wind energy.

Conclusions

The study analyzed the global warming potential and cumulated energy demand associated with the generation of 1 kWh electricity in an airborne wind energy plant and provides first numerical results. Even with a conservative approach the study confirms the expectation of low environmental impact per kWh produced electricity in the considered categories global warming potential and cumulated energy demand and presents first numerical results. Both wind power technologies, however, cause less than 1 % of those emissions compared to German electricity mix.

Learning Objectives

The study allows to foster understanding of the environmental implications associate with us of airborne wind energy. Developers might use the outcomes of the study for consideration in an environmentally optimized system design at early stage. Decision-makers in industry, economics and politics might use the results for their evaluation whether to engage in this technology.

References

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