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DOI
10.1088/1742-6596/2265/4/042069

Publication date
2022

Document Version
Final published version

Published in
Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: R Joshi *et al* 2022 *J. Phys.: Conf. Ser.* **2265** 042069

Journal of Physics: Conference Series **2265** (2022) 042069 doi:10.1088/1742-6596/2265/4/042069

Techno-economic analysis of power smoothing solutions for pumping airborne wind energy systems

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Abstract. In pumping airborne wind energy (AWE) systems, the kite is operated in repetitive crosswind patterns, pulling the tether from a winch that drives a generator on the ground. During the reel-out phase of its operation, it produces power, whereas, during the reel-in phase, it consumes a small fraction of the produced power. This leads to an oscillating power profile that requires smoothing before it can be supplied to the electricity grid. This paper proposes three drivetrain concepts as a solution to this power smoothing challenge. The three concepts are based on three different types of storage technologies: electrical, hydraulic and mechanical. Techno–economic models of the drivetrains were developed and a case-study on sizing and costing of the three drivetrain concepts for a MW–scale AWE system was performed. Conclusions were drawn that provide guidance to AWE developers for choosing a suitable drivetrain concept for their systems.

1. Introduction

Airborne wind energy (AWE) is an innovative renewable energy technology that uses tethered flying devices to harness the wind resource at higher altitudes than conventional towered wind turbines. This paper focuses on the ground generation pumping cycle AWE systems. Figure 1 shows the operation schematic of the concept. In the reel-out phase, the kite is operated in crosswind repetitive patterns, pulling the tether from a winch that drives a generator and produces electricity on the ground. Once the tether has reached its maximum length, it is reeled back in to its starting position. This reel–in phase consumes a small fraction of the produced electricity. Alternating reel–in and reel–out phases in pumping cycles leads to a net production of electricity. Figure 2 shows a simulated cycle power output of a pumping AWE system using the performance models introduced in [1, 2]. The integral area in green represents the power production phase and the one in red represents the consumption phase of the cycle. It should be noted that this power profile does not represent a commercial system operation but is a representation of the pumping cycle.

Until recently, the priority of AWE developers has been the kite and its flight operation. But many companies are now approaching the commercialization phase, which requires focus on the integration of the generation side with the electricity grid. Compliance with grid codes could be challenging for pumping AWE systems due to their oscillating power profile. In Europe, the European Network of Transmission System Operators for Electricity (ENTSO-E) [3] prescribes the requirements from power generators for integration with the electricity grid.

Primary requirement is to maintain the power ramps within prescribed tolerance bands at the point of common coupling. Depending on the country, the power ramps for wind and solar PV in Europe should be within 10-20% of the active power within the timescale of a minute [4, 5, 6]. Therefore, power smoothing is an inherent requirement of the pumping AWE systems for connecting to the grid. It can be achieved by utilizing an intermediate storage device between the system and the point of grid connection.

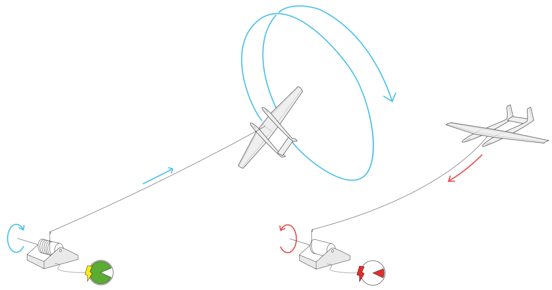

Figure 1: Representation of the pumping cycle of ground generation AWE systems [7]

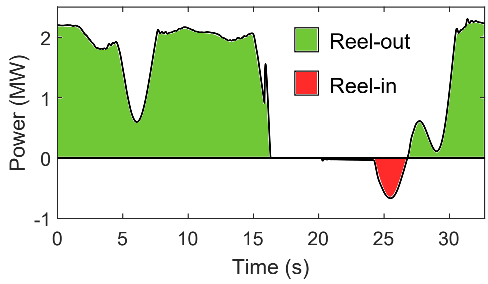

Figure 2: Instantaneous power profile during one full cycle of a pumping AWE system at a certain wind speed

An important aspect is looking at farm-level power smoothing with synchronized operation of AWE systems. But this may be a future solution. It is relevant to study the system level smoothing for the initial systems, since they can then be installed in a wider range of settings with less customization. This increases the addressable market. The first AWE systems are likely to be installed in weak grids, where power smoothing is essential. However, early installations are likely to be individual systems or in small numbers, where farm-level smoothing is not feasible.

The objective of this paper is to gain insights on the potential power smoothing solutions for AWE systems based on their efficiencies, costs, maturity, integration challenges and other trade-offs. Note that this paper does not focus on detailed technical feasibility of the solutions but rather on the first order techno-economic comparison.

2. Power smoothing solutions - drivetrain concepts

Power smoothing essentially means providing a constant power output to the grid irrespective of the fluctuations during cycle operation. The power profile of the AWE systems, i.e. the cycle average, the peaks, the reel-out and reel-in times, are different for different wind speeds. The primary function of the power smoothing solution is to provide constant power to the grid at all times and for every wind speed. This can be done by maintaining the net cycle average to the grid at all times. Figure 3 shows the amount of energy to be stored and discharged during the cycle operation to maintain the net cycle average power to the grid, during the complete cycle. The green region corresponds to the excess energy being stored during the reel-out phase, and the the red region corresponds to the release of this stored energy back to the grid during the reel-in phase. This is assuming that the average mechanical power for every wind speed and the efficiency of the drivetrain is known. A set point for power to grid at every wind speed should be maintained by the controller based on the wind speed and the system data. A buffer in the storage could be maintained to accommodate the real-time changes in wind speeds and the controller reaction time.

The intermediate energy storage for power smoothing must be capable of delivering a high number of charge-discharge cycles with a fast response. Conventional electrical energy storage batteries are not suitable for such operation. Supercapacitors, hydro-pneumatic accumulators and flywheels are storage technologies used in a wide range of energy recovery applications, including smoothing the delivery of power, dampening vibrations and reducing fluctuations to name only a few. Based on these three energy storage technologies, three corresponding drivetrain concepts are proposed in this paper.

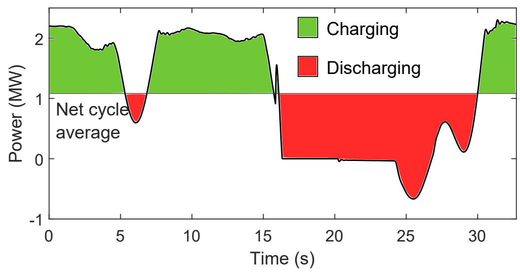

Figure 3: Representative charging and discharging integral areas to maintain the net cycle average to grid at all times for a certain wind speed

2.1. Electrical drivetrain

Primary components of the electrical drivetrain are shown in Figure 4. Supercapacitors are electrochemical energy storage devices that store and release energy at a much faster rate (approx. 300 times) than lithium-ion batteries. Since supercapacitors are electrical storage devices, mechanical energy at the winch needs to be converted to electricity before connecting to the supercapacitor. Electrical generators have an operating speed and torque region for maximizing power conversion efficiency. Depending on the AWE system, the speed of the winch during the pumping cycle might not be in that operating region. Therefore, a gearbox might be necessary to use as a coupling between the winch and the generator.

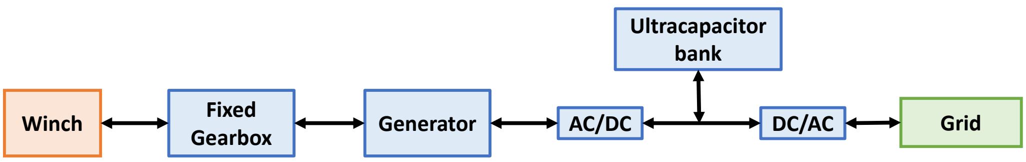

Figure 4: Architecture of a fully electric power smoothing solution

The generator is directly coupled to the winch. Hence, it needs to be sized for peak load in the operating wind speed range instead of rated power. This will lead to under-utilization of the generator and is the most important disadvantage of the electrical concept. Due to this, the generator is operated at part load for a large amount of time. This affects the power conversion efficiency. Supercapacitors are DC devices and have specific operating conditions. Electronic power converters are required at both ends to convert the electric power to the required voltage and frequency levels. The generator-side power converter needs to be sized for peak load similar to the generator and the grid-side convertor for rated power. During the reel-out phase, energy equal to the net cycle average is supplied directly to the grid and the excess energy is stored in the supercapacitor. During the reel-in phase, the stored energy is supplied to the grid and a fraction of it is used to drive the winch for reeling in. Multiple supercapacitor banks are needed for this simultaneous operation.

2.2. Hydraulic drivetrain

Primary components of the hydraulic drivetrain are shown in Figure 5. This drivetrain was first introduced in [8]. A hydro-pneumatic accumulator is a vessel capable of storing energy in the form of a compressed gas. The accumulator has two chambers divided by a separator. The difference in the types of these accumulators lies in the kind of separator element used. The three of the most common types of hydro-pneumatic accumulators are using a bladder, a diaphragm or a piston. The first chamber is a fluid chamber, usually filled with hydraulic oil, and the second is a gas chamber, usually containing nitrogen. The fluid chamber is connected to the hydraulic circuit. During charging, the fluid pressurizes the separator element and compresses the gas. During discharging, the compressed gas is released to exert the pressure back on the fluid.

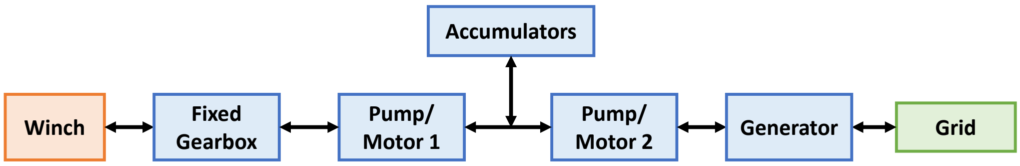

Figure 5: Architecture of a hydraulic power smoothing solution

The idea behind this drivetrain is to avoid oversizing of the electrical generator. The two hydraulic machines can work either as a pump or as a motor. Depending on the hydraulic machine technology used, a gearbox might be necessary to couple the first hydraulic machine with the winch. The winch drives the first hydraulic machine in the reel-out phase which pumps the hydraulic fluid in the accumulator under high pressure. Energy equal to the net cycle average is released with a constant pressure to drive the second hydraulic machine and excess energy is stored in the accumulator. During the reel-in phase, the stored energy is released to drive the first hydraulic machine as a motor for reeling-in and the second hydraulic machine as a motor to drive the electricity generator.

2.3. Mechanical drivetrain

This drivetrain concept is conceptualized by Ampyx Power [7] and MAZARO [9]. The primary components are shown in Figure 6. The flywheel uses the mechanical power at the winch to store the energy based on the conservation of angular momentum. This drivetrain requires a niche transmission technology called the reversible variable transmission (RVT). The flywheel-side shaft rotates in one direction only, but during reel-in, the winch needs to be rotated in the opposite direction. RVT is necessary for this operation. RVT is a niche component and, hence, a fixed gearbox might be needed to couple the RVT to the winch to align the operation speed and torque regions. Efficiency of the flywheel is maximum when it is operating at its maximum speed. The speed of the generator shaft must also be regulated constantly. Consequently, a variable ratio gearbox is needed to couple the generator shaft and the flywheel to maximize efficiency.

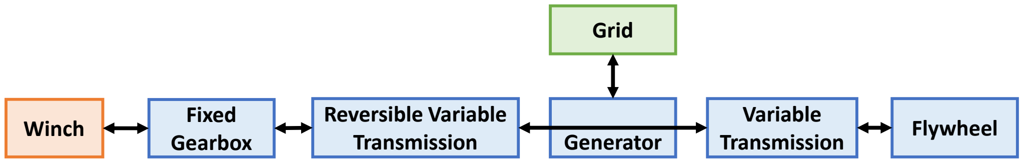

Figure 6: Architecture of a mechanical power smoothing solution

During the reel-out phase, the energy equal to the net cycle average is supplied to the grid and the excess energy is stored in the flywheel. During the reel-in phase, the stored energy is supplied to the grid and the winch. The RVT changes the direction of rotation on the winch side for reeling-in.

3. Case–study: drivetrain sizing and costing for a MW–scale AWE system

The framework used to compare and evaluate differences between the three power smoothing solutions is shown in Figure 7 . It is based on process workflow modelling to simulate the energy flow between the drivetrain components. The drivetrain models require two inputs: (1) The timeseries data of the operation of the AWE system (speed, torque) and (2) reference costs and efficiency values associated with the AWE system and the drivetrain components. The developed drivetrain models estimate the sizing and costing of each component based on the logic of power smoothing as described in Section 2.

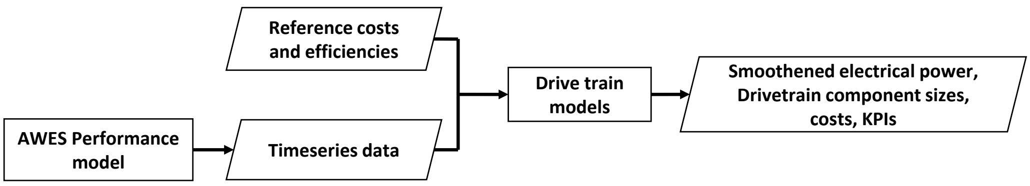

Figure 7: Techno-economic framework used to compare the three drivetrain concepts

This analysis is performed considering a single standalone MW–scale pumping AWE system. The timeseries data are generated using the dynamic six DOF performance model introduced in [1, 2]. The data used is a general representation of the power profiles of the pumping AWE systems and, hence, of the underlying power smoothing requirements.

Techno–economic analysis requires cost and efficiency estimates of the components involved. This information is highly variable with different technologies, suppliers and country-specific regulations. Effort has been made to use realistic cost and efficiency assumptions based on direct communication with industry wherever possible. Ampyx Power is currently testing its 150kW system with a fully electrical drivetrain. Inputs regarding the hydraulic concept have been provided by Bosch Rexroth [10]. The mechanical concept is based on products offered by [9, 11, 12]. Cost references for gearboxes, power converters and electrical generators are obtained from [13]. Additional inputs for cost, efficiency, energy density, power density and other qualitative attributes of storage technologies have been obtained from [14, 15, 16, 17, 18].

The average efficiency values of the components in the three drivetrain concepts are given in Table 1. In the electrical concept, since the generator is operated at part-load for maximum amount of time, the average efficiency is significantly lower than the generators in the hydraulic and mechanical concepts. Because the concepts are based on niche technologies, which are not yet widely developed, the efficiency values used are on the conservative side of the claims made by the technology developers and that reported in the literature. On the other hand, the efficiencies of matured components, like the gearbox, the power converters and the ultracapacitor, are from the optimistic side of the claims.

Table 1: Average efficiencies of the drivetrain components used in the analysis

Electrical	η	**Hydraulic**	η	**Mechanical**	η
Gearbox	0.98	Gearbox	0.98	Gearbox	0.98
Generator	0.80	Generator	0.95	Generator	0.95
AC/DC converter	0.95	Pump/Motor 1	0.92	RVT	0.90
DC/AC converter	0.95	Pump/Motor 2	0.92	VT	0.98
Ultracapacitor	0.97	Accumulator	0.88	Flywheel	0.90

Figure 8 shows the difference between the mechanical cycle average power at the winch and the electrical cycle average power at the grid using the three drivetrain concepts. The mechanical power reaches its maximum at 20m s^{-1}. This is the rated wind speed and stems from a design decision for this particular case study. Figure 9 shows the net efficiencies of the three concepts with respect to the wind speed. One of the key performance indicator (KPI) used to compare the net efficiencies of the systems is the capacity factor. A representative wind speed distribution is used for this comparison. The wind speed data is obtained from the ERA5 reanalysis dataset for an offshore location in the German North Sea. The mean wind speed at the location is 11m s^{-1}, the Weibull scale parameter is 12m s^{-1} and the shape parameter is 2.3. The capacity factor for all three concepts turned out to be 0.47. The electrical power output for all three drivetrains is almost equal at the mean wind speed for the chosen data.

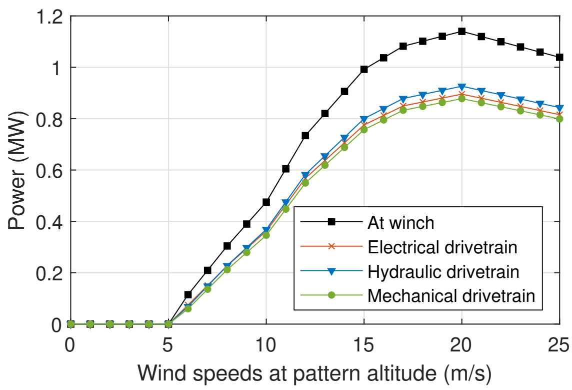

Figure 8: Computed power curves using the three drivetrain concepts

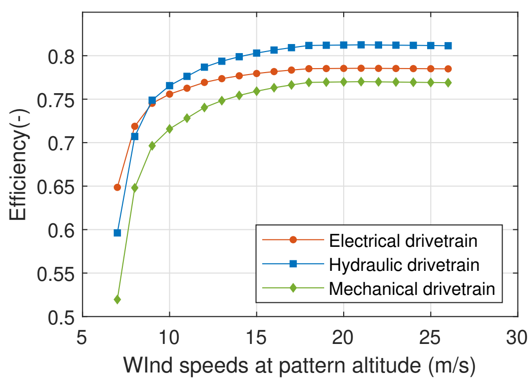

Figure 9: Net efficiency of drivetrain concepts with respect to wind speed

The drivetrain concepts have a high number of components with niche technologies developed by different companies. For this reason, the efficiency values have an uncertainty. An uncertainty analysis showed that, with a change in the efficiencies of the individual components within a band of 5%, the net efficiencies of the drivetrain concepts vary in the same order. Moreover, the capacity factor for all the three concepts remains the same.

In Figure 10, the left axis shows the volume of energy stored and discharged in the electrical concept, and the right axis shows the maximum mechanical power peaks during one full cycle in the operational wind speed range. It can be seen that the energy exchanged through the intermediate storage increases with increasing wind speed, until its maximum at rated wind speed. As a result, the intermediate storage for power smoothing is utilized more at higher wind speeds. This indicates that the storage would be sized for the rated wind speed. Table 2 shows the resulting component sizes for all three drivetrain concepts. The storage components get sized for the rated wind speed which is $20\,\mathrm{m\,s^{-1}}$. The generator in the electrical concept, the first pump/motor machine in the hydraulic concept and the RVT in the mechanical concept get sized for maximum peak power reached in the cycle operation at the rated wind speed which is 2.46MW.

Table 2: Component sizes of the three drivetrain concepts

Electrical	**Size**	**Hydraulic**	**Size**	**Mechanical**	**Size**	**Units**
Gearbox	2.46	Gearbox	2.46	Gearbox	2.46	MW
Generator	2.46	Generator	0.95	Generator	0.88	MW
AC/DC	2.46	Pump/Motor 1	2.46	RVT	2.46	MW
DC/AC	0.9	Pump/Motor 2	0.95	VT	1.58	MW
Ultracap.	14.6	Accumulators	15.3	Flywheel	14.75	MWs

This simulated performance data of the AWE system was not based on designing the system for a particular wind class. But when doing so, the rated wind speed is selected with respect to the mean wind speed of the wind class. Designing a system for higher wind speeds will increase the rated power capacity of the system, but might also lead to oversizing of the drivetrain components. If such a system were to be installed in a location such as the one mentioned earlier, the system would be underutilized for a large amount of time. Figure 11 shows KPIs like the levelized cost of energy (LCoE), the capacity factor (cf) and the annual energy production (AEP) for the electrical concept, resulting if the AWE system is capped at lower wind speeds. The LCoE flattens out at $15\,\mathrm{m\,s^{-1}}$. This allows for other trade-offs for the same LCoE. For example, a lower rated wind speed choice leads to a higher capacity factor, whereas a higher rated wind speed choice leads to a higher AEP.

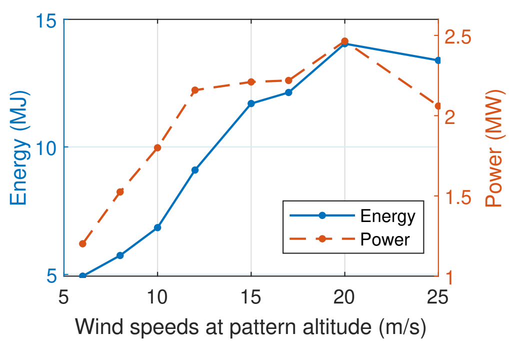

Figure 10: Energy exchanged (electrical concept) and the max. power peaks during one full cycle

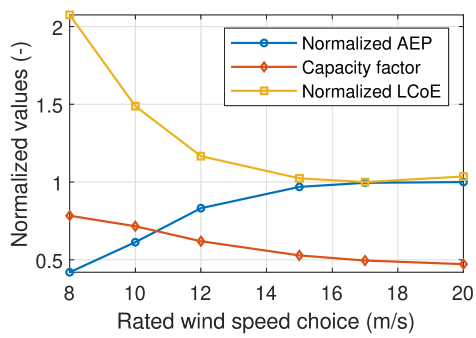

Figure 11: AEP, cf and LCoE using the electrical concept if the system is redesigned for different rated wind speeds

Figure 12 shows the normalized capital cost breakdown of the complete AWE system using the three drivetrain concepts. Values are normalized because the absolute numbers are not necessary for the relative comparison, but also to protect the commercial interests of the companies involved. The cost component 'AWES' includes the cost of the kite, the tether, the winch and the launch and land apparatus. It is the largest cost component with a share of around 65% for all three concepts. Similar to the efficiency comparison, the capital costs of all three drivetrain concepts are of the same order. The uncertainty for costs is higher than the uncertainty for efficiencies since a lot more factors are involved, like the company-specific technologies, economies of scale and supply chain to name only a few. It shows that the drivetrain costs are a significant (around 35%) share of the total system costs and, hence, cannot be neglected from the design decisions of the commercial AWE systems. The components sized for the maximum mechanical peak power are the primary cost drivers. They are the generator in the electrical concept, the first pump/motor machine in the hydraulic and the RVT in the mechanical concept. The storage components in all the concepts approximately have the same share.

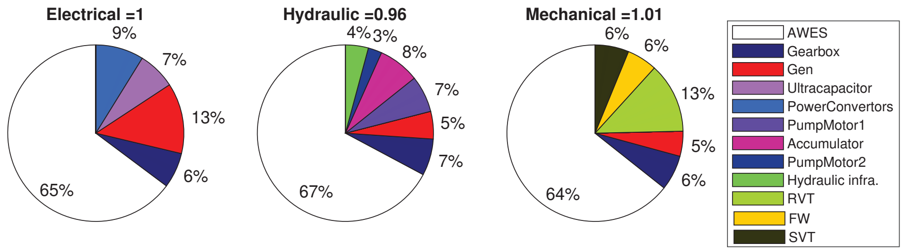

Figure 12: Capital cost breakdown

The performance and cost comparison shows that all the three drivetrain concepts are essentially comparable to each other. In addition to these performance criteria, a qualitative comparison is also essential to support decision making. Table 3 shows the comparison between the three storage technologies. Facility weight and volume–wise, the mechanical concept would be the most compact followed by the electrical and the hydraulic. Though the self discharge rates of these technologies is quite high, the storage would only be used actively for power smoothing and not for storing energy for longer duration as in conventional energy storage applications.

Table 3: Comparison of attributes of the three storage technologies

	Supercapacitors	**Hydro-pneumatic accumulators**	**Flywheel**
Specific energy (Wh/kg)	3 − 50	$\sim$ 0.5	5 − 150
Energy density (kWh/m^3)	10 − 30	$\sim$ 1.5	20 − 80
Specific power (W/kg)	500 − 5000	$\sim$ 3000	1000 − 30000
Power density (kW/m^3)	1000 − 5000	$\sim$ 7500	800 − 5000
Self discharge rate (%/day)	20 − 40	50-95	50 − 100

During the charge–discharge cycles, the accumulators need to maintain required pressure levels, the ultracapacitors need to maintain required voltage levels, and the flywheels need to maintain a certain lower limit on rotational speed to maximize their efficiencies and lifetimes. Therefore, all the three solutions might need to be sufficiently oversized to maintain their respective limits on depth of discharge. Accumulators and flywheels can employ a larger number of duty cycles than ultracapacitors. Mechanical components have relatively higher failure rates followed by hydraulic and electrical. Therefore, flywheels might not be suitable for applications in remote areas where operation and maintenance are more expensive.

4. Conclusions

The share of the drivetrain costs in the total system costs is significant (around 35%). Since most of the AWE companies are now entering the commercialization phase, it is necessary for them to include drivetrains in their design process. To this end, it is essential to capture the effect of the drivetrain on the scaling and system sizing studies of AWE devices. A key aspect is understanding the relationship between the requirements on the drivetrain for power smoothing and system size. This will facilitate evaluating trade-offs between scaling to different system sizes that include optimizing the size in order to reduce the power peaks and, hence, drivetrain costs.

Table 4 summarizes the comparative assessment of the three drivetrain concepts proposed in this paper. Individually, the technologies used in the three concepts have reached a technology readiness level (TRL) of '9', but none of them have been used in the configuration, size and operational requirement such as this. None of the drivetrain concepts could yet be designed with off-the-shelf components. Between the three concepts, the electrical concept is more matured followed by the hydraulic and then the mechanical. Consequently, the electrical concept would be a safer choice for a first market entry, since it is the most widely used and understood configuration in the power generation industry. The hydraulic and the mechanical concepts still require some amount of development. These components must be developed in parallel to the AWE system in close collaboration to be able to be commercially ready at the time of market entry. AWE in itself is an innovative technology and carries a development cost and risk. Using relatively unproven technologies like the hydraulic or the mechanical drivetrain will increase risks and the overall development costs.

Table 4: Qualitative comparison of drivetrain concepts (where, '$\simeq$' indicates relatively comparable, '$\uparrow$' indicates relatively advantageous and '$\downarrow$' indicates relatively disadvantageous)

Criteria	**Electrical**	**Hydraulic**	**Mechanical**
Performance (eff. & cost)	$\simeq$	$\simeq$	$\simeq$
Lifetime	$\downarrow$	$\uparrow$	$\uparrow$
Facility size & weight	$\uparrow$	$\downarrow$	$\uparrow$
Reliability	$\uparrow$	$\uparrow$	$\downarrow$
Commercial readiness	$\uparrow$	$\downarrow$	$\downarrow$

One of the key findings of this work is that the three concepts are comparable in terms of net efficiency and capital cost. Due to the linearity of the cost models, this should also hold, to first order, for different sizes of the proposed concepts. Nevertheless, this finding cannot be generalized across different AWE concepts and designs. Different concepts will produce different operational dynamics. Sizing and costing of the drivetrain components is highly dependent on the operational characteristics of the AWE system, but also on efficiency assumptions and reference cost data. Note also that the performance simulation data of the AWE system used in the present case study is not an optimized dataset. For the analyzed AWE system, the difference between the peaks and the net cycle average increased with increasing wind speeds. This difference will differ based on the type of the AWE concept and its size.

A major drawback of the electrical drivetrain is under-utilization of the generator. If a particular AWE system were to produce lower power peaks, then the electrical drivetrain would further gain in attractiveness as a design choice due to its relative maturity. On one hand, the hydraulic and mechanical systems benefit from the generator being sized for rated power, but on the other, the hydraulic pump/motor machine and the RVT need to be sized for peak power. Kite inertia is an important aspect influencing the power fluctuations. With the current trend to up-scaling the size and rating of AWE systems, the difference between peak and rated power might further increase and, consequently, exacerbate the under-utilization of components. With further development and adoption, the hydraulic pump/motor and the RVT could scale better in terms of cost than the generator because of their relatively simpler construction. In such cases, the electrical system becomes less economical and a hydraulic or the mechanical concept could gain the edge – even considering the higher risks.

Acknowledgement
This work is part of the 'NEON' research program and has received funding from the Dutch Research council NWO under the grant agreement No. 17628, and the Interreg NWE project 'MegaAWE'.

References
[1] Ruiterkamp R and Sieberling S 2013 Description and preliminary test results of a six degrees of freedom rigid wing pumping system *Airborne wind energy* ed Ahrens U et al. (Heidelberg: Springer) chapter 26 p 443-58
[2] Williams P, Sieberling S and Ruiterkamp R 2019 Flight test verification of a rigid wing airborne wind energy system *American control conference* (Philadelphia, PA, USA: IEEE)
[3] European network of transmission system operators *https://www.entsoe.eu/* (Accessed on 10/12/2021)
[4] Netherlands electricity grid code *https://wetten.overheid.nl/BWBR0037940/2021-07-03* (accessed on 06/09/2021)
[5] European commission regulation *https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32016R0631* (accessed on 06/09/2021)
[6] Vrana T K, Attya A, Trilla L 2021 Future-oriented generic grid code regarding wind power plants in Europe *Int. J. of electrical power and energy Systems* **125**
[7] Ampyx power *https://www.ampyxpower.com/* (accessed on 06/08/2021)
[8] Bourgault F, Todd D, Beatch J, Kheiri M, Damron L, Nasrabad V S 2017 *Airborne wind energy conf.* p 81
[9] Mazaro Transmissions for energy, emission and cost savings *https://www.mazaro.eu/en/pioneering-transmission-technology* (accessed on 25/11/2021)
[10] Rueb C and Tueteberg M 2021 Personal communication–technical support *DC-IH/STS1 Bosch Rexroth*
[11] National oilwell varco Powerblade kinetic energy recovery system *https://www.nov.com/-/media/nov/files/products/rig/rig-equipment/power-systems/powerblade-kinetic-energy-recovery-system-spec-sheet.pdf* (accessed on 25/11/2021)
[12] Beacon power Flywheel energy storage systems *https://beaconpower.com/* (accessed on 25/11/2021)
[13] Catapult offshore renewable energy Wind farm costs *https://guidetoanoffshorewindfarm.com/wind-farm-costs* (accessed on 25/11/2021)
[14] Sabihuddin S, Kiprakis A E and Mueller M 2015 A numerical and graphical review of energy storage technologies *energies* **8** 172-216
[15] Zhao H, Wu Q, Hu S, Xu H and Ramussen C 2015 Review of energy storage system for wind power integration support *Applied Energy* **137** 545-53
[16] Mongird K, Fotedar V,Viswanathan V, Koritarov V,Balducci P, Hadjerioua B and Alam J 2019 *Energy storage technology and cost characterization report* U.S Department of energy
[17] Quiroga J L, Newell B, Krishnamurthy M, Mancera A G and Bravo J G 2020 Energy effciency comparison of hydraulic accumulators and ultracapacitors *energies* **13** 1632
[18] Georgious R, Refaat R, Garcia J and Daound A 2021 A Review on energy storage systems in microgrids electronics **10** 2134