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Citation for the original published paper (version of record):
Bricker, J., Nilsson, H., Storli, P. et al (2023). Grid-scale pumped hydro energy storage for the low countries. Hydrolink Magazine, 2: 16-20

Grid-scale pumped hydro energy storage for the low countries

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Penetration of intermittent renewable energy sources into the power grid requires large-scale energy storage to ensure grid stability. Pumped Hydro Energy Storage (PHES) is among the most mature, environmentally friendly, and economical energy storage technologies, but has traditionally only been feasible at sites with large natural topographic gradients. ALPHEUS addresses this by developing reversible pump-turbines efficient at low heads, that operate between an enclosed inner basin (that functions as the upper or lower reservoir) and a shallow sea or lake.

In a global effort to reduce greenhouse gas emissions, renewables are now the second biggest contributor to the world-wide electricity mix, claiming a total share of 29% in 2020. Although hydropower takes the largest share within that mix of renewables, solar photovoltaics and wind generation have experienced steep average annual growth rates of 36.5% and 23%, respectively, since 1990. This trend towards an increase in intermittent generation, coupled with a reduction in spinning reserves, could undermine grid stability. To counteract these effects, grid-scale deployment of energy storage is indispensable[3].

Integration of renewable energy sources into power grids worldwide has led to a need for storage on multiple timescales to balance electricity supply with demand. Among the various types of energy storage in existence (batteries, compressed air, flywheels, molten salt, etc.), pumped hydro energy storage (PHES) is the most mature, and therefore accounts for about 90% of utility-scale energy storage globally[1], has among the highest energy storage on investment, and incurs the lowest energy capital cost[4].

PHES has several advantages, yet large head differences between reservoirs are typically required, rendering countries with lowland topography unsuitable. A competing technology, lithium-ion batteries have made rapid progress toward higher efficiency and lower initial costs, but their lifetime is much shorter and carbon footprint greater than PHES. For example, the Energy Storage on Investment (ESOI), which represents the ratio of total energy stored over a battery's lifetime to the energy required to fabricate the battery, is 32 for a lithium-ion battery, but over 700 for a PHES facility. Similarly, it has been shown[4] that the Energy Capital Cost (ECC) distributed over the lifetime of a lithium-ion battery ranges from \$7.5-\$104 per kWh-cycle, while the cost of PHES is \$0.02-\$1.5 per kWh-cycle, and the total ECC of Li-Ion is \$600-\$3,800/kWh, compared to PHES at \$5-\$100/kWh. The sustainability of PHES is due to its long lifetime (hundreds of years for the civil structures involved, compared to 10-20 years for battery systems) and the recyclability of materials involved (primarily steel and copper for electromechanical components, as opposed to the rare, depletable, and geopolitically sensitive materials needed for batteries).

Further advantages of PHES include suitability for long-term storage –since the only storage losses are seepage and evaporation– and quick availability due to short switch-on and switch-off times. With these factors ensuring a significant share within a heterogeneous pool of storage technologies, one major disadvantage of PHES has historically been its topographic constraints; non-mountainous regions are not yet developed with PHES to their potential. The Netherlands, Denmark, and other low countries do not have the natural topography needed for PHES, so utility-scale backup supplies here are almost exclusively fossil fuel (gas, coal, oil, or diesel) thermal power plants or HVDC cables connected to mountainous regions (such as the NorNed cable connecting the Netherlands to Norway). Therefore, development of PHES feasible for the low countries would be beneficial for the environment, the economy, and grid stability. Challenges to pumped hydro storage in the low countries include the lack of suitable Reversible Pump-Turbine (RPT) technology that can operate with high efficiency in both pump and turbine modes at low heads, the need for novel civil structures and construction techniques to generate the head difference and storage volume needed, ways to mitigate fish mortality, and unknown response of the greater power grid to such local, distributed energy storage. To solve these issues, ALPHEUS (an acronym for "Augmenting grid stability through Low-head Pumped Hydro Energy Utilization & Storage") is a collaboration of engineers and scientists from four disciplines: mechanical engineering, electrical engineering, civil engineering, and fish ecology. The ALPHEUS project is funded by the European Union's Horizon 2020 program (grant agreement 883553), and coordinated by the Delft University of Technology.

Traditional PHES uses Francis-type RPT's, which are efficient at medium to high heads. Kaplan-type RPT's have been applied for low-head applications, but suffer from low efficiency when pumping. Therefore, ALPHEUS is developing a novel RPT technology for high efficiency at low heads in both pump and turbine modes. In the mechanical engineering component of ALPHEUS, Chalmers University of Technology and Advanced Design Technology Ltd. (ADT) apply Computational Fluid Dynamics (CFD) to design a contra-rotating propeller RPT (CR-RPT). In particular, ADT has employed a 3D inverse design method, built into the TURBOdesign suite, to design both shaft-driven and rim-driven CR-RPTs at both prototype and model scales.

The initial shaft-driven 10 MW prototype design showed a hydraulic efficiency of about 90% at a head of approximately 10 m in both pump and turbine modes. Finite Element Analysis (FEA) was employed to guarantee that the machine can handle applied loads. A multi-objective design optimization procedure using CFD was employed, increasing the hydraulic efficiency of the shaft-driven design in model scale by ~2.6% in pump mode and ~1.1% in turbine mode. Rapid switching between pump and turbine modes may be necessary if the PHES facility is to be used for grid frequency regulation in addition to daily or longer term energy storage. Chalmers University of Technology has performed a thorough optimization study of start-up and shut-down sequences with the aims to minimize loads and maximize the lifetime of the shaft-driven CR-RPT machines[2]. Experimental tests of model-scale contra-rotating and positive displacement RPTs are conducted at Chalmers University of Technology and Technical University Braunschweig, making validation of CFD results possible. In addition, as a complementary technology, the Norwegian University of Science and Technology (NTNU) is developing a positive displacement RPT (similar to a screw or lobe compressor), with the goal of functioning as an RPT with large size but low rotational speed.

Ghent University and Uppsala University combine their expertise from wind energy and hydropower to develop a variable speed power takeoff (PTO) and control system for the pump-turbine concepts. The key aim is to reach a highly dynamic, yet efficient, PTO and control in order to maximize opportunities for grid support. A cascaded proportional integral derivative (PID) control architecture has been developed, which has three control parameters: the first and second runner speeds, and the inlet valve opening. This will be upgraded to a model predictive control architecture, where transient behavior will be predicted in a detailed conduit model to change the control parameters accordingly.

Figure 2 shows the PTO designs for the three different pump-turbine concepts[5]. In all three concepts, double rotor axial-flux permanent magnet synchronous machines (AF-PMSMs) are used. Due to the absence of a stator yoke, these machines with a high diameter-to-length ratio have a high efficiency and high-power density, both of which are indispensable in an energy storage system. To investigate how the dynamic control actions influence the fatigue of the PTO, a methodology using rainflow counting has been established. Finally, to validate the control architectures and AF-PMSM design, a dry-test setup is developed at Ghent University in which the behavior of the turbomachinery is mimicked by two dynamically controlled induction motors.

The ELENIA Institute at Technische Universität Braunschweig deals with the question of integrating the ALPHEUS PHES into the electrical grid. The major issues ELENIA faces are investigations into the electrical behaviour of the PHES in terms of a grid compliant and grid supportive manner. As the systems architecture is based on a full-scale converter coupling of the PTO including innovative turbine concepts, this has potential to contribute to the provision of several Ancillary Services. An appropriate converter control design for an ALPHEUS power plant has been laid out in compliance with all requirements for its operation at the EU power grid.

To investigate the dynamic behaviour of the PHES in particular, a surrogate model in the time-domain has been developed. The model offers the possibility to derive the behaviour of the PHES in an integrative manner. It includes both electrical components of the grid-side inverter (internal calculation and controllers, output filter section and transformer) as well as estimations on the dynamic behaviour of the PTO unit such as the turbine and valve section. All components are scalable to multiple megawatts of nominal power. The simulation is able to perform with small sample times enabling simulations in dynamic time domains. The developed surrogate model of the grid-side inverter therefore is capable of investigating the plant behaviour integratively by including preliminary machine side dynamics, as well as electrical components of the inverter topology itself and the grid connection. Based upon an assessment of the abilities of the plant, future results will enable a determination of the capability of the plant to serve as provider of Ancillary Services which allows evaluation of the response of the interconnected grid and electricity markets to decentralized energy storage in the low countries.

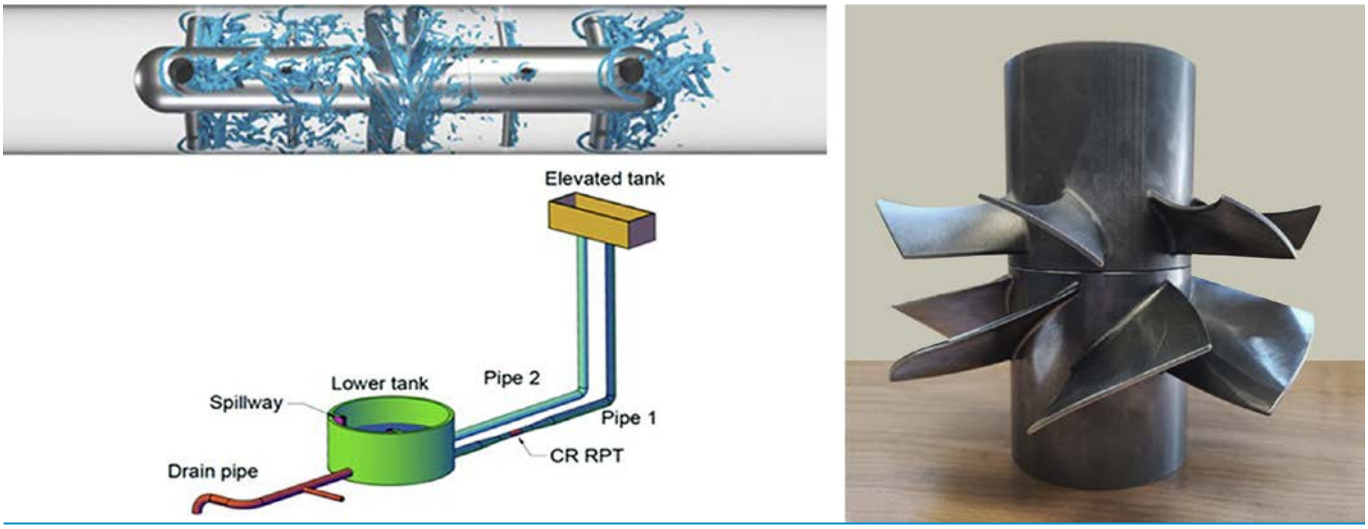

Figure 1 | *(upper left)* CFD of contra-rotating shaft-driven RPT in 30 kW model-scale experimental set-up. Iso-surfaces visualizing vortices in turbine mode. Flow is from left to right. *(lower left)* 3D view of the test setup for validation of the RPT and PD devices. *(Right)* 3D printed runners for the RPT laboratory model.

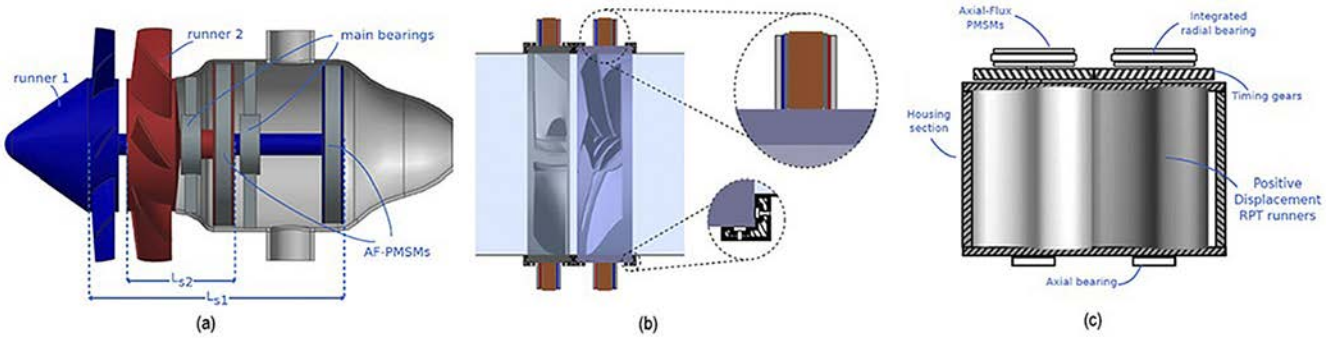

Figure 2 | Power Take-Offs (PTOs) for *a)* 10 MW shaft-driven contra-rotating reversible pump-turbine *b)* a 10 MW rim-driven contra-rotating reversible pump-turbine and *c)* a positive-displacement reversible pump-turbine.

In the civil engineering component of ALPHEUS, the University of Stuttgart, Delft University of Technology, IHE-Delft, Technische Universität Braunschweig, University of Tuscia, and the University of Pau and the Adour Region assess sites along the periphery of the North Sea for application of low head PHES. Conceptual designs of new and retrofit low head PHES basins are drafted, primarily relying on an inner reservoir that is either elevated or drawn down with respect to the sea (**Figure 3**). New structures encompass ring dikes in the North Sea, including Dutch and Belgian ideas such as Plan Lievense and the Princess Elisabeth energy island. Retrofits encompass concepts including the utilization of existing or proposed storm surge barriers or other structures, such as the Delta 21 Valmeer scheme. Comprehensive design of mechanical, electrical, and civil components allows costs of these schemes to be determined, and physical and economic risks assessed. As with all hydropower-related projects, a major concern is fish mortality, so University of Tuscia investigates the effectiveness and limitations of fish-friendly RPT's vs. fish screening technologies.

Figure 3 shows a conceptual design sketch of the dam. The design of the dam under coastal/offshore conditions is most constructible as a caisson structure buttressed by an embankment of fill material, with an underlying clay layer and curtain (not shown) providing waterproofing. The powerhouse structure will be built most efficiently as reinforced concrete structure either onsite using a cofferdam or with prefabricated caissons. Therefore, these methods are investigated in more detail to optimize the construction processes and hence investment costs.

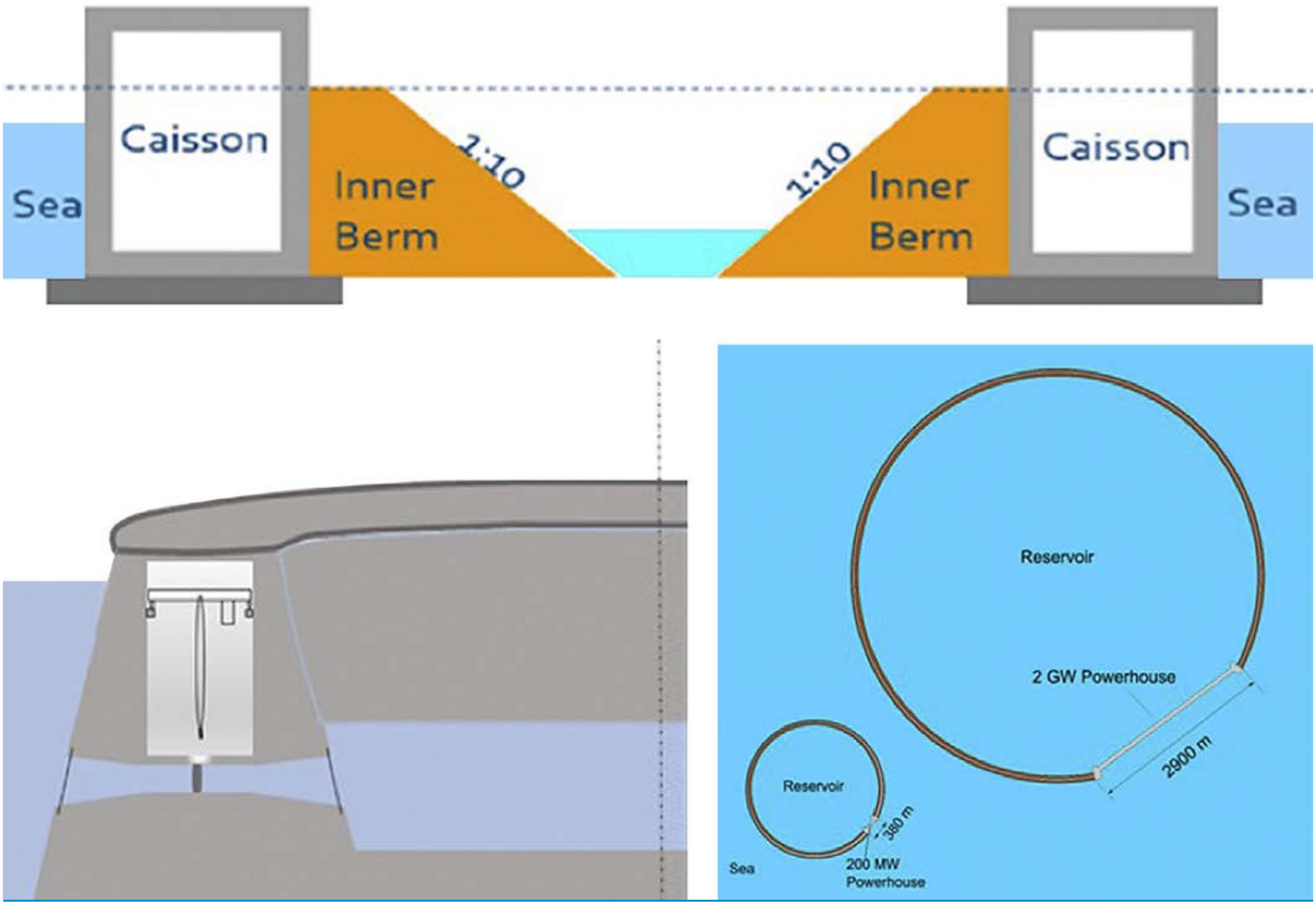

Figure 3 | Conceptual design sketch powerhouse/dam construction. The inner *(lower)* reservoir is pumped down below sea level to store energy, whereas seawater flows back in to generate energy. *(Upper)* Profile view of dam. *(Lower left)* Profile view of caisson powerhouse. *(Lower right)* Plan view of 2 GW and 20 GW capacity basins.

Furthermore, the powerhouse and overall plant design/size are optimized to be most compact. This is validated by operation simulations to optimize the RPT and to minimize material and construction volumes while guaranteeing certain grid services to maximize the revenue of the LH-PHES. In parallel, a risk assessment is performed on potential dam break scenarios and their impact on coastal areas. Fish screens are experimentally evaluated by the University of Tuscia in an outdoor flume at TU Delft to determine the stress on fishes caused by entrainment flows with fish screens indicated by measured hormone levels in fish.

To aid the integration of the various elements of the proposed system and examine its dynamic behavior and performance, a numerical model of the system has been developed in collaboration between TU Delft and Ghent University. It encompasses all relevant dynamic effects associated with the power conduit, the two contra-rotating runners, and the electric machines, while minimizing the computational resources required for simulations. This system model can be employed for a variety of purposes, such as assessing various control strategies, analyzing the impact of individual system components on the system's performance and dynamic behaviour in a potential storage facility, or assessing the system's ability to provide ancillary services to the grid while also determining its limitations.

The efforts of ALPHEUS come together in the construction of a complete 30 kW physical model of both the RPT and the PTO, for each RPT type (contra rotating and positive displacement). These are being tested at model scale under realistic head conditions in the hydraulics laboratory of Technische Universität Braunschweig. The tailored test setup, located at the laboratory of the Leichtweiß-Institute for Hydraulic Engineering and Water Resources, utilizes an elevated water tank whose water surface is at 10 m from the floor of the laboratory. The setup, as depicted in **Figure 1** is able to test both pump and turbine modes for the RPT. Pipe 2 provides water into the cylindrical tank so that the water can be pumped into the elevated tank without having a lowering of the water level within the lower tank. The runner was 3D printed in an aluminum alloy (**Figure 1**). Results from the model test will feed back into the mechanical and electrical engineering components of the project, which aim for the conceptual design of a 10 MW prototype RPT unit (for comparison, 10 MW is the capacity of a large modern wind turbine).

Finally, the ALPHEUS consortium recognizes the critical role that stakeholder communication and feedback play in the acceptance and success of low-head PHES. To this end, a questionnaire was distributed among stakeholders to gather stakeholder attitudes towards a low-head PHES technology and assess if stakeholders would put any redlines for its implementation. A second questionnaire will be distributed at a later stage to anticipate potential policy issues that the low-head PHES technology might face in the possible event of its implementation. Usually, the permitting process delays the implementation of renewable energy technologies and therefore the ALPHEUS project aims to pave the road to future bureaucratic processes prior to raised concerns of the public. To further facilitate stakeholder engagement, the ALPHEUS consortium is also organizing two stakeholder meetings. The first meeting has been held in March 2023, will have been involved the dissemination of the ALPHEUS project's work, a panel discussion between professionals, and audience participation. A following stakeholder meeting will be organized by the end of the project to disseminate the findings of the consortium.

Along the way, ALPHEUS is being monitored and kept on a useful track by an external expert advisory board consisting of Geisseler Law, EDF, The Blue Cluster, Tennet, HydroCoop, Rainpower, Artelia Group, and Prof. Anton Schleiss (EPFL/ ETIP HYDROPOWER). The completed model-scale RPT validation, together with the prototype-scale design, aims to bring low head PHES to a technical readiness level appropriate for prototype construction and grid connection. With the increasing penetration of intermittent renewable energy sources in the grid, such storage will benefit grid stability and security, as well as the economy and environment of the low countries.

Acknowledgement

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 883553.

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